Response to reviewer #1

We received another reviewer's comments on this manuscript, and extra modifications were made. Therefore, this version of response letter has some differences compared with the previously uploaded one, but your valuable suggestions were respected and the revisions were made according to your general and specific comments. Please take this version as the final confirmation. We are sorry for the inconvenience.

General comment:

This paper compares the FY-4A/AGRI 0.65-um visible reflectance (O) with the model simulations generated from CMA-MESO forecasts using the RTTOV (B). The potential sources contributing to the differences between O and B, such as the unresolved aerosol processes, the ice scattering models, are analyzed.

The paper is relevant to the cloud remote sensing field, as the growing international fleet of next-generation geostationary imagers can be expected to aid in our understanding of the diurnal cycles of clouds and aerosols. Well understood and characterized the biases of their observations will therefore be well received by the community. However, the authors make what I think are several unsubstantiated assertions (see my detailed comments). I recommend major revisions before reconsidering for publication. My general and specific comments are below.

Our response:

The authors thank the anonymous reviewer for the constructive comments. We made major revisions to the manuscript, including the evaluation of the forecasts of CMA-MESO, discussions on the spatial and seasonal variations of the O-B biases, corrections on some typo errors (e.g., abbreviations, inappropriate usage of "evaluation", etc.). As a result, the outline of the manuscript was changed compared with the initial version. Some of the revisions were made according to your valuable comments. Some were made according to the comments of another reviewer. The point-by-point response to the reviewer's comments were provided below.

General Comment 1:

A comparison with the model simulations cannot be called an "evaluation", especially when the model simulations are not as accurate as expected. Currently, the RTTOV forward-operator for clouds and/or within the visible and shortwave infrared spectral ranges is still questionable, and the forecasts from CMA-MESO also lack adequate evaluations.

Our response:

Thank you for pointing this out. It is true that the reflectance simulated from the forecasts of CMA-MESO model using RTTOV cannot represent the true reflectance due to the deficiencies of the CMA-MESO and RTTOV models. Therefore, the title of this manuscript was changed to "Exploring the characteristics of FY-4A/AGRI visible reflectance using the CMA-MESO forecasts and its implications to data assimilation". (L1-2)

General Comment 2:

As (1), if the authors persist in characterizing the biases of AGRI reflectance observations by comparing with the model simulations, the performances of RTTOV forward-operator and the forecasts from CMA-MESO should be evaluated first.

Our response:

We agree with you that the evaluation of the CMA-MESO model and the RTTOV-DOM forward operator is necessary when addressing the O (FY-4A/AGRI visible reflectance) - B (model simulations generated from CMA-MESO forecasts using the RTTOV) differences. Accordingly, two major revisions were made.

(1) Evaluation of the forecasts of CMA-MESO (L195-227)

Firstly, the one-hour accumulated precipitation was compared with the observations provided by the multi-source observed precipitation products in Chinese mainland. Good agreement between the simulations and observations was revealed, except that the precipitation areas were overestimated by the CMA-MESO forecasts in Chinese mainland. In addition, the precipitation was overestimated by the CMA-MESO forecasts. The evaluation results suggest that despite general agreement between the observations and simulations were revealed, the CMA-MESO forecasts suffer from deficiencies especially over complex terrain areas.

Secondly, the Probability density Distribution Functions (PDFs) of one-month Brightness Temperature (BT) for the FY-4A/AGRI channel 13 (10.30 μm – 11.30 μm) observations and simulations was analyzed. The results were shown in Fig. 4. The PDF was underestimated at the high-BT end. In contrast, it was overestimated at the low-BT end. Since channel 13 is an infrared window channel, BT in cloudy areas is directly related to cloud top height. Therefore, the PDF analysis implies that high-level clouds were underestimated by CMA-MESO whereas low-level clouds were overestimated. The evaluation suggested deficiencies of the CMA-MESO model in forecasting high-level clouds.

(2) Discussions on the uncertainties of RTTOV (L66-80, L341-385)

We feel helpless to evaluate the performance of the RTTOV model. The largest challenge comes from a lack of accurate observation of reflectance corresponding to the real atmosphere state variables. Therefore, instead of evaluating the performance of RTTOV by comprehensive observations, the performance of RTTOV and the uncertainties of the forward operator were discussed in the revised manuscript.

RTTOV was widely used to generate synthetic visible images. The synthetic images were further compared with satellite observed visible images to better understand the observation errors and representativeness errors and to provide guidance for the improvements of NWP models and forward operators. To save computational cost, a method for fast satellite image synthesis (MFASIS) was developed based on a lookup table (LUT) computed with one-dimensional (1D) solver of RTTOV in rotated Cartesian coordinates to account for some three-dimensional (3D) radiative effects (Scheck et al., 2016; Scheck et al., 2018). Intercomparison of satellite visible reflectance and the equivalents derived from NWP models and MFASIS indicated generally good agreement, and the Bidirectional Reflectance Distribution Function (BRDF) of land surface derived from a monthly mean atlas generated reasonable results in cloud-free conditions (Lopez and Matricardi, 2022). Data assimilation of satellite visible reflectance data based on the MFASIS suggested positive impacts in real-world cases (Scheck et al., 2020). Since March 2023, satellite visible reflectance data have been operationally assimilated in German Weather Service by using the MFASIS forward operator. Although most of the studies are based on the MFASIS solver, the error estimates derived for MFASIS present upper bounds for RTTOV-DOM since the latter is just an emulator for the latter used in this study. Therefore, it is expected that RTTOV could generate reliable visible images if the NWP models were well tuned and the configurations of RTTOV were optimized.

However, knowledge on the cloud optical properties is scarce, which may introduce some uncertainties to the simulated reflectance. For example, the pre-assumed cloud particle size distribution (PSD) inherent in the cloud schemes in RTTOV is inconsistent with that of NWP models, not to mention the representativeness of the pre-assumed PSD in real cases. To illustrate this problem, a sensitivity study was performed by RTTOV configured with two different ice schemes, i.e., the Baum and Baran schemes. Distinct differences were revealed for the simulated reflectance, which confirms the uncertainties in the cloud optical properties of the RTTOV model.

According to the evaluation of the forecasts of CMA-MESO and discussions on the uncertainties of RTTOV, B derived from the CMA-MESO+RTTOV similations will enviably suffer from errors. Therefore, we have to admit that the O-B method is a measure of last resort due to a lack of sufficient reference observations for comparing with the satellite observations. Whether the bias correction brings benefits to the numerical weather prediction should be tested by data assimilation in real-world whether systems and should be evaluated by comprehensive observations.

General Comment 3:

The bias characteristics are not well analyzed. (1) How about the spatial distributions or seasonal variations of AGRI biases? (2) Do they have differences before and after the FY-4A satellite's U–turn at the vernal and autumnal equinoxes?

Our response:

(1) Spatiotemporal variation of the O-B biases (L228-261)

To better characterizing the spatiotemporal variation of the O-B biases, extra simulations were performed for March, June, and December. We did not perform the simulations for the whole 2020 year mainly because the radiative transfer simulation is rather computationally expensive. On our linux cluster which is equipped with 2.20 GHz Xeon Silver 4214 CPU, it will take approximately 30 min ~ 1 hour (32 CPUs for parallel computation) for the RTTOV-DOM (V12.3) to generate a synthetic visible imagery which includes 2501×1671 pixels (the CMA-MESO grids). We think the results for March, June, September, and December could reveal some seasonal variation characteristics of the O-B biases.

For the spatial distribution of O-B biases, systematic biases were revealed over the Southern foothills of the Himalayas, the Sichuan basin, and the Yunnan-Kweichow Plateau, both in September (Fig. 5, L255) and in other months (Fig. S2 in the supplementary material). On one hand, some areas of the Qinghai-Tibet Plateau were covered with snow. Reflectance simulated in these areas should be less accurate compared with other places since the BRDF atlas is questionable in snow-covered areas (Ji et al., 2022). On the other hand, the performance of the CMA-MESO model was reduced over complex terrain areas. The analysis of the spatial distribution of O-B biases suggested that the snow-covered areas and complex terrain areas should be excluded in the following analysis, mainly because that it is clear that one cannot get reasonable results in these areas.

Based on the four-month simulations over the CMA-MESO domain, the spatial (Fig. 5 for the September (L255) and Fig. S2 for March, June and December in the supplementary material) and temporal (Fig. 7 for the September (L331) and Fig. S3-Fig. S5 for March, June and December in the supplementary material) variation characteristics of the O-B biases were explored. The results indicate different spatiotemporal variations of the O-B biases for the four months, which is closely related to the spatiotemporal of the performance of the CMA-MEOS model, the variation of aerosol properties, etc.

(2) Characteristics during U–turn at the vernal and autumnal equinoxes (Fig. 7 in the revised manuscript (L331) and Fig. S3 in supplementary material)

In the Northern Hemisphere, the vernal and autumnal equinoxes falls about 20 March and September 22 or 23, respectively. During this period of time, the Sun crosses the celestial equator, leading to changes in the sun-satellite geometries. Checking through the time series of the O-B biases in March and September, we see no differences during these two days or around when compared with other dates. Therefore, a tentative conclusion could be drawn that the temporal variations of the O-B biases do not have differences before and after the FY-4A satellite's U–turn at the vernal and autumnal equinoxes.

Nevertheless, we found an interesting phenomenon for the temporal variation of the O-B biased in June. An abrupt change was revealed on June 21th (Fig. S4(b)). The abrupt change was caused by the annular solar eclipse on 06:00 UTC 21 June 2020, when the incoming solar radiance was sheltered by the moon over the west parts of the CMA-MESO domain. The annular solar eclipse caused an abrupt decrease of the photons received by the AGRI visible channel. As a result, the visible image was darkened. The darkened visible image was also revealed by the National Aeronautics and Space Administration (NASA) worldview project (https://worldview.earthdata.nasa.gov/). However, the annular solar eclipse was not considered when performing the radiative transfer simulations by RTTOV-DOM. Instead, the incoming solar irradiance was set to a constant, which caused an abrupt decrease of the O-B biased. (L324-330)

Specific Comment 1:

Lines 16, 22, 33 and 72: The abbreviations (FY, TOVS, and so on) should be given full name when first appeared in the abstract and text.

Our response:

The abbreviations were checked throughout the revised manuscript, and the full names were given the first time they appeared in the abstract and text. E.g., FY is the abbreviation of "Fengyun" (L17, L35), and RTTOV is the abbreviation of Radiative Transfer for the Television infrared observation satellite Operational Vertical Sounder, etc. (L67-68, etc.)

Specific Comment 2:

Line 85: Himawari-8 satellite should be introduced because not all readers know it is the first one of the Japanese next-generation geostationary satellite.

Our response:

Corrected. (L135-136)

Specific Comment 3:

Line 82: How about the spatial coverage of CMA-MESO, or the region of interest in this study?

Our response:

In the revised manuscript, the spatial coverage of CMA-MESO was shown by Fig. 1, which is also the region of interest in this study. (L114-116)

Specific Comment 4:

Lines 96 and 117? Here, the authors give two cloud mask definitions. Which one will be used for Tables 1 and 2?

Our response:

We are sorry for not making it clear here. In the original manuscript, two cloud masks are defined for the synthetic images (observations, O) and observed images (simulations, B) separately. For the observed images, cloud masks were directly derived from the cloud mask products. For the synthetic imageries, cloud masks were dragonized from the CWP with a threshold value of 0.01 kg m^{-2}. For spatiotemporally collocated observations and simulations, the O-B biases were calculated for the pixels which are designated to be cloudy and cloud-free for both O and B. The O-B biases for the cloudy and cloud-free pixels were further used to correct the systematic biases of the corresponding scenarios separately.

According to another reviewer's comment, different definitions of cloud mask for observations and simulations could introduce mismatch of cloudy or cloud-free scenarios in the observed and simulated visible images. Therefore, an equivalent criterion of cloud mask for observed and simulated images was introduced to the revised manuscript. In the revised manuscript, cloud mask was determined by comparing the simulated and observed reflectance with the reflectance simulated by ignoring cloud impacts. (L278-303)

For the synthetic visible image, a pixel was designated to be cloudy if the simulated reflectance r_{sim} satisfies Equation (4). Otherwise, the pixel would be classified to be cloud-free.

$$r_{sim} > r_{sim,clear} \tag{4}$$

where $r_{sim,clear}$ denotes the simulated reflectance when cloud contributions were ignored.

The aerosol contributions were neglected by the simulations since the CMA-MESO forecasts do not provide aerosol information explicitly, whereas the observed reflectance inevitably includes aerosol contributions. Considering the aerosol contributions to the reflectance, a pixel is assumed to be cloudy if the observed reflectance r_{obs} satisfies Equation (5),

$$r_{obs} > r_{sim,clear} + r_{aer}^{75} \tag{5}$$

where r_{aer}^{75} denotes the aerosol contributions to the reflectance of cloud-free pixels, which was set to the upper quartile of $r_{obs,clear} - r_{sim,clear}$ for the preliminarily estimated cloud-free pixels. $r_{obs,clear}$ denotes the observed reflectance for cloud-free pixels, which were preliminarily determined by the FY-4A CLM product. The second-step estimate of cloud-free pixels was determined Equation (6),

$$r_{obs} < r_{sim,clear} + r_{aer}^{25} \tag{6}$$

where r_{aer}^{25} denotes the aerosol contributions to the cloud-free reflectance. Similarly, r_{aer}^{25} was set to the lower quartile of $r_{obs,clear} - r_{sim,clear}$ for the preliminarily estimated cloud-free pixels. The two-step estimate of cloud mask for observed images was performed to maintain equivalent criterion of the cloud mask for synthetic images. It is noted that the first-step estimate of cloud mask should have different representativeness compared with the cloud mask diagnosed from Equation (4). For example, the CLM cloud mask was generated by including extra infrared observations (Wang et al., 2019) that are much more sensitive to optically thin cloud, which may appear to be transparent in the visible band. Nevertheless, the quartile estimation should mitigate the impacts. On one hand, thin clouds which are transparent in the visible channel whereas are opaque in the infrared channels should contribute insignificant part to r_{obs}. On the other hand, the quartile estimation in Equations (4) and (5) discarded 25% samples in estimating the lower and upper quartiles of $r_{obs,clear} - r_{sim,clear}$.

Specific Comment 5:

Lines 201-203: I can't understand this sentence. Aren't the "microphysical properties therein" "cloud variables"?

Our response:

We were intended to say that "Compared with the infrared and microwave radiance observations, the visible reflectance is much more sensitive to cloud variables, regardless of the type of cloud hydrometeors or the vertical location of clouds. In contrast, the infrared radiance data are only sensitive to cloud-top properties due to strong absorption effects (Li et al., 2022)". This part was revised in the revised manuscript (L422-424)

Specific Comment 6:

Figure 6: Readers can hardly identify the differences between observed and model simulated reflectance. The authors are suggested using a different colormap or adding figures to show their differences.

Our response:

Thanks for pointing this out. Since O-B is positively biased for the selected cases, reflectance of the bias-corrected visible image should be reduced by a factor of γ, which denotes the bias correction coefficient (Equation (4), L435). The bias-corrected visible image remains general characteristics of the original manuscript. As a result, the contour maps of the original image and bias-corrected image would be rather similar, except that the bias-corrected image was slightly darker than the original one. Therefore, it is difficult to differentiate the original and bias-corrected visible images in contour maps, and the contour maps in the original manuscript were deleted in the revised manuscript.

Instead of presenting the results by contour maps, the O-B biases with and without bias correction were summarized in Table 1 (based on deterministic forecasts) and Table 2 (based on ensemble forecasts). The results should be shown in a clearer way in the revised manuscript. (L454-458)