Black: referee's comments *red: authors' answers*
First of all, we want to thank the referee for the detailed analysis of our paper.
For the details, please look into the paper with keeping track of changes.

Anonymous Referee #1

General comments: The paper describes a new ground-based FTIR measurement site in China, presents a study of greenhouse gases using a ground-based Fourier Transform Infrared Spectrometer of the Bruker IFS 125HR. The measured spectra are analyzed using the GFIT-2014 code and the retrieved Xgas are presented. The XCO2 retrieved from the ground-based FTIR are compared to XCO2 retrieved from OCO-2, XCH4 and XCO retrieved from the ground-based FTIR are compared to the XCH4 and XCO retrieved from TROPOMI satellite observations. However, the description of the paper lacks scientific significance and originality. Also ,the time series of target gases cover only one year period, so some discussion and conclusions are not representative.

The paper is aim to describe the new ground-based FTIR XCO_2, XCH_4 and XCO measurements at Xianghe, and to show that the data quality of our FTIR measurement is comply with the TCCON requirement. The site is located in a very polluted area in North China, with no TCCON site at the moment. These measurements are very useful for the climate and air pollution studies as well as related satellite validation.

Specific comments:
1. The aim of the study is to validate satellite data using the FTIR observations, but the paper doesn't describe how to evaluate the accuracy or precision of the FTIR observations.
In the revised version, we reword the title, abstract, introduction and conclusion to make the target of our paper more clear. In fact, the aim of the study is to describe the ground-based FTIR data at Xianghe, and to show that the data quality of our FTIR measurement is comply with the TCCON requirement.

The data quality at Xianghe is assessed by the instrument line shape, the quality of the spectra, the uncertainty of the metadata, the residual of the fitting, and the standard deviation of the retrievals. The setup of the instrument at Xianghe follows the guidance of the TCCON, and in this paper we prove that all these parameters meet the TCCON requirements. In addition, the spectra at Xianghe are analyzed by the standard retrieval code (GGG2014), where the systematic uncertainty (accuracy) of the retrieval is mainly from the spectroscopy. According to the comparison with aircraft or AirCore measurements (Wunch et al., 2015), the systematic correction factors are already implemented in the GGG2014 code to eliminate the systematic uncertainty of XCO_2, XCH_4 and XCO retrievals (mainly from the spectroscopy uncertainty). The random uncertainties (precision) of the XCO_2, XCH_4 and XCO retrievals at Xianghe are evaluated by their standard deviations (see Table 1 and Table 2 in the revised version), and their random uncertainties are all within the TCCON reported errors (Wunch et al., 2015).

2. The discussion about day to day variations of Xgas in section 3.3 only use 6-day data, for example in Fig. 10 and 11, so the conclusions about the day to day variation trend of Xgas and the emission source are not reliable and representative.
Thanks for the suggestions. More analyses are added in the revised to make the statement reliable and representative:

Figure 1 (a, b) shows the correlations between the XCO and XCO_2 daily means and between the XCO and XCH_4 daily means at Xianghe. XCO_2 is high in winter and low in summer, and XCH_4 is high in summer and autumn and low in winter. In order to reduce the impact from the seasonal variation, a linear regression model is used to fit the time series of the measurements

$$Y(t) = A_0 + \sum_{k=1}^{3}(A_{2k-1}\cos(2k\pi t) + A_{2k}\sin(2k\pi t)) + \Delta Y(t),$$

where $Y(t)$ is the measurements of XCO_2, XCH_4 or XCO; A_0 the mean of the measurements (background), and A_1-A_6 are the amplitudes of the periodic variations during the year (seasonal variation); $\Delta Y(t)$ is the measurement without background and seasonal variations, representing the day-to-day variation. Note that, we assume there are no trends of these species due to a relatively short time coverage of about one year. Figure 1 (c, d) show the correlations between the ΔXCO and ΔXCO_2 daily means and between the ΔXCO and ΔXCH_4 daily means. The correlation coefficient (R) between XCO and XCO_2 increase from 0.50 to 0.66, and the R between XCO and XCH_4 increase from 0.67 to 0.82. The seasonal variation of ΔXCO_2 still can be observed, but the amplitude is much reduced. There is almost no seasonal variation of ΔXCH_4. Figure 2 shows the correlations in all seasons. It is found that a good correlation between ΔXCO and ΔXCH_4 is found for the whole year, with R values in the range of 0.72-0.87. There is a good correlation (R>=0.85) between ΔXCO and ΔXCO_2 in autumn and winter, and a slightly weak correlation (R=0.47) in spring and (R=0.57) in summer.
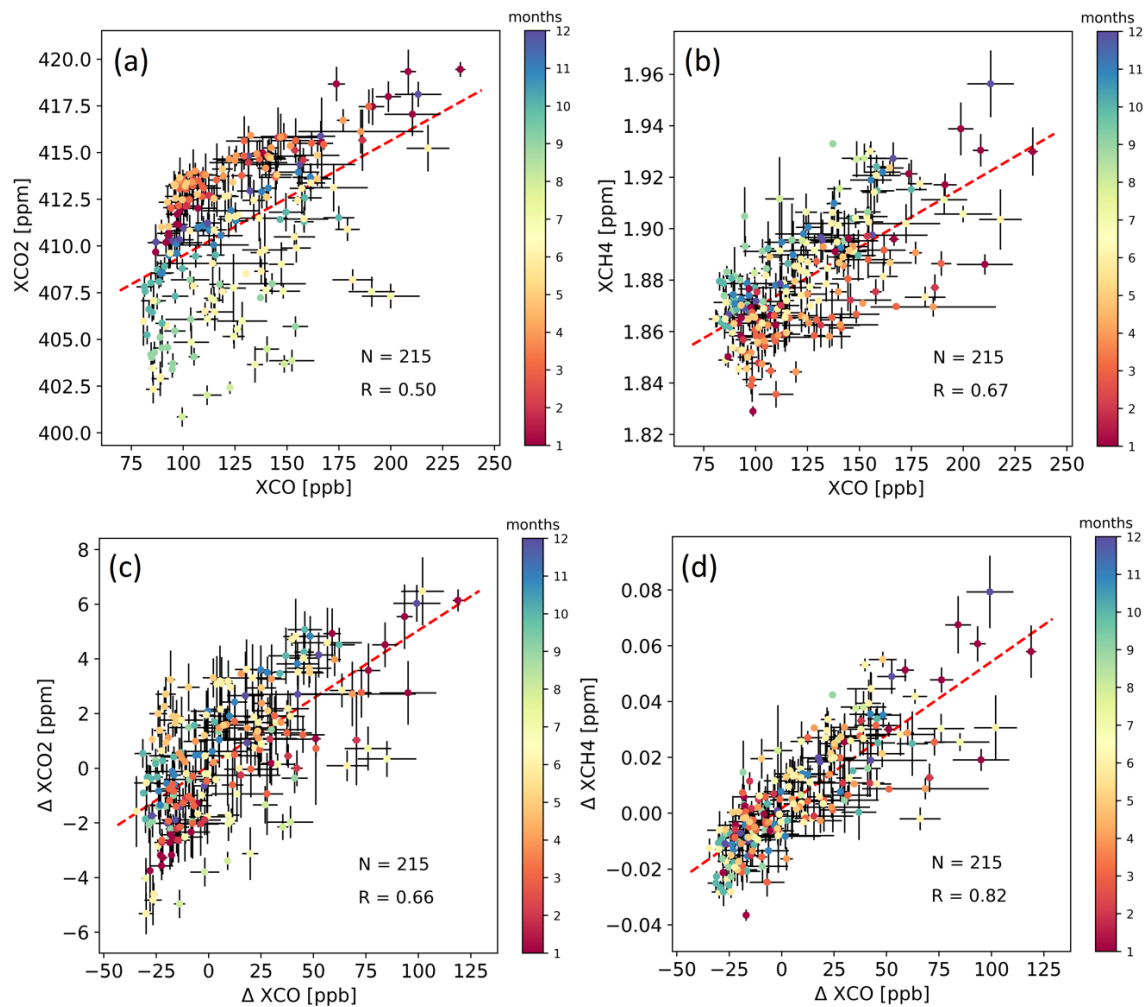

Figure 1. The correlation plots between the XCO and XCO_2 and XCH_4 daily means (a, b) and the correlation plots between the ΔXCO and ΔXCO_2, and ΔXCH_4 daily means (c, d) from

FTIR TCCON-type measurements at Xianghe. The dash red line is the linear fit. The N is the number of the measurement days, and R is the correlation coefficient. The error bar is the standard deviation of the measurements in each day. The data are colored with the measurement months.
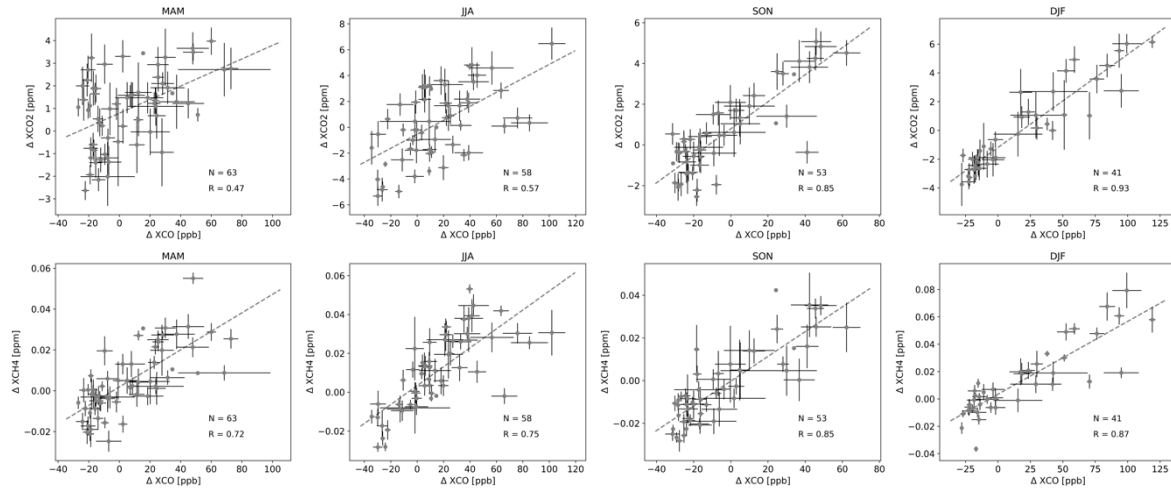

Figure 2. Upper panels: the correlation plots between the ΔXCO and ΔXCO_2 in four seasons (spring: March, April, May (MAM); summer: June, July, August (JJA); autumn: September, October, November (SON); winter: December, January, February (DJF)). Lower panels: the correlation plots between the ΔXCO and ΔXCH_4 in four seasons. The dash line is the linear fit. The N is the number of the measurement days, and R is the correlation coefficient. The error bar is the standard deviation of the measurements in each day.

In revised version, we add the Lagrangian particle dispersion model version 9.02 (FLEXPART) 10-days backward trajectories for all polluted and clean days. It is assumed that the random distribution of the ΔXCO is symmetric, and the lowest ΔXCO is -36 ppb. Therefore, each day with a $\Delta XCO>36$ ppb is classified as a polluted day, vice versa. In total, we have 28 polluted days and 187 clean days. FTIR measurements show the ΔXCO, ΔXCO_2 and ΔXCH_4 are much larger in the polluted days than those in the clean days (see Table 1).

Table 1. The mean and standard deviation of ΔXCO, ΔXCO_2 and ΔXCH_4 at polluted and clean days.

	Polluted days	Clean days
ΔXCO [ppb]	-9.51±21.10	58.40±19.58
ΔXCO_2 [ppm]	-0.64±2.05	2.75±2.01
ΔXCH_4 [ppm]	-0.003±0.016	0.029±0.019

The FLEXPART is able to simulate a large range of atmospheric transport processes, taking mean flow, deep convection, and turbulence into account. The backward running of FLEXPART provides the release–receptor relationship, which is applied to study the source and transport of the observations from a measurement site. In this study, 20000 air particles are released at Xianghe between 10:00 – 14:00 (local time) for days when FTIR measurements are available in the vertical range of surface – 2 km, and a 4-D response function to emission inventory is calculated. The model was driven by the meteorological data from the European Centre for Medium Range Weather Forecast (ECMWF). The residence time of particles in output grid cells describes the sensitivity of the receptor to the source. Figure 3 shows the mean air sources for polluted and clean days. It is found that the

air is mainly from the south and the local polluted region (North China) for the polluted days, and is mainly from the north and remote clean places (Inner Mongolia, Mongolia and Russia) for the clean days.
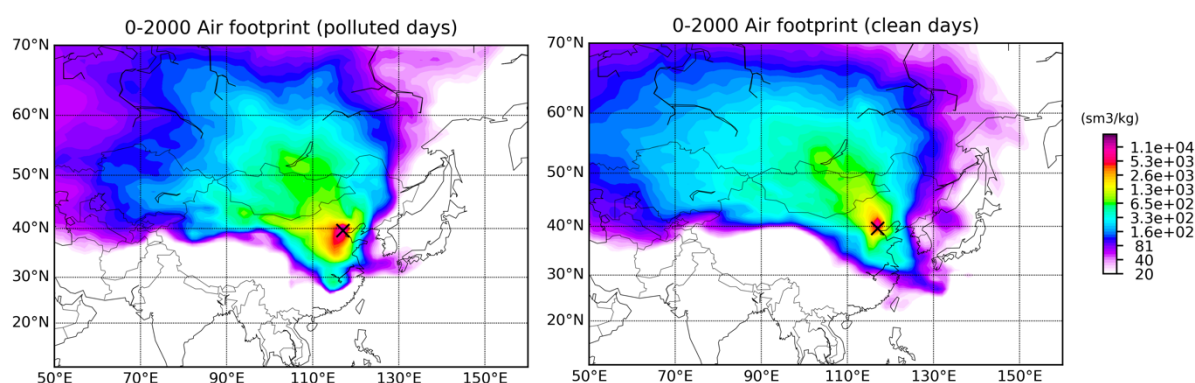

Figure 3. The mean emission response sensitivities of the air mass at Xianghe (the cross symbol) for polluted (left) and clean (right) days in the vertical range from surface to 2000 m a.s.l. simulated with a 10 day backward run with FLEXPART v9.02.

3. The FTIR measurements need to be very precise and accurate to be useful for satellite validation or model studies, a proper demonstration over a longer period of time is therefore needed for the site. However, the data cover only one year period.

Although only about one-year (June 2018 – July 2019) FTIR measurements are presented in the manuscript (in fact, the measurements are continually operating now), these measurements are still very useful for satellite validation or model studies as the following reasons:

1) We have 215 days' measurements of 15435 retrievals with good data quality between June 2018 and July 2019. As ground-based TCCON-type FTIR spectra are only recorded under the condition of the solar and clear sky, the amount of the measurement days and spectra at Xianghe are very good. As an example, at Bremen (a TCCON site), there are 235 days' measurements of 9473 retrievals during 4 years (2015-2018).

2) As the good time coverage mentioned above, the seasonal variations of XCO_2 and XCH_4 are well recognized by our FTIR measurements. The variations are compared to other TCCON sites with a similar latitude. Figure 9 shows that the phase of the seasonal variation of XCO_2 at Xianghe is close to other sites, but with a slightly larger amplitude of the seasonal variation. However, the phase of the seasonal variation of XCH_4 at Xianghe is very different from other sites, which is very interested to model studies. In addition, There is no clear seasonal variation in XCO at Xianghe, but with a much large XCO value together with a large variation. The XCO behavior is quite different compared to other sites. The time series of the FTIR measurements can be applied to study the sources and sinks of CO_2, CH_4 and CO in this region. For example, the reaction with OH is the main sink of atmospheric CH_4 (Rasmussen, et al., 1981). As the OH concentration is high in summer, there is a minimum in XCH_4 at Pasadena, Lamont and Karlsruhe. The maximum XCH_4 value in summer at Xianghe indicates that there is a strong CH_4 source in summer.

3) For satellite validation, the number of co-located FTIR measurements and OCO-2 XCO_2 measurements is 28 days, and the numbers of co-located FTIR measurements and TROPOMI XCH_4 and XCO measurements are 96 and 70 days, respectively. The number of co-located data pairs are comparable with other validation studies. Wunch

et al., (2017) used the TCCON measurements to validate the OCO-2 satellite XCO2 data for over 2 years. The number of co-located TCCON and OCO-2 data (sum of glint and nadir) pairs is less than 28 at Eureka, Sodankyla, Bialystok, Bremen, Rikubestu, Manaus. For TROPOMI validation, the FTIR measurements at Xianghe is more useful, as the TROPOMI was launched on 13 October 2017. The near real time is only available after June 2018. The FTIR measurements at Xianghe can provide very useful information in a polluted area of North China. Even for the offline reprocess data between November 2017 and June 2019, the co-located TROPOMI and FTIR data at Xianghe is much more than that at some TCCON sites (Eureka, Bremen, Paris, JPL, Darwin, Reunion). For the details, please refer to Lambert et al., (2019). In addition, Fig 12, 13, 14 show that co-located FTIR and satellite data pairs are distributed evenly in all seasons.

4. In Line 25 Page 11, "The retrieved TROPOMI CO data is in the unit of total column density (molecules/cm2), so we converted them to to XCO (ppb) values for comparison with FTIR XCO measurements", there should be a short description of the method and cite a reference.
OK, added in the revised version.

5. In Line 12 Page 12, "Regular HCl cell measurements show that the ME loss is within 2% and the PE remains within 0.02 rad", the conclusion is not consistent with the ME results in Fig. 2.
Corrected. "Regular HCl cell measurements show that the ME loss is within 5% and the PE remains within 0.02 rad".

6. There are no unit for the mean and std value in the Fig. 12, Fig .13 and Fig. 14.
The units for the mean and std are the same as shown in the y axis. Added in the revised version.

7. In Line 14 Page 1, "The rapid economic growth of China has contributed to 30% of the global total carbon dioxide (CO2) emissions from fossil fuel consumption and cement production (Jackson et al., 2017)", the exact contribution is about 28.5% according to the results in Jackson et al., 2017.
Corrected

Reference:
Lambert, J. C., Keppens, A., Hubert, D., Langerock, B., Eichmann, K., Kleipool, Q., Sneep, M., Verhoelst, T., Wagner, T., Weber, M., 30 Ahn, C., Argyrouli, A., Balis, D., Chan, K., Compernolle, S., De Smedt, I., Eskes, H., Fjæraa, A., Garane, K., and et al.: Quarterly Validation Report of the CopernicusSentinel-5 PrecursorOperational Data Products–#03:July2018–May2019, S5P MPC Routine Operations Consolidated Validation Reportseries, 3, 1–125, http://www.tropomi.eu/sites/default/files/files/publicS5P-MPC-IASB-ROCVR-03. 0.1-20190621_FINAL.pdf, 2019.

Rasmussen, R. A. and Khalil, M. A. K.: Atmospheric methane (CH4): Trends and seasonal cycles, J. Geophys. Res.-Oceans, 86, 9826–9832, https://doi.org/10.1029/JC086iC10p09826, 1981.

Wunch, D., Toon, G. C., Sherlock, V., Deutscher, N. M., Liu, C., Feist, D. G., and Wennberg, P. O.: The Total Carbon Column Observing Network's GGG2014 Data Version, p. 43, https://doi.org/10.14291/tccon.ggg2014.documentation.R0/122, 2015.

Wunch, D., Wennberg, P. O., Osterman, G., Fisher, B., Naylor, B., Roehl, C. M., O'Dell, C., Mandrake, L., Viatte, C., Kiel, M., Griffith, D. W. T., Deutscher, N. M., Velazco, V. A., Notholt, J.,

Warneke, T., Petri, C., De Maziere, M., Sha, M. K., Sussmann, R., Rettinger, M., Pollard, D., Robinson, J., Morino, I., Uchino, O., Hase, F., Blumenstock, T., Feist, D. G., Arnold, S. G., Strong, K., Mendonca, J., Kivi, R., Heikkinen, P., Iraci, L., Podolske, J., Hillyard, P. W., Kawakami, S., Dubey, M. K., Parker, H. A., Sepulveda, E., García, O. E., Te, Y., Jeseck, P., Gunson, M. R., Crisp, D., and Eldering, A.: Comparisons of the Orbiting Carbon Observatory-2 (OCO-2) X_{CO_2} measurements with TCCON, Atmos. Meas. Tech., 10, 2209–2238, https://doi.org/10.5194/amt-10-2209-2017, 2017.

Black: referee's comments red: authors' answers
First of all, we want to thank the referee for the detailed analysis of our paper.
For the details, please look into the paper with keeping track of changes.

Anonymous Referee #2
General comments The manuscript "A new site: ground-based FTIR XCO2, XCH4 and XCO measurements at Xianghe, China" by Yang et. al. describes a data set of total column dry air mole fractions of carbon dioxide, methane and carbon monoxide derived from near infrared, solar absorption Fourier transform spectroscopy using methods similar to those of the Total Carbon Column Observing Network (TCCON). The described dataset covers a year of measurements and therefore captures a single seasonal cycle. The manuscript follows a logical narrative, but in some areas would benefit from additional copy editing.

Data of this type, from an urban area of China, are likely to be of value to the satellite and model validation communities and I would encourage the publication of this manuscript subject to a number of clarifications and modifications as detailed below.

Specific comments
Reference is made to TCCON throughout the manuscript, however it is not made explicitly clear that the Xianghe site is not currently affiliated to TCCON. This should be stated from the start including what steps are required for the site to become affiliated with TCCON if that is the objective. Additionally, statements such as "this study shows that the Xianghe data comply with the TCCON specifications" at page 12 line 30 are considered quite strong and possibly misleading as, for example, the TCCON requirement for an in-situ validation is not covered in this work. Care should also be taken when making comparison to the TCCON accuracy/precision requirements, throughout the manuscript reference is made to "the 0.8 ppm (SZA less than 80 ∘) retrieval accuracy of TCCON XCO2." (e.g. at P4 L23), this is actually the target for site-to-site biases within the TCCON. The actual single instrument/site precision target for TCCON is 0.1% i.e. 0.4 ppm for XCO2. Precision estimates within the manuscript are based on the standard deviations of daily retrievals of each of the species. This may result in an overly pessimistic estimate as the daily means are potentially influenced by a number of factors such as a diurnal cycle, the influence of local sources in such a heavily urbanized area and a residual airmass dependence of the retrievals as pressure broadening is not accounted for in the GGG2014 spectroscopy. Better and more representative results may be obtained by limiting the windows over which standard deviations are calculated to a smaller range of solar zenith angles or shorter periods.
Thanks for the suggestions.
The aim of the study is to describe the ground-based FTIR data at Xianghe, and to show that the data quality of our FTIR XCO$_2$, XCH$_4$ and XCO measurements is comply with the TCCON requirement (except an in-situ validation). The site has not been affiliated to TCCON yet. Therefore, the main concern of this work is to demonstrate the quality of the spectra at Xianghe and to be ready to join TCCON in near future. Steps are added in the beginning to make the target of this paper clear.

We adapt the description about the precision of the TCCON XCO$_2$ in the revised paper. According to Pollard et al., (2017), the precision target for TCCON is 0.1% (~0.4 ppm) for XCO$_2$ to meet the model requirement (Olsen and Randerson, 2004). However, the precision of the TCCON XCO$_2$ is estimated to be 0.2% (~0.8 ppm) based on the perturbation of the GGG2014 inputs (Wunch et al., 2015).

To estimate the precision of the retrievals at Xianghe, we limit the windows over which standard deviations are calculated to a smaller range of solar zenith angle (SZA less than 30°) to reduce the potential influences, such as a diurnal cycle, the influence of local sources in such a heavily urbanized area and a residual airmass dependence of the retrievals as pressure broadening is not accounted for in the GGG2014 spectroscopy. We select all the days when at least 5 measurements are available. Table 1 is updated as follows

Table 1. The mean standard deviation (STD) of XCO_2, XCH_4 and XCO of the remaining data after solar intensity (SI) filtering for each day and the percentage of the remaining spectra amount from 14 June 2018 to 31 December 2018. Only measurements with SZA less than 30°are selected.

β (%)	γ (%)	STD(XCO_2) (ppm)	STD(XCH_4) (ppm)	STD(XCO) (ppm)	Percentage of remaining spectra (%)
85	10	0.749	0.0042	3.032	89.5
85	5	0.723	0.0036	2.954	88.9
85	0	0.667	0.0035	2.997	88.1
90	10	0.651	0.0036	2.904	86.6
90	5	0.648	0.0035	2.908	85.8
90	0	0.496	0.0035	2.559	84.7
95	10	0.450	0.0029	2.421	78.5
95	5	0.447	0.0029	2.436	77.1
95	0	0.423	0.0026	2.438	75.2

In order to reduce the variation of the measurements and to keep as many as useful measurements, we choose the β=90%，γ=0% as the criteria for the solar intensity filtering. The mean STD of XCO_2, XCH_4 and XCO are 0.496 ppm, 0.0035 ppm and 2.559 ppb, respectively, and there are 84.7% spectra remained. Note that the mean STD of XCO_2 is 0.12%, which is slightly worse than the target of the TCCON XCO_2 precision of 0.1%, but it is better than the estimated uncertainty of 0.2%. To evaluate the precision of the retrievals at Xianghe, we compare the STD of XCO_2 measurements at Xianghe with several standard TCCON sites with similar latitude (Lamont, Karlsruhe, Pasadena, Rikubetsu, Tsukuba, Saga, Orleans and Anmeyondo) in Table 2. The STD of XCO_2 at Xianghe is 0.496 ppm, which is less than most sites except Karlsruhe and Orleans. The precision of XCO_2 measured at Xianghe is comparable with other TCCON sites.

Table 2. The mean standard deviation (STD) of XCO_2 for the measurements at each day with the solar zenith angle less than 30°, together with total numbers of the days and the STD less than 0.1% for XCO_2 since January 1, 2017 at Anmeyondo, Karlsruhe, Lamont, Orleans, Pasadena, Rikubetsu, Saga, Tsukuba. At Xianghe, the measurements are between 14 June 2018 to 31 December 2018 after the SI filtering with the β=90%，γ=0%.

Sites	Latitude (N)	N (total) / N (STD < 0.1%)	Percentage (STD< 0.1%)	STD(XCO_2) (ppm)
Anmeyondo	36.5	9 / 0	0	0.925
Karlsruhe	49.1	73 / 57	78	0.311
Lamont	36.6	287 / 0	0	0.718
Orleans	48.0	49 / 41	94	0.375
Pasadena	34.1	280 / 38	14	0.524
Rikubetsu	40.0	33 / 8	24	0.507

Saga	33.2	192 / 34	18	0.589
Tsukuba	43.5	106 / 31	29	0.506
Xianghe	39.7	19 / 7	37	0.496

In addition, the table 3 is updated based on the measurements with the SZA less than 30°. For the AC+DC mode, the STD of XCO_2 with only SNR filtering is the best. If we apply both SNR filtering and SI filtering, many reasonable retrievals will be filtered out, which have bad SI flags but have been corrected by the DC correction procedure. Therefore, for the period with AC+DC mode, only the SNR filtering is applied.

Table3. Average XCO_2 daily standard deviation after (a) no filtering, (b) SNR filtering, (c) both SNR filtering and SI filtering during the AC mode and AC+DC mode periods. The unit is ppm. Only those measurements with SZA less than 30° are considered.

	AC mode	AC + DC mode
a	1.19	1.06
b	0.94	0.53
c	0.57	0.88

In sub-section 2.2 it would also be useful to present some example plots of ME and PE as a function of OPD, and as PE can have a maximum value at an OPD other than the maximum, consider presenting a time series of maximum PE. Also, LINEFIT 14.5 can be used in a number of modes, it should be explicit which mode is used.
Thanks for the suggestions.
We plot the ME and PE as a function of OPD, together with the maximum ME loss and maximum PE deviation at Xianghe in the revised version, which is showed in Figure 1. The ME has a maximum loss at the MOPD while PE has a maximum deviation at about 20 cm (positive value) or the MOPD (negative value).

These ILS parameters are retrieved by LINEFIT 14.5 using 13 HCl microwindows under non-vacuum status. The degree of freedoms for signal (DOFS) of anodization and phase are about 4.1 and 4.2, respectively.
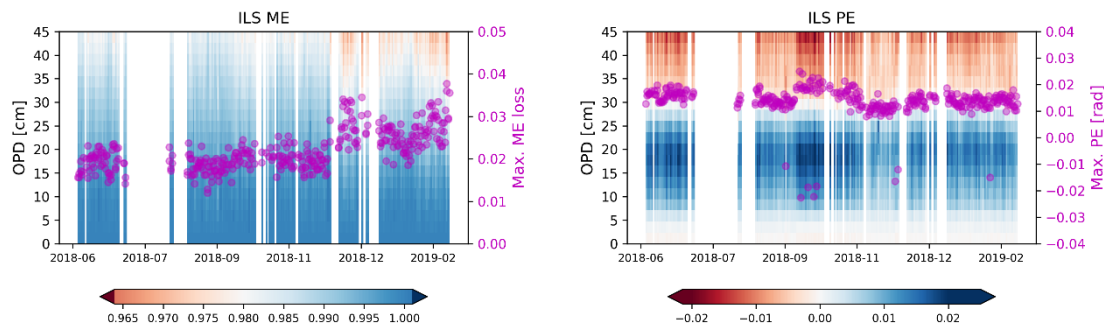

Figure 1. The modulation efficiency (ME, left panel) and phase error (PE, right panel) along the optical path difference (OPD) at Xianghe. The purple dots are the maximum ME loss (left) and the maximum PE deviation (right).
The sub-section on signal-to-noise ratio would benefit from a discussion about how SNR is calculated as there are a number of possible methods. Making this explicit would make it easier to make comparisons between sites.
Thanks for the suggestion. More information has been added in the revised paper.
We calculate SNR as the ratio between the maximum intensity of the spectrum in the spectral range of 3800-11000 cm^{-1} and the noise level. The standard deviation of the intensity

between 2350 and 2450 cm^{-1} is calculated as the noise level, since no signal is recorded in this window.

$$SNR = \max(I)/STD(noise).$$

In the paragraph describing satellite missions that can be validated by this type of measurement in the introduction, GOSAT is notable by its absence, and as one of the first satellites dedicated to measuring greenhouse gases probably deserves to be mentioned. Added.

Ongoing measurements of this type are likely to be of interest to a number of users and so a statement about whether future measurements will be added to the referenced dataset, or the TCCON archive if the site should become affiliated to the network, would be useful.
Thanks for the suggestion.
The data used in this study can be accessed by the data DOI, and the public can download them for their interests, such as satellite validation and model inversions. In the near future, we hope to join the TCCON successfully via the institutional agreement and upload the ongoing measurements to the TCCON archive.

Technical corrections
P2 L4-8 Whilst not strictly necessary, it would be useful to provide more context by comparing the current values to their pre-industrial levels and/or stating the current rate of increase.
Done

P2 L10 Provide the radiative forcing of CO2 as a comparison.
Done

P2 L13-14 Try to clarify the distinction that is being made here, i.e. are the two main types of measurement in-situ and remote sensing, or ground-based and satellite?
To avoid the confusion, we remove this sentence in the revised version.

P3 L1-2 Inclusion of the sentence "To increase the precision of the retrievals, the spectra are cloud filtered based on the separate direct solar irradiation measurements." fragments the description of the manuscript outline, considering removing it.
Done.

P3 L33 After "NIR InGaAs" insert spectra or measurements.
Done

P3 L26 - P4 L7 These two paragraphs highlight the importance of consistent representation of scalars and their vectors e.g. m and meters are both used and sometimes there is a space between the scalar and vector and sometimes not.
Corrected

P5 Eq.1 Appears to have been inserted at the wrong point in the manuscript.
Corrected

P5 L16 Please give details of these sensors, particularly the type and precision/accuracy of the pressure sensor which is very important for the accuracy of trace gas retrievals.

Added

P5 L20 Does the first "a priori partial column" refer to the tropospheric component? This should be made more explicit.
Done.

P6 L10 Consider using affected instead of infected.
Done.

P9 Eq.4 The vector I is not defined.
Added

P11 L8, L14 and L31 The Landgraf et al references do not contain a year.
Corrected

Table 2. AC+DC mode column, it would be expected that additional filtering would result in a lower value for SNR+SI (row c) than for SNR (row b) on its own. This doesn't appear to be the case.
For the AC+DC mode, the STD of XCO_2 with only SNR filtering is the best. If we apply both SNR filtering and SI filtering, many reasonable retrievals will be filtered out, which have bad SI flags but have been corrected by the DC correction procedure. Therefore, for the period with AC+DC mode, only the SNR filtering is applied.

Reference:
Olsen, S. C. and Randerson, J. T.: Differences between sur-face and column atmospheric CO2and implications for car-bon cycle research, J. Geophys. Res.-Atmos., 109, D02301,https://doi.org/10.1029/2003JD003968, 2004.

Pollard, D. F. , Sherlock, V. , Robinson, J. , Deutscher, N. M. , & Shiona, H. . (2017). The total carbon column observing network site description for lauder, new zealand. Earth System Science Data, 9(2), 977-992.

Wunch, D., Toon, G. C., Sherlock, V., Deutscher, N. M., Liu, C., Feist, D. G., and Wennberg, P. O.: The Total Carbon Column Observing Network's GGG2014 Data Version, p. 43, https://doi.org/10.14291/tccon.ggg2014.documentation.R0/122, 2015.

~~A new site:~~ New ground-based ~~FTIR~~ Fourirer-transform near-infrared solar absorption measurements of XCO_2, XCH_4 and XCO ~~measurements~~ at Xianghe, China

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Abstract. The column-averaged dry-air mole fractions of CO_2 (XCO_2), CH_4 (~~XCH_4~~ (XCH_4)) and CO (XCO) have been measured with a Bruker IFS 125HR Fourier transform infrared spectrometer (FTIR) at Xianghe (39.75 °N, 116.96 °E, North China) since June 2018. ~~The siteand the FTIR system are described in this study~~This paper presents the site, the characteristics of the FTIR system and the measurements. The instrumental setup follows the guidelines of the Total Carbon Column Observing

5   Network (TCCON)~~, and~~: the near-infrared spectra are recorded by an InGaAs detector together with a CaF$_2$ beam splitter.~~ The~~, and the HCl cell measurements that are recorded regularly to derive the instrument line shape (ILS) ~~show~~ showing that the instrument is correctly aligned. The ~~Xianghe site lies in a polluted area in North China where there are currently no TCCON sites. It can fill the TCCON gap in this region and expand the global coverage of the TCCON measurements. The TCCON~~ TCCON standard retrieval code (GGG2014) is applied to retrieve XCO_2, XCH_4 and XCO. The ~~time series,~~ resulting time series

10   between June 2018 and July 2019 are presented, and the observed seasonal cycles and day-to-day variations of XCO_2, XCH_4 and XCO ~~measurements at Xianghe between June 2018 and July 2019 are shown and~~ at Xianghe are discussed. In addition, the ~~FTIR measurements have been used to validate~~ paper shows comparisons between the data products retrieved from the FTIR measurements at Xianghe and co-located Orbiting Carbon Observatory-2 (OCO-2) and Tropospheric Monitoring Instrument (TROPOMI) satellite observations~~, as also shown in this paper~~. The comparison results appear consistent with validation results

15   obtained at TCCON sites for XCO_2 and XCH_4, while for XCO they highlight the occurrence of frequent high-pollution events. As Xianghe lies in a polluted area in North China where there are currently no TCCON sites, this site can fill the TCCON gap in this region and expand the global coverage of the TCCON measurements. The Xianghe FTIR ~~CO~~XCO_2, ~~CH~~XCH_4 and ~~CO~~ XCO data can be ~~accessed at~~ obtained at https://doi.org/10.18758/71021049 (Yang et al., 2019).

1   Introduction

20   The rapid economic growth of China has contributed to ~~30~~28.5% of the global total carbon dioxide (CO_2) emissions from fossil fuel consumption and cement production (Jackson et al., 2017). China dominates global CO_2 fossil emissions with an average

increase of 3.8%yr^{-1} between 2008 and 2017 (Le Quéré et al., 2018). In addition, 14% to 22% of the global anthropogenic methane (CH_4) emissions in the 2000s were attributed to China (Kirschke et al., 2013). It is clear that China should play an important role in the reduction of global carbon emission and climate change mitigation. A decreasing linear trend of -0.41 $\pm$ 0.09%yr^{-1} in carbon monoxide (CO) concentrations from 2005 to 2016 has been observed over East Asia and 76% of this decrease is due to the CO emission control in China (Zheng et al., 2018). However, the estimation of Chinese carbon emissions still have large uncertainties, ranging from $\pm$ 5% to $\pm$ 10% (Gregg et al., 2008; Le Quéré et al., 2018; Andres et al., 2012). A good understanding of carbon emissions requires accurate monitoring of CO_2, CH_4, CO and other direct and indirect greenhouse gases.

CO_2 is the most important anthropogenic greenhouse gas with a radiative forcing of 1.82 $\pm$ 0.19 W/m^2 in 2013 (IPCC, 2013). The globally averaged surface dry-air mole fraction of CO_2 increases steadily in the atmosphere ~~since~~ from 278 ppm pre-industrial ~~times~~ level and has reached up to 405.5 $\pm$ 0.1 ppm in 2017 (WMO, 2018). The annual increasing rate of CO_2 in the atmosphere during the last 10 years is 2.24 ppm/year (WMO, 2018). The enhancement of CO_2 is primarily caused by human activities, such as the fossil burning and the land-use change (Peters et al., 2012). Atmospheric CH_4 is the second important anthropogenic greenhouse gas, and its globally averaged surface dry-air mole fraction increased from pre-industrial of 722 ppb up to 1859 $\pm$ 2 ppb in 2017 (WMO, 2018), with an average growth rate of 7 ppb/year during the last decade. Although the CH_4 abundance is much lower than that of CO_2, the comparative impact of CH_4 is about 28 times greater than CO_2 over a 100-year period (IPCC, 2013). It is reported that the radiative forcing of CH_4 has increased to 0.48 $\pm$ 0.05 W/m^2 in 2013 (IPCC, 2013). 50-65% of CH_4 is released from human activities such as energy production/consumption, industry, agriculture, biomass burning, and waste management activities and another 40% from natural emissions (IPCC, 2013). Atmospheric CO is an indirect greenhouse gas and is mainly emitted from fossil fuel combustion and biomass burning (Yin et al., 2015). ~~There are mainly two methods to measure these three gases, in situ and remote sensing measurements including ground-based Fourier Transform Infrared (FTIR) measurements and satellite measurements that are discussed hereafter.~~

The Total Carbon Column Observing Network (TCCON) uses ground-based FTIR spectrometers to measure the direct solar radiation in the near infrared spectral region, from which the total column-averaged dry-air mole fractions of CO_2, CH_4, N_2O, CO, HF, H_2O and HDO are retrieved (Wunch et al., 2011b). Because of their relatively high precision and accuracy, TCCON data are widely used in satellite validations and model comparisons (Zhou et al., 2016; Ostler et al., 2016; Crisp et al., 2017; Borsdorff et al., 2018; Velazco et al., 2019). Today, there are 25 active TCCON sites (https://tccon-wiki.caltech.edu/) covering the latitude band from 80 °N to 45 °S. Most TCCON sites are in North American, Europe, East Asia (South Korea and Japan) and Oceania. The Hefei station, located in Eastern China, is the first Chinese site that will potentially join the TCCON network. In 2016, a FTIR Bruker IFS 125HR instrument was installed at Xianghe (39.75 °N, 116.96 °E, 30m a.s.l.) and started observations following the TCCON settings in June 2018. As there are no TCCON sites in North China, the FTIR at Xianghe aims to fill the gap in the network in this region.

The Japanese Greenhouse gases Observing Satellite (GOSAT) was successfully launched in 2009 by the Japan Aerospace Exploration Agency (JAXA). It is the first spacecraft to measure atmospheric CO_2 and CH_4 with high-resolution spectra at SWIR wavelength (Kuze et al., 2009). The Orbiting Carbon Observatory-2 (OCO-2) was launched on 2 July 2014 by NASA

and is devoted to enhancing our understanding of regional scale CO_2 exchanges between the surface and the atmosphere (Crisp et al., 2004; Eldering et al., 2017; Crisp et al., 2017). The Tropospheric Monitoring Instrument (TROPOMI) was launched by ESA on 13 October 2017 as the single payload of the Sentinel-5 Precursor (S5P) satellite. It aims at providing accurate and timely observations of abundances of atmospheric species, such as CH_4 and CO, for air quality and climate change research and services (Borsdorff et al., 2018). However, previous validation work (Wunch et al., 2017; Lambert et al., 2019) based on FTIR measurements has no study in North China due to the absence of TCCON sites in this area, so that it is important to add Xianghe site for evaluation of satellite products in this area.

In this paper, we describe the ground-based FTIR system at Xianghe, with a focus on the measurements of atmospheric CO_2, CH_4 and CO (Yang et al., 2019). The column-averaged dry-air mole fractions of these gases are retrieved by the GGG2014 (Wunch et al., 2015) code in the period between 14 June 2018 and 19 July 2019. The paper is structured as follows. Section 2 introduces the Xianghe site and the FTIR system. In Section 3, the retrieval and filtering methods are described. ~~To increase the precision of the retrievals, the spectra are cloud filtered based on the separate direct solar irradiation measurements.~~ The time series of XCO_2, XCH_4 and XCO are shown and discussed. In the next Section, the OCO-2 (XCO_2) and TROPOMI (XCH_4 and XCO) satellite observations are ~~validated~~ compared with the FTIR measurements at Xianghe. Finally, conclusions are drawn in Section 5.

2 FTIR measurements

2.1 Location and experimental set-up

Xianghe site has been operated by the Institute of Atmospheric Physics, Chinese Academy of Sciences since 1974. The site is about ~~50km~~ 50 km to the east-southeast of Beijing and 70 km to the north-northwest of Tianjin (see Figure 1, right panel). The Xianghe county acts as an integrated transportation and transfer center in Beijing-Tianjin-Hebei region, which is one of the most populous and economically dynamic areas in China (Ran et al., 2016). Xianghe has a middle latitude monsoon climate, with a prevailing south-east wind in summer and a north-west wind in winter (Song et al., 2011). The maximum temperature at Xianghe site is around 38 °C in summer, and the minimum temperature is around -10 °C in winter. The raining days occur mainly in summer including some days with extreme precipitations larger than 100 mm/day.

The Bruker IFS 125HR instrument was installed in the upper level of a four-story building in June 2016. About 2 years later, in June 2018, a solar tracker was installed on the roof (50 m a.s.l.), to guide the direct solar radiation into the FTIR instrument. The distance between the solar tracker and the entrance window of the FTIR instrument is about 3 ~~meters~~m. The solar tracker uses a camera inside the IFS 125HR spectrometer to ensure that the center of the solar disk always focuses on the entrance aperture of the spectrometer, with an active feedback loop. This system is set up following the developments from Neefs et al. (2007) and Gisi et al. (2011). The FTIR operates only under clear-sky daytime conditions. A rain sensor and a solar irradiation (both total and direct) sensor, are installed next to the solar tracker, to monitor the weather conditions and to control the opening and closing of the solar tracker hatch. To protect the mirrors (Aluminum, coating with MgF_2) of the solar tracker, the hatch of the tracker automatically closes under rainy conditions and during nighttime. A heating system is operated

in the tracker system to keep the temperature of the rotary stages and the mirrors close to 15°C in winter. Inside the lab, the air-conditioning keeps the room temperature stabilized around 25 °C.

The near infrared (NIR) spectra are recorded by a indium gallium arsenide (InGaAs) detector and the middle infrared (MIR) spectra are recorded by a liquid nitrogen cooled indium antimonide (InSb) detector. The entrance window and the beamsplitter

5 are made of CaF_2. The spectral ranges of the NIR and MIR spectra are 3800-11000 cm^{-1} and 2000-5000 cm^{-1}, respectively. The InSb detector at Xianghe records spectra in the AC mode. The InGaAs detector at Xianghe was operated in the AC mode before 31 May 2019, but since then in the AC + DC mode to be compliant with TCCON standards. The spectrometer settings automatically alternate between NIR and MIR measurements during each clear-sky day. The entrance aperture of the spectrometer in the NIR spectrum is set to 0.5 mm and changed to 0.8 mm after 19 June 2019. There are approximately 70

10 NIR InGaAs spectra for each clear day. The InGaAs spectra are recorded with a maximum optical path difference (MOPD) of ~~45cm~~ 45 cm, corresponding to a spectral resolution of 0.02 cm^{-1}. Each measurement contains 2 scans (one forward and one backward), taking about 145 s.

About ~~50m~~ 50 m south-west of the laboratory building, a weather station is operated on a ~~110m-height~~ 110 m-height tower, at 62 ~~meters~~ m above the ground, measuring pressure, temperature, humidity, wind direction and wind speed. The pressure

15 sensor is located inside the LI-7550 Analyzer, which has an accuracy of 1 hPa. On 30 May 2019, a new weather station was installed at the same height as the solar tracker. The distance between the weather station and the solar tracker is about 2 ~~meters~~m. The pressure sensor is PTB210A Digital Barometer, with an accuracy of 0.07 hPa.

2.2 Instrument line shape

The instrument line shape (ILS) reflects the performance and alignment of the instrument (Schneider et al., 2008), which might

20 be distorted by the shear or angular misalignment of the instrument or the field of view (FOV) (Hase et al., 1999; Wunch et al., 2015). A perfectly-aligned interferometer will perfectly center the Haidinger fringes on the field stop at all optical path differences (OPD). The offset between the moving cube-corner retro-reflector (CCRR) and the fixed CCRR will cause the Haidinger fringes moving away from the center when the mirror moves away from ~~ZOPD~~ zero optical path difference (ZOPD) and this is called shear misalignment. The angular misalignment is caused when the IR beam is not parallel to the

25 rails. At Xianghe 2 HCl cell spectra are recorded every day after sunset. The modulation efficiency amplitude (ME) and phase error (PE) ~~along the OPD are retrieved using the~~ are retrieved by LINEFIT14.5 ~~code~~ using 13 HCl microwindows under non-vacuum status (Hase et al., 1999). The degree of freedoms for signal (DOFS) of apodization and phase are about 4.1 and 4.2, respectively. The ME is derived from the ratio of the misaligned fringe amplitude to the theoretical fringe amplitude. LINEFIT14.5 normalizes ME to be 1.0 at ~~zero optical path difference (ZOPD). According to the TCCON requirement the ME~~

30 ~~changes must be within 5% and the PE must be less than 0.02 rad at MOPD (Wunch et al., 2011b). Figure~~ ZOPD. Figure 2 shows the ~~time series of the~~ ME and ~~the~~ PE ~~at~~ along with the OPD, together with the maximum ME loss and maximum PE deviation at Xianghe. The ME has a maximum loss at the MOPD while PE has a maximum deviation at about 20 cm (positive value) or the MOPD ~~(45 cm)at Xianghe. The last date ends on 31 March 2019 when~~ negative value). Note that the Tungsten lamp used to measure the HCl cell spectra broke down in February 2019. According to the TCCON requirement, ME changes

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must be within 5% at MOPD and PE less than 0.02 rad (Wunch et al., 2011b). The mean of the ~~ME is 0.978~~ maximum ME loss is 0.022 ± 0.004, and the mean of the ~~PE is -0.008~~ maximum absolute PE deviation is 0.014 ± ~~0.002 rad. Figure 2 shows that~~ 0.003 rad. Only few days in September 2018 have maximum absolute PE slightly larger than 0.02 rad. In general, the alignment of the instrument slightly declines over time, but the ME and PE remain compliant with the TCCON requirements during the whole time period. A sensitivity study performed by Hase et al. (2013) showed that the uncertainty in XCO_2 is about 0.035% (0.14 ppm) for a ME change of 4%, which is within the 0.8 ppm (SZA less than 80 °) estimated retrieval accuracy of TCCON XCO_2. Since the ME of the FTIR instrument at Xianghe is about 2-3%, the uncertainty from the ILS on the greenhouse gas retrievals can be ignored.

2.3 Signal-to-noise ratio

The time series of the signal-to-noise ratio (SNR) of the InGaAs spectra at Xianghe is shown in Figure 3. The SNR (Eq.1) is calculated as the ratio between the maximum intensity ($max(I)$) of the spectrum in the spectral range of 3800-11000 cm^{-1} and the noise level. The standard deviation of the intensity between 2350 and 2450 cm^{-1} ($STD(noise)$) is calculated as the noise level, since no signal is recorded in this window.

$$SNR = max(I)/STD(noise). \tag{1}$$

There are no measurements between 7 July and 22 August 2018 due to a power cut. The SNR decreases quickly with time because Xianghe is located in a polluted area (Robert and Richard, 2015; Li et al., 2007) causing rapid degradation of the mirrors of the solar tracker (Feist et al., 2016). In order to obtain a high SNR, the mirror of the solar tracker was cleaned on 14 November 2018 (first yellow line in Figure 3), with the SNR increased from 300 to 500. However, the SNR decreased back to the level of 300 about 3 weeks later, probably because of the increased level of air pollution and relatively lower solar irradiation in winter. The polluted mirror of the solar tracker was replaced with a new one on February 1, 2019 (second yellow line in Figure 3), enhancing the SNR from about 300 to 450. With the DC signal recording (first red line in Figure 3), between May 31 2019 and June 19 2019 the SNR dropped quickly below 200. Therefore, the aperture size was increased from 0.5 to 0.8 mm on 19 June 2019 (second red line in Figure 3) and the mirror was cleaned again on 25 June 2019 (third yellow line in Figure 3), making the SNR rise again above the level of 300.

3 FTIR retrievals

3.1 Retrieval Methodology

The non-linear least-squares fitting code GGG2014 (Wunch et al., 2015) is used to retrieve XCO_2, XCH_4, XCO and some other gases from the NIR solar absorption spectra at Xianghe.

$$TC_r = TC_a + \boldsymbol{A}(\boldsymbol{x_t} - \boldsymbol{x_a}) + \varepsilon, \tag{2}$$

where TC_a and TC_r are the a priori and retrieved total columns, $\boldsymbol{A}$ is the column averaging kernel, $\boldsymbol{x_t}$ and $\boldsymbol{x_a}$ are true and a priori partial column profiles, ε is the uncertainty. In the forward model, there are 70 equidistant 1km thick layers from the mean sea level up to ~~70km~~ 70 km altitude. The a priori profiles of gases are generated by an empirical model based on surface in situ, Atmospheric Chemistry Experiment - Fourier Transform Spectrometer (ACE-FTS~~and MkIV~~) and the Jet Propulsion

5 Laboratory MkIV (Mark IV) interferometer measurements. The inter-annual trends and seasonal variations of the species are taken into account, and the a priori profiles are adjusted based on the local tropopause pressure at local noon (Toon and Wunch, 2015). The temperature, pressure and water vapour profiles are taken from the National Centres for Environmental Prediction (NCEP) reanalysis data (Kalnay et al., 1996). The surface pressure, temperature and water vapour are from the local weather station.

10 The column averaging kernel represents the vertical sensitivity of the retrieved total column to the true partial column profile. The typical averaging kernels of XCO_2, XCH_4 and XCO are shown in Figure 4 of Wunch et al. (2011a). In general, the retrieved CO_2 and CH_4 total columns have good sensitivity in the troposphere and the stratosphere. The retrieved CO column underestimates a deviation from the a priori partial column in the troposphere but overestimates a deviation from the a priori partial column in the stratosphere.

15 The retrieval windows of CO_2, CH_4, CO and O_2 are listed in Table 1 in Wunch et al. (2010). As an example, Figure 4 shows the residuals of the spectral fitting for CO_2 and O_2 for one NIR spectrum at a SZA of 22.9 °at Xianghe. The root mean square of the residuals for CO_2 in the spectral window ~~6180-6260cm~~ 6180-6260 cm $^{-1}$, CO_2 in the window 6297-6382 cm^{-1} and O_2 in the window 7765-8005 cm^{-1} are 0.24%, 0.25% and 0.37%, respectively, which compare well to the results in Toon et al. (2009).

20 The spectroscopy is the ATM line list (Toon, 2017). The total column-averaged dry-air mole fraction of gas (X_{gas}) is then derived from the ratio between the retrieved total column of the target species and the retrieved total column of O_2 and from the dry-air mole fraction of O_2 (0.2095)

$$X_{gas} = 0.2095 \times column_{gas}/column_{O_2}. \tag{3}$$

Using the ratio between the target species and O_2 reduces the uncertainties common to both gases, e.g., the surface pressure, 25 water vapour, solar tracker pointing and zero level offsets. In addition, a post-processing of the results is done: (1) the airmass dependence of the retrieval results which is known to be an artifact caused by spectroscopic uncertainties, is reduced by applying an empirical airmass-dependent correction, and (2) a constant scaling factor for each gas is applied to calibrate the TCCON measurements to the WMO scale (Wunch et al., 2015, 2010).

3.2 Data quality control

30 As the recording time for one InGaAs spectrum takes about 145 s, the stability of the incoming solar intensity during this period is important for the quality of the spectrum (Beer, 1992). If there are clouds or heavy aerosols in the light path between the FTS and the sun during the spectrum recording, the fractional line depth in FTIR spectra will be distorted (Ridder et al., 2011; Keppel-Aleks et al., 2011). To select the good quality spectra, we have discarded all the spectra with SNR less than 200.

The DC correction can be used to remove the solar irradiation variation in each spectrum (Keppel-Aleks et al., 2007). To filter out spectra ~~infected~~ affected by the occurrence of clouds or high aerosol load before May 31, 2019 (in AC recording mode), we use the variations of the direct solar irradiation observed from the solar irradiation detector installed close to the solar tracker system (see Section 2.1). The solar direct irradiation is recorded every 3 seconds providing us with about 25 measurement points per forward or backward scan. If there are no clouds or strong loads of aerosol during the scan, the direct solar irradiation should remain relatively stable. We have classified measurement points during the scan as problematic if the solar intensity is lower than a certain percentage threshold β of the maximum intensity. A spectrum is selected as a good one if the number of problematic measurement points is smaller than or equal a certain percentage threshold γ of the total number of measurement points during the measurement. We tested the filtering method with γ values of 0%, 5% and 10%, and β values of 85%, 90% and 95% on all InGaAs spectra (about 12000) from 14 June 2018 to 31 December 2018. ~~The daily~~ To estimate the precision of the retrievals at Xianghe, we limit the windows over which standard deviations (STD) ~~of XCO_2, XCH_4 and XCO~~ are calculated to ~~compare with the expected random retrieval uncertainties. Note that only days with more than 20 measurements per day are used to calculate the daily STD~~ a smaller range of solar zenith anglee (SZA less than 30°) to reduce the potential influences, such as a diurnal cycle, the influence of local sources in such a heavily urbanized area and a residual airmass dependence of the retrievals as pressure broadening is not accounted for in the GGG2014 spectroscopy. We select all the days when at least 5 measurements are available. The results are shown in Table 1. The STDs of XCO_2, XCH_4 and XCO decrease with ~~increased~~ increasing β or ~~decreased~~ decreasing γ thresholds. The β and γ values are selected mainly based on the XCO_2 data. According to ~~Wunch et al. (2015), the retrieved XCO~~ Pollard et al. (2017), the precision target for TCCON is 0.1% ($\sim$0.4 ppm) for XCO_2 ~~random uncertainty of TCCON data is about 0.2 % (0.8 ppm) with SZA less than 80 degrees. To reach this precision, the STD of our~~ to meet the model requirement (Olsen and Randerson, 2004). However, the precision of the TCCON XCO_2 ~~measurements should be less than~~ is estimated to be 0.2% ($\sim$0.8 ppm~~, but at the same time, we try to keep the number~~) based on the perturbation of the GGG2014 inputs (Wunch et al., 2015). In order to reduce the variation of the measurements ~~as large as possible. Therefore, we have chosen to set~~ and to keep as many as useful measurements, we choose the β=90~~%and~~%, γ=0~~% . This filtering, together with the SNR filter, makes us reach the required precision for~~% as the criteria for the solar intensity filtering. The mean STD of XCO_2, XCH_4 and XCO are 0.496 ppm, 0.0035 ppm and 2.559 ppb, respectively, and there are 84.7% spectra remained. Note that the mean STD of XCO_2 is 0.12%, which is slightly worse than the target of the TCCON XCO_2 ~~also in the period before 31 May 2019.~~ precision of 0.1%, but it is better than the estimated uncertainty of 0.2%. To evaluate the precision of the retrievals at Xianghe, we compare the STD of XCO_2 measurements at Xianghe with several TCCON sites with similar latitude (Lamont, Karlsruhe, Pasadena, Rikubetsu, Tsukuba, Saga, Orleans and Anmeyondo), and the STD of XCO_2 at Xianghe is comparable with these sites.

The ~~110m-height~~ 110 m-height meteorology tower is collinear with the solar irradiation sensor and the sun tracker. It generates a shadow on the mirror of the tracker system, affecting the spectra in the afternoon. The duration of the shadow is about 8-15 minutes, corresponding to about 2-3 InGaAs measurements. The shadow occurs at around 6:30 UTC (14:30 LTC) in summer and around 9:30 UTC (16:30 LTC) in winter. The upper panel in Figure 5 shows the solar direct intensity from 1 October 2018 to 3 October 2018, with a zoom in over the time period between 6:36 and 7:02 (UTC) on 2 October 2018 when

the tower shadow is observed by the FTIR (see the inside camera image in the middle panel). The affected XCO_2 retrieval during the shadow appearing time are displayed in the bottom panel. The spectra sampling time is recorded at time of ZOPD. The blue dots in the upper panel denote the SNR of spectra filtered out with solar intensity (SI), the cyan dots denote the SNR of spectra filtered out with SNR, and the red dots denote the SNR of spectra after both filtering. All of these SNR values are

5   also zoomed in the middle panel of Figure 5. It is clear that the spectra polluted by the tower shadow can be filtered out by the combination of SNR filtering and SI filtering with $\beta = 90\ \%$ and $\gamma = 0\ \%$ (see cyan and blue dots in middle panel, appearing in the same period with the shadow). The other blue dots in the upper panel appearing outside the shadow shows that SI filtering can also filter out spectra which are polluted by clouds.

     Figure 6 shows the time series of XCO_2 with and without filtering between 14 June 2018 and 19 July 2019. In the bottom

10   panel, the cyan dots denote all the XCO_2 values ~~before~~ without any filtering, the blue dots denote the XCO_2 values after SNR filtering applied and the red dots denote the XCO_2 values after both SNR and SI filtering ~~have been~~ applied. In the upper panel, the blue dots denote the daily STDs of XCO_2 when only the SNR filtering is applied, while the red ones denote the daily STDs of XCO_2 when both the SNR and the SI filtering are applied. Based on the measurements with the SZA less than 30°, Table 2 shows that SNR filtering apparently reduces the average daily STDs both before (from ~~1.39 ppm to 1.14~~ 1.19 ppm to 0.94

15   ppm) and after (from ~~1.34 ppm to 0.76~~ 1.06 ppm to 0.53 ppm) DC signal recording. It is clear that before ~~31 May 2019, more DC recording, many~~ XCO_2 outliers are removed by the SI filtering, with the average daily STD of XCO_2 decreasing from ~~1.14 ppm to 0.71 ppm. After 31 May 2019, the SNR filtering already discards most of the bad spectra, and the average~~ 0.94 ppm to 0.57 ppm. However, the SI filtering makes the STD of XCO_2 ~~daily STDs with SNR filtering and SNR~~ increases from 0.53 ppm to 0.88 ppm for the AC+~~SI filtering are 0.76 ppm and 0.83 ppm , respectively in this~~ DC period. The ~~DC signal can help~~

20   ~~to reduce the influence from clouds and the tower, thus the SIfiltering has little influence to these data. In following analysis, we only use the data after both SNR and SI filtering for the whole period~~main reason is that many retrievals corrected by the DC correction procedure are still filtered out with SI. Therefore, for the period with AC+DC mode, only the SNR filtering is applied.

     Poor instrument alignment, spectral ghost, error in the time assigned to the spectrum or faulty pressure sensor may cause a

25   dramatic jump in X_{air} (Washenfelder et al., 2006; Wunch et al., 2011a). The retrieved X_{air} (after ~~both SNR and SI~~ filtering) are shown in Figure 7 to confirm the good quality of the retrievals. X_{air} is defined as

$$X_{air} = \frac{TC_{dry,air}}{TC_{O_2}/0.2095} = \frac{0.2095}{TC_{O_2}} \left[\frac{P_s}{gm_{dry,air}} - TC_{H_2O}\frac{m_{H_2O}}{m_{dry,air}} \right]. \tag{4}$$

where $m_{dry,air}$ and m_{H_2O} are the molecular mass of dry air and water vapour and g is the column-averaged gravitational acceleration, P_s is the surface pressure and $TC_{dry,air}$, TC_{O_2} and TC_{H_2O} are total columns of dry air, O_2 and H_2O, respectively.

30   The X_{air} is around 0.98 due to a $\sim$2.0% bias in the O_2 spectroscopy (Kivi and Heikkinen, 2016). Figure 7 shows that the X_{air} at Xianghe all pass TCCON standard quality check (between 0.96 and 1.04) and is stable over time with a mean value of 0.982 and a STD of 0.003.

3.3 Retrieval results and discussions

The time series of XCO$_2$, XCH$_4$ and XCO after both SNR and SI filtering from June 2018 to July 2019 are shown in Figure 8. The monthly mean of XCO$_2$, XCH$_4$ and XCO at Xianghe, Pasadena (34.1°N) (Wennberg et al., 2014), Lamont (36.6°N) (Wennberg et al., 2016) and Karlsruhe (49.1°N) (Hase et al., 2014) from June 2018 are also displayed in Figure 9. Based on these measurements, the seasonal variations and day-to-day variations of XCO$_2$, XCH$_4$ and XCO are assessed.

XCO$_2$ is low in summer and high in winter and spring at Xianghe, with maximum monthly mean 414.27 $\pm$ 0.94 ppm in April and minimum monthly mean 401.58 $\pm$ 1.32 ppm in August. This seasonal behaviour is similar to those at Pasadena, Lamont and Karlsruhe, which are located in the northern mid-latitude zone. The peak-to-peak amplitude of the seasonal variation of XCO$_2$ ~~(computed as the difference between the maximum monthly mean and minimum monthly mean)~~ is 12.41 ppm, which is larger than 7.45 ppm at Pasadena, 7.78 ppm at Lamont and 7.98 ppm at Karlsruhe. XCH$_4$ is low in spring and high in autumn and summer, with a maximum monthly mean of 1.893 $\pm$ 0.017 ppm in August and a minimum monthly mean of 1.857 $\pm$ 0.014 ppm in March. It is found that the seasonal cycle of the XCH$_4$ at Xianghe is very different with other sites at a similar latitude, as the observations at the other 3 stations show low values in summer and high values in autumn and winter~~(Figure 9, middle panel)~~. The peak-to-peak amplitude of the XCH$_4$ seasonal variation is about 0.039 ppm at Xianghe, which is also larger than 0.029 ppm at Pasadena, 0.028 ppm at Lamont and 0.024 ppm at Karlsruhe. XCO at Xianghe is relatively high during the whole year. The background value of XCO is about 90 ppb, and the high XCO measurements can reach up to 200 ppb. The monthly mean XCO values at Xianghe are always higher than those at the other 3 stations~~(Figure 9, lower panel), .~~ indicating that regional pollution sources are frequently observed at Xianghe.

Similar day-to-day variations are observed among XCO$_2$, XCH$_4$ and XCO. ~~For example, the mole fractions of these three species increase together from 8 to 12 January 2019 and drop down on 13 January 2019 (see Figure 10).~~ The high values are related to the local emissions while the low values are influenced by the air transported from remote places. ~~Back trajectories of 72 hours at Xianghe are shown in~~ In this section, we use CO as a trace gas to evaluate the correlations between XCO and XCO$_2$, XCO and XCH$_4$. Figure 10 (a, b) shows the correlations between the XCO and XCO$_2$ daily means and between the XCO and XCH$_4$ daily means at Xianghe. XCO$_2$ is high in winter and low in summer, and XCH$_4$ is high in summer and autumn and low in winter. In order to reduce the impact from their seasonal variations, a linear regression model is used to fit the time series of measurements

$$Y(t) = A_0 + \sum_{k=1}^{3}(A_{2k-1}cos(2k\pi t) + A_{2k}sin(2k\pi t)) + \Delta Y(t), \tag{5}$$

where $Y(t)$ is the measurements of XCO$_2$, XCH$_4$ or XCO; A_0 is the measurements (backgrounds), and A_1 - A_6 are the amplitudes of the periodic variations during the year (seasonal variation); $\Delta Y(t)$ is the measurement without background and seasonal variations, representing the day-to-day variation. Note that, we assume there are no trends of these species due to a relatively short time coverage of about one year. Figure ~~11 using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model . The air is released at altitudes of 500, 2000 and 5000 m a~~ 10 (c, d) show the correlations between the ΔXCO and ΔXCO_2 daily means and between the ΔXCO and ΔXCH_4 daily means. The correlation coefficient (R)

between XCO and XCO_2 increases from 0.50 to 0.66, and the R between XCO and XCH_4 increases from 0.67 to 0.82. The seasonal variation of ΔXCO_2 still can be observed, but the amplitude is much reduced. There is almost no seasonal variation of ΔXCH_4. ~~g.l. at local noon on 8, 12 and 13 January 2019. The Meteorological data are from NCEP Global Forecast System, with a horizontal resolution of 0.5°×0.5°and 55 hybrid sigma-pressure levels.~~ Figure 11 shows ~~that the air arriving at Xianghe are mainly coming from the west and north during this period. The emission sources are mainly influencing the air arriving at 500 m altitude above Xianghe: on 8 and 13 January 2019 these are mainly coming from the north-west of Xianghe with a relative fast wind speed, while on 12 January 2019 they are mainly coming from the west of Xianghe with a much slower wind speed. As shown in Figure 1, Beijing is situated west of Xianghe,~~ the correlations in each season. The good correlations between ΔXCO and ΔXCH_4 are found for the whole year, with the R in the range of 0.72-0.87. There is a good correlation (R>=0.85) between ΔXCO and ΔXCO_2 in autumn and winter, and a worse correlation (R=0.47) in spring and (R=0.57) in summer. It is assumed that the random distribution of the ~~mountains are located at the west and north of Beijing. The air in the lower troposphere on~~ ΔXCO is symmetric, and the lowest ΔXCO is about -36 ppb. Therefore, each day with a $\Delta XCO >$ 36 ppb is classified as a polluted day, vice versa. In total, we have 28 polluted days and 187 clean days. FTIR measurements show the ΔXCO, ΔXCO_2 and ΔXCH_4 are much larger in the polluted days than those in the clean days (see Table 3).

The 10-days backward trajectories for polluted and clean days classified by CO measurements are also plotted using the Lagrangian particle dispersion model version 9.02 (FLEXPART). The FLEXPART is able to simulate a large range of atmospheric transport processes, taking mean flow, deep convection, and turbulence into account. The backward running of FLEXPART provides the release-receptor relationship, which is applied to study the source and transport of the observations from a measurement site. In this study, 20000 air particles are released at Xianghe between 10:00 - 14:00 (local time) for days when FTIR measurements are available in the vertical range of surface-2 km, and a 4-D response function to emission inventory is calculated. The model was driven by the meteorological data from the European Centre for Medium Range Weather Forecast (ECMWF). The residence time of particles in output grid cells describes the sensitivity of the receptor to the source. Figure 12 ~~January 2019 is strongly affected by the strong local pollution, while the air arriving on 8 and 13 January 2019 are originating in relatively~~ shows the mean air sources for polluted and clean days. It is found that the air is mainly from the south and the local polluted region (North China) for the polluted days, and is mainly from the north and remote clean places (Inner Mongolia~~and Mongolia)~~, Mongolia and Russia) for the clean days.

4 Satellite validation

4.1 Methodology

In this section, the FTIR XCO_2, XCH_4 and XCO measurements at Xianghe are used to ~~validate~~ compare with the OCO-2 XCO_2 and TROPOMI XCH_4 and XCO satellite observations. There are 215 days' measurements of 15435 individual FTIR retrievals. The co-located FTIR-satellite data pairs are selected based on spatial-temporal collocation criteria. The detailed selection criteria for each target (OCO-2 XCO_2, TROPOMI XCH_4 and TROPOMI XCO) are described in the subsections 4.2 and 4.3: they account for the scan width of the satellite instrument and the characteristics of the target species.

According to Rodgers and Connor (2003), the differences in a priori profiles should be taken into account when comparing ground-based FTIR and satellite observations. TCCON CO_2, CH_4 and CO a priori profiles (70 layers) have been discussed in Section 3.1. OCO-2 CO_2 a priori profiles (19 layers) are created based on the GLOBALVIEW dataset and change with time and location (O'Dell et al., 2012). TROPOMI uses the global chemical transport model TM5 to get CH_4 and CO a priori profiles (12 layers) (Borsdorff et al., 2018; Hasekamp et al., 2019). The TM5 model data are monthly means with a horizontal resolution of 3̶2̶°latitude ×2̶3̶°longitude and 60 vertical levels (Krol et al., 2005). In this study, the satellite a priori profile (OCO-2 or TROPOMI) is taken to be the common a priori profile in the comparison. To substitute the satellite a priori profile in the FTIR retrieval we follow Rodgers and Connor (2003):

$$X'_{FTIR} = X_{FTIR} + (\boldsymbol{A} - \boldsymbol{I})(\boldsymbol{x}_{a,FTIR} - \boldsymbol{x}_{a,SAT}), \tag{6}$$

where X'_{FTIR} is the FTIR retrieved total column using the satellite a priori profile, X_{FTIR} is the original FTIR retrieval, $\boldsymbol{A}$ is the FTIR TCCON column averaging kernel, $\boldsymbol{I}$ is the unit vector, $\boldsymbol{x}_{a,FTIR}$ and $\boldsymbol{x}_{a,SAT}$ are the a priori partial column profiles of FTIR and satellite retrievals, respectively. As the vertical layering of the FTIR retrieval is different from that of the satellite retrieval (OCO-2 or TROPOMI), the satellite a priori profile is re-gridded to the FTIR layer. After re-gridding, the total a priori column remains unchanged (Langerock et al., 2015).

To compare the FTIR and satellite column measurements, the satellite measurements are corrected for a possible difference between the altitudes of its ground pixel and that of the FTIR site at Xianghe. If the surface altitude of the satellite footprint is higher than the altitude of the FTIR instrument, the FTIR a priori profile ($\boldsymbol{x}_{a,FTIR}$) is used to fill the gap between the satellite lowest level ($P_{s,SAT}$) and the FTIR height ($P_{s,FTIR}$), otherwise the satellite a priori profile is considered to be the profile between the satellite lowest level and the FTIR height. Then the partial column of dry air ($PC_{dry,air}$) or target species (PC_{gas}) between the satellite footprint surface altitude and the FTIR surface altitude is calculated as

$$PC_{dry,air} = \int_{P_{s,SAT}}^{P_{s,FTIR}} \frac{dP}{g_{(P)}(m_{dry,air} + m_{h2o}\overline{\nu}_{h2o})}, \tag{7}$$

$$PC_{gas} = \int_{P_{s,SAT}}^{P_{s,FTIR}} \frac{dP}{g_{(P)}(m_{dry,air} + m_{h2o}\overline{\nu}_{h2o})} x_{(P)}, \tag{8}$$

where $g_{(P)}$ is gravitational acceleration at height P, $x_{(P)}$ is the a priori VMR profile of each target gas, $\overline{\nu}_{h2o}$ is the VMR of water vapor in the dry air, calculated as

$$\overline{\nu}_{h2o} = \frac{\nu_{h2o}}{1 - \nu_{h2o}}, \tag{9}$$

where ν_{h2o} is the VMR of water vapor in the wet air. Then each satellite pixel measurement is scaled with one scaling factor (α) related to satellite pixel level, which is computed as

$$\alpha = \frac{(TC_{gas}^{SAT} + PC_{gas})}{TC_{gas}^{SAT}} \bigg/ \frac{(TC_{dry,air}^{SAT} + PC_{dry,air})}{TC_{dry,air}^{SAT}}, \tag{10}$$

where $TC_{dry,air}^{SAT}$ and TC_{gas}^{SAT} are the total column of dry air and target species in the satellite measurement column. The random error of FTIR measurements together with the systematic and random errors of satellite measurements are considered here for the comparison.

4.2 OCO-2

5 OCO-2 incorporates three imaging grating spectrometers to measure near-infrared spectra. The spectral resolution of OCO-2 is approximately 20 times lower than that of the TCCON FTIR (0.02 cm^{-1}) instruments (Frankenberg et al., 2015). OCO-2 collects 8 soundings over its 0.8°swath width every 0.333s with a 16-day repeat cycle (https://ocov2.jpl.nasa.gov/observatory/ instrument/). The OCO-2 XCO$_2$ measurements are retrieved by the ACOS retrieval algorithm (O'Dell et al., 2012), based on the optimal estimation method. Three bands (0.756 μm, 1.61μm and 2.06 μm) are used in the XCO$_2$ retrieval. The a priori surface

10 pressure, profiles of temperature and water vapor are from 3-hourly ECMWF model forecast fields and linearly interpolated in space and time to the satellite footprint. Note that there are three versions (v7, v8 and v9) available on the NASA website for the OCO-2 data. Each version comes in two variants: full and lite. The full variant contains all the retrieved parameters, but without any post-correction applied to the data. The lite variant only includes some important parameters, but the data are corrected in terms of a footprint-dependent bias, a parameter-dependent bias and a scaling bias according to the WMO

15 trace-gas standard scale. Compared to v7, many parameters have been improved in v8, such as latitude-dependent problems, surface model, spectroscopy, potential instrumental problems, atmospheric scattering by clouds and aerosols, a spatial-temporal sampling error of a priori surface pressure and the systematic pointing offsets (O'Dell et al., 2012). Based on v8, v9 has a better estimation of the surface pressure, and it shows a better performance in regions with rough topography such as over Lauder (New Zealand) (Kiel et al., 2019). In this study, the latest v9 lite data are selected (https://ocov2.jpl.nasa.gov).

20 The satellite measurements are selected within 5° latitude × 10° ~~longtitude~~ longitude around Xianghe, these are the same criteria as adopted by Wunch et al. (2017). For each FTIR measurement, the nearby satellite measurement in the spatial collocation box, with less than 2-hours~~'~~' measurement time difference, is chosen to form one FTIR-satellite data pair. Note that there are nadir and glint observational modes of OCO-2 measurements over Xianghe, and these two types of measurements are combined together to get a statistically robust result ~~because of the limited number (~~with 28 ~~days) of data pairs~~ data pairs

25 (Wunch et al., 2017).

The time series of the ~~collocated~~ co-located OCO-2 and ground-based FTIR data from 27 June 2018 to 31 May 2019 (last date of satellite data availability) is shown in Figure ~~12.~~13. To avoid the influence from the cloud, we select the co-located data pair, which has at least 20 OCO-2 measurements within the box. The upper panel in Figure ~~12~~13 (left) shows the daily mean bias of measured XCO$_2$ from OCO-2 and FTIR. The mean of OCO-2 measurements is 0.62 ppm lower than that of the

30 FTIR measurements, with a STD of 1.20 ppm. The absolute differences between OCO-2 v9 lite data and Xianghe FTIR data are comparable with the results found for the v7 lite products in Wunch et al. (2017) for other TCCON stations with biases ranging from -0.7 ± 1.32 ppm (Wollongong) to 0.9 ± 1.49 ppm (Karlsruhe) in land glint mode and ranging from -0.1 ± 1.04 ppm (Wollongong) to 1.6 ± 2.05 ppm (Garmisch) in nadir mode. The scatter plot of OCO-2 and FTIR at Xianghe is shown in the right panel in Figure ~~12~~13: the derived correlation coefficient (R) is 0.959. We can conclude that OCO-2 data are in good

agreement with the Xianghe FTIR data, and in particular, that OCO-2 captures the seasonal cycle of XCO_2 at Xianghe, with a maximum in winter-spring and a minimum in late summer.

4.3 TROPOMI

In this section, the TROPOMI XCH_4 and XCO are compared with the FTIR measurements at Xianghe. TROPOMI is a grating spectrometer measuring solar radiation reflected by the Earth and observes in the ultraviolet and visible, near-infrared and shortwave infrared spectral regions. It has a wide swath of around 2600 km across the track and a daily global coverage of the Earth. The spatial resolution of TROPOMI is about 7km × 7km before 6 August 2019 and then it changes to 7.2km × 5.6km. The TROPOMI CO data are provided in three different data streams: the near-real-time (NRTI) stream ~~, the~~ (since June 2018, with the same starting month as FTIR measurements at Xianghe), the Offline stream (OFFL) and the Reprocessing (RPRO) stream (Landgraf et al., 2019a). CH_4 data are provided in bias-corrected and not-corrected versions (Landgraf et al., 2019b). In our validation, we considered the off-line and reprocessed CO data, from processor versions 01.02 and higher. For CH_4, we also look at bias-corrected data with processor versions of 01.02 and higher. The FTIR measurements at Xianghe can provide very useful information in a polluted area of North China, which is also important for TROPOMI product validation.

TROPOMI uses the RemoTeC algorithm to retrieve CH_4 column using the 0.757-0.774 μm O_2 absorption band and 2.305-2.385 μm CH_4 absorption band (Hasekamp et al., 2019). The requirements for the accuracy and precision for TROPOMI XCH_4 are 1% and 1.5%, respectively (Hasekamp et al., 2019). We select TROPOMI XCH_4 measurements that occur within 1 hour of FTIR measurements and within a distance of 100 km from the Xianghe station based on the collocation criteria adopted at other TCCON sites (Lambert et al., 2019). In agreement with Landgraf et al. (2019b), the TROPOMI pixels are selected with a quality assurance value above 0.5, which removes pixels with processing errors, anomalously high signals and increasing specular reflection of sunlight by the sea surface (Hasekamp et al., 2019). Similar to OCO-2, to reduce the influence from the clouds, we only select the days when there are at least 5 co-located TROPOMI CH_4 pixels.

The left panel in Figure ~~13~~ 14 shows the time series of co-located TROPOMI and FTIR XCH_4 daily means and their relative biases (%,(satellite-FTIR)/FTIR) from 27 June 2018 to 19 July 2019 (86 days). The co-located TROPOMI and FTIR XCH_4 data pairs at Xianghe are distributed evenly in all seasons. The mean bias is -0.60 %, which is within the S5P validation requirement of a bias of 1%. In addition, the STD of the relative biases is 0.55 %, which also meets the S5P mission requirement of 1.5% (Lambert et al., 2019). The R between TROPOMI and FTIR XCH_4 daily means is 0.834 (Figure ~~13~~14, right panel). According to the TROPOMI validation report (Lambert et al., 2019), the bias at Xianghe is comparable to the ones at Tsukuba, Lamont and Rikubetsu (similar latitude band).

The TROPOMI XCO measurements are retrieved from the SICOR algorithm (Hasekamp et al., 2019) in the 2.3 μm spectral range. The retrieved TROPOMI CO data is in the unit of total column density (molecules/cm^2), so we converted them to to XCO (ppb) values for comparison with FTIR XCO measurements ~~.~~(Langerock et al., 2015):

$$XCO = \frac{TC_{CO}}{TC_{dry,air}^{SAT}},$$ (11)

where XCO is the total column-averaged dry-air mole fraction of TROPOMI CO measurements. TC_{CO} is the total column density of TROPOMI CO measurements, $TC_{dry,air}^{SAT}$ is total column density of dry air in the satellite measurement column. Because CO is relatively reactive compared to CH_4, we must reduce the measurement time and location differences in the colocation criteria. Therefore, the TROPOMI observations are selected within 30 minutes of each FTIR measurement and within a maximum distance of 50 km away from the FTIR site and along the light path of the ground-based FTIR measurements. Similar to CH_4, we only select the days when there are at least 5 co-located TROPOMI CO pixels. In addition, to reduce the impact from long light paths through the atmosphere (Landgraf et al., 2019a), the TROPOMI measurements with a SZA larger than 80°or a satellite zenith angle larger than 65°are filtered out. And we only select the TROPOMI CO products in clear sky cases with cloud height below 500 m and cloud optical depth < 0.5.

The left panel of Figure ~~14~~ 15 shows the time series and relative biases of co-located TROPOMI and FTIR XCO daily means at Xianghe from 27 June 2018 to 31 May 2019 (70 days). In addition, the co-located TROPOMI and FTIR XCO data pairs at Xianghe are also distributed evenly in all seasons. The mean bias and STD between TROPOMI and FTIR are 2.05% and 7.82%, respectively, which are within the S5P mission requirement (bias < 15% and STD < 10%). Compared to other TCCON sites(Lambert et al., 2019), the mean relative bias is ~~quite lower, which is because high pollution events are frequently observed at Xianghe while the satellite CO partial column a priori profile is under-estimated in the lower troposphere over Xianghe~~relatively low. The good agreement between TROPOMI and FTIR XCO with a R of 0.961 (Figure ~~14~~15, right panel) highlights the good performance of TROPOMI over Xianghe.

5 Conclusions

A new ~~atmospheric~~ ground-based FTIR ~~site equipped with a Bruker IFS~~ Bruker 125HR instrument has been in operation since 14 June 2018 at Xianghe (39.75 °N, 116.96 °E) in North China. ~~The NIR spectra are recorded~~ It performs NIR solar absorption measurements of XCO_2, XCH_4 and XCO following the TCCON operation ~~procedures. As it is a rather polluted location, it can provide useful information for the study of the carbon cycle in North China and the validation of related satellite observations.~~ and data analysis procedures since June 2018. Regular HCl cell measurements show that the ME loss is within ~~2%~~ 5% for the whole time period, and the PE deviation remains within 0.02 rad ~~, confirming~~ in most time, confirming that the ILS of the FTIR ~~is well aligned~~ spectrometer is stable during the considered time period and meets the TCCON ~~requirement.~~ requirements. XCO_2, XCH_4 and XCO have been retrieved using the TCCON standard algorithm GGG2014. ~~The~~ Because the InGaAs spectra have been recorded in AC mode before 31 May 2019 and AC+DC mode ~~since then: the~~ afterwards, we designed a filtering method based on SNR and SI~~filtering are applied for both periods,~~. Application of this filtering to the spectra before 31 May 2019 shows that about 85% ~~spectra are selected as the good spectra . The uncertainty of~~ of the spectra have the required quality. The thus achieved precision of 0.8 ppm for the retrieved XCO_2 ~~at both time periods keep consistent (about 0.8 ppm; close to the TCCON uncertainty), reflecting~~ complies with the TCCON requirements, demonstrating that the SI filtering can overcome the absence of the DC signal in the ~~first period .~~ period before end of May 2019.

During this 1-year period of measurements, a clear seasonal variation of XCO_2 has been observed, with lowest values of 401.58 ± 1.32 ppm in summer and highest values of 414.27 ± 0.94 ppm in winter. Low XCH_4 concentrations are observed in spring (1.857 ± 0.014 ppm) and high values in autumn and summer (1.893 ± 0.017 ppm). For XCO there is no clear seasonal variation, but a large day-to-day variability. According to the FTIR measurements, it is found that the high values of XCO_2, XCH_4 and XCO are highly related, which is affected by the large local anthropogenic emissions.

Comparisons between the XCO_2, XCH_4 and XCO FTIR measurements at Xianghe and satellite data are shown to illustrate that this site is an interesting additional site for satellite validation in northern China. The mean bias between FTIR and OCO-2 XCO_2 measurements is -0.62 ppm with a STD of 1.20 ppm. The mean and STD of the relative differences between FTIR and TROPOMI XCH_4 measurements are -0.60% and 0.55%, respectively. Both results are consistent with comparisons between these satellite data and other TCCON sites. The mean and STD of the relative differences between FTIR and TROPOMI XCO measurements are 2.05% and 7.82%, respectively, which is within the S5P mission requirements. However, the mean relative bias is lower than what is observed at other TCCON sites. This is due to the fact that Xianghe is a highly polluted site while the TROPOMI a priori CO profiles underestimate CO in the lower polluted troposphere. The variability is however well captured by TROPOMI. Therefore, the ground-based FTIR measurements at Xianghe appear very useful to evaluate the performance of the greenhouse gases observing satellites (OCO-2 and TROPOMI) above this region.

In summary, this study shows that the ground-based FTIR Xianghe data for XCO_2, XCH_4 and XCO comply with the TCCON specifications. The objective is to become a TCCON affiliated site in future. As Xianghe is a rather polluted location, it can provide useful information for the study of the carbon cycle in North China, and for the validation of satellite observations over this region.

6 Data availability

The Xianghe FTIR CO_2, CH_4 and CO data can be accessed at https://doi.org/10.18758/71021049 (Yang et al., 2019). The OCO-2 data are publicly available (https://ocov2.jpl.nasa.gov). The TROPOMI data are publicly available (https://scihub.copernicus.eu/).

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Competing interests. The authors declare that they have no conflict of interest.

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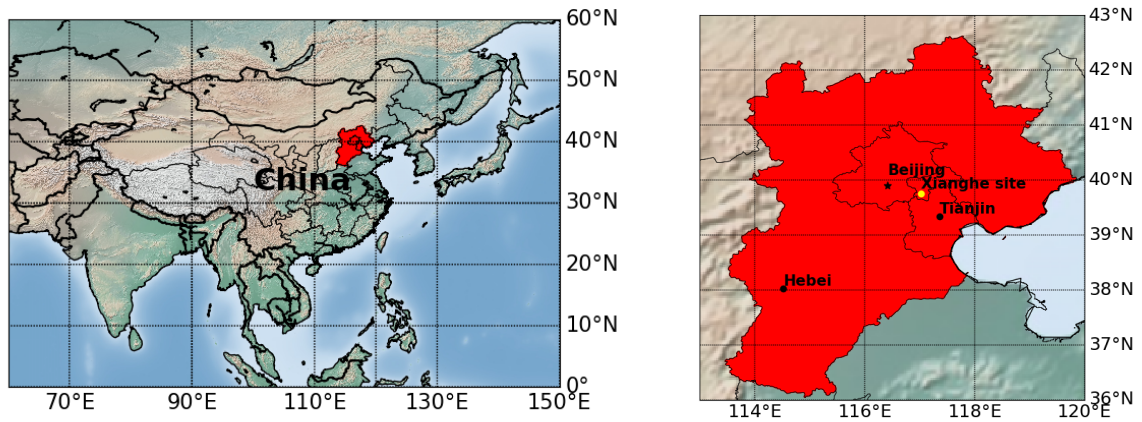
Figure 1. Map of China, the Beijing-Tianjin-Hebei region is the red shadow area which is also zoomed in the right panel. It is one of the most populous and economically dynamic regions in China. Xianghe site (yellow spot in the right panel) is located in Xianghe county, about ~~50km~~ 50 km to the east-southeast of Beijing and 70 km to the north-northwest of Tianjin, acting an integrated transportation and transfer center in this region.
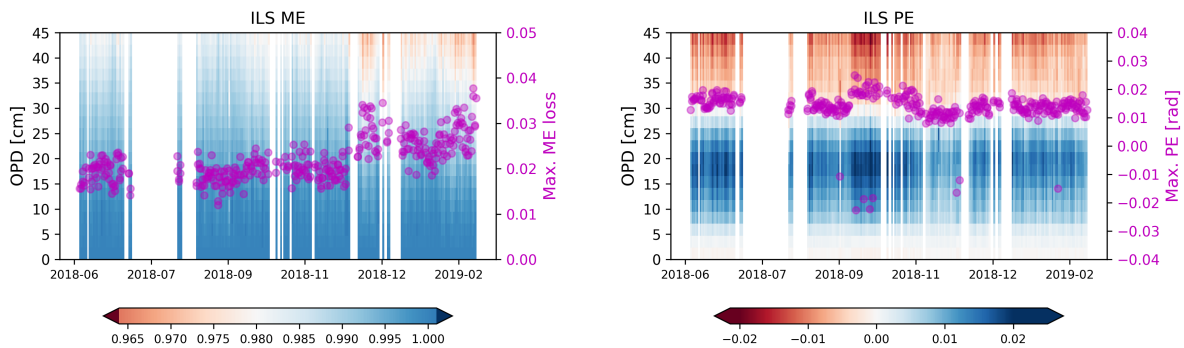

Figure 2. The ~~time series of retrieved~~ modulation efficiency (ME, left panel) and phase error (PE, right panel) ~~at maximum~~ along the optical path difference (~~45cm~~OPD) at Xianghe. The purple dots are the maximum ME loss (left) and the maximum PE deviation (right).

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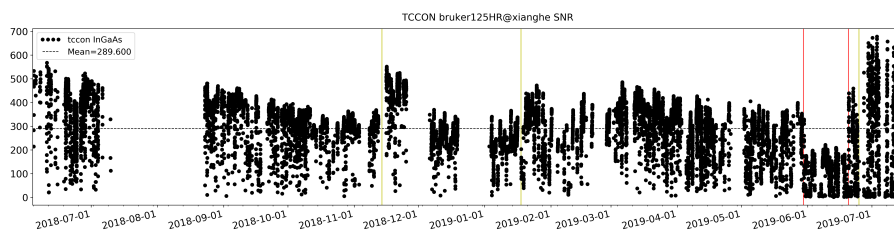
Figure 3. Time series of the signal-to-noise ratio (SNR) of the InGaAs spectra from the FTIR in Xianghe. The yellow lines indicate solar tracker maintenances: cleaning of the mirrors on 14 November 2018 and 25 June 2019, and replacement of the degraded mirror on February 1, 2019. The first red line indicates the day when we add DC signal recording (31 May 2019) and the second red line indicates the day when the aperture was increased from 0.5mm to 0.8mm (19 June 2019).
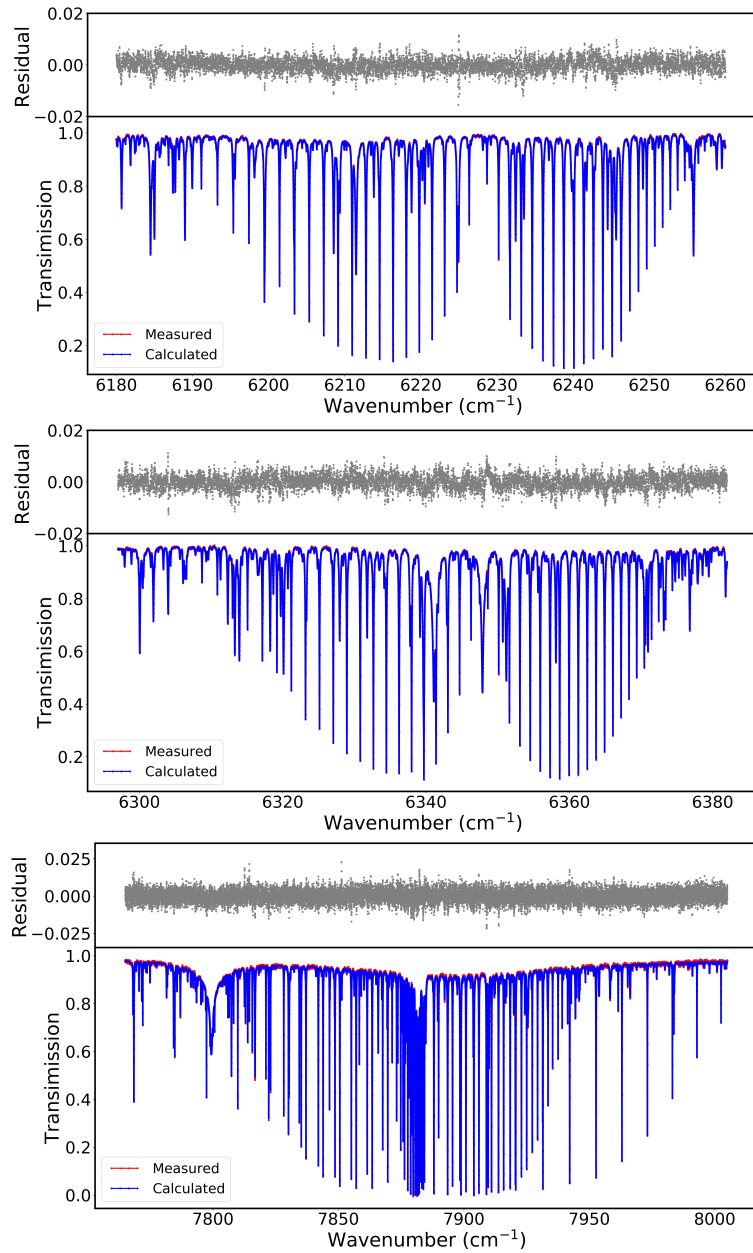
Figure 4. Measured and calculated spectrum of CO_2 in spectral window of 6180-6260 cm^{-1} (upper panel), CO_2 in spectral window of 6297-6382 cm^{-1} (middle panel) and O_2 in spectral window of 7765-8005 cm^{-1} (bottom panel).
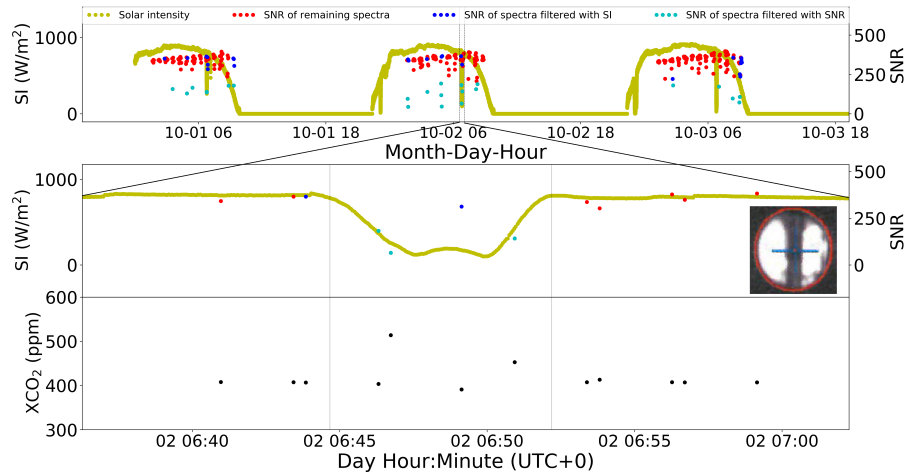
Figure 5. The solar direct intensity from 1 October 2018 to 3 October 2018, with a zoom on the time period between 6:36 and 7:02 (UTC) on 2 October 2018 when the tower shadow is observed by the FTIR (see the inside camera image, middle panel). The blue dots in the upper panel denote the SNR of spectra filtered with solar intensity (SI), the cyan dots denote the SNR of spectra filtered with SNR, and the red dots denote the SNR of spectra after both filtering. The affected XCO_2 retrieval during the shadow appearing time are displayed in the bottom panel.
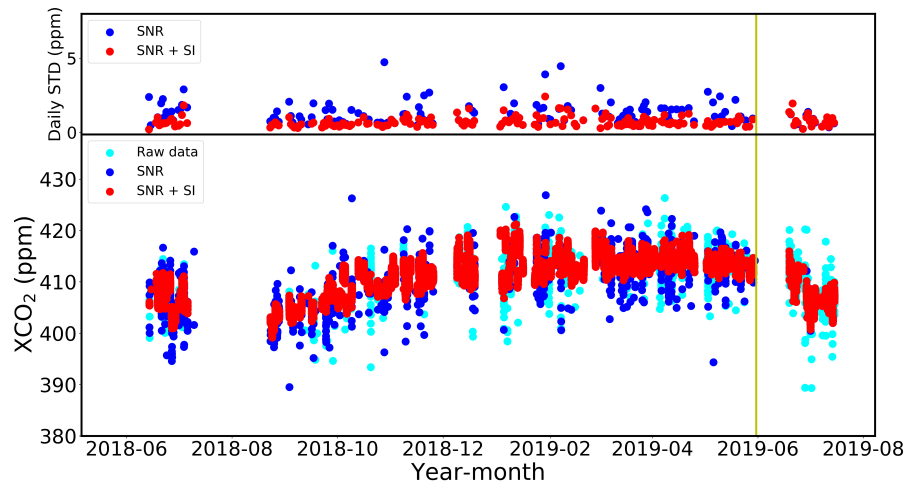
Figure 6. Time series of XCO_2 from 14 June 2018 to 19 July 2019 before and after spectra selection. The cyan dots denote all the raw data, the blue dots in bottom panel are those retrieved XCO_2 after SNR filtering and the red dots are those retrieved XCO_2 after SNR + SI filtering. In upper panel, the blue dots denote the daily standard deviation of XCO_2 only with SNR filtering while the red ones denote those with SNR + SI filtering. The yellow line denotes the day (31 May 2019) when we added the DC signal recording.
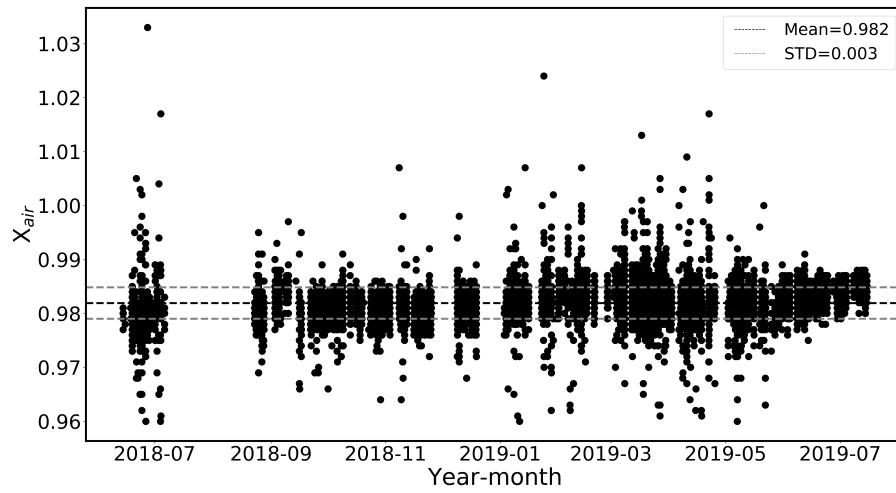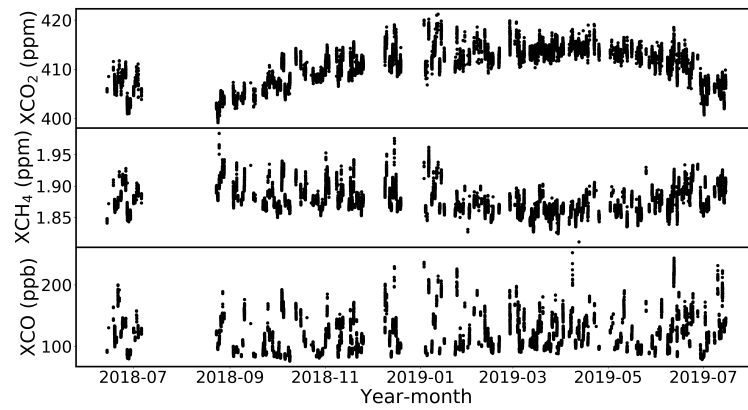
Figure 7. Time series of X_{air}.

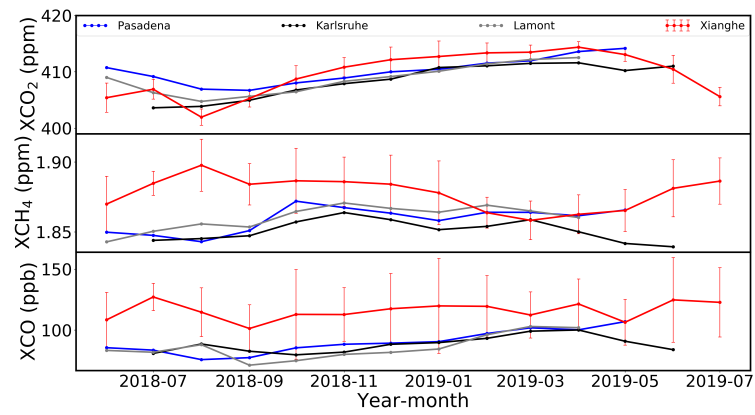**Figure 8.** Time series of XCO_2, XCH_4 and XCO covering the period from 14 June 2018 to 19 July 2019.

Figure 9. Monthly mean of XCO_2, XCH_4 and XCO at Pasadena, Karlsruhe, Lamont and Xianghe. The error bars are the monthly STDs of XCO_2, XCH_4 and XCO at Xianghe.
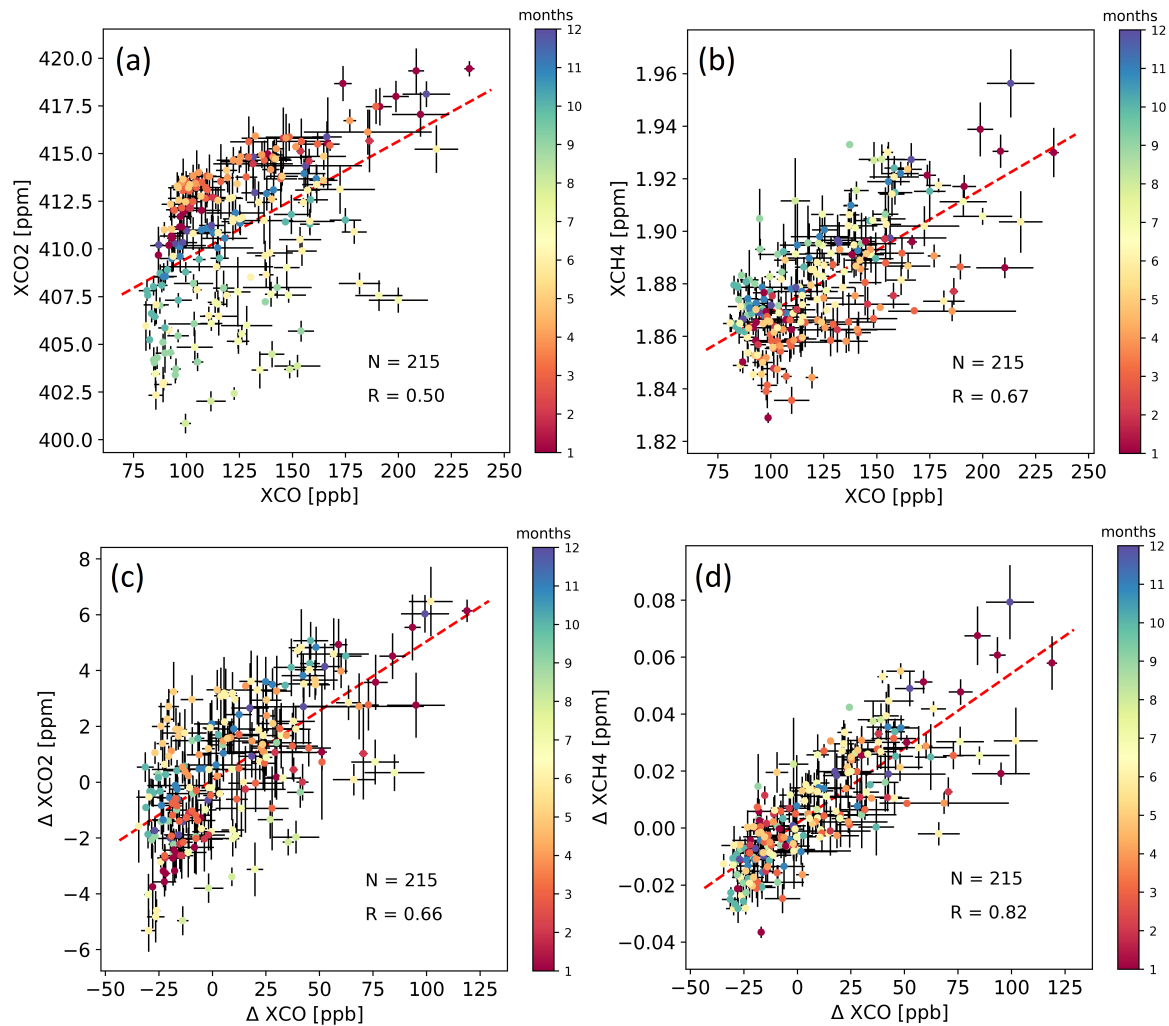
Figure 10. The ~~day-to-day variations from 8 January to 13 January 2019 for~~ correlation plots between the XCO and XCO$_2$ ~~,~~ and XCH$_4$ daily means (a, b) and ~~XCO~~ the correlation plots between the ΔXCO and ΔXCO_2, and ΔXCH_4 daily means (c, d) from FTIR TCCON-type measurements at Xianghe. The dash red line is the linear fit. The N is the number of the measurement days, and R is the correlation coefficient. The error bar is the standard deviation of the measurements in each day. The data are colored with the measurement months.
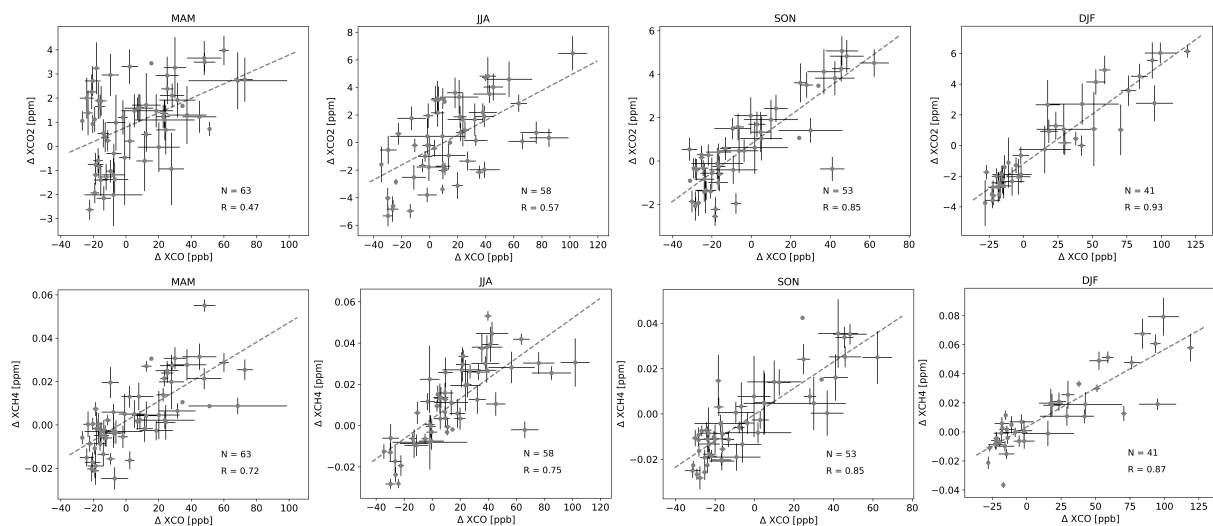
Figure 11. ~~Back trajectories of 72 h at Xianghe were calculated using NOAA HYSPLIT. Trajectories arrive at altitudes of 500m, 2000m~~ Upper panels: the correlation plots between the ΔXCO and ~~5000m above ground level at each local noon on 8 January 2019~~ ΔXCO_2 in four seasons (~~left panel~~spring: March, April, May (MAM); summer: June, ~~12 January 2019~~July, August (~~middle panel~~JJA)~~and 13~~; autumn: September, October, November (SON); winter: December, January~~2019~~, February (~~right panel~~DJF)). Lower panels: the correlation plots between the ΔXCO and ΔXCH_4 in four seasons. The dash line is the linear fit. The N is the number of the measurement days, and R is the correlation coefficient. The error bar is the standard deviation of the measurements in each day.
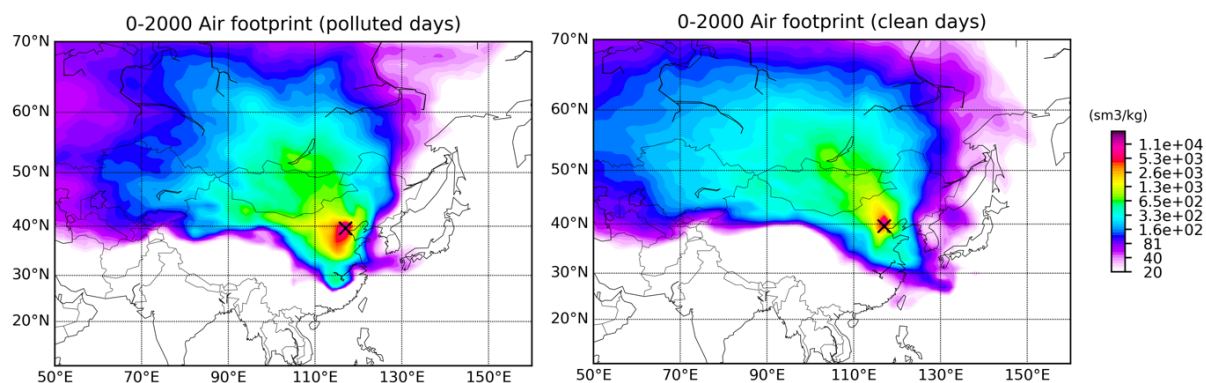

Figure 12. The mean emission response sensitivities of the air mass at Xianghe (the cross symbol) for polluted (left) and clean (right) days in the vertical range from surface to 2000 m a.s.l. simulated with a 10 day backward run with FLEXPART v9.02.
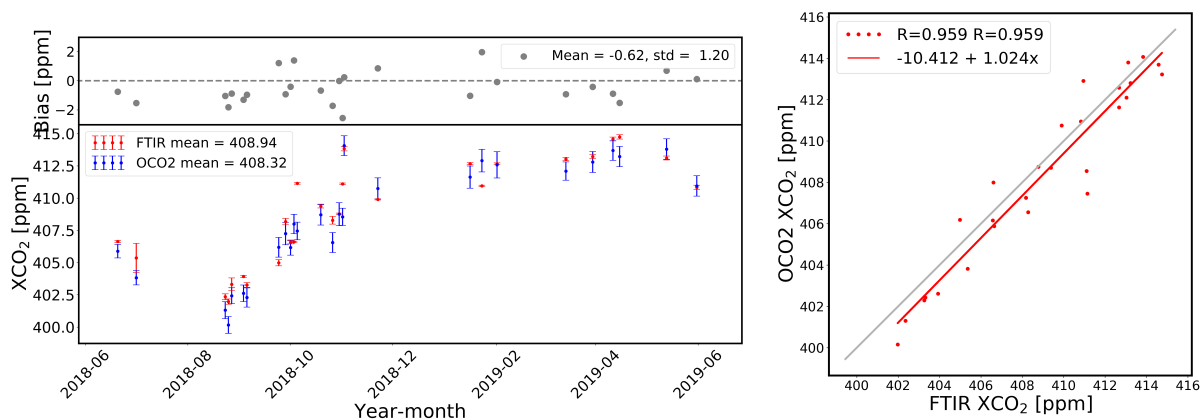
Figure 13. Left panel: Time series of daily mean ~~collocated~~ co-located OCO-2 and ground-based FTIR XCO_2 data at Xianghe (lower plot) and the bias between them (upper plot). Right panel: Correlation plot between ~~collocated~~ co-located daily mean XCO_2 data from OCO-2 and FTIR at Xianghe.
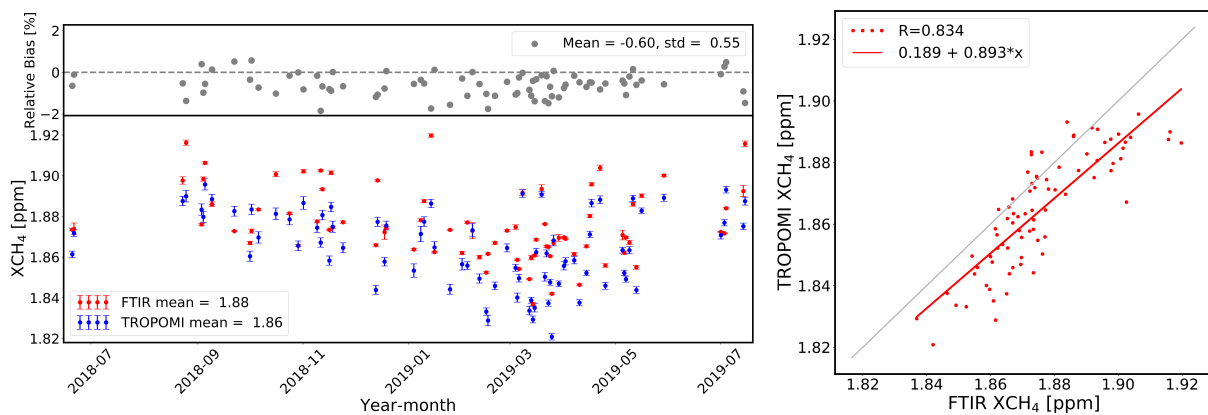

Figure 14. Left panel: Time series of daily mean ~~collocated~~ co-located TROPOMI and ground-based FTIR XCH_4 data at Xianghe (lower plot) and the bias between them (upper plot). Right panel: Correlation plot between ~~collocated~~ co-located daily mean XCH_4 data from TROPOMI and FTIR at Xianghe.
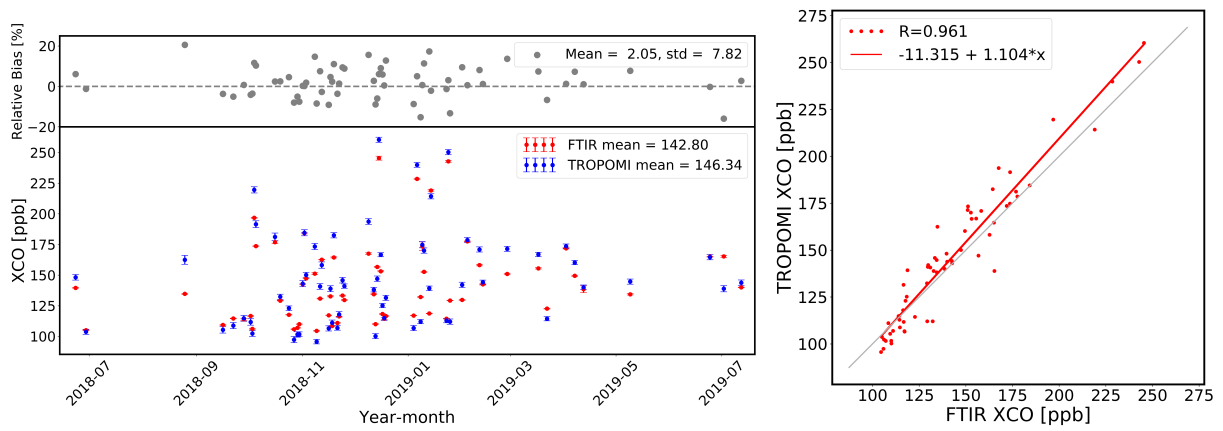
Figure 15. Left panel: Time series of daily mean ~~collocated~~ co-located TROPOMI and ground-based FTIR XCO data at Xianghe (lower plot) and the bias between them (upper plot). Right panel: Correlation plot between ~~collocated~~ co-located daily mean XCO data from TROPOMI and FTIR at Xianghe.

Table 1. The standard deviation (STD) of XCO$_2$, XCH$_4$ and XCO of the remaining data after each solar intensity (SI) filtering for each day and the percentage of the remaining spectra ~~number~~ amount from 14 June 2018 to 31 December 2018. Only measurements with SZA less than 30°are selected.

β (%)	γ (%)	STD(XCO$_2$) (ppm)	STD(XCH$_4$) (ppm)	STD(XCO) (ppb)	Percentage of remaining spectra (%)
85	10	~~0.918~~ 0.749	~~0.0066~~ 0.0042	~~5.525~~ 3.032	89.5
85	5	~~0.889~~ 0.723	~~0.0065~~ 0.0036	~~5.516~~ 2.954	88.9
85	0	~~0.881~~ 0.667	~~0.0064~~ 0.0035	~~5.512~~ 2.997	88.1
90	10	~~0.782~~ 0.651	~~0.0062~~ 0.0036	~~5.423~~ 2.904	86.6
90	5	~~0.772~~ 0.648	~~0.0061~~ 0.0035	~~5.391~~ 2.908	85.8
90	0	~~0.732~~ 0.496	~~0.0061~~ 0.0035	~~5.298~~ 2.559	84.7
95	10	~~0.682~~ 0.450	~~0.0059~~ 0.0029	~~5.299~~ 2.421	78.5
95	5	~~0.680~~ 0.447	~~0.0058~~ 0.0029	~~5.233~~ 2.436	77.1
95	0	~~0.670~~ 0.423	~~0.0058~~ 0.0026	~~5.206~~ 2.438	75.2

Table 2. Average XCO$_2$ daily standard deviation after (a) no filtering, (b) SNR filtering, (c) both SNR filtering and SI filtering during the AC mode and AC+DC mode periods. The unit is ppm. Only those measurements with SZA less than 30°are considered.

	AC mode	AC+DC mode
a	~~1.39~~ 1.19	~~1.34~~ 1.06
b	~~1.14~~ 0.94	~~0.76~~ 0.53
c	~~0.71~~ 0.57	~~0.83~~ 0.88

Table 3. The mean and standard deviation of ΔXCO, ΔXCO_2 and ΔXCH_4 at polluted and clean days.

	Polluted days	Clean days
ΔXCO [ppb]	-9.51 ± 21.10	58.40 ± 19.58
ΔXCO_2 [ppm]	-0.64 ± 2.05	2.75 ± 2.01
ΔXCH_4 [ppm]	-0.003 ± 0.016	0.029 ± 0.019