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Atmospheric Measurement Techniques Discussions

Interactive comment on "Ground-based validation of the Copernicus Sentinel-5p TROPOMI NO_2 measurements with the NDACC ZSL-DOAS, MAX-DOAS and Pandonia global networks" *by* Tijl Verhoelst et al.

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Dear referee,

Many thanks for your valuable feedback on our paper. We address your concerns below (and in a modified version of the manuscript).

Lines 150-155: 1) Please address the accuracy of the stratospheric NO2 column retrieved from the ZSL-DOAS. (2) Temporal resolution of the ZSL-DOAS data and

differences of measurement time between the ZSL-DOAS and TROPOMI needs to be discussed. (3) Spatial coverage of the ZSL-DOAS data need also to be specified.
Answer: *This information is presented in the manuscript in lines 164 to 173 (geographical distribution and accuracy), and in the Section thereafter (differences in measurement time and horizontal sensitivity). For the exact dimensions of the footprint, see our answer to the following comment.*

Line 184: Please specify how large footprint which tropospheric (we assume stratospheric is meant) NO2 are averaged over. It can be a specific area size or a range of the area sizes. It will help the readers quantitatively understand the horizontal representativeness of the stratospheric NO2 column from the ZSL-DOAS.
Answer: *We added at line 187 that the length of this footprint if of the order of 300-600 km in the direction of the sun, and the width is typically of the order of 50-100 km at mid latitudes, depending on the duration of sunrise and sunset.*

Line 189: "A small negative bias": I recommend not to use "bias" unless ZSL DOAS accuracy is proven to be much higher than that of TROPOMI or space borne UV hyperspectral sensors.
Answer: *Agreed, we replaced "bias" with "median difference", also in the part of the discussion related to the stratospheric columns.*

Lines 211-220: The manuscript addresses that there is an issue of 10% overestimation of the PGN NO2 data at high altitude stations due to using cross sections at a single temperature. Please consider removing the Section 3.4 since of the PGN NO2 data at high altitude stations is not accurate enough for validating stratospheric NO2 from TROPOMI as the authors also mention it.
Answer: *The use of cross sections at a single (tropospheric) temperature in the PGN data processing indeed deserves a clear caveat. However, as the effect is "only" of the order of 10%, we believe it still makes sense to show the results: With or without a hypothetical 10% correc-*

tion, they independently confirm that TROPOMI stratospheric columns are not severely biased. We have added another explicit caveat on this issue in the PGN data presentation in Section 5.1.

Figure 7: Y Axis: (1) Why using SAT-GND? All other figures use "TROPOMI". For consistency, please consider using something like "TROPOMI-ZSLDOAS" or anything better. (2) Please enlarge the figure and explain what the colors represent in the caption?
Answer: *This is fixed in a new version of the figure.*

Section 4.1 and 4.3: (1) Authors need to address quantitative differences of tropospheric NO2 columns retrieved from various MAX-DOAS instruments and their algorithms. (2) Errors and accuracy of the retrieved tropospheric NO2 column needs to be both quantitatively and qualitatively addressed before discussing comparison results in Section 4.3.
Answer: *Information on the retrieval methods used for the different MAX-DOAS data sets has been added in table A2 and, while the assessment of the differences in tropospheric NO2 VCD due to the use of MAX-DOAS spectrometers with various instrumental performance levels and different retrieval algorithms, and hence different systematic and random uncertainty sources, is complex, the following discussion is added to Sect. 4.1 (including a new figure added to the supplement and copied at the bottom of this Author Comment):*

Published total uncertainty estimate on the NO2 tropospheric VCD are of the order of 7-17% in polluted conditions, including both random (around 3 to 10% depending on the instrument) and systematic (11 to 14%) contributions (Irie et al., 2008; Wagner et al., 2011; Hendrick et al., 2014; Kanaya et al., 2014). These ranges are more or less confirmed by the uncertainties reported in the data files, as visualized in Fig A.1 in the supplement. Nevertheless, differences in the reported uncertainties and in the actual measurement of the same scene between individual instruments are sometimes larger and the main potential sources of these inhomogeneities are listed below:

- *Different uncertainty reporting strategy: the reported systematic uncertainty may include only that from the NO2 cross sections (approx. 3%; UNAM, BIRA-IASB, MPIC, AUTH, IUPB) or it may include also a contribution from the VCD retrieval step (up to 14% in JAMSTEC data and 20% in KNMI data).*
- *Different SCD retrieval: Recommended common DOAS settings are used by all groups in the present study, and if doing so, instrument intercomparison campaigns like CINDI-1 and -2 (Roscoe et al., 2010; Kreher et al., 2020) revealed relative biases between 3 and 10% in DSCD.*
- *Different VCD retrieval methods: Using either (1) vertical profile inversion using optimal estimation (BIRA-IASB, UNAM), (2) profile inversion using parameterized profile shapes (JAMSTEC and ChibaU), (3) direct retrieval via the calculation of a tropospheric AMF (QA4ECV datasets), or (4) direct retrieval using a geometrical approximation, can lead to systematic differences in the 5-15% range (Vlemmix et al., 2015b, and Friess et al., 2019).*

Consequently, expert judgment on the total uncertainty at the network level yields a conservative estimate of 30% uncertainty in polluted conditions. Ongoing efforts to harmonise MAX-DOAS tropospheric NO2 data processing, e.g. as part of the ESA FRM4DOAS project, should help minimizing such network inhomogeneities in the near future.

Lines: 264-280: (1) Please address major factors that cause the difference between tropospheric NO2 column data obtained from MAX-DOAS and TROPOMI. (2) Please discuss the possible reason for larger discrepancy at more polluted sites. I personally think one of the things that authors need to do is to compare aerosol properties and aerosol extinction profiles used to retrieve tropospheric NO2 column between MAXDOAS and TROPOMI.
Answer: *An extensive discussion of known and potential causes for the discrepancy at polluted*

sites is indeed only provided (much) further on in the manuscript (in Section 6, near line 360). We have entered a reference to this discussion section at line 281.
Concerning the impact of the aerosols properties: This is difficult to assess qualitatively as only a subset of the MAX-DOAS stations report the AOD used in the retrieval (and this can be the one coming from the O4 analysis, from an AOD climatology as for the QA4ECV cases, or from co-located AERONET instruments), and in the TROPOMI files, only the aerosol_index_354_388 information is provided. Still, we agree it requires further discussion in the manuscript. Consequently, this possible source of discrepancies is now discussed in more detail in the 2nd bullet point in the Discussion. In particular, the following information was added:
Somewhat related to the vertical sensitivity is the treatment of aerosol optical depth and its vertical profile. Poor representation of the aerosol opacity has been shown (from simulations) to cause both underestimated NO2 in satellite retrievals and overestimated NO2 in MAX-DOAS measurements (Leitao et al., 2010; Ma et al., 2013; Jin et al., 2016). Satellite-ground discrepancies in previous validation studies have already been attributed to such aerosol issues (Boersma et al., 2018; Compernolle et al., 2020). Moreover, explicit aerosol corrections in the S5p retrievals have already been shown to improve the agreement (Liu et al., 2020).

Section 5: Total column validation: Is there any problem associated with cross section at a single temp.? Please clarify it since there is the issue at Section 3.
Answer: *Very pertinent point. The results at "clean sites" should indeed be interpreted with care as the PGN data are believed to be overestimated here by approx. 10%. This would suggest an actual positive mean difference (bias) for TROPOMI of similar size when little pollution is present, i.e. when the column is mostly stratospheric. Such a statement was added to the paper near line 340 (besides the clear caveat already formulated at the introduction of the PGN data). Note that this is somewhat at odds with the slight negative mean difference found in the ZSL-DOAS comparisons and probably reflects the true accuracy of the ground-based data, which should thus be taken to be of the order of +/- 10% at best.*

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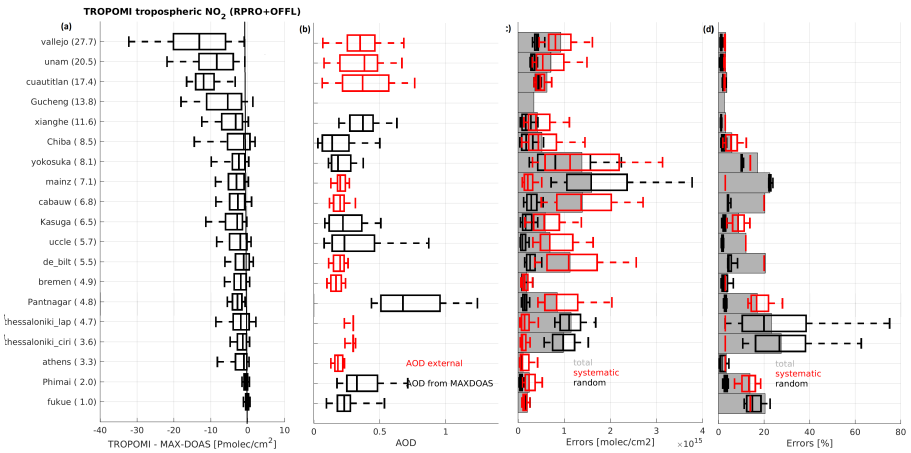
TROPOMI tropospheric NO2 (RPRO+OFFL)
(a)
vallejo (27.7)
unam (20.5)
cuautitlan (17.4)
Gucheng (13.8)
xianghe (11.6)
Chiba (8.5)
yokosuka (8.1)
mainz (7.1)
cabauw (6.8)
Kasuga (6.5)
uccle (5.7)
de_bilt (5.5)
bremen (4.9)
Pantnagar (4.8)
thessaloniki_lap (4.7)
thessaloniki_ciri (3.6)
athens (3.3)
Phimai (2.0)
fukue (1.0)
-40 -30 -20 -10 0 10
TROPOMI - MAX-DOAS [Pmolec/cm2]
(b)
AOD external
AOD from MAXDOAS
0 0.5 1
AOD
(c)
total
systematic
random
0 1 2 3 4
Errors [molec/cm2]
×10^15
(d)
total
systematic
random
0 20 40 60 80
Errors [%]

Fig. 1.