Final response to Referees' comments

MS No.: amt-2021-92
MS type: Research article
Title: Atmospheric Carbon Dioxide Measurement from Aircraft and Comparison with OCO-2 and Carbon Tracker Model Data
Author: Qin Wang, Farhan Mustafa, Lingbing Bu, Shouzheng Zhu, Jiqiao Liu and Weibiao Chen; the university

Dear Sir,

Thank you very much for spending your valuable time in reviewing our research paper and providing comments/suggestions. The comments given by the learned reviewers helped us in improving the quality of the article. As per the comments of two reviewers, we have gone through the entire paper for giving suitable answers to their queries about the content of the paper, and have revised the whole paper to rectify the English grammatical errors with the help of a native speaker. We have also modified some of the figures and tables as suggested by the learned referees. The authors thank the Associate Editor for his encouragement and support in contacting the reviewers and securing reviews on the paper in time. Hopefully, the present version of revised manuscript will be considered to published in Atmospheric Measurement Techniques.

We sincerely thank the Editor and two reviewers for their valuable suggestions in improving the previous version of our manuscript.

Our replies to the reviewer's comments/suggestions are included in the revised paper and we have highlighted the revised/modified text with red font.

If you have any queries, please don't hesitate to contact us at the address below.

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Thank you and best regards.

Yours sincerely,

Qin Wang, Farhan Mustafa, Lingbing Bu, Shouzheng Zhu, Jiqiao Liu and Weibiao Chen

Response to Anonymous Referee 1 Comments

MS No.: amt-2021-92
MS type: Research article
Title: Atmospheric Carbon Dioxide Measurement from Aircraft and Comparison with OCO-2 and Carbon Tracker Model Data

We are thankful to the respectable reviewer for spending his/her valuable time in reviewing our manuscript and providing the list of constructive comments/suggestions to improve the quality of the manuscript. We have carefully revised the manuscript following all the comments provided by the learned reviewer.

Report #1:

The authors describe their approach on how to measure CO_2 mixing ratios and columns with an airborne LIDAR system. The study is motivated by addressing the limitations of fixed ground-based measurements and the limited spatio-temporal resolution of satellite measurements. Airborne measurements can have similar spatial resolution as ground-based measurements, and at the same time cover a larger area.

The study will be a valuable contribution to the community, and motivate others to use airborne LIDAR systems to infer CO_2 and probably other trace gases with high resolution on a regional scale.

However, the manuscript needs a major revision because of some omissions that should be addressed in a scientific publication.

Response: We are grateful to the reviewer for acknowledging our efforts. We have followed your suggestions carefully and revised the manuscript accordingly, we highlighted the revised/modified text with red font. The corrections have been made in the revised manuscript. Thank you for your suggestions.

General comments and major points

Point 1: The authors should give error ranges to all their average estimates, from the abstract to the conclusions, the values given in the text should have the form xxx. xx ± x.xx ppm, with an appropriate number of significant decimal places. I'd suggest to round to 1 significant decimal place (xxx.x ± x.x) or at most 2 (xxx. xx ± x.xx), as too many can give a false impression of the precision.

Response 1: We are thankful to the reviewer for the valuable comment. We have given error ranges to all average estimates round to 2 significant decimal places. Relevant changes have been made in the revised version of the manuscript at:

Line 18: The concentrations of the XCO_2 calculated from LIDAR measurements over ocean, mountain, and urban areas were 421.11 ± 1.24 ppm, 427.67 ± 0.58 ppm, and 432.04 ± 0.74 ppm, respectively.

Line 23: Compared to the other days, the CO_2 concentration measured by UGGA at different heights was the largest on March 18 with an average value of 422.59 ± 6.39 ppm.

Line 236: The average values of XCO_2 over ocean, mountainous and residential areas were 421.11 ppm, 427.67 ppm, and 432.04 ppm, respectively. Correspondingly, the standard deviation of XCO_2 over ocean, mountainous and residential areas were 1.24, 0.58, and 0.74 (20 seconds averaged), respectively.

Line 308: The results showed that the XCO_2 over the ocean surface was the smallest, with an average value of 421.11 ± 1.24 ppm, and that was the largest over residential area with an average value of 432.04 ± 0.74 ppm. The average XCO_2 value over the mountainous area was 427.67 ± 0.58 ppm.

Point 2: The authors need to add units to all quantities, in particular the ones used in the equations.

Response 2: We are thankful to the reviewer for the valuable comment. We have added units to all the quantities in the revised manuscript. The relevant changes have been made at:

Line 13: In this work, an airborne experiment was carried out in March 2019 over Shanhaiguan area, China (39N-41N,119E-121E).

Line 18: The concentrations of the XCO_2 calculated from LIDAR measurements over ocean, mountain, and urban areas were 421.11 ± 1.24 ppm, 427.67 ± 0.58 ppm, and 432.04 ± 0.74 ppm, respectively.

Line 21: During the whole flight campaign, March 18 was heavily polluted with an Air Quality Index (AQI) of 175 and $PM_{2.5}$ of 131 $\mu g/m^3$.

Line 45: Greenhous gases Observing SATellite (GOSAT) and the OCO-2 were the first two CO2 monitoring satellites which were successfully put into the orbit. Both of them measure the CO2 optical depth with the bands centred around 1.6 μm and 2.0 μm, and O_2 with band A, centred around 0.76 μm (Kiel et al., 2019).

Line 55: Like the GOSAT and OCO-2, most of the IPDA LIDAR systems also focus on the wavelengths of 1.6 μm and 2.0 μm to measure the atmospheric CO_2.

Line 90: The cruise and the maximum speeds of the aircraft were 550 km h^{-1} and 660 km h^{-1}, respectively.

Line 92: The working wavelengths of the ACDL were 532 nm, 1064 nm, and 1572 nm, respectively.

Line 94: while 532 nm and 1064 nm channels were used to detect the aerosols and clouds.

Line 145: The sun-synchronous near-polar satellite included three high-resolution spectrometers making coincident measurements of the reflected sunlight in the near-infrared CO_2 at 1.61 μm and 2.06 μm and oxygen at 0.76 μm (Wunch et al., 2017).

Line 236: The average values of XCO_2 over ocean, mountainous and residential areas were 421.11 ppm, 427.67 ppm, and 432.04 ppm, respectively. Correspondingly, the standard deviation of XCO_2 over ocean, mountainous and residential areas were 1.24, 0.58, and 0.74 (20 seconds averaged), respectively.

Point 3.1: My major issue is the description of their "pulse integration method" with a reference to an earlier paper using the same instrument. To my understanding, what is described is not a pulse integration method, which uses the sum or average of multiple pulses to increase the SNR. Here the authors use "points on the pulse", which is something different. Thus, the first paragraph in Sect. 3.2 needs to be re-written, it is not clear what the authors did. It would be helpful if the authors could provide an independent reference that is not a self-citation.

Response 3.1: Thank you for your valuable comments. In this study, the PIM uses the integrated value of the points on the pulse to calculate DAOD. We have rewritten this part and we have modified misleading sentences, Eq. 7 and Eq. 8 have been explained in detail. Where N is the point number of the pulse, k is the is the count variable, l has no practical physical meaning. The relevant changes have been made in the revised manuscript at:

Line 197: In this study, the PIM uses the integrated value of the points on the pulse to calculate DAOD. In our experiment, the random noise followed Gaussian distribution. When the points on the pulse are superposed, the sum continues following the Gaussian distribution of $N(\rho^l,(\varepsilon^l)^2)$, where the mean and the variance are(Zhu et al., 2020; Yoann et al., 2018)

$$\rho^l = \frac{1}{N}\sum_{k=1}^{N}\alpha_k^l \, , \tag{7}$$

$$(\varepsilon^l)^2 = \frac{1}{N^2}\sum_{k=1}^{N}\left(\sigma_k^l\right)^2 , \tag{8}$$

Where, N is the point number of the pulse, ρ^l and ε^l represent the mean and standard deviation. α_k^l is the value of each point on the pulse, and σ_k^l is the standard deviation of each point. Hence, the empirical estimate of the SNR of the equivalent measurement on the whole averaging window can be written

$$SNR_{PIM}^l = \frac{\rho^l}{\varepsilon^l} = \frac{\sum_{k=1}^{N}\alpha_k^l}{\sqrt{\sum_{k=1}^{N}\left(\sigma_k^l\right)^2}} , \tag{9}$$

Therefore, we can choose the number of points on the pulse to improve the SNR of each pulse.

Reference:

Zhu, Y., Yang, J., Chen, X., Zhu, X., Zhang, J., Li, S., Sun, Y., Hou, X., Bi, D., Bu, L., Zhang, Y., Liu, J. and Chen, W.: Airborne Validation Experiment of 1.57-μm Double-Pulse IPDA LIDAR for Atmospheric Carbon Dioxide Measurement, Remote Sens., 12(12), 1999, doi:10.3390/rs12121999, 2020.

Yoann, T., P, Clémence., Martin, W., Fabien, G., Fabien, M.: Averaging Bias Correction for Future IPDA Lidar Mission MERLIN. Atmos. Meas. Tech., 11, 5865–5884, 2018

Point 3.2: Then, depending on the interpretation, Eqs. (8) and (9) might have to be

adjusted; to my understanding in the case of un-weighted averaging, the average variance is calculated by dividing by N, not by N^2. As given, Eq. (8) resembles the standard error of the mean, not the standard deviation as described in the text. On the other hand, if the variance at each point is known, then that is the variance of the signal, which gives the SNR. Averaging points sounds as if the authors are binning in time. But that has to be done for all points on the pulse, including the peak. It does not make sense to average points before and after the peak, and then to exclude the peak itself. In addition, if the points before and after the pulse peak are averaged, this average should be zero, as this amounts to averaging noise as presented in Figs. 4--6. If it is not zero, there might be additional terms from the variance of the alpha values themselves. In the case the authors use these points to get an estimate of the noise in their signals to calculate the SNR in the first place, then this should be described, and Eq. (8) should be replaced by the equation for the usual variance. As a third option, the noise could be estimated from the residuals after subtracting the matched filter signal. Then, it is also not clear what quantities are averaged, the voltage? How are alpha and sigma estimated?

Response 3.2: We are grateful to the referee for constructive comment. We have rewritten this part and we have modified misleading sentences, Eq. 7 and Eq. 8 have been explained in detail. Eq. 7 and Eq. 8 calculate the mean and variance respectively. This calculation method has also been used in the reference (Yoann et al., 2018) (Eq. 19, Eq. 20 and Eq. 21), which has been cited in the manuscript. In this study, the PIM uses the integrated value of the points on the pulse to calculate DAOD.

Reference:

Yoann, T., P, Clémence., Martin, W., Fabien, G., Fabien, M.: Averaging Bias Correction for Future IPDA Lidar Mission MERLIN. Atmos. Meas. Tech., 11, 5865–5884, 2018

Minor points and detailed comments

Abstract

Point 4:

- l 19: As mentioned in general comment 1, ± error ranges should be given.

- l 24: As mentioned in general comment 1, ± error ranges should be given.

- ll 26--27: Measurements can "indicate" but not "prove" something, which is a very strong statement.

I'd suggest to remove "trend" and replace "which proved the existence of" by "showing".

Response 4: We are thankful to the reviewer for the valuable suggestion. We have added error ranges and removed "trend" and replace "which proved the existence of" by "showing". The relevant changes have been made in the revised manuscript at:

Line 18: The concentrations of the XCO_2 calculated from LIDAR measurements over ocean, mountain, and urban areas were 421.11 ± 1.24 ppm, 427.67 ± 0.58 ppm, and 432.04 ± 0.74 ppm, respectively.

Line 23: Compared to the other days, the CO_2 concentration measured by UGGA at different heights was the largest on March 18 with an average value of 422.59 ± 6.39 ppm.

Line 26: All the datasets showed a similar variation with some differences in their CO_2 concentrations, which showing a good agreement among them.

Introduction

Point 5.1:

- Please re-introduce the acronyms again in the main text at their first appearance.

Response 5.1: We are thankful to the reviewer for the valuable suggestion. We have re-introduced the acronyms again in the main text at their first appearance. The relevant changes have been made in the revised manuscript at:

Line 45: Greenhous gases Observing SATellite (GOSAT) and the Orbiting Carbon observatory-2 (OCO-2) were the first two CO_2 monitoring satellites which were successfully put into the orbit.

Line 49: The Integrated Path Differential Absorption (IPDA) Light Detection and Ranging (LIDAR) is also an effective tool to observe the atmospheric CO_2 and other atmospheric variables (Gong et al., 2020; Xie et al., 2020; Zhu et al., 2020).

Line 56: The National Aeronautics and Space Administration (NASA) Goddard Space Flight centre developed a pulsed IPDA LIDAR instrument incorporating a HgCdTe Avalanche Photodiode detector (APD) and multiple-wavelength-locked laser to measure the CO_2 column-averaged dry-air mixing ratio (XCO_2) and carried out its first airborne campaign in 2011 (Abshire et al., 2013).

Point 5.2:

- l 42: Remove "the": "the methane" -> "methane"

- l 44: Change "vulnerable to the" to "affected by"

- l 80: Continue with "discussed in Sect. 3, and our conclusions are presented in Sect. 4."

Response 5.2: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. The relevant changes have been made in the revised manuscript at:

Line 41: Since the past decade, several satellites have been launched which are dedicatedly monitoring the greenhouse gases including the atmospheric CO_2 and methane (Crisp, 2015; Yokota et al., 2009).

Line 44: The measurements obtained from these satellites are affected by clouds and aerosols and much of the data is screened out due to the contamination of clouds and aerosol content in the measurements.

Line 80: The results including the IPDA LIDAR measurements, UGGA observations and their comparisons are discussed in Section 3. And our conclusions are presented in Section 4.

Section 2

Point 6:
- Please add a few (1--3) sentences to motivate the measurements and data, i.e., why you need CarbonTracker when you have OCO-2 data?

Response 6: We are thankful to the reviewer for the valuable suggestion. We have added a few sentences to motivate the measurements and data. Relevant changes have been made in the revised version of the manuscript at:

Line 83: The northern China, in particular, Beijing-Tianjin-Hebei is the most populated region with the largest anthropogenic emissions in the world. Several studies reported larger uncertainties in the satellite CO_2 retrievals over North and East China (Sun et al., 2020). Therefore, the accurate measurement of CO_2 in the atmosphere is of great significance. Moreover, validation of model measurements against accurate CO_2 profiles is also crucial, because the satellite retrieval algorithms require a priori profiles which are generally based on models and in situ data. CarbonTracker is one of model widely used by the CO_2 community and IPDA lidar is an effective tool for high-precision observation of atmospheric CO_2.

Section 2.1

Point 7:
- l 84: "-1" should be a superscript in "h^-1"
- l 86: Please add the spectral resolution of the channels, also to table 1.
- l 87: Introduce "the": "the 532 and 1064 nm channels", remove "the": "detect the aerosols" -> "detect aerosols"
- l 90: Remove "our previous article": "described in (Zhu et al., 2020)."
- Table 1 should be on one page. Add a column with the spectral resolution.

Response 7: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. And we have added the pulse spectral linewidth (OPA) of the 1572 nm channel in the table 1, the value is 30 MHz. The relevant changes have been made in the revised manuscript at:

Line 90: The cruise and the maximum speeds of the aircraft were 550 km h^{-1} and 660 km h^{-1}, respectively.
Line 94: while the 532 nm and 1064 nm channels were used to detect aerosols and clouds.
Line 96: More detail about the ACDL is described in (Zhu et al., 2020).

Table 1: The main parameters of the airborne dual-wavelength IPDA LIDAR system.

Parameters	Value	Parameters	Value
Online wavelength	1572.024 nm	Telescope diameter	150 mm
Offline wavelength	1572.085 nm	Field of view	1 mrad
Pulse energy(on/off)	6/3 mJ	Beam divergence	0.62 mrad
Pulse width(on/off)	17 ns	Emission optical efficiency	0.8955
Repetition frequency	30 Hz	Receiver optical efficiency	0.3797
Frequency stability	2.7 MHz	Data acquisition	125 MS/s

Pulse spectral linewidth (OPA)	30 MHz

Section 2.2

Point 8: Table 2 should be on one page.
Response 8: We are thankful to the reviewer for the valuable suggestion. Table 2 has been adjusted to one page.

Section 2.3

Point 9.1:
- l 126: typo: "UUGA" -> "UGGA"
- l 131: Insert "the": "the various types of surfaces."
- l 138: Remove "the": "at regional and global scales."
- l 139: Change "making coincident measurements" to "simultaneously measuring"
Response 9.1: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 133: The in-situ CO_2 dry-air mole fraction data was measured using the UGGA which was installed in an unsealed cabin of the aircraft.

Line 136: In addition, a colour Complementary Metal Oxide Semiconductor (CMOS) camera (model: IDS ui-3360cp-c-hq Rev.2) with a resolution of 2048x1088 pixels was also installed next to the lidar telescope to observe the various types of surfaces.

Line 144: The main objectives of the mission included measuring the atmospheric CO_2 with sufficient precision, accuracy and spatiotemporal resolution required to quantify the CO_2 sources and sinks at regional and global scales.

Line 145: The sun-synchronous near-polar satellite included three high-resolution spectrometers simultaneously measuring of the reflected sunlight in the near-infrared CO_2 at 1.61 μm and 2.06 μm and oxygen at 0.76 μm (Wunch et al., 2017).

Point 9.2: - l 142: Section 2.3.3 The authors should motivate their use of the CarbonTracker data, in particular since they also have OCO-2 data available.
Response 9.2: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 150: Validation of model measurements against accurate CO_2 profiles is also crucial, because the satellite retrieval algorithms require a priori profiles which are generally based on models and in situ data. CarbonTracker is one of model widely used by the CO_2 community and IPDA lidar is an effective tool for high-precision observation of atmospheric CO_2. In addition, the measurement range of passive remote sensing is limited, and the model can simulate the situation in a large range.

Section 2.4

Point 10:

- As mentioned in general comment 2, all the quantities used in the equations should be given with proper units, SI or SI-derived.

- l 153: Replace "except" by "than"

- l 159: Use lower case "where" without a comma after it.

- l 162: Refer to Eq. (2) after "caused by CO2": "caused by CO2 (given by Eq. (2) below)"

- l 163: "detection signals" do you mean "monitor signals"?

- l 164: Insert "tau_CO2": "...of the CO2, tau_CO2, can..."

- l 167: Use lower case "where" without a comma after it.

- l 168: The sentence "R_G is the height ... aircraft platform." is the same as in line 160 and can be removed.

- l 169: Change "using" to "according to"

- l 172: Use lower case "where" without a comma after it.

- ll 172--173: What is R_v exactly? If I got it right, then it has the unit 1 / A, (A for Ampere), which does not look like a rate (~ 1 / s), and not like a power unit such as W or V·A (Volt·Ampere), as mentioned at the end of the sentence. Thus this is also related to my general comment 2 to add proper units to all quantities.

- l 173: Change "Therefore," to "Using Eq. (3),"

- l 175: Change to "detection signal voltages", or probably "monitor signal voltages", see comment on line 163.

- l 176: Change to "echo signal voltages".

- l 177: Change to "calculated using the following equations:"

- l 179, Eq. (6) upper and lower case "P" are used for pressure, please use the same consistently throughout the manuscript (see also the comment below)

- l 180: Use lower case "where" without a comma after it.

- l 180: Upper vs lower case "P" for pressure, in line 168 lower case "p" is used, please rectify to be consistent.

Response 10: We are thankful to the reviewer for the valuable suggestion. We have added units to all quantities (**Response 2**) and revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 163: The online and offline wavelengths selected in this study were not affected by other molecules than CO_2.

Line 169: where P_e is the echo power, λ is the wavelength, η_r is the receiving optical efficiency.

Line 171: τ_{CO_2} is the two-way integral optical depth caused by CO_2 (given by Eq. (2) below).

Line 172: The monitor signals of online and offline pulses are defined as $P_0(\lambda_{on})$ and $P_0(\lambda_{off})$, respectively.

Line 174: The IPDA single-pass Differential Absorption Optical Depth (DAOD) of the CO_2, τ_{CO_2}, can be expressed as (Refaat et al., 2015).
Line 177: where $\Delta\sigma_{CO_2}$ is the differential absorption cross section of the online and offline wavelengths.

Line 178: The sentence "R_G is the height of the hard target above sea level, R_A is the altitude of the aircraft platform" is removed.

Line 178: When the APD detector receives the signal, it can convert the power into voltage according to equation 3 (Zhu et al., 2020).
Line 181: where $\Re_v$ represents the voltage response rate of the APD detector.

Line 180-181: $\Re_v$(V/W) represents the voltage response rate of the APD detector.

Line 183: Using Eq. (3), equation 2 can also be expressed as:

Line 185: where $V_0(\lambda_{on})$ and $V_0(\lambda_{off})$ are the monitor signals voltage of online and offline pulses. $V(\lambda_{on}, R)$ and $V(\lambda_{off}, R)$ are the echo signal voltages of the online and offline pulses.

Line 186: For the airborne experiment, the vertical path XCO_2 (in ppm) can be calculated using the following equations:

Line 176, 178, 190: Upper case "P" for pressure, we have revised the mistake.

Line 190: where N_A is the Avogadro's constant.

Section 3

Section 3.1

Point 11:
- l 194: Remove "Moreover": "No significant difference..."
- l 195: Change to: "over the residential and mountain areas."
Response 11: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 217: We have removed "Moreover, no significant difference was observed between the echo signal strengths of residential and mountain areas."

Section 3.2

Point 12.1:

- The first paragraph "data processing" could be in the "methods" section.

- l 199: Refer to Eq. (2) after "DAOD".

Response 12.1: We are thankful to the reviewer for the valuable suggestion. We have adjusted the first paragraph "data processing" to the "methods" section. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 195: In addition, the differences between the Pulse Peak Method (PPM) and PIM were also compared while calculating the DAOD (refer to Eq. (2)).

Point 12.2:

- ll 199--211: As mentioned in general comment 3, this part needs to be rewritten and better explained what was done. As I read it, the authors bin the signal of a single pulse, but do so differently for the background noise ("before and after the peak") and the actual peak signal, where no averaging is indicated. In addition, Eqs. (8) and (9) might need to be adjusted. What quantities are alpha and sigma? What are N and k exactly, and what is denoted by the superscript l?

Response 12.2: We are thankful to the reviewer for the valuable suggestion. We have rewritten this part and we have modified misleading sentences, Eq. 7 and Eq. 8 have been explained in detail. Where N is the point number of the pulse, k is the is the count variable, l has no practical physical meaning. We highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 197: In this study, the PIM uses the integrated value of the points on the pulse to calculate DAOD. In our experiment, the random noise followed Gaussian distribution. When the points on the pulse are superposed, the sum continues following the Gaussian distribution of $N(\rho^l, (\varepsilon^l)^2)$, where the mean and the variance are(Zhu et al., 2020; Yoann et al., 2018)

$$\rho^l = \frac{1}{N}\sum_{k=1}^{N} \alpha_k^l \, , \tag{7}$$

$$(\varepsilon^l)^2 = \frac{1}{N^2}\sum_{k=1}^{N} \left(\sigma_k^l\right)^2 , \tag{8}$$

Where, N is the point number of the pulse, ρ^l and ε^l represent the mean and standard deviation. α_k^l is the value of each point on the pulse, and σ_k^l is the standard deviation of each point. Hence, the empirical estimate of the SNR of the equivalent measurement on the whole averaging window can be written

$$SNR_{PIM}^l = \frac{\rho^l}{\varepsilon^l} = \frac{\sum_{k=1}^{N} \alpha_k^l}{\sqrt{\sum_{k=1}^{N} \left(\sigma_k^l\right)^2}} , \tag{9}$$

Therefore, we can choose the number of points on the pulse to improve the SNR of each pulse.

Point 12.3:

- ll 214, 216, 222--223: As mentioned in general comment 1, ± error ranges should be given. Please use the same order of ocean, residential, and mountainous areas for tau, IWF, and XCO2 consistently. If I use Eq. (5) with the values of tau and IWF as given, I get different results for XCO2, could the authors clarify?

Response 12.3: We are thankful to the reviewer for the valuable suggestion. We have given ± error ranges and used the same order of ocean, residential, and mountainous areas for tau, IWF, and XCO2 consistently. When we calculate the DAOD, we calculate the two-way DAOD. Therefore, the result of DAOD in the manuscript has been halved. We highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 227: The average DAOD values over ocean, mountainous and residential areas were 0.46, 0.44 and 0.46, respectively.

Line 229: The average values of the IWF over ocean, mountainous and residential areas are 1083.26, 1037.05, and 1079.75, respectively.

Line 236: The average values of XCO_2 over ocean, mountainous and residential areas were 421.11 ppm, 427.67 ppm, and 432.04 ppm, respectively. Correspondingly, the standard deviation of XCO_2 over ocean, mountainous and residential areas were 1.24, 0.58, and 0.74 (20 seconds averaged), respectively.

Section 3.3

Point 13.1:

- l 226: The first sentence should be removed.

- l 229: Replace "because it produced errors and sudden spikes" by "because of sudden spikes"

- l 229: Insert "associated": "the associated sudden pressure changes."

- l 230: Consider replacing "concentration" by "volume mixing ratio", concentration can be confused with the more typically used molar concentration with units of mol / m3. It is also possible to introduce the acronym "vmr" at the same place and use that instead of "concentration" later on.

- l 230: Remove "the": "is largest".

- l 232: Remove "the": "in northeast China", and "Moreover, northeast China..."

- Table 3: Consider adding a column for the measured XCO2 values for an easier overview

- l 239: Remove "to be": "was likely caused by"

- l 243: What is shown in Fig. 16 exactly? Consider indicating the boundary layer height as mentioned in the text.

- l 247: Consider replacing "concentration" by "volume mixing ratio", see comment on line 230.

- l 247: Remove "the": "is highest"

- ll 248--249: As mentioned in general comment 1, ± error ranges should be given.

- l 250: Remove "relatively"

Response 13.1: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 254: The data recorded below 0.5 km were discarded because of sudden spikes due to slowing down of the aircraft and the associated sudden pressure changes.

Line 255: Figure 14 shows that the atmospheric CO_2 volume mixing ratio is largest near the ground.

Line 256: This might be due to the weak photosynthesis as the plants are in dormant stage during winter in northeast China (Mustafa et al., 2021). Moreover, northeast China is also a source of carbon due to heating and industrial activities.

Line 262:

Table 2: The weather report released by the Qinhuangdao Meteorological Department on each flight day.

Date Day Month	Weather	Temperature Highest / lowest	Wind direction/ Wind scale	AQI	PM2.5 (μg/m^3)	XCO2 (ppm)
11 March	sunny	16℃/ -3℃	Northeast/5	80	48	416.23±2.68
14 March	sunny	14℃/ -1℃	Northeast/3	60	28	414.43±1.19
16 March	cloudy	11℃/ -1℃	North/breeze	58	30	412.82±2.14
18 March	cloudy	10℃/ 4℃	Southwest/ breeze	175	131	422.59±6.39
19 March	cloudy	15℃/ 7℃	Southeast/1	139	105	415.02±3.79

Line 264: The highest CO_2 concentration on March 18 was likely caused by the higher pollution levels.

Line 265: A Micro Pulse Lidar (MPL) was installed at the Funing ground station to monitor the change of local pollutants and the boundary layer. The change of pollutants and the boundary layer in Funing ground station during the flight test on March 18 is shown in Figure 16.

Line 246: The results from the two datasets also show that the volume mixing ratio of the atmospheric CO_2 is highest over the residential area and the lowest over ocean surface.

Line 249: the standard deviation of the UGGA observations was smaller than that of the ACDL measurements.

Point 13.2:

- l 246: The reason needs to be strengthened, a similar variation or trend alone does not imply a good agreement. There good be a large bias between the two.

- ll 251--252: This is a general statement, what exactly does it imply for the UGGA vs ACDL comparison? Is it feasible to compare them or not?

Response 13.2: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. It is unreasonable to directly compare the two measurement results. By comparing the long-term change trend of XCO_2 measured by IPDA lidar system with the CO_2 volume mixing ratio measured by UGGA, which can indirectly evaluate the working performance of IPDA lidar. Relevant changes have been made in the revised version of the manuscript at:

Line 241: The XCO_2 measured by IPDA lidar is a distance average value, which is different from the measured value of in-situ instrument at aircraft altitude. Therefore, it is unreasonable to directly compare the two measurement results. This paper only compares the long-term change trend of XCO_2 measured by IPDA lidar system with the CO_2 volume mixing ratio measured by UGGA, which can indirectly evaluate the working performance of IPDA lidar. Figure 14 shows the comparison of the XCO_2 calculated from the ACDL measurements with the dry-air mole fraction of CO_2 measured using the UGGA. Both of the datasets show a good agreement by exhibiting a similar variation trend, bias was 12.36 ppm.

Section 3.4

Point 14:
- l 257: typo: "were removed."
- ll 257--258: As mentioned in general comment 1, ± error ranges should be given.
Response 14: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 277: A quality flag was applied to the satellite dataset and the cloud-contaminated retrievals were removed.

Section 3.5

Point 15:
- l 266: Replace "more" by "higher".
- ll 266--267: Be careful with the term "upper atmosphere", which usually refers to altitudes above 50 km, or sometimes 100 km. I suggest to use "atmosphere above" instead.
Response 15: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 298: When the altitude is higher than 4 km, the CO_2 concentration is almost constant.

Line 299: Thig might be due to the stability of the atmosphere above.

Conclusions

Point 16:
- l 274: Remove "relatively"
- ll 275--279: Related to general comment 3, this part should be improved to describe the method better. Please consider the following question: Is this part of the method essential to the results of the paper? In my opinion these details could be removed from the conclusions as they are very specific to the instrument used.
- ll 281--282: As mentioned in general comment 1, ± error ranges should be given.
- l 283: Remove "the": "was largest"
- ll 283--289: Consider replacing "concentration" by "volume mixing ratio", see comment on line 230.
- l 286: Is it variation or trend? As commented on line 246, neither a similar variation nor a similar trend imply a good agreement. The authors should discuss their definition of agreement, in particular with respect to a potential bias.
- l 288: Remove "relatively"
- ll 289--290: This is a general statement, is that a conclusion of the paper connected to the particular measurements? This sentence should be better connected to the method and the rest of the paper.

Response 16: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 305: From the original signals obtained by the IPDA LIDAR, the echo signals over the ocean area were smaller than those over the mountain and the residential areas.

Line 307: Thank you very much for your valuable comments. These details have been removed from the conclusions.

Line 308: The results showed that the XCO_2 over the ocean surface was the smallest, with an average value of 421.11 ± 1.24 ppm, and that was the largest over residential area with an average value of 432.04 ± 0.74 ppm. The average XCO_2 value over the mountainous area was 427.67 ± 0.58 ppm.

Line 310: Moreover, the dry-air mole fraction of CO_2 measured by UGGA was also analysed for several days and the results showed that the CO_2 concentration was largest on 18 March.

Line 310: Moreover, the dry-air mole fraction of CO_2 measured by UGGA was also analysed for several days and the results showed that the CO_2 volume mixing ratio was largest on 18 March, that was the most polluted day during the entire flight campaign. The UGGA CO_2 volume mixing ratio was compared with the XCO_2 calculated using the IPDA LIDAR measurements, and both of the datasets showed a good agreement by exhibiting a similar variation. In addition, the vertical profiles of CO_2 were also measured using UGGA and compared with OCO-2 and the Carbon Tracker CO_2 datasets. The CO_2 volume mixing ratio from the Carbon Tracker was larger than the dry-air mole fraction of CO_2 measured using the UGGA. The atmospheric CO_2 volume mixing ratio was the highest near the ground and it decreased gradually with the progression in the altitude.

Line 316: The atmospheric CO_2 volume mixing ratio was the highest near the ground and it decreased gradually with the progression in the altitude. Below 4 km, the detection results of OCO-2, airborne greenhouse gas analyzer and CarbonTracker model show a same decreasing of CO_2 volume mixing ratio value with the increase of altitude but the values are different. The difference between the average values of CO_2 volume mixing ratio obtained by the OCO-2 and the airborne greenhouse gas analyzer below 4 km on March 14, March 16 and March 19 were -1.3 ppm, 0.79 ppm, and 1.3 ppm, respectively. These three methods can well detect that the land in northeast China was the source of CO_2 in March. This change result of airborne greenhouse gas analyzer and Carbon Tracker is more obvious than OCO-2. On March 19, CO_2 volume mixing ratio measured by the airborne greenhouse gas analyzer decreased from 430.3 ppm at 0.34 km to 413.09 ppm at 3.18 km. The computed results of CarbonTracker decrease from 429.75 ppm at 0.59 km to 415.7 ppm at 2.68 km. The CO_2 volume mixing ratio result of OCO-2 decreased from 414.55 ppm on the ground to 412.39 ppm at 3.02 km. When the altitude is higher than 4 km, the CO_2 volume mixing ratio is almost constant. This might be due to the stability of the atmosphere above.

Figures

Point 17:

- Fig. 3: Add a label to the x-axis, probably "time". "distance measured by the lidar", distance between what? If it is the distance between the plane and ground, that should be described. Last line: "dividing line for different".

- Figs. 7--9: Include axis labels with units for all panels (a). The panels (b) need to be reconsidered after addressing general comment 3. What units are used for SNR?

- Figs. 10--12: Replace "in" by "over": "XCO2 results over ocean..." Add a label to the x-axis, probably "time". By referring to Fig. 10, the last two sentences in the captions of Figs. 11 and 12 can be removed.

- Fig. 14: Legend: There is no need to list the values with 4 decimal places if the error range has only 2. Please round to 2 significant digits on both, too many will give a false impression of the precision.

- Fig. 15: Designate the lines as "lines", i.e. "blue line", "black line", and "red line".

- Fig. 16: Add a label to the x-axis, probably "time".

- Fig. 17: Add a label to the x-axis, probably "time". Use the same scaling for IPDA XCO2 and UGGA CO2 to make them better comparable in absolute terms.

- Fig. 18: Put (a), (b), and (c) on one page, include panel indicators (b) and (c) in the second row.

- Fig. 19: Consider replacing "concentration" by "volume mixing ratio", see comment to line 230. Include the dates in the panels or as column headers to make it easier to find which panel shows the measurements from a certain date. "Red and blue scatter" is better referred to as "red and blue errorbars".

Response 17: We are thankful to the reviewer for the valuable suggestion. We have revised the manuscript accordingly and we highlighted the revised/modified text with red font.

Line 508:

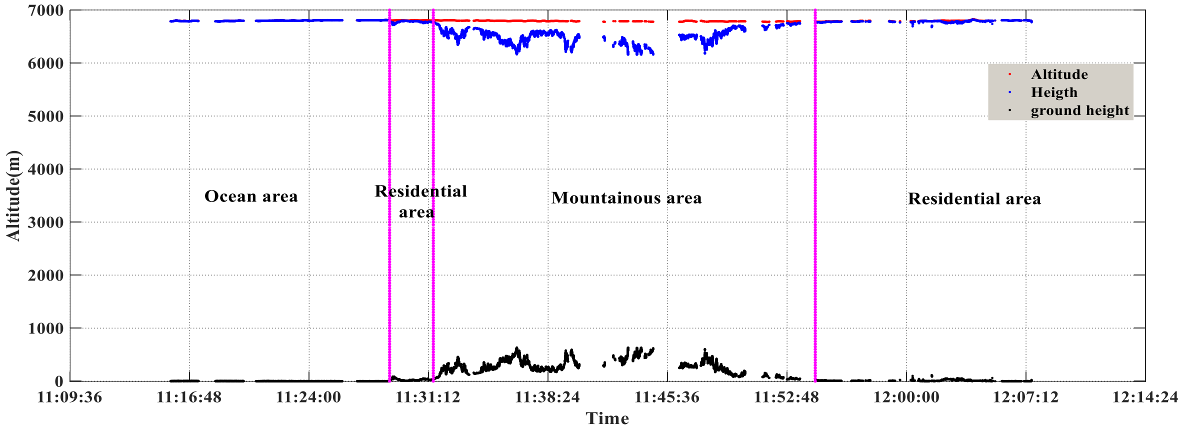


Figure 1: Aircraft flight height and corresponding surface elevation on 14 March 2019. The red dots are the altitude of the aircraft measured by the onboard GPS system. The blue scatter points are the distance between the plane and ground measured by lidar. The black scattered points are the difference between the altitude measured by the GPS and the distance measured by the lidar, and also represent the surface elevation. The purple-red vertical line is the dividing line for different surface types.

Line 526: SNR has no units.

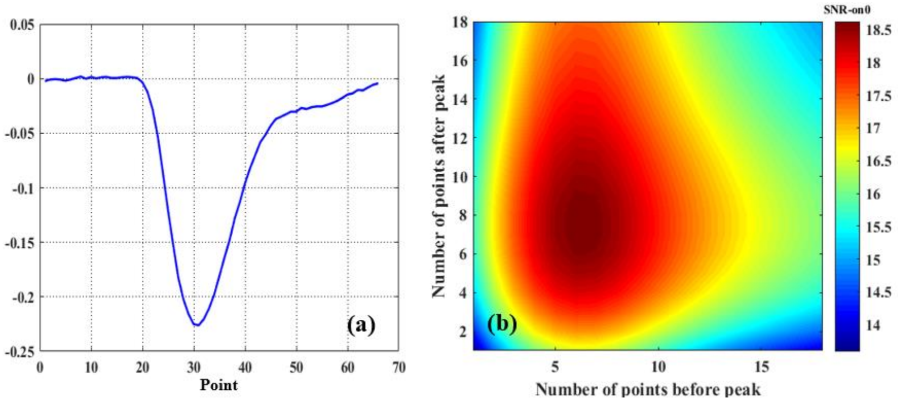


Figure 2: (a) Online wavelength monitoring pulse signal. (b) The change of pulse signal SNR with the number of selected pulse points.

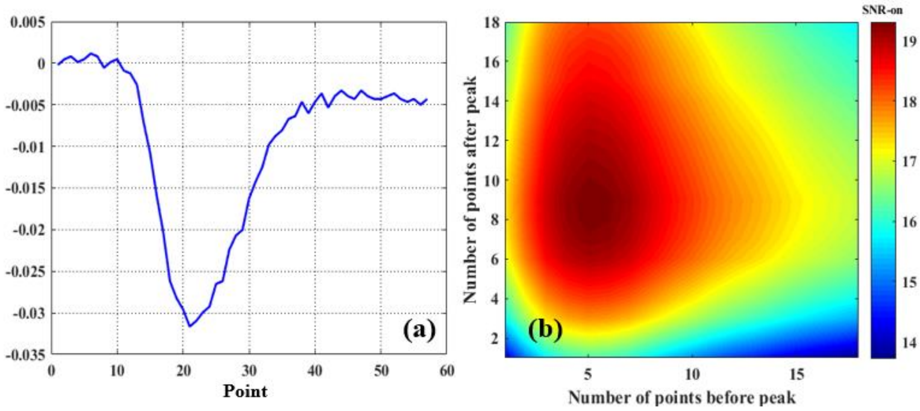


Figure 3: (a) Online wavelength echo pulse signal in land area. (b) The change of the SNR of the echo pulse signal in the land area with the number of selected pulse points.

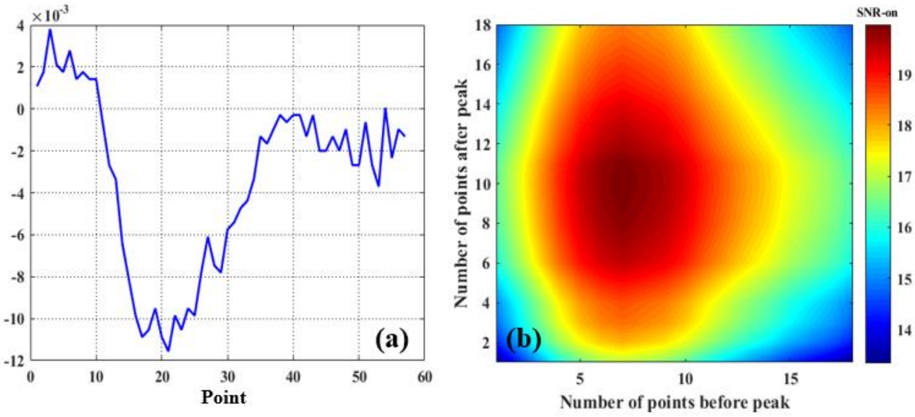


Figure 4: (a) Online wavelength echo pulse signal in ocean area. (b) The change of the SNR of the echo pulse signal in the ocean area with the number of selected pulse points.

Line 536:

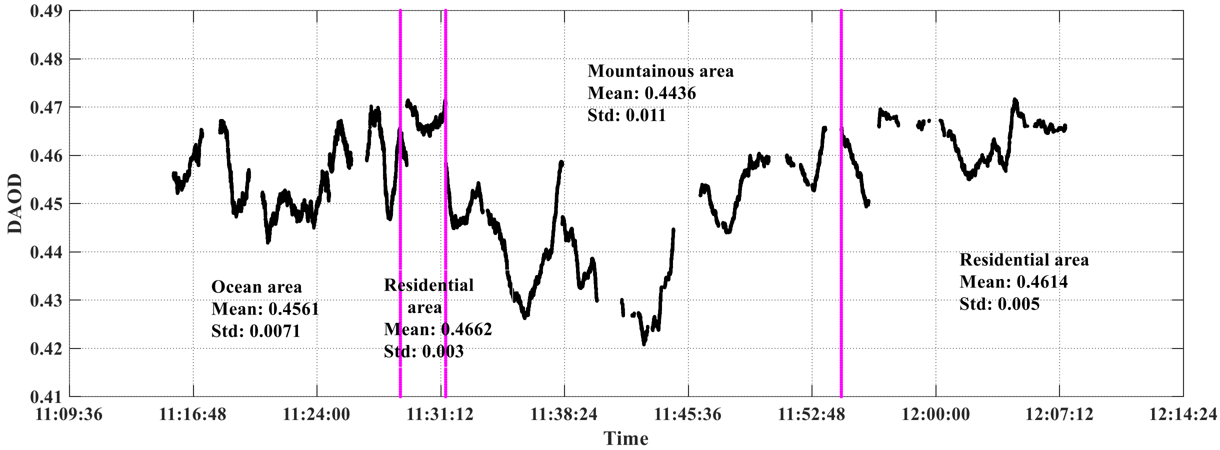


Figure 5: DAOD results over ocean areas, urban residential areas and mountain areas on 14 March 2019. The purplish red vertical line represents the boundary of different surface types. The plane passes through the ocean area, urban residential area, mountain area and urban residential area in turn, which is the same in the following results.

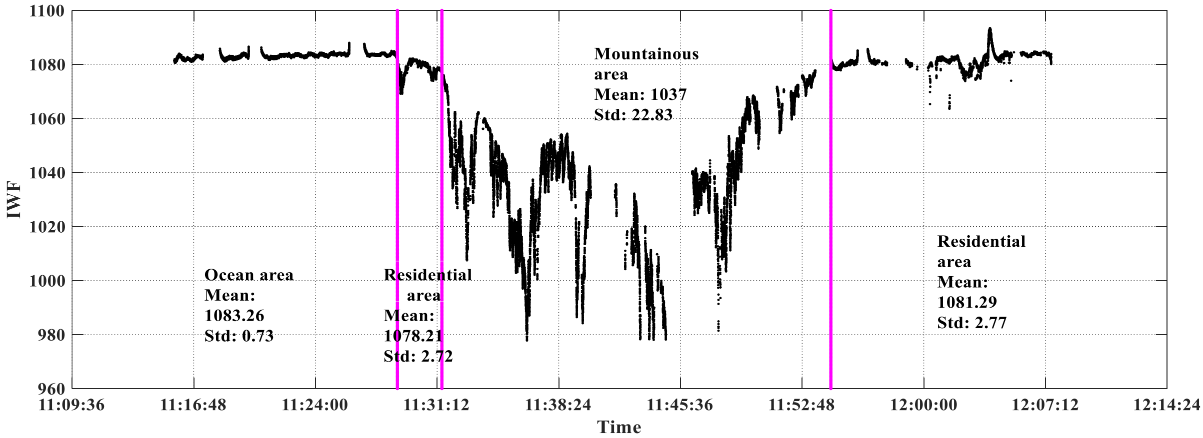


Figure 6: IWF results over ocean, urban residential and mountainous areas on 14 March 2019. The purplish red vertical line represents the boundary of different surface types.

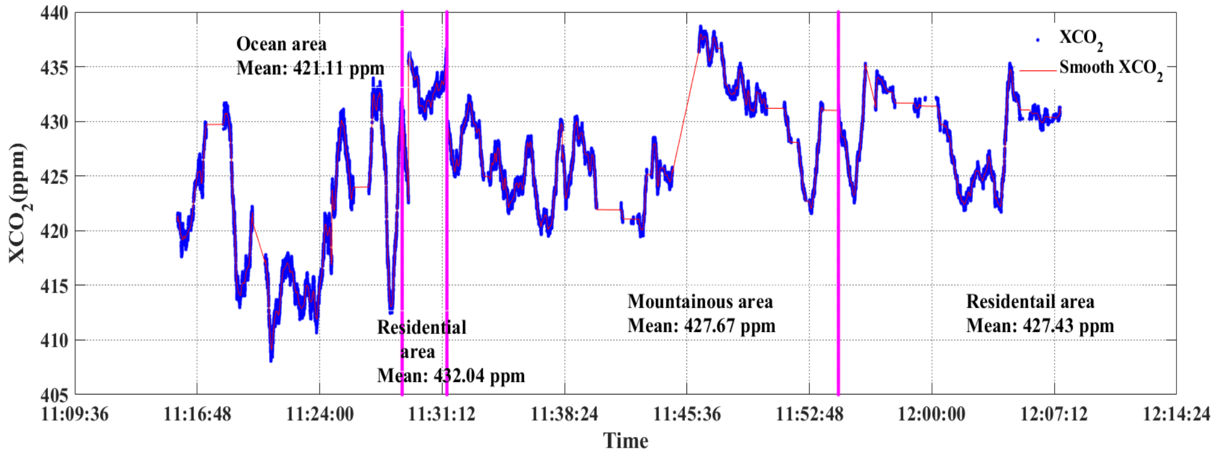


Figure 7: XCO2 results over ocean, urban residential and mountainous areas on 14 March 2019. The purplish red vertical line represents the boundary of different surface types.

Line 557:

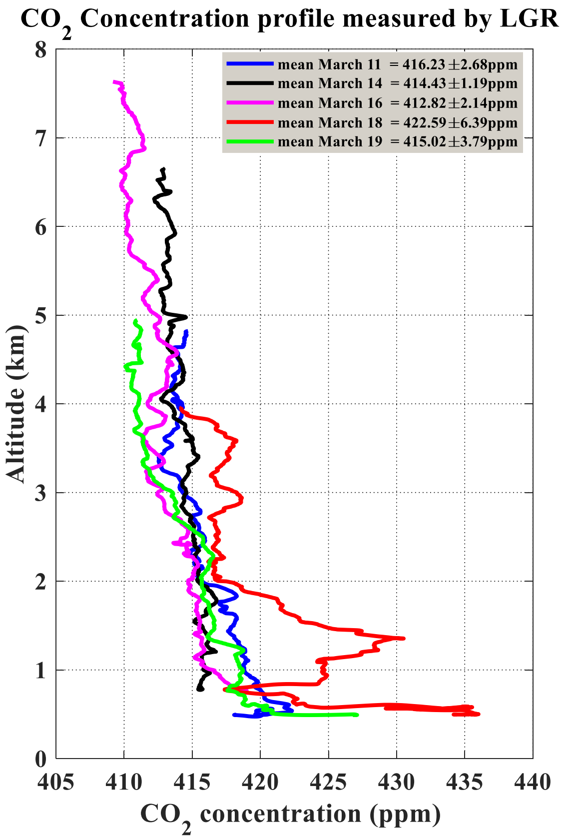


Figure 14: CO_2 concentration profile results measured by greenhouse gas analyzer during aircraft descending flight on different dates. The blue solid line is the result on March 11. The black solid line is the result of March 14. The purple solid line is the result of March 16. The solid red line is the result of March 18. The green solid line is the result of March 19.

Line 562:

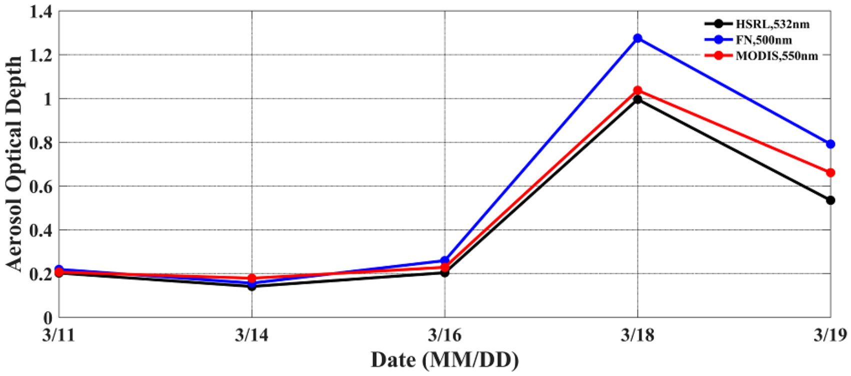


Figure 15: Aerosol optical depth results on different dates. The blue scatters are measured by the sun photometer of Funing ground station. The black scatters are the measurement results of the airborne lidar 532nm channel. The red scatters are the measurement results of Moderate Resolution Imaging Spectroradiometer (MODIS).

Line 567:

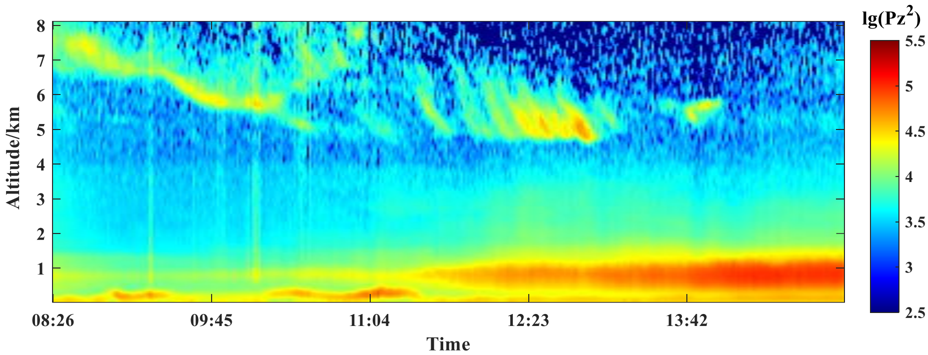


Figure 16: MPL measurement results of Funing ground station on March 18.

Line 551:

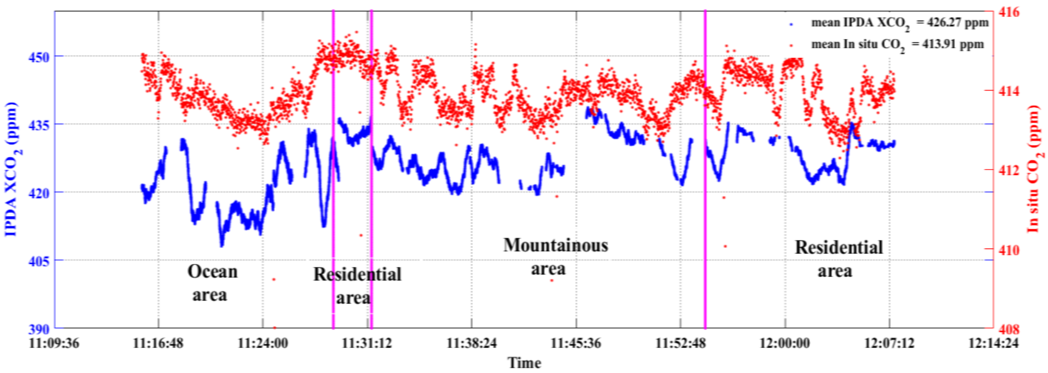


Figure 14: XCO_2 comparison results of airborne IPDA lidar and LGR on 14 March 2019. The red scatter is the result of greenhouse gas analyzer. The blue scatter is measured by airborne IPDA lidar. The purplish red vertical line represents the boundary of different surface types. The plane passes through the ocean area, urban residential area, mountain area and urban residential area in turn.

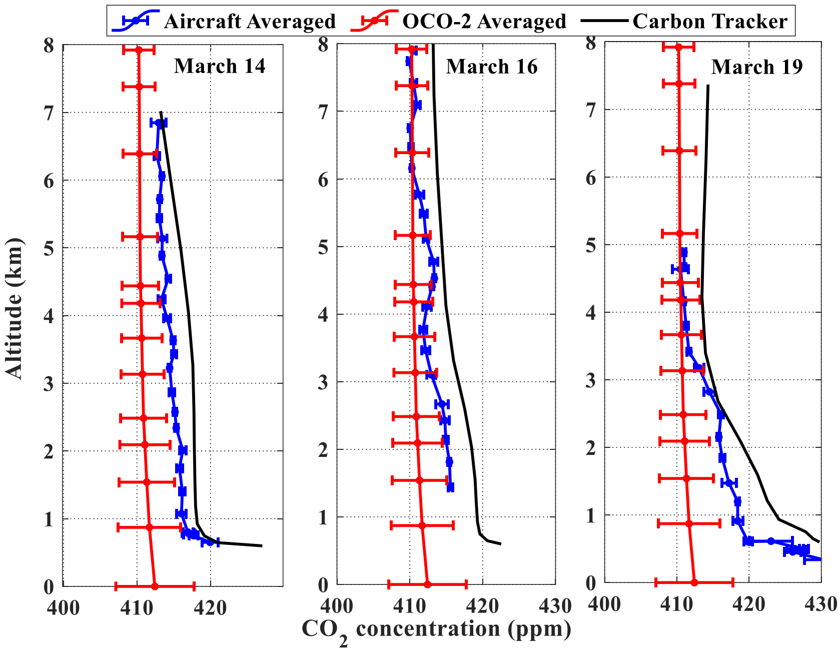


Figure 19: CO2 volume mixing ratio profile comparison results of airborne greenhouse gas analyzer and OCO-2 satellite, CT model. Figure (a) is the vertical structure of CO2 volume mixing ratio on March 14. Figure (b) shows the vertical structure of CO2 volume mixing ratio on March 16. Figure (c) shows the vertical structure of CO2 volume mixing ratio on March 19. The red errorbars is the inversion result of OCO-2. The blue errorbars is the measurement result of the airborne greenhouse gas analyzer. The black solid line is the result of CT model.

Response to Referee #2' Comments

MS No.: amt-2021-92
MS type: Research article
Title: Atmospheric Carbon Dioxide Measurement from Aircraft and Comparison with OCO-2 and Carbon Tracker Model Data

Dear Professor,

Thank you very much for spending your valuable time in reviewing our research paper and providing the list of comments/suggestions. You have put forward detailed and specific modification suggestions for the article, including the layout of the article, the citation of references, the interpretation of formula parameters, etc. We have responded to your modification suggestions one by one and made corresponding modifications to the manuscript. The amendments are mentioned below. Your valuable comments play a very important role in improving the article. Thank you again for your valuable comments

Report #2:

General

The paper introduces aircraft based measurements of column weighted CO2 mixing ratio using a lidar at the Chinese coast including comparison with satellite data. The paper is within the scope of the journal but especially section 3.2 requires revision because of misleading sentences. Here the authors should use the papers of the other groups applying similar methods (Refaat, Amediek in introduction). Sections 3.4 and 3.5 are too short.

Response: We are very thankful to you for your kind words and positive feedback about our article. We have followed your suggestions carefully and revised the manuscript accordingly. We have modified misleading sentences, Eq. 7 and Eq. 8 have been explained in detail. Besides, we expanded Sections 3.4 and 3.5 to explain the experimental results in more detail. The corrections have been made in the revised manuscript. Thank you for your suggestions.

Line 197: In our experiment, the random noise followed Gaussian distribution. When the points on the pulse are superposed, the sum continues following the Gaussian distribution of $N(\rho^l, (\varepsilon^l)^2)$, where the mean and the standard deviation are

$$\rho^l = \frac{1}{N}\sum_{k=1}^{N}\alpha_k^l\ , \qquad (7)$$

$$(\varepsilon^l)^2 = \frac{1}{N^2}\sum_{k=1}^{N}\left(\sigma_k^l\right)^2\ , \qquad (8)$$

Where, N is the point number of the pulse, ρ^l and ε^l represent the mean and standard deviation. α_k^l is the value of each point on the pulse, and σ_k^l is the standard deviation of each point. Hence, the SNR of the sum can be written as

$$SNR_{PIM}^{l} = \frac{\rho^{l}}{\varepsilon^{l}} = \frac{\sum_{k=1}^{N} \alpha_k^l}{\sqrt{\sum_{k=1}^{N} (\sigma_k^l)^2}}, \quad (9)$$

Therefore, we can choose the number of points on the pulse to improve the SNR of each pulse.

Line 271:

3.4 OCO-2 Measurement Results

During this flight experiment, the OCO-2 passed over the flight area on March 16 and the observations over the study area are shown in Figure 18. The solid red line in figure 18(a) is the flight path of the aircraft. The yellow mark point is the position of the suborbital point of the OCO-2 trajectory in the flight area. Figure 18(b) shows the XCO_2 results detected by OCO-2. Figure 18(c) shows the corresponding standard deviation production of OCO-2. As can be seen from Figure 18(a), OCO-2 observations covered both ocean and land surfaces. Due to the fast flight speed of the satellite, the data time period falling in the study area was from 12:57:25 to 12:57:38 UTC. A quality flag was applied to the satellite dataset and the cloud-contaminated retrievals were removed. In the flight area, there is little difference between the values of XCO_2 measured by OCO-2 over land and ocean areas. The average value of XCO_2 over land area is 414.28 ± 0.81 ppm and that over ocean area is 414.23 ± 0.55 ppm. However, due to the uneven distribution of CO_2 volume mixing ratio in the land area, the standard deviation of XCO_2 products over the land area is larger than that over the ocean. The XCO_2 measured by OCO-2 varied from 401.66 ppm to 418.80 ppm, with an average of 414.25 ± 0.62 ppm.

3.5 Vertical Profile Comparison of CO_2 Concentration

The measurement results of the airborne greenhouse gas analyzer were compared with those of OCO-2 inversion and Carbon Tracker model, which is a global carbon cycle data assimilation system. The comparison results are shown in Figure 19. The CarbonTracker dataset was interpolated to the location of the experimental site. During the flight campaigns, the OCO-2 satellite passed over the flight area on March 16. Therefore, the data results of OCO-2 on March 16 were compared with those of CarbonTracker and in-situ data on March 14, March 16 and March 19, respectively. As can be seen from the detection results in Figure 19, the structural change of CO_2 concentration with height can be roughly divided into two parts. From the ground to the height of 4 km and above 4 km. Below 4 km, the detection results of OCO-2, airborne greenhouse gas analyzer and CarbonTracker model show a same decreasing of CO_2 concentration value with the increase of altitude but the values are different. The difference between the average values of CO_2 concentration obtained by the OCO-2 and the airborne greenhouse gas analyzer below 4 km on March 14, March 16 and March 19 were -1.3 ppm, 0.79 ppm, and 1.3 ppm, respectively. These three methods can well detect that the land in northeast China was the source of CO_2 in March. This change result of airborne greenhouse gas analyzer and Carbon Tracker is more obvious than OCO-2. On March 19, CO_2 concentration measured by the airborne greenhouse gas analyzer decreased from 430.3 ppm at 0.34 km to 413.09 ppm at 3.18 km. The computed results of CarbonTracker decrease from 429.75 ppm at 0.59 km to 415.7 ppm at 2.68 km. The CO_2 concentration result of OCO-2 decreased from 414.55 ppm on the ground to 412.39 ppm at 3.02 km. When the altitude is higher than 4 km, the CO_2 concentration is almost constant. This might be due to the stability of the atmosphere above.

Specific

Point 1:
Line 143ff: "two-way nested chemistry-transport model Tracer Model 5" (see also Peters et al, 2004). Improve sentence, it is not consistent with the provided references. The reference to CarbonTracker (Babenhauserheide et al, 2015) should be earlier. Unfortunately, the references use different full names for TM5 but not 'transfer model'.

Response 1: We are thankful to the reviewer for the valuable suggestion. We have revised the citation of references, and highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 154: CarbonTracker is an inverse model framework developed by (Peters et al., 2004). It combines the two-way nested transfer model 5 (TM5) with offline Atmospheric Tracer transfer model and updates the atmospheric CO_2 distribution and surface fluxes every year (Krol et al., 2005).

Line 413: Krol, M. C., S. Houweling, B. Bregman, M. van den Broek, A. Segers, P. van Velthoven, W. Peters, F. J. Dentener, and P. Bergamaschi (2005), The two-way nested global chemistry-transport zoom model TM5: Algorithm and applications, Atmos. Chem. Phys., 5, 417– 432.

Line 449: W. Peters, M. C. Krol, E. J. Dlugokencky, F. J. Dentener, P. Bergamaschi, G. Dutton, P. v. Velthoven, J. B. Miller, L. Bruhwiler, and P. P. Tan, Toward regional-scale modeling using the two-way nested global model TM5: Characterization of transport using SF6, J. Geophys. Res., 109, D19314, doi:10.1029/2004JD005020, 2004.

Point 2: I suppose the trace gas is CO_2 here, i.e., online means on a CO_2 line. If yes please say so.

Response 2: We are thankful to the reviewer for the valuable suggestion. We have replaced " trace gas " by "CO_2". Relevant changes have been made in the revised version of the manuscript at:

Line 162: The laser pulse of the online wavelength was strongly attenuated because it was absorbed by the CO_2 molecules while propagating through the atmosphere.

Point 3: "hard target": is that the surface or the cloudtop? Please be more precise here.

Response 3: We are thankful to the reviewer for the valuable suggestion. "hard target": is the surface, we have revised the mistake. Relevant changes have been made in the revised version of the manuscript at:

Line 170: R_G is the height of the surface above sea level.

Point 4: Please define all quantities in equations in the text. What is for example Pp? Use lower case for atmospheric pressure (p).

Response 4: We are thankful to the reviewer for the valuable suggestion. We have defined all quantities in equations. And we used lower case for atmospheric pressure in all equations and text. we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 180:

$$V = P_P * \Re_v , \quad (3)$$

where $\Re_v$(V/W) represents the voltage response rate of the APD detector, P_P is the power of echo signal, V is the voltage.

Line 176:

$$\tau_{CO_2} = \int_{R_G}^{R_A} \Delta\sigma_{CO_2}(p(r), T(r)) N_{CO_2}(r) dr = \frac{1}{2} \cdot ln\left(\frac{P(\lambda_{off}, R) \cdot P_0(\lambda_{on})}{P(\lambda_{on}, R) \cdot P_0(\lambda_{off})}\right) , \quad (2)$$

where $\Delta\sigma_{CO_2}$ is the differential absorption cross section of the online and offline wavelengths, N_{CO_2} is the molecular density of the CO_2. p and T are pressure and temperature profiles.

Line 189:

$$IWF = \int_{R_G}^{R_A} \frac{N_A \cdot p(r) \cdot \Delta\sigma_{CO_2}(p(r), T(r))}{RT(r)(1 + X_{H_2O}(r))} dr , \quad (6)$$

where N_A is the Avogadro's constant, R is the gas constant, $p(r)$ and $T(r)$ are the pressure and temperature profiles, respectively. X_{H_2O} is the dry-air ratio of water vapor, IWF represents the integral weight function.

Point 5: Section 3.1: Please improve text for the non-expert reader.

Response 5: We are thankful to the reviewer for the valuable suggestion. We have improved text about section 3.1. We highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 209: The performance of the ACDL system was evaluated by comparing the original echo signals over three different surface types, including the ocean, the mountain, and the urban residential surface types. The original signals of the ACDL over the ocean, urban residential, and mountainous areas are shown in Figures 4, 5, and 6, respectively. Including local amplification of each signal. The amplification signals from left to right are online monitor signal, online echo signal, offline monitor signal and offline echo signal. In each group of original echo signals, the online and offline monitor signals are fixed at the same position but the echo signals appear in different positions due to the different heights of the ground surface. The original signals were filtered before using, and the signals whose pulse peak values were not in the linear region of APD were discarded. The echo signals in the ocean area were significantly smaller than those over the residential and the mountain areas. This might be due to the low reflectivity of the ocean, which leads to the reduction of the signal noise ratio (SNR) over the ocean.

Point 6: Section 3.2: I suppose Eq. 7 describes the signal and Eq.8 the noise, if yes please write that (see also reviewer #1). Please correct misleading sentences. What is on the abscissa of panel a of Figs. 7-9 (with units)?

Response 6: We are thankful to the reviewer for the valuable suggestion. Eq. 7 and Eq.

8 have been explained in detail, and the abscissa of Figs. 7-9 is marked. We highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 197: In this study, the PIM uses the integrated value of the points on the pulse to calculate DAOD. In our experiment, the random noise followed Gaussian distribution. When the points on the pulse are superposed, the sum continues following the Gaussian distribution of $N(\rho^l, (\varepsilon^l)^2)$, where the mean and the variance are(Zhu et al., 2020; Yoann et al., 2018)

$$\rho^l = \frac{1}{N}\sum_{k=1}^{N} \alpha_k^l , \tag{7}$$

$$(\varepsilon^l)^2 = \frac{1}{N^2}\sum_{k=1}^{N} \left(\sigma_k^l\right)^2 , \tag{8}$$

Where, N is the point number of the pulse, ρ^l and ε^l represent the mean and standard deviation. α_k^l is the value of each point on the pulse, and σ_k^l is the standard deviation of each point. Hence, the empirical estimate of the SNR of the equivalent measurement on the whole averaging window can be written

$$SNR_{PIM}^l = \frac{\rho^l}{\varepsilon^l} = \frac{\sum_{k=1}^{N} \alpha_k^l}{\sqrt{\sum_{k=1}^{N} \left(\sigma_k^l\right)^2}} , \tag{9}$$

Therefore, we can choose the number of points on the pulse to improve the SNR of each pulse.

Line 526:

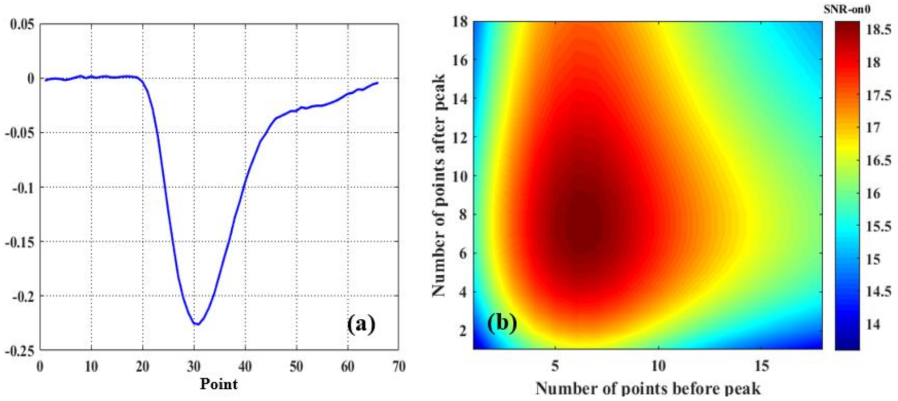


Figure 8: (a) Online wavelength monitoring pulse signal. (b) The change of pulse signal SNR with the number of selected pulse points.

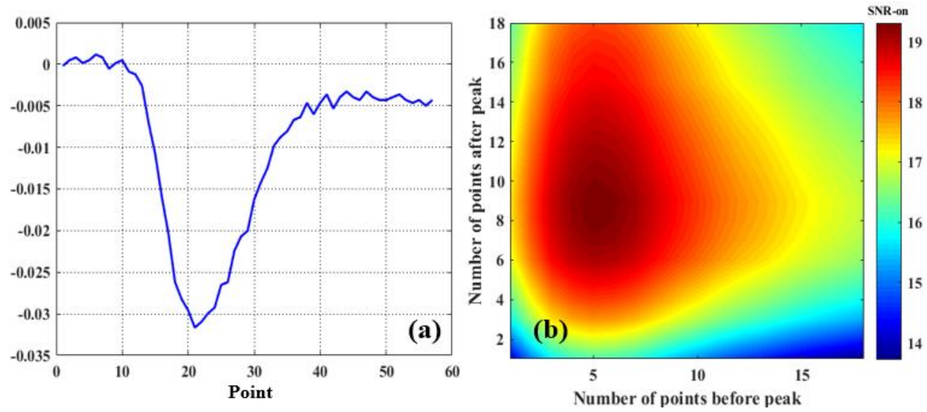


Figure 9: (a) Online wavelength echo pulse signal in land area. (b) The change of the SNR of the echo pulse signal in the land area with the number of selected pulse points.

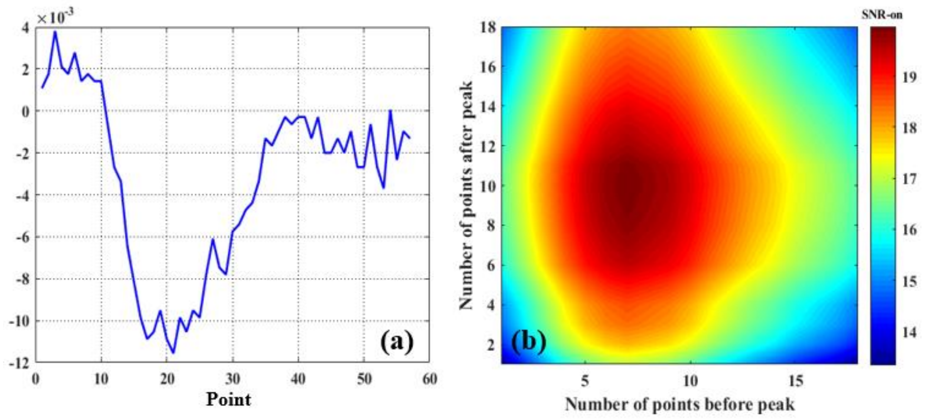


Figure 10: (a) Online wavelength echo pulse signal in ocean area. (b) The change of the SNR of the echo pulse signal in the ocean area with the number of selected pulse points.

Point 7: I would suggest to rearrange section 3.3 to have every result for the 14 March flight together, i.e. exchange the paragraph beginning with line 245 with the part from line 226 to line 244.

Response 7: We are thankful to the reviewer for the valuable suggestion. We have rearranged section 3.3 and highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 244: Figure 14 shows the comparison of the XCO_2 calculated from the ACDL measurements with the dry-air mole fraction of CO_2 measured using the UGGA. Both of the datasets show a good agreement by exhibiting a similar variation trend. The results from the two datasets also show that the volume mixing ratio of the atmospheric CO_2 is highest over the residential area and the lowest over ocean surface. The average value of XCO_2 obtained by the ACDL calculations was 426.27 ppm, and the average value of CO_2 mole fraction obtained by the UGGA measurements was 413.91 ppm. Moreover, the standard deviation of the UGGA observations was smaller than that of the ACDL measurements, and this might be due to the different working principles of the two instruments. The ACDL measures the weighted average concentrations at different altitudes. However, the UGGA measures the CO_2 value at the aircraft location.

In this study, the in-situ observations measured using the UGGA were also analysed for several days. The vertical profiles of the atmospheric CO_2 were measured using the UGGA during spiral and the descent of the aircraft and the results are shown in figure 15. The data recorded below 0.5 km were discarded because of sudden spikes due to slowing down of the aircraft and the associated sudden pressure changes. Figure 15 shows that the atmospheric CO_2 volume mixing ratio is largest near the ground, and it decreases gradually with the progression in the altitude. This might be due to the weak photosynthesis as the plants are in dormant stage during winter in northeast China (Mustafa et al., 2021). Moreover, northeast China is also a source of carbon due to heating and industrial activities, which also contributes significantly to the atmospheric CO_2 (Shan et al., 1997). In addition, the CO_2 concentration at different altitudes were the highest on 18 March. This could be caused by the weather conditions and pollution levels. Table 3 shows the weather report released by the Qinhuangdao meteorological station on each day of the flight.

Table 3: The weather report released by the Qinhuangdao Meteorological Department on each flight day.

Date Day Month	Weather	Temperature Highest / lowest	Wind direction/ Wind scale	AQI	PM2.5 ($\mu g/m^3$)	XCO2 (ppm)
11 March	sunny	16°C/ -3°C	Northeast/5	80	48	416.23±2.68
14 March	sunny	14°C/ -1°C	Northeast/3	60	28	414.43±1.19
16 March	cloudy	11°C/ -1°C	North/breeze	58	30	412.82±2.14
18 March	cloudy	10°C/ 4°C	Southwest/ breeze	175	131	422.59±6.39
19 March	cloudy	15°C/ 7°C	Southeast/1	139	105	415.02±3.79

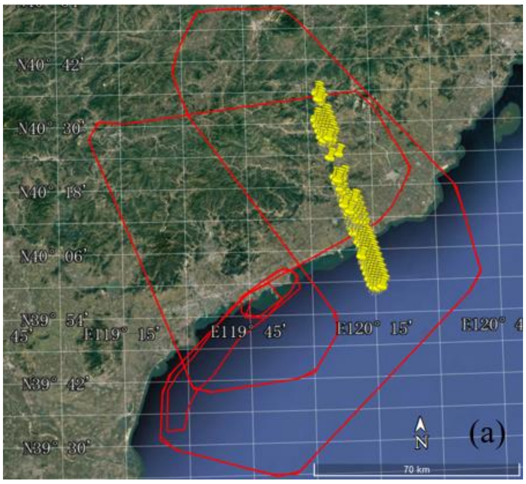
The AOD values measured using various instruments on each flight day are shown Figure 16, and the results show that the AOD was the largest on 18 March. The highest CO_2 concentration on March 18 was likely caused by the higher pollution levels. A ground station was arranged in the flight area to verify the airborne results. A Micro Pulse Lidar (MPL) was installed at the Funing ground station to monitor the change of local pollutants and the boundary layer. The change of pollutants and the boundary layer in Funing ground station during the flight test on March 18 is shown in Figure 17. The dry-air mole fraction of CO_2 reaches its maximum value at about 1.4 km on March 18 (figure 15). This might be due to the fact that the height of the boundary layer was about 1.5 km on March 18 (figure 17), and the pollutants and the greenhouse gases cannot escape through the boundary layer.

Point 8: Sections 3.4 and 3.5: Please say more to Fig. 18, including the shown standard deviations. Please include the flight data in panel 18b in the same color scale, or maybe a slightly shifted scale, to consider that the satellite data must have a systematic low bias because of the influence of the altitude region with lower CO2 above the flight track (upper troposphere and the stratosphere). This bias should be mentioned in the text, here and also in section 3.5 as justification of the use of CarbonTracker (please spell out in caption of Fig.19). The last sentence of section 3.5 has to be replaced; I don't think you refer to the stratosphere here when in the figure is only the troposphere. It might be useful to indicate the flight

altitude in Fig.19.

Response 8: We are thankful to the reviewer for the valuable suggestion. We have supplemented the contents of Section 3.4 and added the results of standard deviation, including the results of adding standard deviation in Figure 18 (b). Combined with the comment of reviewer #1, we revised the last sentence of section 3.5. We highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 272: During this flight experiment, the OCO-2 passed over the flight area on March 16 and the observations over the study area are shown in Figure 18. The solid red line in figure 18(a) is the flight path of the aircraft. The yellow mark point is the position of the suborbital point of the OCO-2 trajectory in the flight area. Figure 18(b) shows the XCO_2 results detected by OCO-2. Figure 18(c) shows the corresponding standard deviation production of OCO-2. As can be seen from Figure 18(a), OCO-2 observations covered both ocean and land surfaces. Due to the fast flight speed of the satellite, the data time period falling in the study area was from 12:57:25 to 12:57:38 UTC. A quality flag was applied to the satellite dataset and the cloud-contaminated retrievals were removed. In the flight area, there is little difference between the values of XCO_2 measured by OCO-2 over land and ocean areas. The average value of XCO_2 over land area is 414.28 ± 0.81 ppm and that over ocean area is 414.23 ± 0.55 ppm. However, due to the uneven distribution of CO_2 volume mixing ratio in the land area, the standard deviation of XCO_2 products over the land area is larger than that over the ocean. The XCO_2 measured by OCO-2 varied from 401.66 ppm to 418.80 ppm, with an average of 414.25 ± 0.62 ppm.



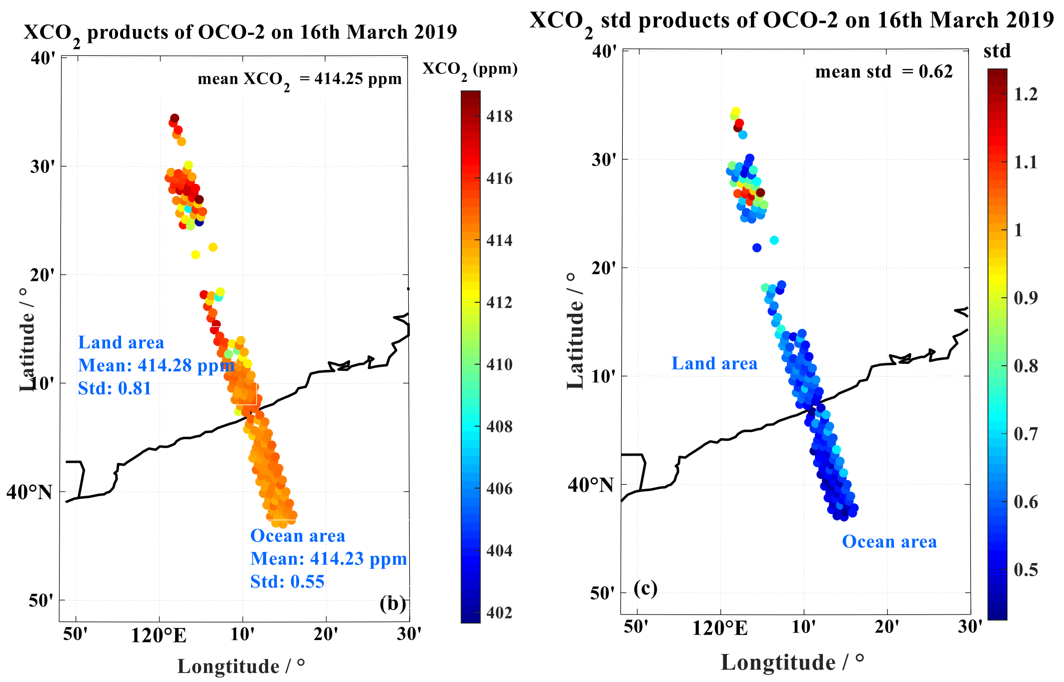


Figure 18: Orbit and detection results of OCO-2 satellite on March 16. The solid red line in figure (a) is the flight path of the aircraft. The yellow mark point is the position of the suborbital point of the OCO-2 trajectory in the flight area (© Google Earth Pro). Figure (b) shows the XCO_2 results detected by OCO-2. Figure (c) shows the corresponding standard deviation.

Line 299: This might be due to the stability of the atmosphere above.

Point 9: Line 376: Please replace the preprint by: Krol, M. C., S. Houweling, B. Bregman, M. van den Broek, A. Segers, P. van Velthoven, W. Peters, F. J. Dentener, and P. Bergamaschi (2005), The two-way nested global chemistry-transport zoom model TM5: Algorithm and applications, Atmos. Chem. Phys., 5, 417– 432.

Response 9: We are thankful to the reviewer for the valuable suggestion. We have replaced the preprint. Relevant changes have been made in the revised version of the manuscript at:

Line 412: Krol, M. C., S. Houweling, B. Bregman, M. van den Broek, A. Segers, P. van Velthoven, W. Peters, F. J. Dentener, and P. Bergamaschi (2005), The two-way nested global chemistry-transport zoom model TM5: Algorithm and applications, Atmos. Chem. Phys., 5, 417– 432.

Technical corrections

Additional to the remarks of reviewer #1 there are the following issues:

Point 10:
Line 64: Don't create fantasy names for existing institutes. The correct name is 'German Aerospace Center (DLR)'.
Line 143: Typo in citation.
Table 3: Is 'wind scale' 'wind strength in Beaufort'?
Line 266: Typo
References: Please remove control sequences (e.g. line 312) or blanks (e.g. line

449) and use subscripts instead.

Several times the name of the journal and the volume are missing, indicated by ',,', please insert it. In case of Yokota also the DOI is missing, meaning that it is impossible to find the paper. For books please provide publisher and city.

Use µ instead of mu, and CO2.

Response 10: We have revised the manuscript accordingly and we highlighted the revised/modified text with red font. Relevant changes have been made in the revised version of the manuscript at:

Line 65: In addition, the German Aerospace Center (DLR) developed a 1.57 µm double-pulse IPDA LIDAR instrument and measured the atmospheric CO_2 concentration with great accuracy during their airborne campaign in 2015 (Amediek et al., 2017).

Line 154: CarbonTracker is an inverse model framework developed by (Peters et al., 2004).

Line 449: W. Peters, M. C. Krol, E. J. Dlugokencky, F. J. Dentener, P. Bergamaschi, G. Dutton, P. v. Velthoven, J. B. Miller, L. Bruhwiler, and P. P. Tan, Toward regional-scale modeling using the two-way nested global model TM5: Characterization of transport using SF6, J. Geophys. Res., 109, D19314, doi:10.1029/2004JD005020, 2004.

Table 3: Yes professor, the 'wind scale' is 'wind strength in Beaufort'.

Line 299: This might be due to the stability of the atmosphere above.

Line 348: Kawa, S. R., Yang, M. Y. M. and DiGangi, J.: Airborne measurements of CO&amp column concentrations made with a pulsed IPDA lidar using a multiple-wavelength-locked laser and HgCdTe APD detector, Atmos. Meas. Tech., 11(4), 2001–2025, doi:10.5194/amt-11-2001-2018, 2018.

Line 485: Yokota, T., Yoshida, Y., Eguchi, N., Ota, Y., Tanaka, T., Watanabe, H. and Maksyutov, S.: Global Concentrations of CO_2 and CH 4 Retrieved from GOSAT : First Preliminary Results, , 5, 160–163, 2009.