1 Reply to Referee 1

We thank the referee for the very accurate feedback and comments, which helped to revise our work and will improve its presentation.

During the revision process, thanks to the first comment, we found an error in the procedure used to select the clear-sky nadir-looking IASI pixels. Although the error did not significantly affect the results of the study, Figures 3,5 and 6 of the paper will be updated as a result of this error correction. The updated figures are also contained in this document (Figure 8 at the end of the document and Figures 5, 6).

2 Major Comments

Below, the answers to the four major comments of the reviewer :

1. The selection of the clear-sky areas to analyse goes through a series of steps and eventually a set of clear sky spectra are obtained from the dataset of simulated radiances. Would it be possible to show a map with the regional density of pixels surviving the selection, to help identify which regions are most contributing to the analysis? For example, are the pixels used to create figure 3 distributed homogeneously or with a higher density somewhere? Or the analysis is robust enough to any regional bias?

   We agree with the reviewer that the spatial distribution of the measurements used to build the statistics is a useful information that may have an impact on the measured biases.

   The selection process of simulated and measured spectra that contribute to the presented statistics goes through the following steps.

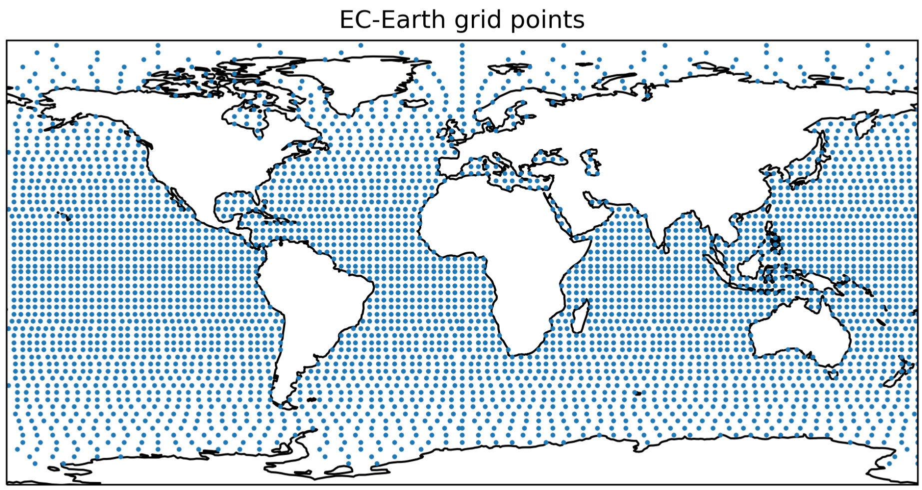


Figure 1: The dots indicate the center of the ECE model cells for which a spectral radiance is simulated.

Simulated spectra. To save computing time, ECE simulates spectra in correspondence of only once every 4 latitude x longitude grid cells. The dimension of model cells is 0.7×0.7°. The actual model cells for which spectra are simulated are shown in Figure 1. For each of these cells, we compute the monthly average radiance using only the simulated spectra with local solar time between 6 and 12 hours, only if the current cloud cover of the model cell is less than 30 %. We then compute the monthly zonal averages by averaging the monthly mean radiances relating to the model cells within the considered latitude belt. With this procedure all model cells contribute to the zonal mean with equal weight.

Measured spectra. IASI measured spectra are selected from 2°x2° cells centered on the ECE model cells for which spectra are simulated. On the one hand, the dimension of these cells is large enough to allow the selection of a sufficiently large number of IASI spectra. On the other hand, these cells do not overlap each other, thus each IASI measurement contributes only once to the statistics. For each of these cells, we compute the monthly average radiance using IASI measured spectra that meet the following conditions:

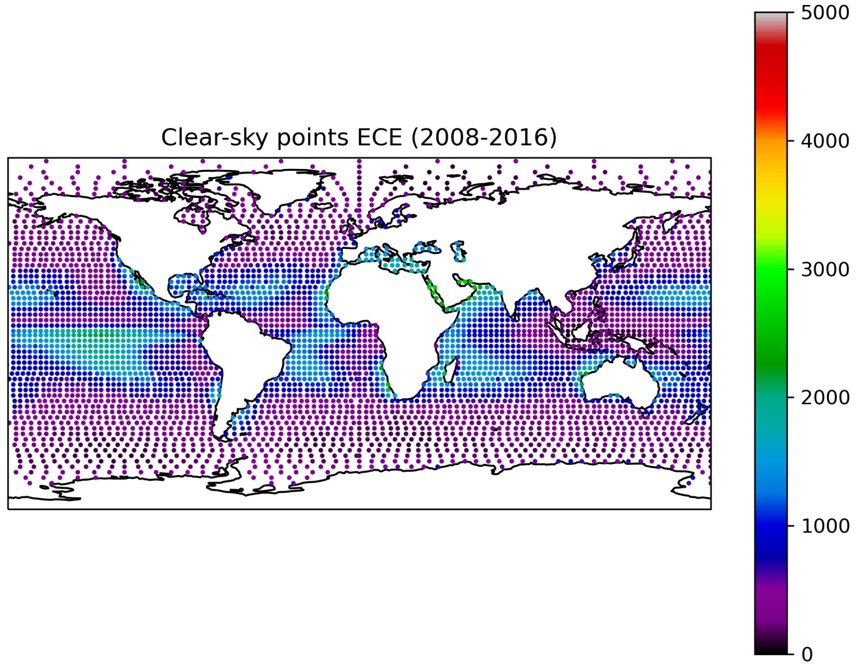
- The radiance is measured in day-time, in the near-nadir geometry, over the ocean, and corresponds to clear-sky conditions (cloud mask of AVHRR = 0).
- The measured radiance falls into a CERES grid cell, measured within 3 hours from the IASI observation time, with cloud cover less than 30 %. Since CERES grid cells have a dimension of 1x1 degree, similar to the ECE model cells, we apply the same threshold to the cloud cover in the CERES cells.

Finally, we compute the monthly zonal averages of observed radiances by averaging the monthly means obtained at the 2°x2° cells falling within the selected latitude belt.

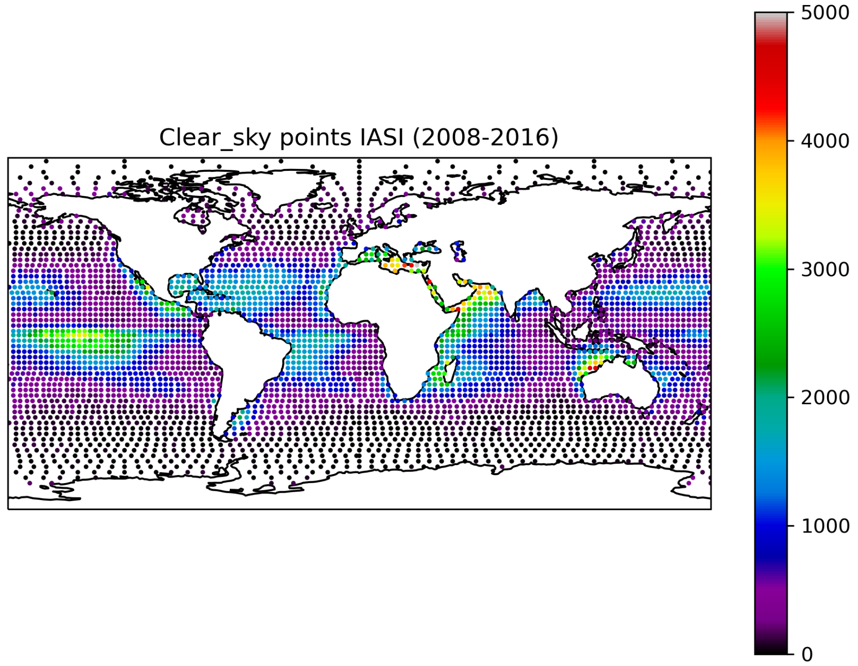
The top and bottom panels of Fig. 2 show, respectively, the number of simulated and measured spectra that meet the above specified conditions, in the time interval from 2008 to 2016. The number of selected spectra is not homogeneously distributed across the globe. Most of the selected spectra are located in the subtropics ([15-30 N] and [15-30 S]), corresponding to the descending branch of the Hadley Cell. The pattern of the number of simulated and measured spectra that are selected, and thus contribute to cell- averages, is very similar in the tropical and sub-tropical regions, giving confidence on the fairness of the comparison method and on the main results of our work.

Note, however, that the filters used particularly affect the mid-latitudes ([45-60 N] and [45-60 S]), where only few IASI pixels survive to the selection process (see plots in Fig 3). The small number of observations meeting the mentioned criteria, together with the cloud cover bias described in Section 3.4 of the paper, could contribute to the bias found in the atmospheric window at these latitudes. This is one of the reasons why the intercomparisons presented in the paper focus on the tropical regions ([-30 S 30 N]), where we have a very large number of both modeled and observed spectra.

In the revised version of the paper we will include more comprehensive explanations on this issue. We also plan to include in a Supplement the plots presented in this reply.

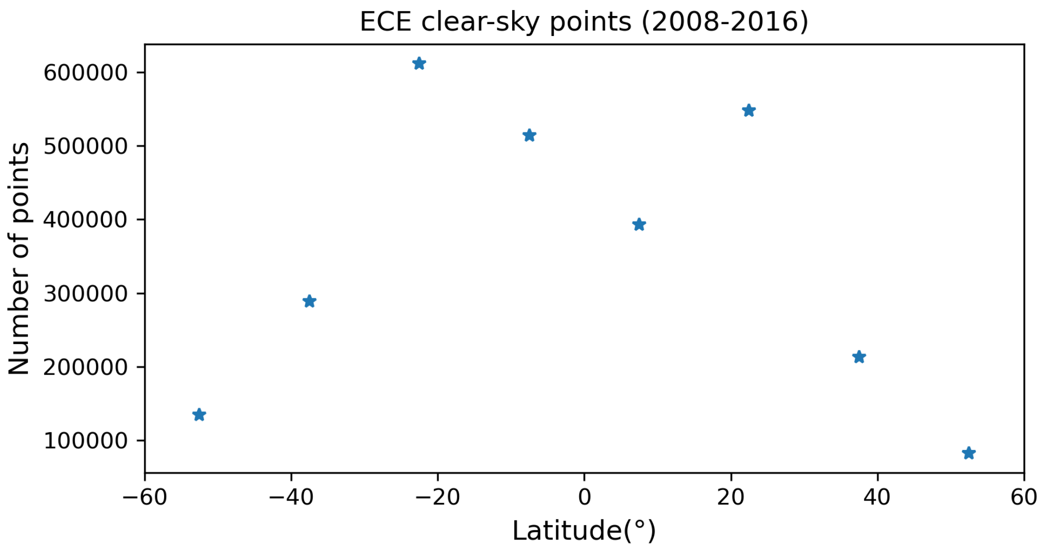


(a)

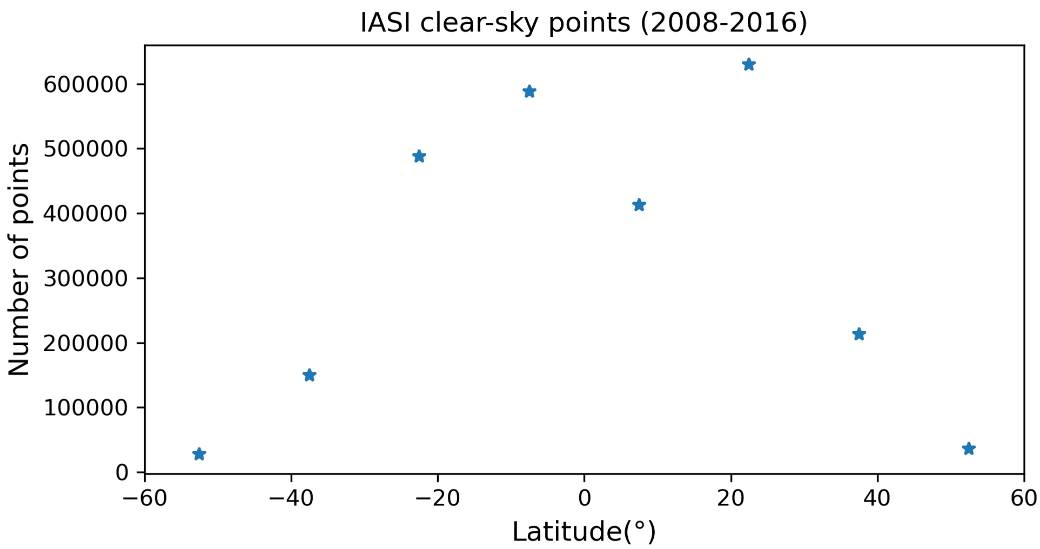


(b)

Figure 2: Number of simulated (top) and observed (bottom) spectral radiances that contribute to the clear-sky statistics presented in the paper, for each lat x long cell.



(a)



(b)

Figure 3: Number of simulated (top) and observed (bottom) spectral radiances that contribute to the clear-sky zonal means presented in the paper.

2. Jacobians in Figure 2 are shown as normalized to the relative maximum. I understand that this is to show qualitatively the spectral sensitivity of the radiance to various parameters, but would it make sense to also show the absolute values somehow (for example in Figure 6)? It would be interesting for example to estimate if the biases in temperature and water vapour concentration shown in figure 8 would indeed reasonably map into the observed radiance/brightness temperature biases discussed for figure 6 and figure 5c

We agree that this information will be useful in the discussion of specific spectral biases.

In this regard, panels A and B of Fig.4 show the absolute values of the jacobians of temperature (A) and water vapour (B). This plot will be added to the supplementary material in the revised manuscript.

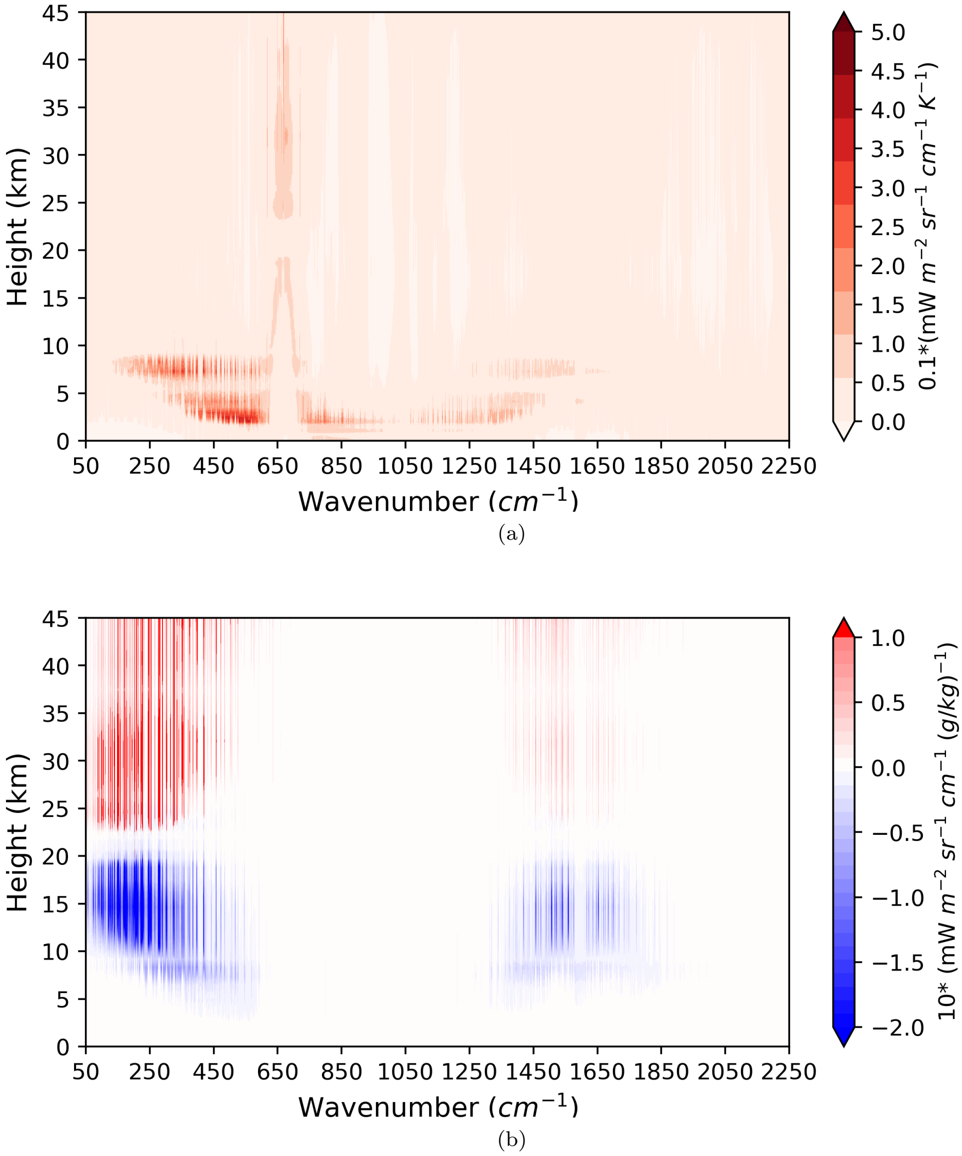


Figure 4: Jacobians of Temperature and Water Vapour

In addition, we will update Figures 5 and 6 of the paper with the new Figures 5 and 6 of this document. These new plots represent the BT of the climate model and IASI in different spectral bands and the absolute values of the jacobians of the temperature and water vapour concentration, in order to highlight the layers of the atmosphere that affect the most the

TOA radiance.

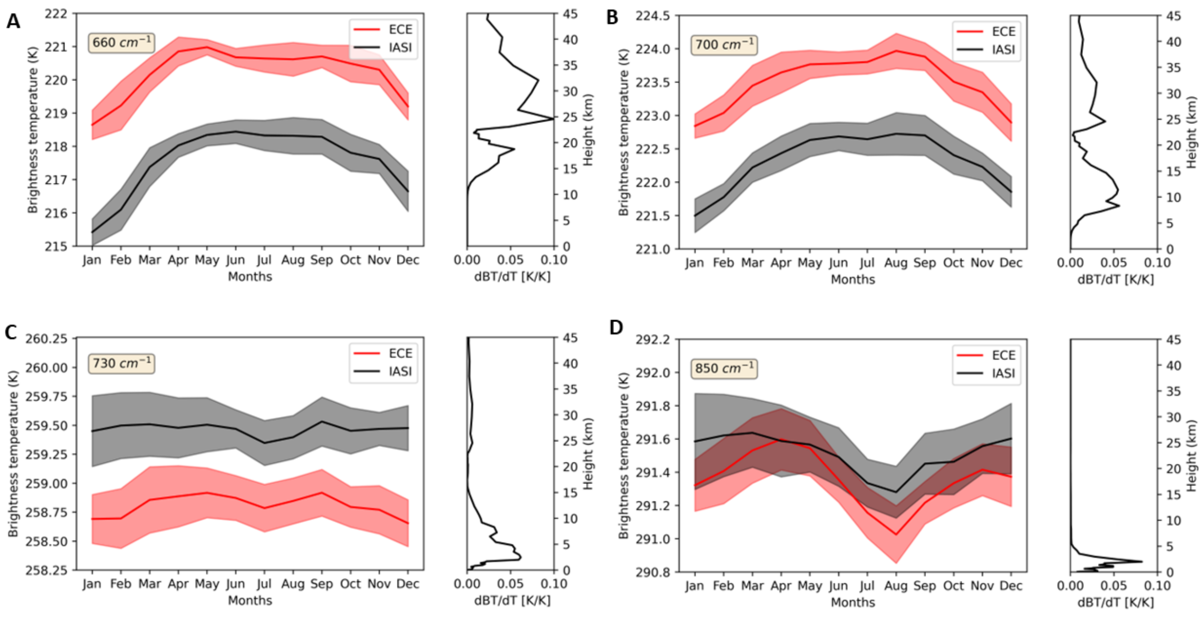


Figure 5: Brightness Temperature (BT) averaged in different spectral intervals and absolute values of temperature jacobians in the respectively spectral bands. This is the new figure 5 of the paper

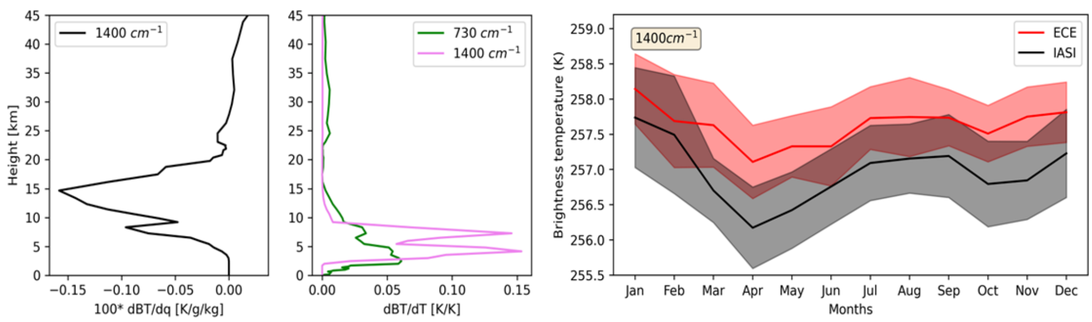


Figure 6: In the panels on the left, the absolute values of water vapour and temperature jacobians at 1400 and 730 cm^{-1}. On the right, the Brightness Temperature (BT) of IASI and ECE at 1400 cm^{-1}. This is the new figure 6 of the paper

In all these plots, to simplify the spectral channels description, we shifted the 10 cm^{-1} spectral bands used. When we indicate a specific wavenumber, we refer to the value of the spectral radiance convolved/averaged in the ± 5 cm^{-1} interval centered about the given wavenumber. For example, when we indicate "700 cm^{-1}", we refer to the spectral radiance convolved/averaged in the range from 695 to 705 cm^{-1}. The presented jacobians are represented in the same intervals.

As suggested, we also provide an estimation of the BT bias inferred from the temperature and water vapour biases obtained from the comparison between the EC-Earth model and ERA5 (Figure 8 of the paper).

First, we computed the mean profile of these temperature and water vapour biases along the tropical latitudes [-30S, 30N]. Then, we performed the scalar product of these profiles with the respective Jacobians, computed from the profiles of a standard tropical atmosphere.

The result of this estimation is summarized in Table 1.

Spectral Channel(cm^{-1})	660	700	730	850	1400
Most sensible region to temperature (km)	[25-45]	[5-15] and [20-35]	[3-10]	[0-5]	[3-10]
Most sensible region to water vapour (km)	–	–	–	–	[5-20]
BT bias - ERA5 (K)	+2.5	+0.8	-0.2	-0.2	+0.7
BT bias - IASI (K)	+3.5	+1.5	-0.8	-0.2	+0.5

Table 1: Inferred BT biases estimated from the comparison between climate model outputs and ERA5 data and from the comparison of climate model and IASI BT climatologies

The result of our analysis provides a stronger positive bias in the stratosphere. This difference also causes a slightly higher BT bias at 700 cm^{-1}.

In addition, we also have a more pronounced negative bias at 730 cm^{-1}, most likely produced by a higher negative temperature bias of the model in the middle troposphere. Finally, the BT biases for the spectral bands at 850 and 1400 cm^{-1} show a very good agreement with the result obtained from the reanalysis.

In both the estimations, the positive BT bias at 1400 cm^{-1} is caused by the negative bias of water vapour concentration in the upper troposphere of the model.

We agree that this result can be interesting for the paper and we will add it to the revised version of the manuscript.

3. Figure 5 panel B shows that EC-Earth has a positive temperature bias in the region 5-15km in the 30S- 30N area as seen in the 700-710 cm-1 spectral region. Yet in the comparison against ERA5 that area shows generally a negative bias up to 15km (positive biases are seen north and south of 30 degrees, above the tropopause). This seems in contradiction to what it is said at line 360 Ch. 3.4

   In the spectral band centered at 700 cm^{-1} we find a positive bias of the BT model with respect to BT measured by IASI. This result seems not to be in agreement with the negative bias highlighted in the comparison with the ERA5 reanalysis.

   However, as explained in line 360 and how visible in Panel B of Fig. 5, it is evident that this spectral region is also affected by stratospheric temperatures, which are positively biased in the model.

   As a result, the strong negative bias at the tropopause (Figure 8), is masked by the positive bias of the stratosphere. In fact, also the BT bias, estimated from the profile of temperature bias of the reanalysis at 700 cm^{-1}, is positive (see Table 1).

   We will stress this aspect in the revised manuscript adding the results of the previous estimation, presented in table 1, and adding the new Figure 5, where the profiles of the jacobians are shown.

4. In the conclusion I'd like to see a clearer discussion of the limitations of the presented method, namely the difficulty of making sure that a meaningful comparison between simulated and measured radiances can be obtained (this is briefly touched in chapter 3.4 regarding sampling biases). The analysis presented in this work does indeed show the advantage of having spectrally resolved OLR computed from the model fields overcoming some of the limitations of retrieval products, but, on the other hand, assumptions and parameterisations are still needed to perform accurate radiative transfer computations. Restricting the analysis to clear-sky ocean areas circumvents the difficulties of a correct simulation of surface radiative properties or the representation of cloud microphysical characteristics whose uncertainties might create larger differences than the model biases one attempts to investigate. Can these shortcomings be somehow mitigated, or is the method really only suited for a limited set of cases?

Thanks for this comment, which deserves some discussion in the paper. In this particular case, we have been working within a simplified framework considering only clear-sky spectra measured and simulated over the Tropical Ocean. However, as shown, the study of the clear sky also involves different problems with the average data distribution. In our case, filters applied to ensure the consistency of the comparisons between model and observation, significantly reduce the number of selected spectra at high latitudes. As a result, reliable results are obtained only limited to the Tropical Oceans.

In contrast, in the all sky analysis we do not have the issues of not homogeneous sampling. In this case, the major problem involves the treatment of clouds in the climate model. Climate models have horizontal grid spacing of tens of kilometers and cloud variability inside a grid cell has to be treated statistically. One possible way consists in decomposing the cell of the model in a set of subcolumns, whose spatial dimension is comparable with the field of view of the instruments. Thus, the radiative computation can be performed over the single subcolumns.

In both cases, to have reliable results, it is necessary to start working under the simplest conditions (clear-sky, ocean, etc.) Once the biases have been investigated for the simplest cases, it can be possible to gradually work in more general conditions.

This can be possible if we exploit and compare the results from other existing procedures (reanalysis, comparison of Level 2 products of instruments).

3 Minor Comments

1. Sect. 1, line 39: "and, thus, to a specific parameter": what is it meant here by parameter? An active model variable such as temperature or concentration of a particular atmospheric constituent or rather a model parameter governing a particular process/parametrisation in the model? I think that it is difficult that a single model parameter, if the latter is intended, would be able to explain a bias in a particular spectral region. Indeed, many of the parameters tuned in EC-Earth to achieve satisfactory radiative fluxes at TOA, affect cloud parametrisations. Please, clarify

   We refer to an active model variable (temperature, concentration of gases, etc.).

2. Sect. 1, line 43: "1970s, but only starting from the 2000s long term. . . ." OK, we will correct it in the new version.

3. Sect. 1, line 56: "In anticipation of FORUM measurements. . . .". This is repeated few time in the document: does it mean here something along the lines of "To demonstrate the potential of the future FORUM measurements"? OK, we will correct it in the new version.

4. Sect. 1, line 65: "MIR" has not been defined while FIR yes. Ok, we will correct it in the new version.

5. Sect 1, line 79: "paves the way for direct assimilation" Not clear here: why the implementation of an online simulator would help in that direction?

   Here we mean that the assimilation process in a model is generally performed trough the assimilation of the radiances. Therefore, the possibility to provide radiances in a climate model, in this case through an online simulator, could help in this direction. However, to avoid confusion, we will remove this sentence from the manuscript because it needs a more accurate explanation.

6. Sect. 2.1.1, line 101: CLOUDSAT is an active radar. ISCCP is not a sensor if it means the International Satellite Cloud Climatology Project. References and full description of the acronym would help here, as done for RTTOV mentioned later, for example. OK, we will correct it in the new version.

7. Sec 2.2.1, line 137: is there a reference for the AVHRR cloud mask? Thanks, we will add the reference.

8. Sec 2.2.2: I think there should be references to the CERES dataset used Thanks, we will add the reference.

9. Sec 3.1, line 197: "partial derivatives of radiance with respect to the most relevant atmospheric parameter". Perhaps a more general definition like "with respect to any relevant atmospheric variable. Here we show the most relevant…" OK, we will correct it in the revised manuscript.

10. Sec 3.3, line 298: The example discussed in this section shows that spectral OLR are indeed useful to provide a complete view of model biases, but it also shows the difficulty to select meaningful area to compare with measurement, thus limiting somehow the possibility to map directly a bias to a parameter in a global model. Perhaps the sentence can be rephrased to reflect this limitation.

    Ok, we will stress this aspect.

11. Sec 3.3, line 330: "witnessed by the negative sign of the water Jacobian" -¿ "as represented by the negative values of the water vapour Jacobian"

    Ok, thank you for the suggestion.

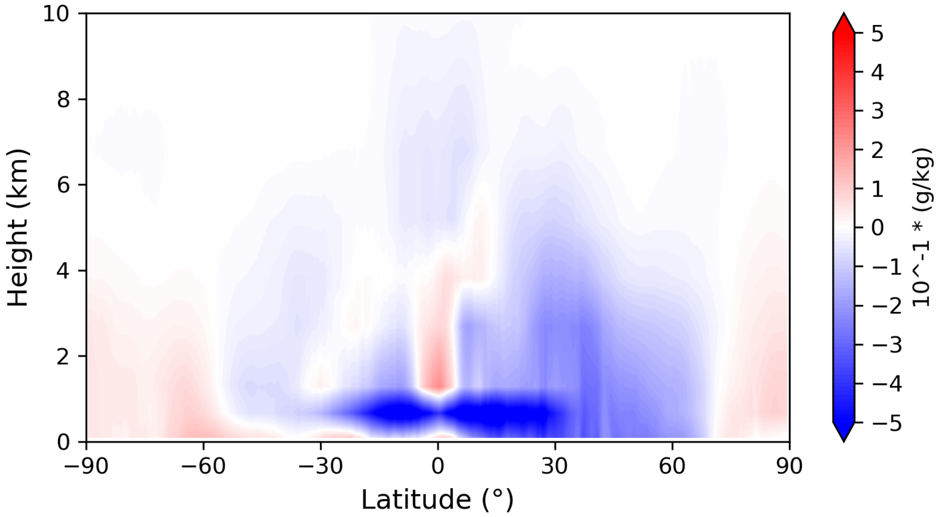
12. Sec 4, line 392: The results are only shown for ocean areas, land biases are not really discussed in depth in the text. Is it worth it reporting it in the conclusions?

    Ok, we agree with you. Thereofre, we will remove the sentences related to the biases over lands since we did not focus on in the paper.

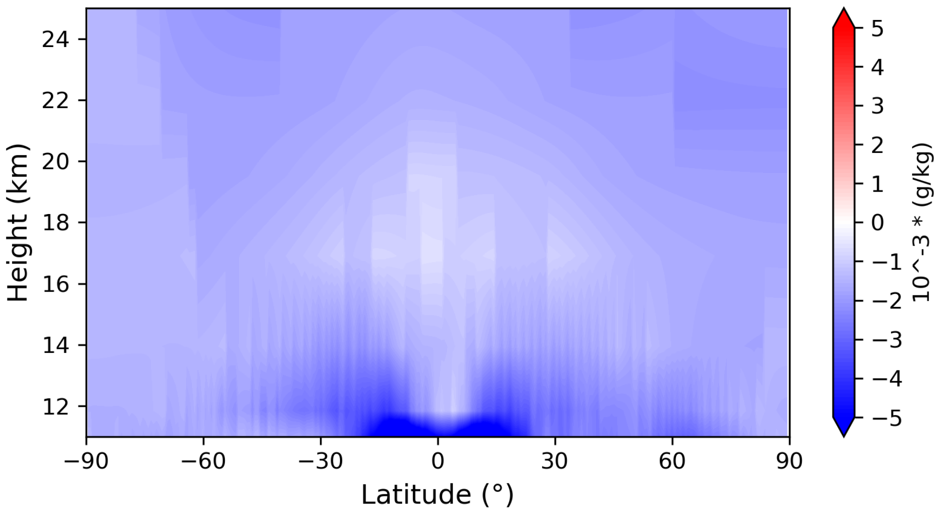
13. The representation of the differences in specific humidity as percentage tends to highlight the stratosphere due to the very low concentration of water vapour there. The absolute differences could perhaps be better related to the absolute value of the Jacobian that could be shown e.g. in Figure 6?

    Figures 7 describe the absolute difference of water vapour concentration between the reanalysis and the ECE model. More information about the possibility to link these differences to the absolute jacobians values are contained in the answer to question 2 of the major comments.

    We will add these figures in the Supplementary material of the revised paper.



(a)



(b)

Figure 7: Absolute difference of humidity concentration between model and ERA5 data in the lower troposphere (a) and in the upper troposphere-lower stratosphere (b)

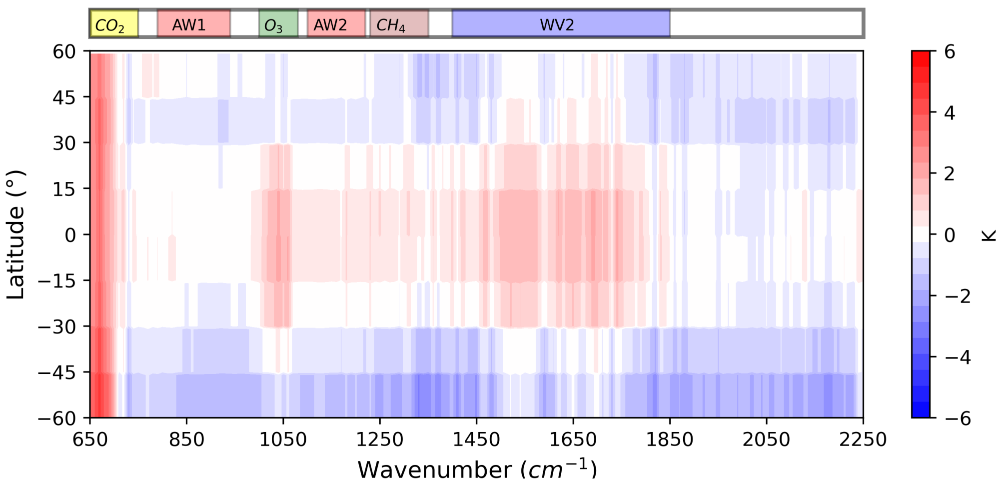


Figure 8: BT difference (model-IASI). New figure 3 of the paper