Reply to the comments of anonymous Referee #2 to Li et al., "Atmospheric column CO_2 measurement from a new automatic ground-based sun photometer in Beijing from 2010 to 2012", Atmos. Meas. Tech. Discuss., 5, 8313-8341, 2012

The authors thank very much the constructive suggestions from the anonymous referee. We decide to make substantial corrections to the manuscript. Details are described below:

Question 1

As pointed out by anonymous referee #1, the use of English needs significant revision.

Reply: Following the referee's suggestion, we improved the English writing carefully throughout the manuscript.

Question 2

Insert a new section following 3.2.2: explain how to further process a DAI to achieve an estimate of the CO2 column.

Reply: We refine the definition of DAI with consideration of slant path correction (see below):

Based on Beer-Lambert law, the direct sun measurement of the CO_2 instrument can be expressed by:

$$V = V_0(\frac{d_0}{d})^2 \exp(-m\tau) \qquad (2)$$

Where V is the signal of the instrument at surface of the Earth; V_0 denotes the instrument signal at the top of atmosphere, i.e. the absolute calibration coefficient; $(d_0/d)^2$ is the Sun-Earth distance correction factor; m is the airmass, and τ is the atmospheric total optical depth (TOD) which can be separated into three parts: the aerosol optical depth (AOD) τ_{aer}, the Rayleigh optical depth (ROD) τ_{Ray} and the gases optical depth (GOD) τ_{gas}:

$$\tau = \tau_{aer} + \tau_{Ray} + \tau_{gas} \qquad (3)$$

By noting the subscript *a* and *b* for absorption and base channels respectively, we can derive channel signal ratio following the difference absorption principle:

$$\ln\frac{V_b}{V_a} = \ln\frac{V_{0,b}}{V_{0,a}} + m(\tau_a - \tau_b) \qquad (4)$$

By jointing eq. (3) and (4), we can define the DAI index, related to the optical depth of CO_2 as:

$$\mathrm{DAI} = \tau_{gas,a} - \tau_{gas,b} = (\tau_a - \tau_b) - (\tau_{aer,a} - \tau_{aer,b}) - (\tau_{Ray,a} - \tau_{Ray,b})$$
$$= \frac{1}{m}\left(\ln\frac{V_b}{V_a} - \ln\frac{V_{0,b}}{V_{0,a}}\right) - \tau_{aer,b}\left[\left(\frac{\lambda_a}{\lambda_b}\right)^{-\alpha} - 1\right] \quad (5)$$

In this equation, we consider the difference in GOD coming only from CO_2 and ignore other gases contribution to the optical depth at the selected channels. Differences of Rayleigh optical depth at two channels are small enough and assumed to be ignored. The uncertainty caused by these assumptions will be discussed in the error analysis part of the paper, while we deduce the aerosol influence in term of AOD at base channel and Angstrom coefficient α in Eq. (5). Moreover, the airmass *m* can be computed from solar zenith angle (Kasten, 1989). The absolute calibration coefficient $V_{0,b}$ and $V_{0,a}$ are not calibrated in this study, but their ratios can be directly calculated following:

$$\frac{V_{0,b}}{V_{0,a}} = \frac{\int E_s(\lambda)R_b(\lambda)d\lambda}{\int E_s(\lambda)R_a(\lambda)d\lambda} \quad (6)$$

Where R_b and R_a are filter transmission profiles of two channels, and E_s the extraterrestrial solar irradiance which can be obtained, for example from ASTM-STD-2000 (http://rredc.nrel.gov/solar/spectra/am0/). Advantages for the use of DAI as the CO_2 column content index include not only avoiding absolute calibration of V_0, but also resisting the instrument changes thanks to the “ratio format” of the measurements and calibration coefficients as illustrated in Eq. (5) and (6).

According to the new treatment of the DAI index, we re-plotted the Fig. 7 and Fig. 8 as shown below. From these figures, the seasonal and yearly behaviors of the observed CO_2 DAI show similar properties compared with our previous manuscript. This is explained by the fact that the airmass correction affects firstly the daily behavior of the DAI instead of the seasonal and yearly behaviors, considering the airmass varies greatly in the day but not in the scale of daily average.

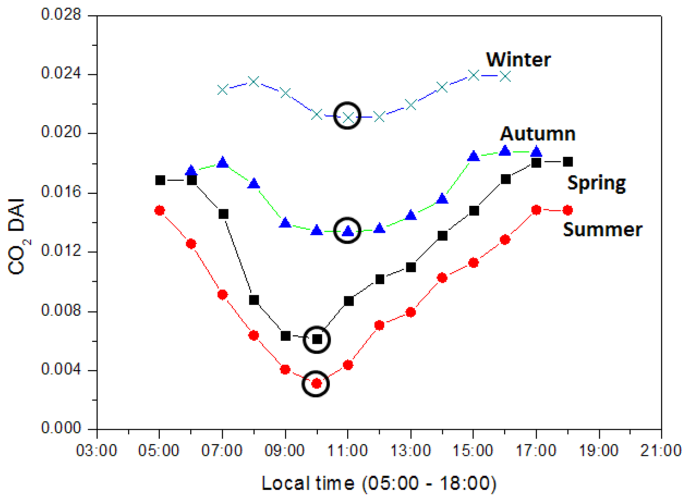

Fig. 7. Daily averaged CO_2 DAI at different seasons in Beijing during 2010-2012.

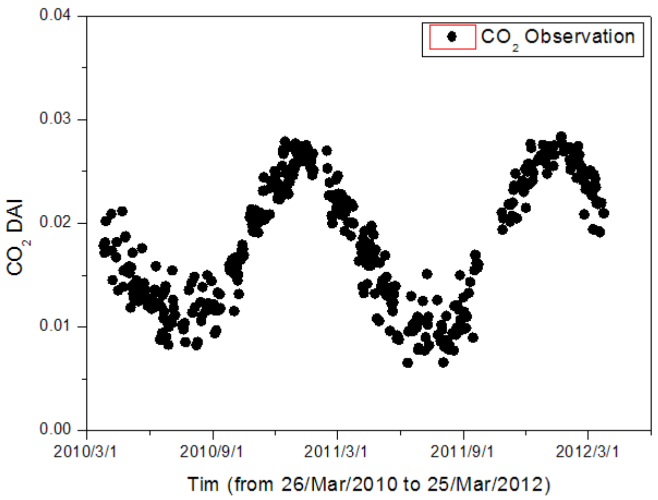

Fig. 8. The seasonal variation of CO2 DAI in two years from 2010 to 2012, IRSA site, Beijing.

Question 3

Insert a new section concerning error estimation and internal consistency before section 4. A few items: how consistent are CO2 columns derived from different combination of channels (different DAIs)? Do the CO2 columns behave as expected (the CO2 column should correlate with ground pressure)? In the next step, calculate the XCO2 (using ground pressure and H2O column): is there an apparent unphysical correlation between XCO2 and H2O column or airmass?

Reply：

(1) We added error estimation following new treatment of DAI definition as follows:

The uncertainties on DAI are estimated following parts on:

(i) Aerosol

In Eq. (5), we developped the AOD correction item, and in this study the needed aerosol parameters can be obtained from the aside CIMEL CE318 sunphotometer. Assuming the errors in $\tau_{aer,b}$ is 0.02 (Holben et al., 1998) and employing the multi-year averaged α (=1.08) observed in Beijing by the Aerosol Robotic Network (AERONET) (Holben et al., 1998), we estimated a typical error of about 1.4×10^{-4} on DAI caused by uncertainty on aerosol measurements.

(ii) Rayleigh scattering

Rayleigh scattering optical depth in the 1560-1580 nm region is very small since ROD is proportional to λ^{-4}. The order of magnitude of 10^{-7} on DAI caused by Rayleigh scattering can be safely neglected in this study.

(iii) Other gas absorption

Absorption of other gases such as water vapor, ozone and trace gases in these channels are also very small and can be neglected.

(iv) Instrumental issues

The DAI uncertainties can also come from instrumental issues, like sun-tracking error, measuring time precision, filter response profile degradation, are expected to be small in this study, considering the difference absorption principle used for DAI. We estimate an uncertainty of about 0.5% on DAI from instrumental issues.

(v) Cloud contamination

The current cloud screening procedure may miss some optical thin cirrus as discussed in the cloud screening part. In these cases, the DAI might be overestimated. Errors caused by this uncertainty is difficult to be estimated but according to CIMEL aerosol sunphotometer experience (Siminov et al., 2000), these cases are few and can be reduced by improving the cloud screening algorithm.

Following above discussion, the total uncertainty is thus estimated to be about 1.2% assuming a typical DAI of 0.02.

(2) On the DAI consistent when considering different channels, we have provided some basic discussion in section 3.2.2 and Fig. (6). The DAI based on channel 6 (1570.97nm), channel 9 (1573.56nm) are calculated and compared with the one based on the selected channel (1577.16nm). In general we can get the similar time variation behavior, but the variation amplitudes are smaller. Following the sensitivity consideration as described in page 8322, we finally chose the DAI based on

1577.16nm.

(3) We cannot yet retrieve XCO_2 currently due to lack of other synchronous observation, such as oxygen column content, water vapor column content or ground pressure. This paper mainly focuses on the introduction of the instrument and providing preliminary CO_2 column observation results. In the next step, we will increase the joint observation capability to achieve the retrieval of XCO_2.

(4) On the airmass correction, please refer to reply to the question 2.

Question 4

In section 4, discuss the XCO2 results indicated by your measurements. It is improper to interpret DAI values as if they were XCO2 values.

Reply: Following the referee's suggestion, the previous DAI is not the vertical content and should not be compared with the column XCO2. In the correction, we reproduced the vertical corrected CO_2 DAI, and compared with CarbonTacker results as shown below in Fig.10. We also made a small improvement in the figure to show the ±1 ppm threshold boundary lines, instead of previous dash line, considering 1ppm is the general expectation for ground-based CO_2 measurements. Clearly, there are DAI points beyond this threshold, which is partly explained by the new added error analysis part, and are also expected to be improved by the calibration and inversion in the next studies.

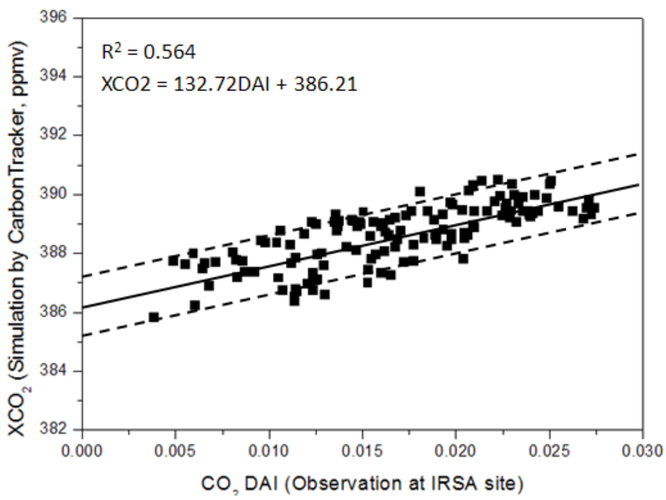

Fig. 10. The correlation plot of daily averaged CO_2 amounts between CarbonTracker model and the observation at IRSA site for the same period (March to December in 2010). The solid line denotes the linear fitting of the observed and modeled CO_2 while dash lines showing ±1 ppm threshold.

Question 5

No attempt is made to relate the own investigations to relevant prior work.

Reply: We supplied new references to the relevant prior works:

Kobayashi, N., Inoue, G., Kawasaki, M., Yoshioka, H., Minomura, M., Murata, I., Nagahama, T., Matsumi, Y., Tanaka, T., Morino, I., and Ibuki, T.: Remotely operable compact instruments for measuring atmospheric CO_2 and CH_4 column densities at surface monitoring sites, Atmos. Meas. Tech., 3, 1103-1112, 2010.

Petri, C., Warneke, T., Jones, N., Ridder, T., Messerschmidt, J., Weinzierl, T., Geibel, M., and Notholt, J.: Remote sensing of CO_2 and CH_4 using solar absorption spectrometry with a low resolution spectrometer, Atmos. Meas. Tech., 5, 1627-1635, 2012.

Gisi, M., Hase, F., Dohe, S., Blumenstock, T., Simon, A., and Keens, A.: XCO_2-measurements with a tabletop FTS using solar absorption spectroscopy, Atmos. Meas. Tech., 5, 2969-2980, 2012.

Morino, I., Uchino, O., Inoue, M., Yoshida, Y., Yokota, T., Wennberg, P. O., Toon, G. C., Wunch, D., Roehl, C. M., Notholt, J. , Warneke, T., Messerschmidt, J., Griffith, D. W. T., Deutscher, N. M., Sherlock, V., Connor, B., Robinson, J., Sussmann, R., and Rettinger, M.: Preliminary validation of column-averaged volume mixing ratios of carbon dioxide and methane retrieved from GOSAT short-wavelength infrared spectra, Atmos. Meas. Tech., 4, 1061-1076, 2011.

Holben, B. N., Eck, T. F., Slutsker, I., Tanre, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A.: AERONET - A federated instrument network and data archive for aerosol characterization, Remote Sens. Environ., 66, 1-16, 1998.

Kasten, F. and Andrew Young, T., Revised optical air mass tables and approximation formula, Appl. Opt., 28, 4735-4738, 1989.