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“IASI carbon monoxide validation over the Arctic during POLARCAT spring and summer campaigns” by M. Pommier et al.

Reply to Anonymous Referee #1

The authors would like to thank Reviewer 1 for his careful reading of the manuscript and for his constructive comments. We tried to reorganize the structure and improve the content as recommended. A detailed point by point reply (in blue) is provided hereafter.

Referee #1

Structure
The description of IASI CO retrievals should be done properly at the beginning of the manuscript in a dedicated section. Indeed, we find partial description of IASI CO retrievals in Section 3.1.1 with a vague introduction to the notion of averaging kernels without proper illustrations. Furthermore, in section 3 the IASI measurements, at the heart of the study, are presented on the same level than ACE-FTS or in-situ observations which are ancillary data. Section 4.2 deals with “performance of the IASI retrieval...” without presenting averaging kernels. Finally, we can find some averaging kernels plotted in section 5 that is at the end of the manuscript, while a good understanding of the comparison results need a previous good description of the IASI CO retrievals.

The former structure was initially chosen to highlight the usefulness of IASI satellite observations in the framework of the POLARCAT campaign. This is why this manuscript is submitted in POLARCAT special issue. We changed the organization in order to follow the recommendations of both reviewers. The abstract and conclusion sections were reorganized accordingly. We now start with the IASI retrievals, and the manuscript is organized as follows: after an overview of the IASI CO retrievals over the Arctic (section 2), the general context of the 2008 polar campaigns and details about the CO measurements used for the validation are given in section 3. Section 4 describes the collocation criteria issue and the methodology adopted to validate IASI CO. Both a quantitative comparison and a statistical evaluation of the quality of the IASI CO retrievals in spring and summer 2008 are provided. Section 5 discusses further some of the interesting cases in terms of the spatial distribution of the observed plumes. Conclusions are presented in section 6.

The IASI CO retrieval section (2) now includes a more complete description of the FORLI-CO retrieval code and discusses its performance in the Arctic troposphere. As recommended an example of AK is now provided (new Fig 2) along with this explanation:
“In the Arctic, the DOFS is lower than in the tropics due to the cold surface temperatures. Higher DOFS are obtained when thermal contrast is important (Clerbaux et al., 2009) and the latter varies as a function of the surface type and the diurnal surface temperature contrast. This second effect is illustrated in Figure 2, representing the diurnal variability of a mean averaging kernel over Siberia in July 2008.”

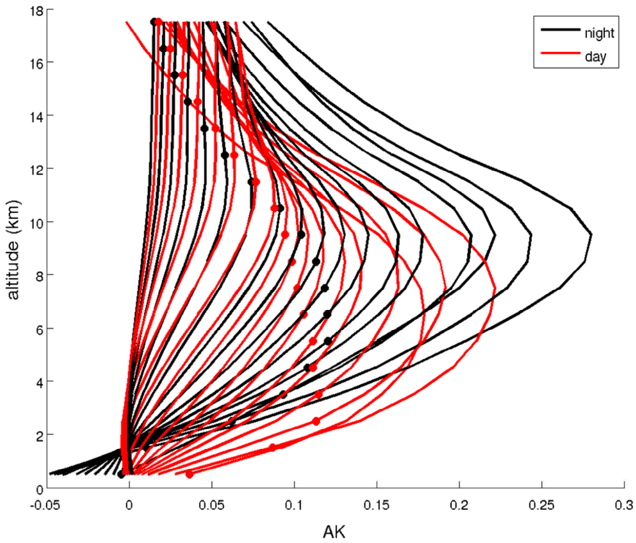


Fig. 2 Monthly mean of averaging kernel on July 2008 over Siberia (100-140E, 50-70N) for daytime (red) and night-time (black). The dots on the averaging kernel show the corresponding altitude.

Furthermore, a complete description of the retrievals should introduce error covariance matrices for the profiles and scalar errors for the integrated columns. The primary aim of the paper is the validation of IASI data in the Arctic. Nevertheless, before validation is performed, the paper deals with "long range transport during the 2008 Arctic campaigns" (4.1) and "analysis of IASI information along selected flights" (4.3.2). These 2 sections provide interesting results, but they should come after the validation results provided in section 5 in order to be given some credit.

As recommended sections 4.1 (now 5.1) and 4.3 (now 5.2) were shifted after the validation result discussion. The following sentence was also added to the text:
"…including an *a posteriori* error variance-covariance matrix and an averaging kernel (AK) matrix. From these matrices a scalar error and a vector averaging kernel can be calculated, and are provided with the total column product."

Section 3.1.1
The ref. describing the FORLI retrieval algorithm is "in preparation". The authors should therefore give some details about this algorithm and its performances. The description of the a priori data lack of details but these data are crucial for the regularization of the retrievals. The authors should give some information concerning the way MOZAIC/ACE-FTS and model outputs are mixed and sampled. A plot of the covariance matrix (not shown in Turquety et al., 2008) would be of interest.

We updated the reference for the FORLI retrieval code. Unfortunately the detailed description paper (Hurtmans et al) is still in progress. More details on the retrieval code and performance are provided in the new text.

The following text was added to the manuscript:

"The OEM solution can be found by iteratively applying:

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

With $\mathbf{D_y} = \hat{S}_\mathbf{i}\mathbf{K}_i^T\,\mathbf{S}_\varepsilon^{-1}$ and $\hat{S}_\mathbf{i+1} = (\mathbf{K}_{i+1}^T\,\mathbf{S}_\varepsilon^{-1}\,\mathbf{K_{i+1}}+\mathbf{S}_a^{-1})^{-1}$. $\mathbf{K_i}$ is the Jacobian at state x_i, $\mathbf{K}_i^T$ is its transpose and $\hat{x}_{i+1}$ is the updated state vector. The matrix $\mathbf{D_y}$ 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 $\mathbf{S_a}$, and terminates when convergence has been reached."

As requested a plot of the covariance matrix is now provided (Fig.1).

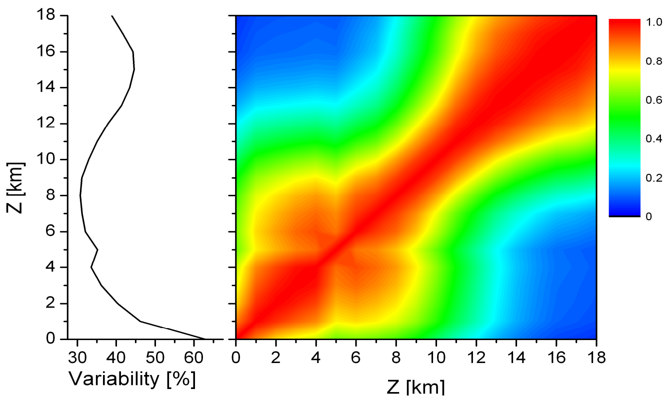


Fig. 1 Variability of *a priori* CO in percent and correlations matrix obtained from covariance matrix S_a used in the FORLI-CO retrieval algorithm.

And this sentence was changed:

"In order to build a matrix representative of both background and polluted conditions the *a priori* information was constructed using a database of CO profiles including aircraft profiles during landing and take-off from the MOZAIC (Measurements of OZone and water vapour by AIrbus in-service airCraft) program (Nédélec et al., 2003), ACE-FTS satellite observations in the upper troposphere and lower stratosphere (Clerbaux et al., 2005) and distributions computed by the LMDz-INCA global chemistry-transport model (e.g. Turquety et al., 2008)."

Section 4.1

This section dedicated to LRT is interesting but it should be given some more care. IASI observations alone are not enough to characterize LRT and the study should rely on complementary data such as backtrajectories or at least an analysis of the wind fields and meteorological conditions corresponding to the LRT events described in the paper (Asia to US west coast and across the North Pole).

We agree with the referee that IASI alone is not enough to characterize LRT but this part is an illustrative section. It is interesting to see that IASI is able to observe the transport pathways of pollutants, using CO which has a long lifetime.
We changed the titles of this section and it is now "5. Further insights into Arctic CO distributions" and "5.1. Spring and summer CO total columns"

Please also note that this section was deliberately limited as an extended study focused on transport, that compares IASI CO results with 3 models will be submitted to ACPD later this month. This paper focus on two episodes (2–5 July and 7–10 July 2008) occurred where low-pressure systems travelled from Siberia across the Arctic Ocean towards the North Pole. The paper compares transport simulations of carbon monoxide from the Lagrangian transport model FLEXPART, the Eulerian chemical transport model TOMCAT, and for numerical aspects the limited-area chemical transport model WRF-Chem. Retrievals of total column CO from IASI are used as a total column CO reference for the two simulations.

Sodemann, H., Pommier, M., Arnold, S., Monks, S., Stebel, K., Burkhart, J. F., Hair, J. W., Diskin, G. S., Clerbaux, C., Coheur, P.-F., Hurtmans, D.,Schlager, H., Blechschmidt, A.-M., Kristjánsson, J. E., and Stohl, A.: Episodes of cross-polar transport in the Arctic during July 2008 as seen from models and observations.

We put this reference in the manuscript with this sentence:
"By the 9 July (Fig. 15c), the Asian plume was transported directly over the Arctic to Greenland and the North American plumes either reached western Europe or were transported further north over Greenland. The case of Asian plume transport over the Arctic to Greenland is discussed in detail in Soderman et al. (2010)."

Section 4.2

The results provided here should be somewhat summarized and presented in the section dedicated to the retrieval description. In particular, all the details about the retrieval RMS are not necessary and table 2 could be shortened. I didn't understand to which bias the author refer in the last part of this section.

See before, the section dedicated to retrieval description has been improved.

- The bias corresponds to the mean of absolute values of the residuals. It shows if residuals are well centered around zero. We added this information in the text description.
- All values in former Table2 (now Table 1) were rounded to the nearest one-hundredth and we deleted the bias in order to shorten the Table as recommended.

Section 4.3

In section 4.3.1 the authors describe the collocation criteria between IASI and aircraft data: about 20x20 km and 1h. These are very stringent criteria. Could the authors give evidence of the worsening of the comparisons when the criteria are relaxed to 50x50 km and 2hours or more ?This should clearly improve the statistics. It seems that comparisons provided in section 4.3.2 don't give highly satisfactory results. This is not completely surprising to me because (i) IASI sensitivity is rather low in the Arctic (ii) the sampled plumes maybe too thin to be detected by the spaceborne instrument. Nevertheless, when the results are presented the way they are, they give rather poor idea about the ability of IASI to measure tropospheric CO. If the data were properly described and validated previously, the large IASI/aircraft discrepancies could be better explained by the authors and understood by the readers.

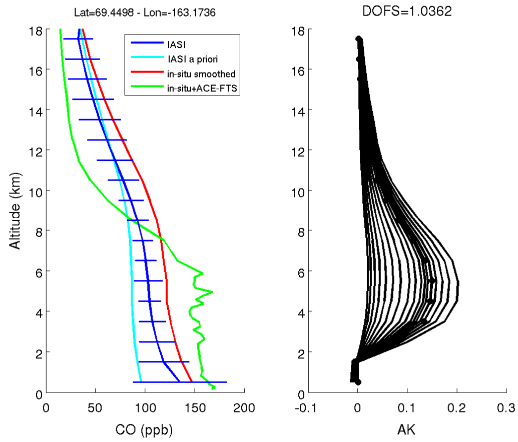
- As mentioned in Section 4.3.1 (now in Section 4.1) of the former manuscript, many collocation criteria were tested (from +/-0.2°,+/-1h to +/-0.5°,+/-2h):
"Different coincidence criteria around the flight position were tested and here, comparisons were conducted using a stringent collocation criteria, i.e. a box of 0.2°×0.2° and time of ±1 h."
From these studies we realized that relaxing the criteria did not improve the comparisons. As IASI is flying on a polar orbit and has a large horizontal coverage, a lot of IASI data are available at high latitudes, even on a small area. Using these stringent criteria, we compared IASI data with 150 profiles measured during 113 flights (spring and summer campaigns combined). Also an objective of these criteria was to show that IASI is able to detect regional episodic plumes as shown in former figure 7 (eg see examples of P3B & Antonov-30 flights) and when the criterion was relaxed we found that it "smoothed" the IASI CO signatures in some cases. In order to better explain this in the manuscript we modified these sentences in Section 4.1:
"In order to compare satellite observations and aircraft measurements, an important first step is to check the place and time coincidence. Different coincidence criteria around the flight position were tested (from ±0.2°, ±1h to ±0.5°, ±2h) and here, comparisons were conducted using a stringent collocation criterion, i.e. a box of 0.2°×0.2° and time of ±1 h. When the criteria were relaxed it appeared that IASI CO signatures were less visible and results from the comparisons were not improved."
- (i) the main conclusion is that it is difficult for IASI to detect CO enhancement due to limited vertical information in spring but (ii) in summer IASI is sometimes able to detect pollution due to better thermal contrast. And it is shown with example of YAK campaign where is able to detect this CO in good altitude range (in BL).
- This validation exercise with *in situ* measurements shows a good agreement and the results are coherent with former studies. We added this sentence in new section 4.5.1. Comparison by aircraft: "The difference between both profiles reaches ~10 ppbv (17% maximum) close to 10 km for the WP-3D and the ATR-42. This difference is similar to the 15% bias found between ACE-

FTS and MOZAIC in Clerbaux et al., (2008).” And for summer comparison, we completed the explanation with this sentence: “Due to the lack of IASI vertical sensitivity at the lowest altitudes, maximum differences are found at the surface (120 ppbv with the P-3B and 20-30 ppbv with the other four aircraft). Nevertheless, the relative difference is always below 20% and similar in magnitude to similar validation studies using MOPITT (Emmons et al., 2007) and TES (Lopez et al., 2008) at mid-latitudes.” Another reference was added for total column comparison: “The mean total columns from IASI and estimated from the smoothed *in situ* profiles are in good agreement with an absolute value of relative differences ranging from 1.4% to 5.2% in spring with the WP-3D and the DC-8, respectively, and ranging from 5 to 10% in summer. These results are consistent with previous validation studies (e.g. Emmons et al., 2007) and show that for low DOFS, the differences for total columns between IASI and the smoothed *in situ* measurements are low.”

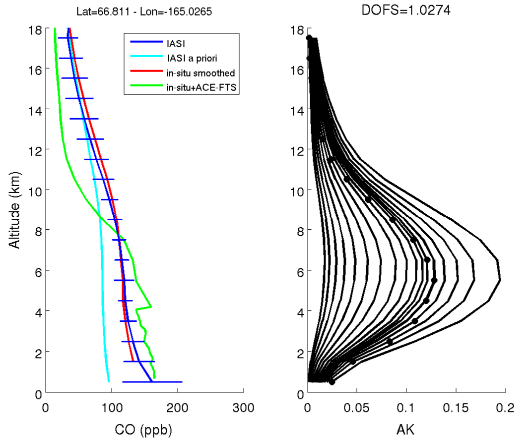
In this section, the authors often refer to sea-ice or snow cover to explain loss of information with IASI data and explain the discrepancies. To give credit to such an explanation, the authors should (i) show averaging kernels over snow and sea-ice to show at which altitude sensitivity is lost (ii) explain how the surface emissivity database account for sea-ice and snow cover interannual variability and whether “bad” emissivity is not a better explanation for “bad” retrievals.

(i) In order to better highlight the impact of snow and sea ice we clearly separated profiles examples, creating a section “5.3.1 Spring cases” and “5.3.2 Summer cases”. We did the same separation on cross sections with sections “5.2.1 Selected spring flights” and “5.2.2 Selected summer flights”.
(ii) Unfortunately we don't have these emissivity values for each pixel in the official L2 IASI products (should be available anytime soon now). The emissivity we used comes from a climatology of AIRS emissivity.
Even if we could get these data, there still is a problem with the thermal contrast (Clerbaux et al., 2009) linked to surface type or diurnal variation. Plots on former Fig 9 are well representative of the AK we observe.
Other examples of profiles and AK are shown hereafter (not included in the manuscript):

a)



b)

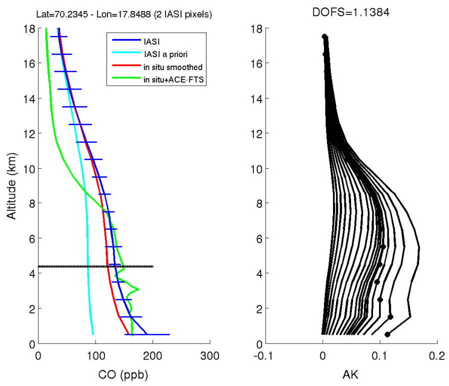


Plot a) is above the frozen sea and b) close to the coast in Alaska it means between the snow and sea ice. It is for the DC8 flight on 9 April.

This demonstrates a low sensitivity close the surface.

We added this information for the former Fig 9b (new Fig 8a):
"Also note that the presence of sea ice in this area in spite of the season (see Fig. 9b) could explain the problem of retrieval with the limited vertical sensitivity. Moreover, the AK has higher values for the two first levels but many rows of the AK matrix are negative at the surface making difficult the retrieval at these altitudes. This explains that the *in situ* smoothed profile is lower than the *a priori* below 3 km."

For the ATR flight the AK are provided hereafter over the sea (not frozen) close to Norway. This profile is now included in Figure 7c and it seems to create a better link with spring cross sections examples presented in new Fig. 16 (spring cross sections). Over sea, we had slightly better sensitivity close to surface (and better DOFS) than over frozen sea.



The following sentences were added to the text:
"The third example (case (c)) was measured over the sea close to the western Norwegian coast by the ATR-42 on 10 April. Over this area, the sea was not frozen (see Fig. 9a). This case shows a better sensitivity close to the surface (and higher DOFS) compared to the two previous examples over sea ice. Except on the first level, the IASI and *in situ* smoothed profiles are quite similar (difference below 20 ppbv)."

A new Fig 9 was added showing the locations studied in spring and in summer.

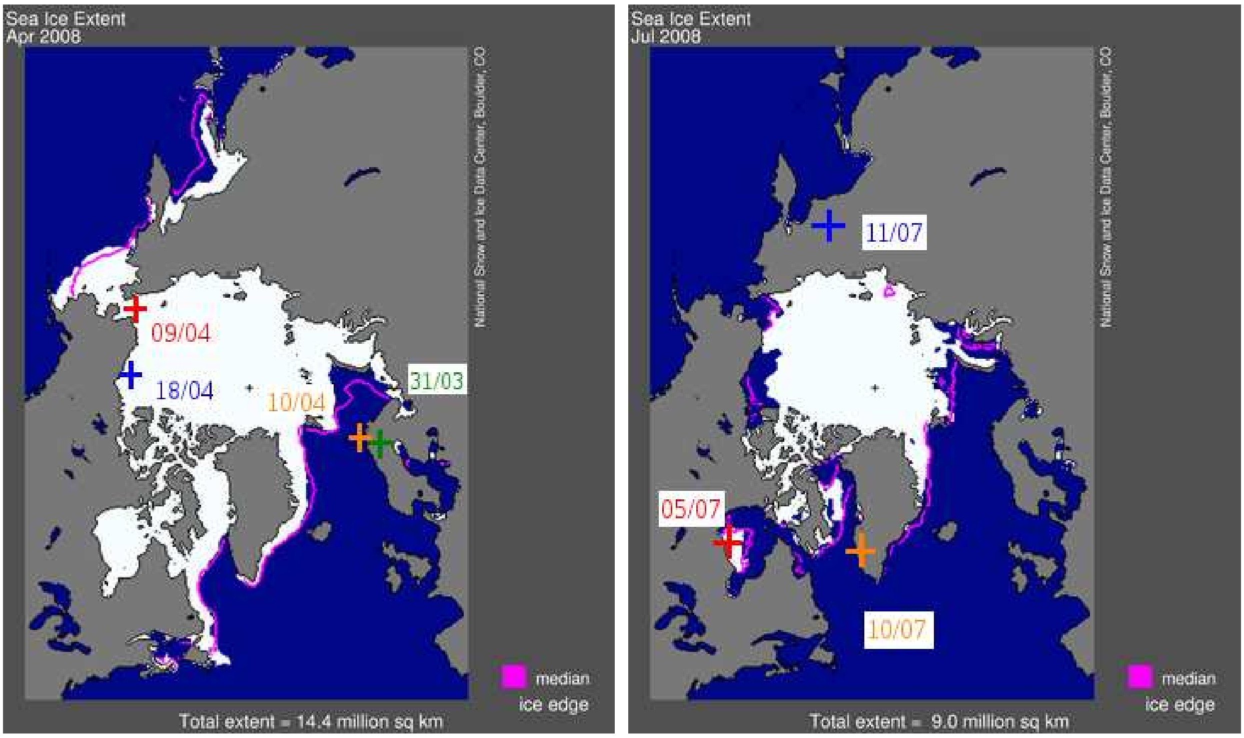


Fig. 9 Monthly averaged sea ice cover maps (white area) for April (a) and July 2008 (b). The magenta line shows the 1979 to 2000 median Arctic sea-ice extent for each month (http://www.ncdc.noaa.gov/snow-and-ice/). The coloured crosses represent the positions of measured CO profiles shown in Figures 7 and 8.

Describing the comparisons displayed in Fig. 6, the authors focus on the lower troposphere where the IASI data lack of sensitivity (as shown in Figure 8). Important discrepancies are also found in the free troposphere around 5-6 km but they are not enough discussed. It seems that they are also attributed to a lack of sensitivity (especially over sea-ice) while the IASI observations have the best sensitivity in this altitude range according to the averaging kernels (Figure 8). Information about the impact of sea-ice upon CO retrievals and averaging kernels (as required above) would really help to answer.

We agree with this comment and we reformulated the explanation. The DOFS is an important criterion too. We can see on former Fig9 for summer cases (b & d) that IASI observed CO enhancement, and at the opposite in spring (a, c, d) it is more difficult for IASI to distinguish a vertical CO variability.
Hence, for the example provided in new Fig 7a we added this comment:
"Even if the plume altitude is located at levels where IASI has good sensitivity, the signal is mixed with other layers since it corresponds to a DOFS close to 1, so that the plume is smoothed out."

Section 5:

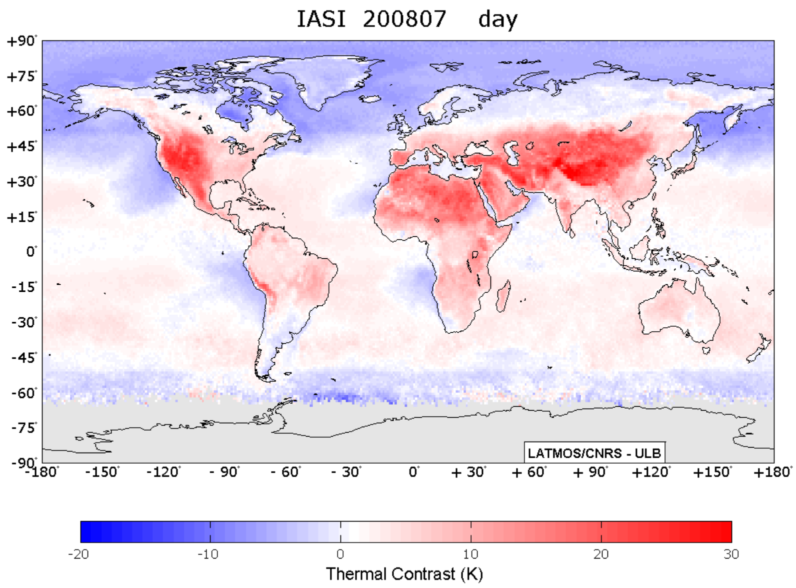
As mentioned previously this section should come earlier in the manuscript. Furthermore, equation (1) will be more understandable if the general retrieval equation ($x=xa+A(x-xa)$) was introduced earlier. Here again, relaxing the coincidence criteria may improve the statistics. As shown in Figure 6 and 7 and discussed above, thin CO plumes are not detected by IASI anyway.

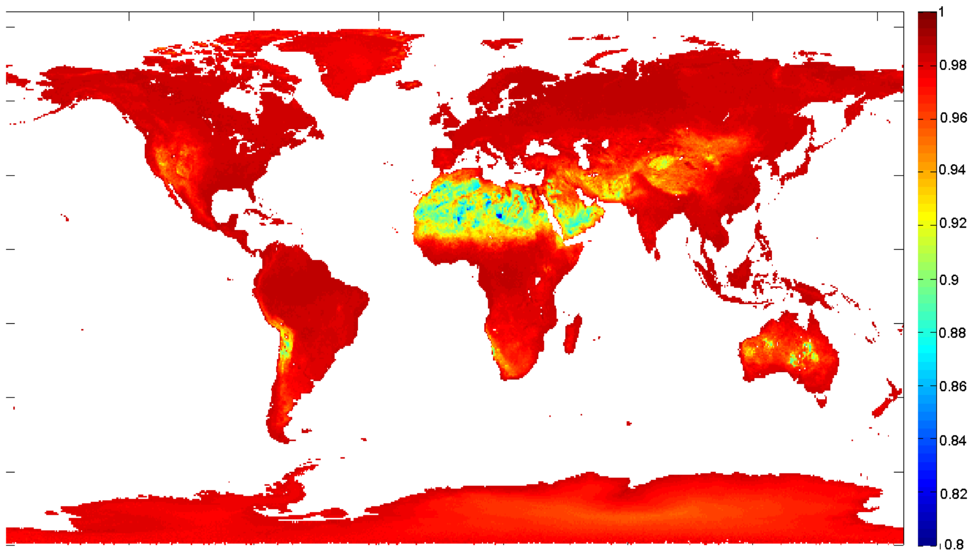
- The equation is now introduced earlier as recommended.
- We agree that is difficult to detect plumes with IASI due to the low vertical sensitivity, more particularly in spring (low thermal contrast between surface and first air levels) but the summer cases are interesting. For example IASI was able to detect forest fire emissions in BL with flight on 11 July during YAK-AEROSIB campaign despite the criteria are stringent.

In 5.2, sea-ice is again mentioned as an explanation for IASI/aircraft discrepancies following a lost of sensitivity. If it was the case, the effect would be accounted for by the smoothing and there would be no differences. An emissivity problem may be a better explanation. Furthermore, the incriminated profile 9(b) has a larger DFS (1.3) than 9(a) and 9 (c) (1.0) which both show better agreements. Same comment for 9(e) and the snow cover. . .

Both the sensitivity and the emissivity can play a role here: if the measurement is not sensitive enough close to the surface (eg in sea ice cases) the retrieved profile will stick to the *a priori*. If the emissivity is not handled properly (also the case over ice, snow) it might impact the quality of the retrieval. Hereafter we provide a map of the IASI thermal contrast for July 2008 and an emissivity map used in FORLI-CO. We can observe a low thermal contrast (close to 0 = white color) over areas in Arctic, as over North Canada, Sweden, Iceland, Siberia and Greenland coasts.

The emissivity issue affects mainly deserts and mountains areas, although we would certainly benefit of having more detailed emissivity values over ice too.





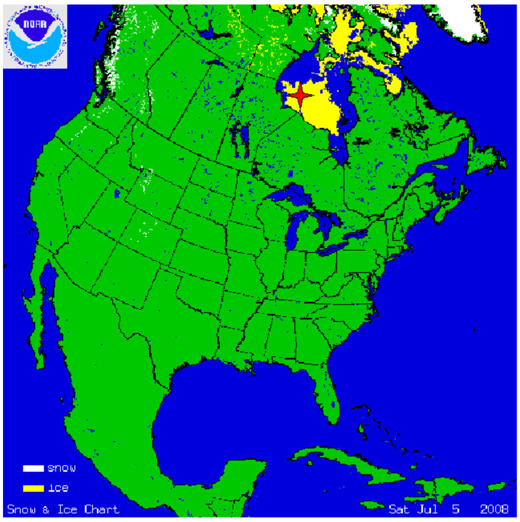
An important problem of section 5 is that it doesn't provide its valuable information in a concise way. Instead of compact plots, very detailed descriptions of the comparisons are given in the text. For instance, Section 5.3.1 is dedicated to "comparison by aircraft". Is it meaningful to make such an exercise? Looking at Fig. 10, 11 and 12, we would learn more (and remember what we have learned) if we had averaged profiles with spring and summer differentiated. We also need the averaged relative differences together with the RSD to be plotted instead of long descriptions of the biases in the text. The scatter plot should be with a single color and single CC! Does it mean much that R(P-3B)=0.73738 (0.74 would be fine!) in spring ? The important figure is that R=0.37 in spring. The issue of the altitude reached by the different aircrafts could still be discussed in the text. Another point in differentiating the aircraft would be to deal with biases between in-situ measurements. The authors mention "a 7 ppbv negative difference between the ATR-42 and the Falcon 20". . . but this is not discussed in section 5. Is this bias too low to be meaningful when comparing with IASI?

- We think is meaningful to make "comparison by aircraft" because all aircraft were not involved in the same area and the same period. Thus they did not measure the same polluted air masses. For example in summer, the DC-8 flew directly inside Canadian forest fires, the Antonov-30 inside Siberian fires and the ATR-42 in different pollutions plumes transported from Asia or North America over Greenland. That is why we added this comment: "We chose to compare the IASI retrievals by aircraft because, as explained in section 3, the aircraft did not fly in the same regions or at the same time of year. Therefore, aircraft measured very different types of air mass ranging from flights over boreal fire regions and in air masses downwind of anthropogenic emission regions." This R for each aircraft is thus important information.
- RD and RSD are added on plots (cf. last comment).
- the R precision is corrected.
- Concerning the altitude reached by the different aircraft, we changed the sentence after the description of 0-5 km columns correlation graphs:
"Limiting the comparison to partial columns, comparing thereby the *in situ* part and not a combination of *in situ* and climatology, improves the correlations in the 0 to 5 km layer, and varies between aircraft from 0.47 to 0.77 in spring and from 0.66 to 0.88 in summer (see Fig. 12). In both seasons, the correlations with the ATR-42, which flew to the lowest maximum altitudes (up to 6-7 km), are the most improved giving 0.53 in spring and 0.70 in summer. In spring, the IASI collocated profiles with the ATR-42 have the higher sensitivity close to surface. These two factors highlight the importance of a good climatology to complete the profile. Correlations between IASI and the combined dataset using all the aircraft data were also computed. In this case, differences between aircraft measurements and sampling of different air masses need to be kept in mind. The overall correlations are 0.37 in spring and 0.67 in summer and improve to 0.59 in spring and 0.79 in summer when only considering partial columns.
Moreover, these correlations also show, for total columns as well as for partial columns, that when the correlation is higher than 0.5, IASI values are generally lower than the smoothed *in situ* values in spring and the inverse in summer."
- We added this sentence: "The bias between the ATR-42 and the Falcon-20, mentioned in section 3.1, is not found in this kind of comparison due to the smoothing with the IASI AK. The CO *in situ* profiles over Greenland from the ATR-42 and the Falcon-20 are quite similar."

Section 5.3.2 comes at the end of the manuscript while the surface type is mentioned within the whole manuscript as a major source of discrepancy between in-situ and IASI CA data! This section is therefore very important in this paper and should be dealt with more in depth and earlier (as the whole section 5). As previously mentioned, we really need to know how the emissivity problem is taken care of concerning sea-ice and snow and whether or not this is an issue. It would also be a good idea to have maps of sea-ice and snow cover if such things are available when dealing with "impact of surface type".

As mentioned earlier, the proper deal of emissivity and thermal contrast are still issues for IASI retrievals. Hereafter more information of summer snow & ice situation are provided.

This map shows (not added in the paper) the location of the profile from DC-8 the 5 July over Hudson Bay (former Fig9b).

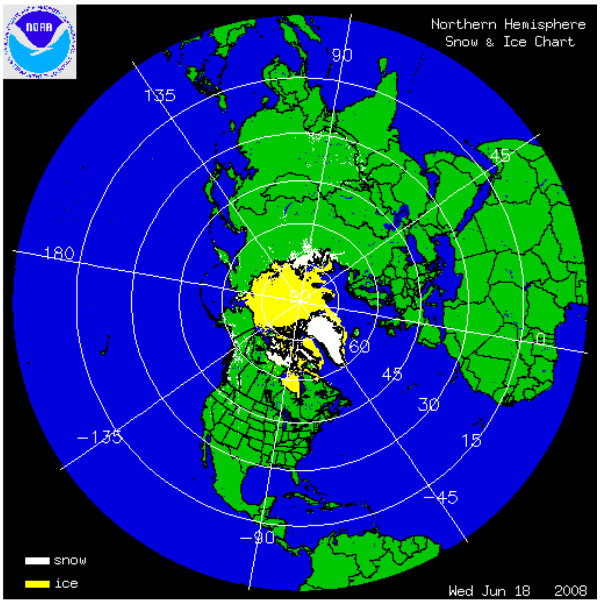


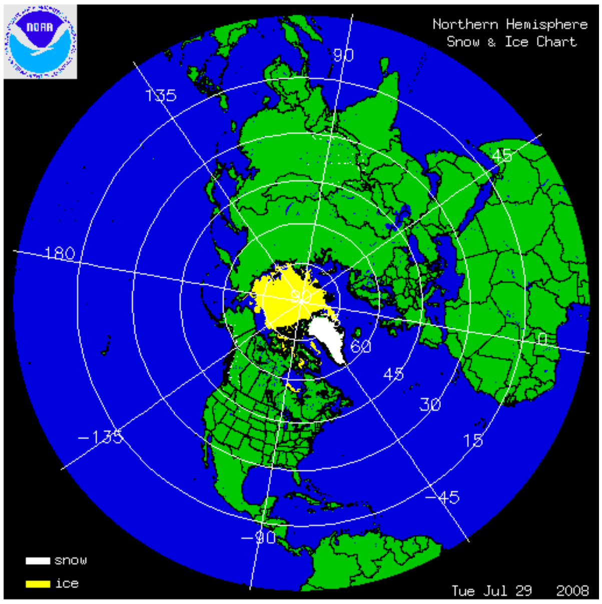
This map shows the snow and ice cover on 5 July 2008 over North America. Data are from the NOAA National Climatic Data Center at http://www.ncdc.noaa.gov/snow-and-ice/ (former link put in the ACPD manuscript). Snow is denoted by white, ice by yellow and the rough location of *in situ* profile of former Fig.9b (DC-8 profile) by red cross.

The ice cover over the Hudson Bay could explain the strange shape of the AK.

This link is also used for the case (d) in Fig. 7, with this comment:
"IASI had problems detecting high CO signatures measured by the aircraft between the surface to 6 km probably due to the snow covering the land area (see data from http://www.ncdc.noaa.gov/snow-and-ice/), and low thermal contrast (see the AK plot)"

And these 2 daily maps (not added in the paper) are for the 18 June and 29 July 2008, corresponding to the limit dates of summer campaigns. Snow is denoted by white, ice by yellow.



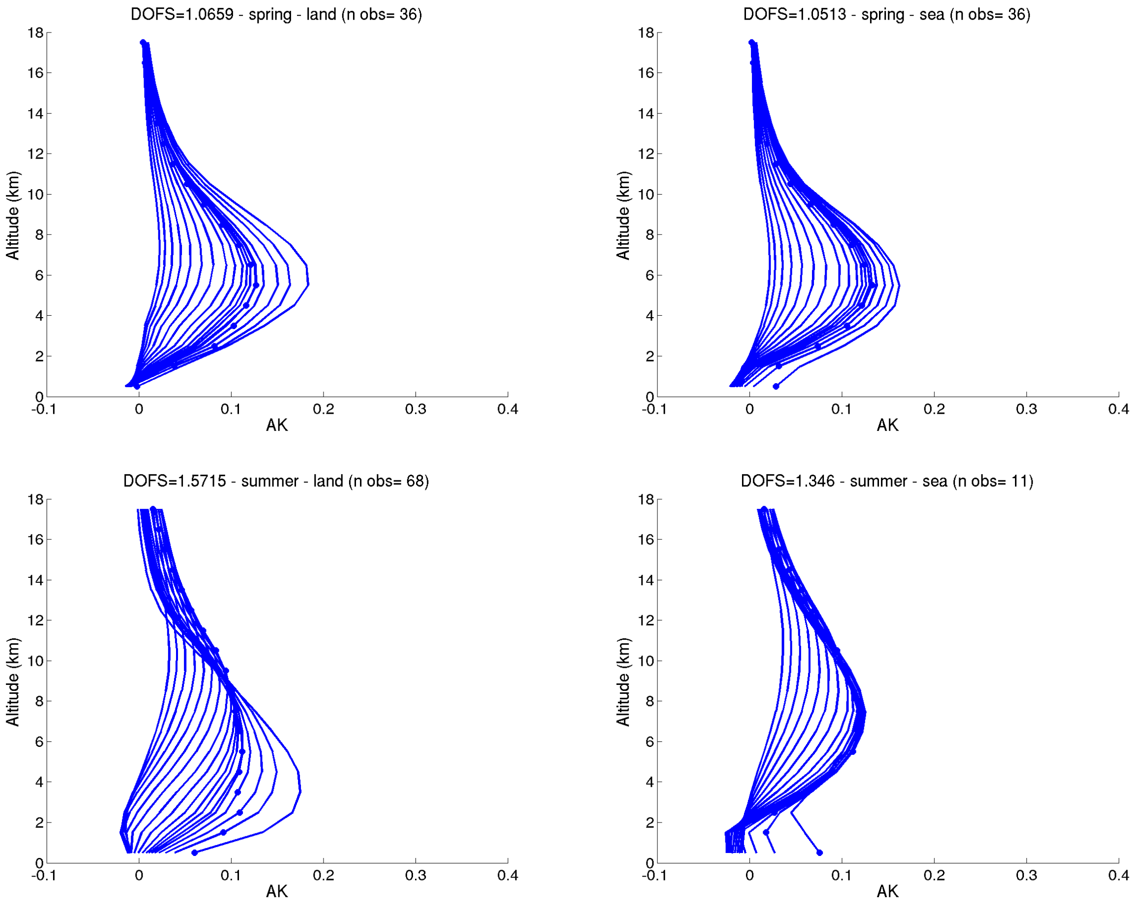


In the paper we added a new Fig9. (see page 8 of this document) which summarizes the sea ice situation in April and July 2008.

The summer averaging kernels are “not shown” while it is very important that the reader could see them. Results shown in Figure 13 are interesting but the authors should add plots of the relative differences and RSD as mentioned above. The differences between retrievals above different surface types are described but not really analyzed and explained. An analysis of the different surface emissivities and the way they are accounted for would help to understand why the bias is negative in spring over sea and positive in summer for instance (if the spring/summer difference is significant).

- With these AK plots (figure below), we clearly see that there is a vertical information varies as a function of seasons. In spring, the AK over both surfaces (sea=often ice & land=often snow) are quite similar. And in summer, there are 2 peaks over land (1-8, 8-12 km) and over sea (1-3, 4-11 km). Moreover there is a better surface sensitivity in summer due to a better thermal contrast than in spring.
- We chose not to put these figures in the paper because it seems we have already too much plots and these are less necessary than others.

- For plots on former fig10, 11 & 13 (now fig9, 10, 12, respectively), relative differences and RSD are added.



Mean AK for profiles of former Fig 13.