Dear Referee,
dear Editor,

we would like to thank the referee for the detailed review of our manuscript. In the following the referee's comment/text appears in blue font and our response in black font.
Our detailed reply to Referee 2 might also be of interest for this Referee 3 (both referee have some similar comments).

The paper by Schneider et al. presents an interesting approach to derive tropospheric methane retrievals by synergism of IASI and TROPOMI level 2 products. The presented method is an a posteriori combination of the two level 2 products, using methane total columns from TROPOMI and profiles from IASI. The theoretical basis of the synergism is presented as well as comparisons with in situ measurements and ground-based retrievals. While previous work on fusion or synergism of level 2 products have been done, the present study shows an application of this kind of approach for methane retrievals, including the application and comparison with real data.

However, major revisions are needed in order to make the paper publishable. The present manuscript lacks some key elements to demonstrate the real contribution and validity of the combined retrieval and in some cases of criticism. Moreover, I disagree that the authors demonstrate the equivalency between this combination of level 2 products and a synergism of level 1 measurements. I strongly recommend modifying the manuscript with respect to the following major issues:

1: Performance of the TROPOMI only approach vs the combined product: figure 3, 4 and 5 show that the TROPOMI total column retrievals are more sensitive (between 5 and 15 km), have less contribution of the a priori and less error than the combined product.
How is this possible that the combination degrades the total column retrieval, both in sensitivity and the error? How is it possible that the IASI product does not really provide additional information according to the averaging kernels (except for a small change between 2-3 km of altitude, which is much smaller than the loss above) and it even slightly increase the error? Other synergetic satellite approaches show a very clear gain in total column retrievals, for example in total column degrees of freedom, as compared to single-instrument products. Why in the case of the combined product shown in this paper we do not see such gain and we even remark a small degradation? It is important to clarify the reason for this degradation and clearly indicate it in the manuscript. The manuscript should also point out limitations of the combined approach.

An optimal estimation retrieval updates the a priori knowledge with information provided by a measurement. The a posteriori uncertainty is the uncertainty achieved by optimally combing the a priori knowledge with the measurement. According to Chapter 3.4.2 of Rodgers (2000) this a posteriori knowledge is the sum of the noise covariance matrix and the representativeness error matrix (called smoothing error in Rodgers 2000). The representativeness error matrix can be calculated from the averaging kernel ($\mathbf{A}$) and the a priori knowledge (covariance matrix $\mathbf{S_a^{-1}}$) as: $(\mathbf{I}-\mathbf{A})\mathbf{S_a}(\mathbf{I}-\mathbf{A})^{-T}$. Here $\mathbf{I}$ is the identity matrix. This is a different calculation as the term $(\mathbf{I}-\mathbf{A^l})x_a^l$ shown in Fig. 4 of the manuscript. For the representativeness error $x_a^l$ is replaced by $x-x_a^l$, because we are interested in priori uncertainty, not in the absolute a priori value. Figure 1 shows this representativeness error for the different retrieval products (this figure will replace Fig. 4 of the manuscript). The representativeness error reveals the effect of the additional measurement. Concerning the total column product, IASI has the highest representativeness error. The respective error for TROPOMI is very small and it is further reduced (although only very slightly) for the combined product.

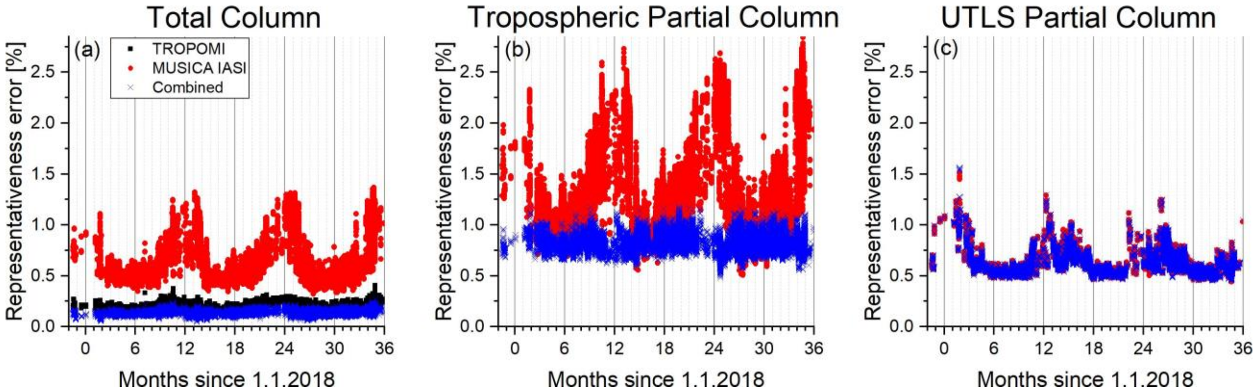



*Figure 1: Representativeness error for the retrieved products. This figure will replace Fig. 4 of the manuscript.*

TROPOMI offers only a column product (degree of freedom for signal, DOFS, ≈1). MUSICA IASI offers a profile product with DOFS of about 1.9 in middle latitudes (less at high latitude and more at low latitudes). It enables some profiling above the boundary layer. If we add the information of TROPOMI to the information provided by IASI we get a DOFS of about 2.5 (see Fig. 2).

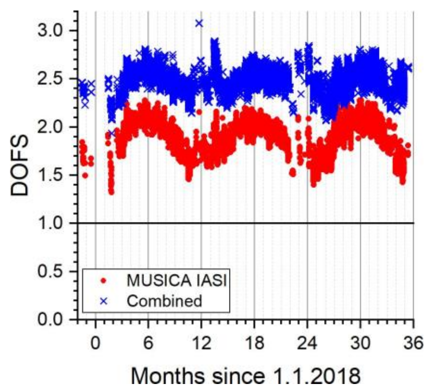



*Figure 2: DOFS values achieved by IASI alone (red dots) and by the combined product (blue crosses). Please note that TROPOMI offers only a total column product and we can assume a DOFS of* ≈1 (indicated as black line).

2: Since the gain of the combination for the total column retrieval is not clear (even a small degradation is seen), what is the actual information provided by IASI measurements? And what would the advantage of the combined product as compared with a profile retrieval using TROPOMI measurements only?

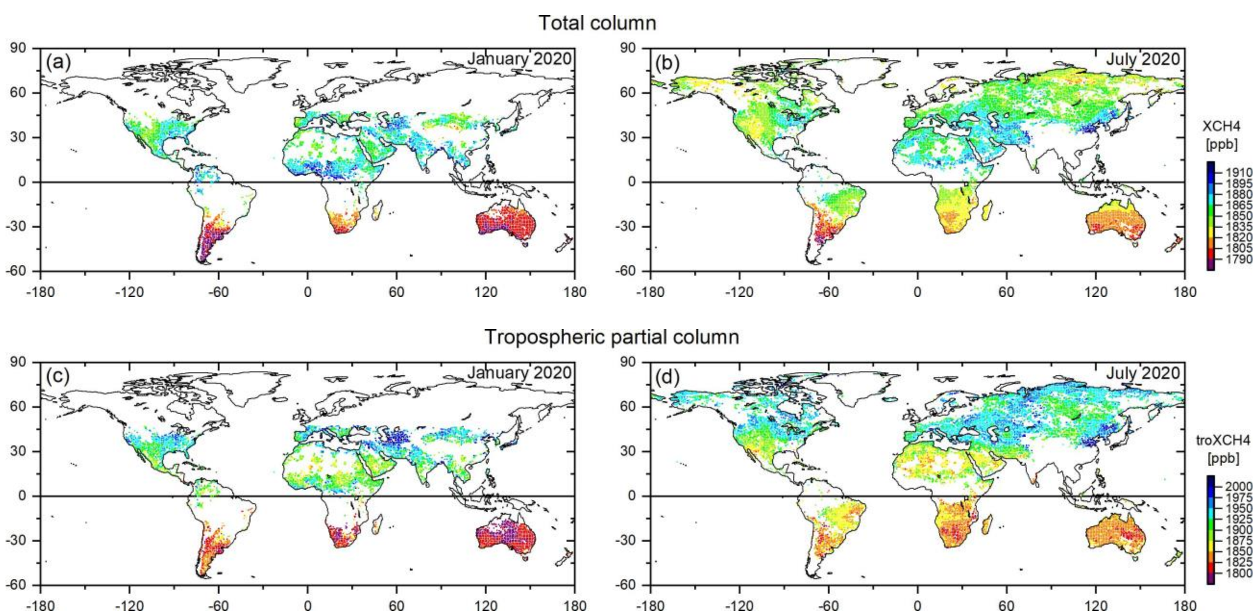
We think that our reply to comment #1 and the respective Figs. 1 and 2 clarify the gain that is achieved by the combination.

3: In Lines 8, 63-64 and 491-492, the authors strongly claim an equivalence between the level 2 combination and a level 1 synergism. I disagree that this statement is demonstrated in the paper. Such a strong statement can not only be based in theoretical estimations of appendix A2, but a practical comparison with real data should be given. The only way to demonstrate it is to fully develop and implement a full synergism of level 1 measurements of TROPOMI and IASI and then compare its performance with that of the a posteriori combination of level 2 products. However, the authors do not show such level 1 synergism product in their paper. I strongly suggest removing these statements, unless such thorough practical demonstration is provided.

We replace this statement. Instead of claiming equivalence we will state that we demonstrate a strong similarity between our method and a combined level 1 processing.
Our method works with the level 2 column products of TROPOMI. This means that we have only the vertically aggregated Jacobian information for TROPOMI available (see discussion in the context of Eq. A13 of our revised Appendix). Furthermore, our method assumes moderate non-linearity, which is a reasonable assumption (see our response to comment #3 of Referee 2). So we can show the mathematical equivalence with a level 1 processing that uses the vertically aggregated Jacobian information of TROPOMI within a linear subspace.

4: Global daily maps: The authors claim their product enables the generation of global daily maps of combined data (line 60), however the manuscript does not provide any map of the combined product. The validation of a satellite product in specific locations (figure 6) does not imply the capability to derive global daily maps with a satellite product. In order to provide such a general statement, it should be demonstrated by showing the capacity of this approach to map tropospheric methane distribution.

In the revised manuscript we will include a figure with the global maps for the total columns, the tropospheric partial columns and the UTLS partial columns, as shown in the following Fig. 3.



UTLS partial column

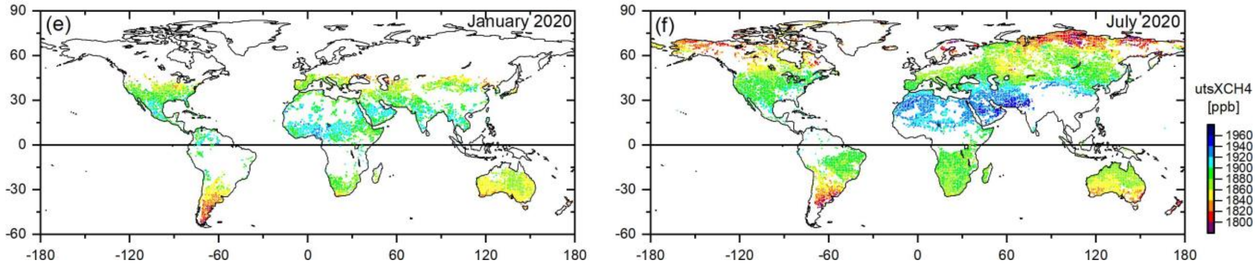



*Figure 3: Global maps of $CH_4$ distributions averaged over 10 days (January 2020 means average for 1-10 January 2020 and July 2020 means average for 1-10 July 2020). (a)+(b): Total column; (c)+(d): Tropospheric partial column; (e)+(f): UTLS partial column.*

5: Co-location of TROPOMI and IASI products: the authors arbitrary propose co-location criteria in section 2.2. Such criteria should be geophysical justified by comparison between the time-space variability of methane. What is the influence of the difference in the overpass time? How does it compare with the diurnal evolution of methane? The same in terms of space variability. It should also be clearly specified the horizontal resolution of the combined product and the coarser resolution of this product as compared to TROPOMI should be explicitly indicated as a limitation. Moreover, section 4.2 on data inconsistency should also deal with heterogeneity and time evolution of methane as observed by IASI and TROPOMI, and in addition to their biases.

This comment is similar to comment #1 of Referee 2. As outlined in our response to the comment #1 of Referee 2 we use the CAMS high resolution forecasts to estimate the heterogeneities in the $CH_4$ fields. We document the uncertainty in the combination method due to the temporal and spatial dislocation of TROPOMI and IASI observation. This error is generally significantly smaller than the measurement noise error. Only for middle and high southern hemispheric latitudes, where the temporal dislocation between IASI and TROPOMI is largest, the dislocation error comes close to the measurement noise error. For more details please see our response to comment #1 of Referee 2.

6: Title: "Synergetic use of IASI and TROPOMI space borne sensors .." calls for ambiguity when it comes for the use of the IASI and TROPOMI spaceborne sensors measurements. I recommend to clearly indicate in the title "level 2 products" or "level 2 retrievals" instead of only the sensors.

Yes, we agree. We will specify already in the title that our combination is based on level 2 products (not level 1 measurements). Our suggestion for the new title is "Synergetic use of IASI and TROPOMI level 2 retrieval data products"

7: The authors claim that the major contribution of the combined product is a tropospheric column of methane that is not obtained with the individual single-instrument product. However, this statement should be more moderate since Figure 12 only show an increase in correlation $R^2$ from 0.245 (IASI only) to 0.346 (combined product), which remains a rather moderate gain.

We estimate a noise error in the tropospheric combined product of about 0.9% (see Fig. 5 of the manuscript). In the comparison with the GAW in-situ data we observe no significant bias (see revised comparison according to Fig. 9 in our reply to Referee 2) and a scatter of about 1.1%. The scatter is slightly larger than the noise error. This is what can be expected due to the heterogeneities in the CH4 fields (see red squares in Fig. 3 of our reply to Referee 2). With this scatter and the limited CH4 variability we cannot expect an $R^2$ value of larger than 0.35.
Our study also provides an indirect validation of the tropospheric partial column product. The fact that the combined data product can well measure total columns (see comparison to TCCON, for instance Fig. 7 of the manuscript) and the UTLS partial columns (see comparison to AirCore in Fig. 10 of the manuscript), means the tropospheric columns have also a good quality.

<u>References:</u>

Rodgers, C.: Inverse Methods for Atmospheric Sounding: Theory and Praxis, World Scientific Publishing Co., Singapore, 2000