Carbon monoxide distributions from the IASI/METOP mission: evaluation with other space-borne remote sensors
By M. George et al.
Atmos. Chem. Phys. Discuss., 9, 9793-9822, 2009

Reply to Anonymous Referee #1

General comment:
The paper "Carbon monoxide distributions from the IASI/METOP mission: evaluation with other space-borne remote sensors" by George et al. provides a first evaluation of the global distributions of atmospheric CO retrieved from the Metop/IASI sensor by comparisons with 3 other spaceborne sensors. The CO IASI distributions are new and therefore exciting and the results from this paper are interesting for the scientific community using CO data from spaceborne sensors. The paper is therefore adequate for publication in ACPD. The aim of comparing instruments is to provide an evaluation of the data and to explain possible discrepancies in order to improve future processing and to help data users. Nevertheless, the analysis of the presented material is not going deep enough and the novelty of IASI is not a sufficient argument to warrant publication. The results presented are too close to descriptive statistics and the paper needs some revisions to strengthen the analysis before publication. My suggestions to improve the content and analysis of the paper are detailed by the following specific comments.

Dear Referee 1,

Thank you for the useful and constructive comments.
We wrote the initial paper with the goal to describe the IASI CO product (what is available in terms of vertical/horizontal information, accuracy) and we also provided some very preliminary early stage validation, with similar products obtained by other thermal infrared instruments (TES, MOPITT, AIRS). For these other missions, it is worth noting that the CO products were first described, see paper of Deeter (MOPITT), McMillan (AIRS), and Rinsland (TES) and then compared to each other, but only at a later stage.

Both you and the other reviewer suggested that we might improve the paper by taking into account the a priori/averaging kernel information when comparing CO products obtained by the different instruments. The new manuscript now describes the validation for 3 months (different seasons, requested by Referee 2), and the comparison is performed taking into account the different prior information, and to some extend the averaging kernels (when available). The agreement is now even better, so it was relevant suggestions. We apologize for the delay to provide an improved manuscript but it took us some time to set up the new calculations. A detailed point-by point reply is provided hereafter, and we explain the changes that were brought to the manuscript.

Specific comments:

1. The radiative transfer and retrieval tools used for IASI CO are only mentioned in the introduction with a reference to Turquety et al. (2009). Because they are important for the analysis, the main ingredients, principles and assumptions of both the radiative transfer and the retrieval software should be described in this paper.
We agree. A new paragraph was added in Section 2.2:

Based on the Optimal Estimation Method (OEM) described by Rodgers (2000), this algorithm consists in minimizing the difference between the observation and simulation by iteratively updating the state vector (here the CO profile). Given a measurement y (IASI spectra), with error covariance S_ε, and a forward model $\hat{y} = F(x)$, the OEM then gives the optimal solution for the state vector x (CO profile) to be retrieved. Since more than one solution could fit the observations (ill-posed problem), it is necessary to constrain the results with a priori information containing both the averaged value expected, x_a, and allowed variability around this average given by a covariance matrix S_a. The solution can be found by iteratively applying:

$$\hat{x}_{i+1} = x_a + D_y[y - F(\hat{x}_i) - K_i(x_a - \hat{x}_i)]$$ (1)

with $D_y = \hat{S}_i K_i^T S_\varepsilon^{-1}$ and $\hat{S}_{i+1} = \left(K_{i+1}^T S_\varepsilon^{-1} K_{i+1} + S_a^{-1}\right)^{-1}$

where $K_i = \left(\frac{\partial F}{\partial x}\right)_i$ is the Jacobian at state x_i, K_i^T is its transpose, and $\hat{x}_{i+1}$ is the updated state vector. The matrix D_y is known as the matrix of contribution functions. The error covariance of the solution is given by $\hat{S}_{i+1}$. The iteration starts with some initial estimate of the state, chosen to be the a priori information x_a, of covariance S_a, and terminates when convergence has been reached. The direct computations of the spectra are based on the Atmosphit inversion code (e.g. Coheur et al., 2005) and, for computational efficiency, uses appropriate approximations and precomputed look-up tables (see Turquety et al., 2009, for more details on the code).

2. We also need more details about the a priori used for the retrievals with at least the vertical profile and associated standard deviations displayed and discussed. The a priori profiles differences may be important to understand discrepancies between sensors (see 3.a).
A new figure (Fig. 3) with the a priori used for the retrieval with detailed information in the caption has been added in the new manuscript (also see reply to point 5).

3. The methodology used for the comparison of the spaceborne data is a basic direct comparison. Nevertheless, "when intercomparing measurements made by remote sounders, it is necessary to make due allowance for the differing characteristics of the observing systems, particularly their averaging kernels and error covariances". This is the first sentence of Rodgers and Connor (2003) who have developed the mathematical and theoretical basis to compare remote sounding instruments. It is therefore surprising not to find any mention to this work in the present paper. The methods described in Rodgers and Connor (2003) may seem complicated but they are useful to make quantitative comparisons and to have a better understanding of discrepancies. In particular, I suggest to take the following simple recipes into account to improve the comparisons:
a. section 3 and equation 10 of Rodgers and Connor (2003) allow to "adjust [the different retrievals] for different a priori".

b. section 4.3 should improve comparisons of the different estimates of the total columns. In particular, Equation 24 will enable a quantitative estimation of the impact of the differences in vertical sensitivity upon the variances.

As mentioned in the introduction we were not planning on doing an extended validation at this stage. But we followed your recommendation, and all the CO integrated values compared in the new manuscript are now adjusted with the ad-hoc a priori following the methodology recommended by Luo et al. (2007). It improved the agreement between IASI and the other instruments. Table 2 has been modified accordingly, as well as the text.

We have modified/added the following sentences in the new manuscript:

In the introduction:
"In order to take into account the different a priori used for CO retrieval by each instrument, we have followed the method suggested by Rodgers and Connor (2003) and Luo et al. (2007a). The columns have been adjusted according to the a priori used by the different teams. A full treatment that takes into account the averaging kernels (Rodgers and Connor, 2003) is presented for TES and IASI, the two instruments with the higher differences in terms of vertical resolution."

In section 3:
"The CO measurements are retrieved using different a priori assumptions and vertical resolutions so we should due allowance for the differing characteristics of the observing systems, particularly their averaging kernels. In order to deal with the different a priori, we followed the method proposed by Rodgers and Connor (2003) and presented into more details for TES and MOPITT comparisons in Luo et al. (2007a). For each point of the grid, the Eq. (3) is applied to the IASI mean CO profile and then the total column is derived:

$$x^{IASI}_{adjusted} = x^{IASI}_{retrieved} + (A^{IASI} - I)(x^{IASI}_a - x^{INSTR}_a) \tag{3}$$

With $x^{IASI}_{adjusted}$ the IASI profile adjusted to the *INSTR* (ie MOPITT, AIRS or TES) a priori, $x^{IASI}_{retrieved}$ the IASI retrieved profile, A^{IASI} the IASI averaging kernel matrix, x^{IASI}_a and x^{INSTR}_a the a priori profile used for the IASI and the *INSTR* retrievals.

The two above-mentioned papers also recommend to smooth the CO profile of the higher resolution instrument with the averaging kernel functions of the lower resolution instrument. The equation to obtain the smoothed column is:

$$x^{INSTR}_{smoothed} = a^{IASI} \, x^{INSTR}_{retrieved} + (i - a^{IASI}) \, x^{IASI}_a \tag{4}$$

With $x^{INSTR}_{smoothed}$ the *INSTR* column smoothed by the IASI averaging kernels, a^{IASI} the IASI averaging kernel vector corresponding to the total column, $x^{INSTR}_{retrieved}$ the *INSTR* retrieved profile and x^{IASI}_a the IASI a priori profile."

In section 3.3:
"All CO columns are corrected for the a priori assumptions according to Eq. (3). Some extended tests were performed to compare IASI and TES CO total columns using Eq. (4), in order to take the averaging kernel information into account. As the smoothed TES column is compared to the IASI column adjusted with the TES a priori, we use the Eq. (4) with the TES a priori profile. For these two instruments, it is obviously the TES CO profiles that need to be smoothed by the IASI

averaging kernel information, because of the higher spectral resolution of the TES instrument. As we lacked some of the averaging kernel information for other instruments, as the spectral resolutions are more similar, and as the impact on the coefficient correlations for TES-IASI was found to be limited (see Table 2, italic values), we restricted this study to TES. It is worth noting that this impact is limited because we compare integrated columns, and that it is much more visible when profiles are directly compared."

4. The water vapor and temperature profiles are EUMETSAT level 2 products. There is a reference to Schlussel et al. (2005) for a description of the product. We need more up to date information about these products! What is the status of their validation?
Level 2 products are currently under validation (Eumetsat organized a specific campaign: JAIVEX) and some results are presented in papers part of the special issue, eg:

Zhou, D. K., Smith, W. L., Larar, A. M., Liu, X., Taylor, J. P., Schlüssel, P., Strow, L. L., and Mango, S. A.: All weather IASI single field-of-view retrievals: case study – validation with JAIVEx data, Atmos. Chem. Phys. Discuss., 8, 21001-21035, 2008.

Pougatchev, N., August, T., Calbet, X., Hultberg, T., Oduleye, O., Schlüssel, P., Stiller, B., Germain, K. S., and Bingham, G.: IASI temperature and water vapor retrievals – error assessment and validation, Atmos. Chem. Phys. Discuss., 9, 7971-7989, 2009.

In the text, we added after "The code uses the water vapour and temperature profiles from IASI Level 2 data and operationally distributed by EUMETSAT through the EUMETCAST dissemination system (Schluessel et al., 2005) as input variables.": "These Level 2 products are validated, although some issues remain for water vapour (see Zhou et al., 2008 and Pougatchev et al., 2009)."

How are the pixels selected or rejected by EUMETSAT and therefore by FORLI (quality, cloud filtering. . .)? Do you reject other pixels and on which criteria?
Before delivering the data to the users, EUMETSAT checks the quality of the spectra. This filter is based on spikes detection and keeps 99% of the data. We did not add anything specific on that in the paper because we couldn't find a suitable reference for this.

The FORLI retrieval code only treats the spectra flagged with the quality flag 0 and not contaminated by clouds. We added in section 2.2: "for the study presented here, only cloud free data (see Clerbaux et al., 2009, section 3.2.1) are analysed."

5. In section 3.1, we need a plot with the a priori vertical profiles and standard deviations of the covariance matrices compared even if it may be complicated with TES.
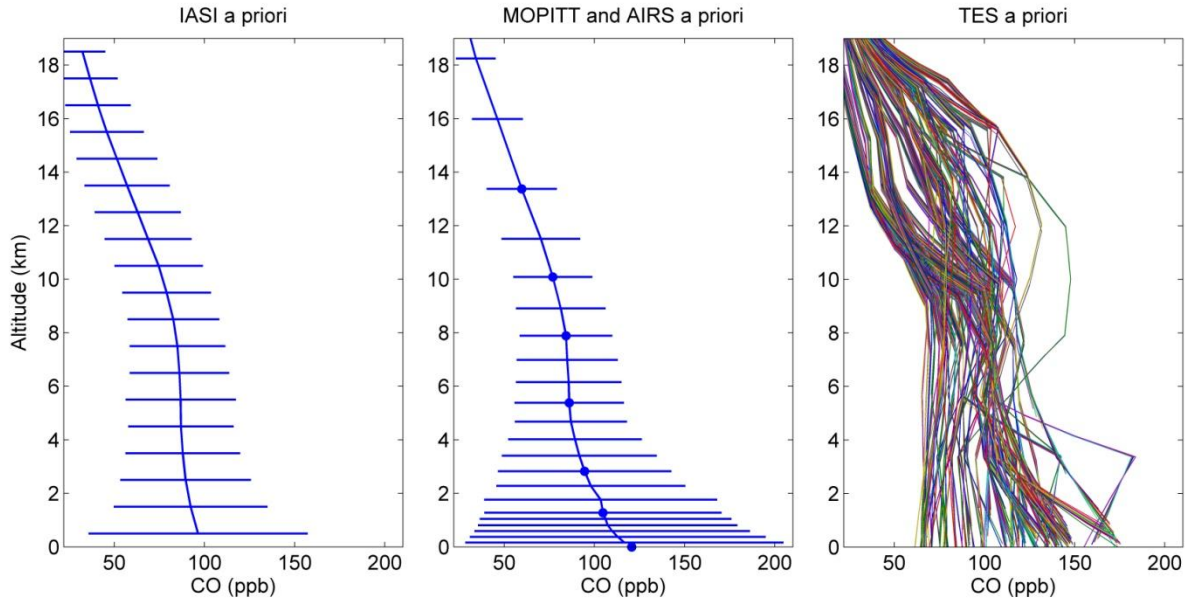We added the following figure: Figure 3 (quoted in the sections 3.1.1, 3.1.2 and 3.1.3):
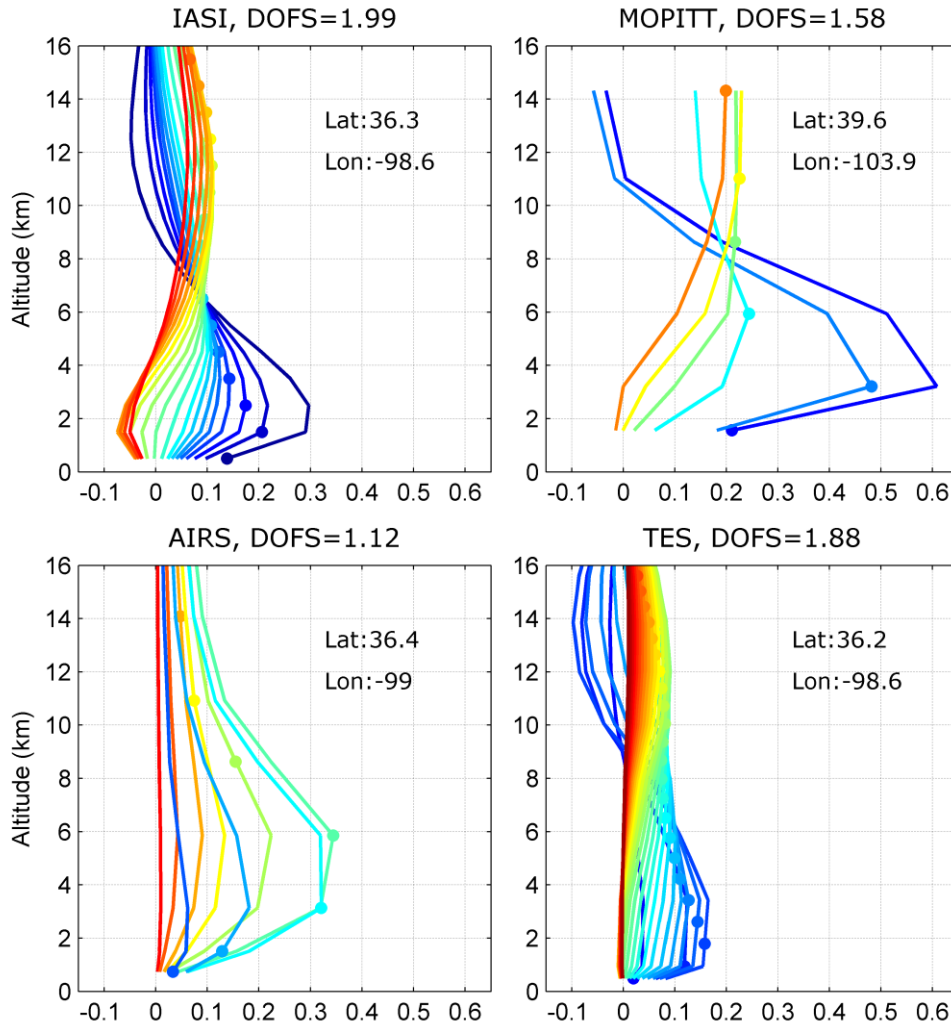
Figure 3. A priori and standard deviations used in the different retrievals: IASI (left), MOPITT and AIRS (middle) and TES a priori profiles for August (right). For IASI and MOPITT, the standard deviations are from the diagonal elements of the a priori covariance matrix S_a. MOPITT V3 retrievals use the mean profile and covariance matrix values at the seven levels shown by the blue dots. AIRS V5 retrievals do not employ a covariance of the a priori. TES a priori profiles vary in time and location (monthly, 10° lat x 60° lon blocks), and only the profiles for an August climatology are presented here. See Figure 6 in Luo et al. (2007a) for a representation of S_a for TES.

6. The comparisons of the averaging kernels of section 3.2 are not correct because, as mentioned by the authors, the retrieval levels are different for the different sensors. Therefore Figure 4 is not really useful to compare the vertical sensitivity and has to be modified. First, the best data provide about 2 independent pieces of information (except for AIRS). The authors should therefore choose one more scene with higher information content. Second, from the averaging kernels they should analyse what partial columns are best representative of those 2 independent pieces of information (0-X km and X-Y km). Third, they should compute and compare the averaging kernels for the corresponding partial columns and also for the total column. From such an analysis, they may reach a better conclusion about the sensors vertical sensitivities and about their impact upon the discrepancies (see 3.b).
We choose another scene (in the U.S.A.) with a higher information content, so for the 4 sensors, the DOFS are larger than 1. See the new figure (now Fig. 5). This plots also shows the number of vertical levels retrieved, specific to each retrieval codes.

IASI, DOFS=1.99 — Lat:36.3, Lon:-98.6

MOPITT, DOFS=1.58 — Lat:39.6, Lon:-103.9

AIRS, DOFS=1.12 — Lat:36.4, Lon:-99

TES, DOFS=1.88 — Lat:36.2, Lon:-98.6

As you suggested, we did some tests to compare the averaging kernels for the given partial columns and for the total column and we found that the results depend a lot on the geophysical situation. Eg see Fig. A in Annex which is a bit unfair for TES. It is quite difficult to find a perfect colocation, and also the time of the observation differs. The shape of these averaging kernels also largely depends on the a priori assumptions. It is very obvious when we look at total columns.

7. In section 3.3, retrievals above North Africa and the Arabic peninsula are mentioned as problematic for IASI and AIRS. What is the difference with MOPITT and TES? Are those problems related to the surface emissivity used for the retrievals? to the reflected solar light ? What are the assumptions made about those aspects in the different algorithms?

Radiative transfer issues occur when processing the IASI data over very cold/icy and very hot/sandy surfaces. The local emissivity influences the sensitivity at the surface level and for the moment, local METOP-derived emissivity data are not yet available from EUMETCAST. For the IASI CO treatment we currently use emissivity coming from the MODIS general database. It seems that both the MOPITT and TES team use a "dedicated" emissivity first guess over Sahara, and the intercomparaison exercise reported in this paper alerted us that a special treatment is also

required for IASI over Sahara and Saoudi Arabia. Also, detailed emissivity value should be available from Eumetcast hopefully soon.

8. In the conclusions:
a."sensitivity varies as a function of . . . local emissivity": this is not detailed in the core of the paper.
We added in section 3.3: "The local emissivity influences the sensitivity at the surface level..."

b."in the SH. . . IASI is. . .15% lower . . .than AIRS and MOPITT": why? Does it have anything to do with the a priori (see 3.a)?
With the adjustment with the a priori, the new sentence is now "In the Southern Hemisphere, under 15°S, IASI is about 11% lower on average than MOPITT and AIRS".
Further validation for background CO values is need, but we think that when mixing ratios are at ~50 ppbv the CO signature is less intense and hence any instrument is less sensitive. A more specific validation that includes ground-based stations is needed to further discuss this SH difference issue.
For AIRS we think that the limited CO lines available for the retrieval (see Fig. 4) makes it not very reliable when CO is low.

c."column comparisons. . . biased by different a priori".
We removed this sentence as now the CO columns are adjusted with the a priori.

d."profile comparisons. . . will account for averaging kernels and a priori differences":
 We removed this sentence.

Ref: Rodgers, C., D., and Connor, B.J., Intercomparison of remote sounding instruments, J. Geophys. Res., 108, doi:10.1029/2002JD002299, 2003.
We added this reference in the Reference list.
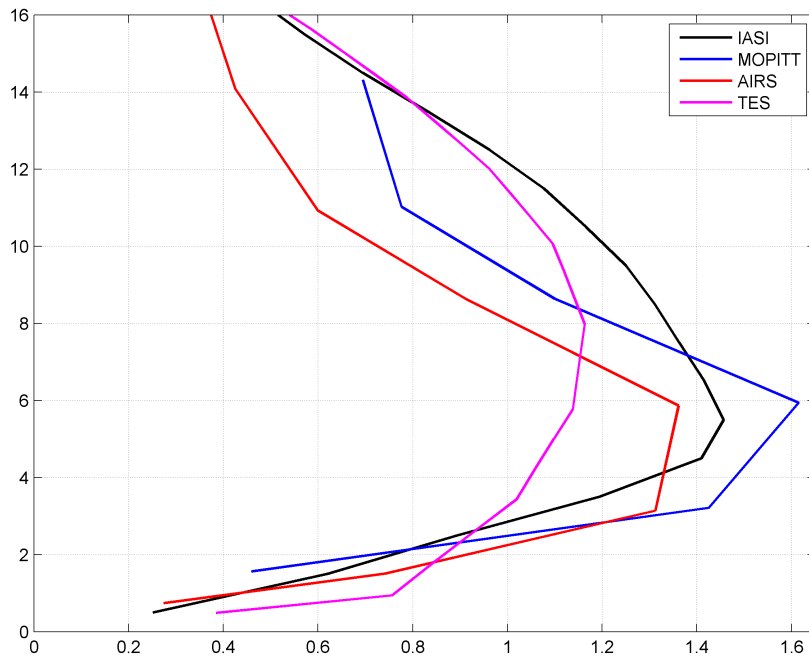
Annex plot

Fig. A: Averaging kernels corresponding to the total column for the location presented in Fig. 5.