ACP-2015-875 (Editor – William Lahoz)

Response to Reviewer 2

The authors thank the reviewer 2 for a thoughtful review of the manuscript. We agree with the reviewer's points and have made the necessary changes. The responses for the reviewer's specific comments are as follows.

**Comment:**

*This study evaluates the influence of additional CO2 observations (from the JRSTATION towers) on the analysis of Eurasian and global CO2 surface fluxes. The novelty of this study is in using these additional tower observations, which have not been used within an inverse modeling study before. The results demonstrate that these observations do have a certain amount of impact, namely it adjusts the flux patterns and magnitudes between Eurasian Boreal (local) and other NH land regions (non-local). This is expected based on the way an inverse modeling system works, especially the resultant interplay between the observation density/network and the prior weighed by their respective covariances. This is not a novel finding in itself. What is of greater interest, are the adjustments that are made to the surface fluxes and whether they are correct or not (especially the reduced sink in Eurasian Boreal region). No independent evaluation, either of the posterior CO2 concentrations or the posterior fluxes with any kind of independent data has been provided, however. The authors have compared their flux estimates to a suite of previous studies. But these studies cover different temporal extent (i.e., span across a wide variety of years), and second all of the estimates fall within the reported uncertainty bounds. There is no rationale behind the authors claim that the flux estimates from the JR experiment are more comparable to the previous studies than the CNTL experiment (Page 14, Lines 4-5). It is also highly misleading that in Section 3.2 the authors show results comparing the posterior CO2 concentrations to the observations that are being assimilated in the first place. Finally in Section 3.3, the uncertainty reduction should be calculated individually for the CNTL and the JR experiments relative to the prior uncertainties that were specified. It is again misleading to compare two posterior uncertainties (without knowing which one provides a baseline) and call this calculation as an "uncertainty reduction".*

*The following points provide a checklist on critical sensitivity tests/issues that should be addressed to first validate the results presented in this study, and thereby make it relevant and appealing to the* carbon *science community.*

**Author's response**: Following the reviewer's suggestions, we have revised the manuscript substantially. Based on in-depth analysis of the two experiments, we have tried to show the ability of CarbonTracker to reproduce JR and other observations in Siberia by assimilating the additional JR station data. Specific responses to the reviewer's comments and revisions are shown below.

**Specific Comment:**

*1) Evaluation of posterior CO2 concentrations with independent data – This is the most important step that is missing from this study. This should be done either by comparison with independent data or via data denial experiments. In the latter case, specific set of in situ observations that are common to both CNTL and JR experiments may be held in reserve (i.e., those data should not be assimilated into the CT system). The posterior $CO_2$ concentrations from the two experiments should be compared to this independent data both qualitatively and quantitatively.*

**Author's response**: Following the reviewer's opinion, we evaluated the posterior $CO_2$ concentrations from the two experiments with independent data. We used the airborne observations over BRZ (Berezorechka; 56.15°N, 84.33°E) in the taiga region of West Siberia (detailed explanation in Section 2.3) as the independent data. The results show that the optimized fluxes of JR experiment exhibit better agreement with independent observations in terms of root mean square difference, mean absolute error, and Pearson's correlation coefficient at all altitudes, which supports the usefulness of Siberian tower measurements on the estimation of surface $CO_2$ fluxes over Siberia. Table 5 and discussion of the results (Section 3.2) are added in the revised manuscript as follows.

Table 5. Bias, root mean square difference, mean absolute error, and Pearson's Correlation Coefficient of the model $CO_2$ concentration of CNTL and JR experiments in comparison with the vertical profile of $CO_2$ concentrations at BRZ site.

| Altitude (km) | Bias (ppm) | | Root-Mean-Square Difference (ppm) | | Mean Absolute Error (ppm) | | Pearson's Correlation Coefficient | |
|---|---|---|---|---|---|---|---|---|
| | CNTL | JR | CNTL | JR | CNTL | JR | CNTL | JR |
| ~ 0.5 | -0.13±4.81 | 0.20±4.57 | 4.82 | 4.57 | 3.45 | 3.23 | 0.95 | 0.95 |
| 0.5 ~ 1.0 | 0.58±4.30 | 0.83±4.10 | 4.34 | 4.18 | 3.14 | 3.03 | 0.95 | 0.95 |
| 1.0 ~ 1.5 | 0.40±3.94 | 0.56±3.69 | 3.96 | 3.74 | 2.88 | 2.68 | 0.93 | 0.94 |
| 1.5 ~ 2.0 | 0.25±3.46 | 0.42±3.24 | 3.47 | 3.27 | 2.49 | 2.34 | 0.93 | 0.94 |
| 2.0 ~ 2.5 | 0.43±3.20 | 0.59±2.91 | 3.22 | 2.97 | 2.35 | 2.18 | 0.92 | 0.94 |
| 2.5 ~ 3.0 | 0.56±2.89 | 0.73±2.58 | 2.94 | 2.69 | 2.21 | 2.08 | 0.90 | 0.92 |
| 3.0 ~ | 0.13±3.19 | 0.44±2.65 | 3.19 | 2.68 | 3.89 | 2.03 | 0.86 | 0.90 |

We have revised the sentences in Section 2.3 as follows.

"(3) JR-STATION observation data over Siberia operated by CGER/NIES (Sasakawa et al., 2010; 2013). The JR-STATION sites consist of nine towers (eight towers in west

Siberia and one tower in east Siberia). Atmospheric air was sampled at four levels on the BRZ tower and at two levels on the other eight towers. At the BRZ (Berezorechka) site in west Siberia, both tower and aircraft measurements are sampled. The light aircraft at BRZ site measures the vertical profiles of $CO_2$ from the PBL to the lower free troposphere and these vertical profiles are used as independent observations for verification."

We have added the following sentences at the end of Section 3.2.

"In addition, model $CO_2$ concentrations calculated by optimized fluxes of the two experiments are compared with independent, not assimilated, vertical profiles of $CO_2$ concentration measurements by aircraft at BRZ site in Siberia. Table 5 presents the average bias, root-mean-square difference (RMSD), mean absolute error (MAE), and Pearson's correlation coefficient of the model $CO_2$ concentrations calculated by optimized fluxes of the two experiments based on the observations at BRZ site as the reference. The statistics are calculated at each vertical bin with 500 meter interval. Overall, the biases of two experiments are less than 0.83 ppm showing good consistency between model and observed $CO_2$ concentrations. The biases of the CNTL experiment are smaller than those of the JR experiment at all altitudes, whereas the standard deviations of the CNTL experiment are greater than those of JR experiment, which implies that the biases of the CNTL experiment fluctuate as its average more than those of the JR experiment. In contrast, the RMSD and MAE of the JR experiment are smaller than those of the CNTL experiment, and the correlation coefficient of the JR experiment is greater than that of the CNTL experiments. Therefore, overall the statistics show that the model $CO_2$ concentrations of the JR experiment is relatively more consistent with independent $CO_2$ concentration observations compared to those of the CNTL experiment over Siberia. "

*2) Uncertainty estimates associated with the analyzed flux estimates – On Page 9, Lines 13-14, the authors claim that the ". . .uncertainty is calculated as one-sigma standard deviation of the fluxes estimated, using Gaussian errors". It is unclear why the authors choose this approach when they are using an ensemble Kalman filter based system, where they should be able to directly recover the posterior uncertainty over the entire time period. Why is such an ad-hoc approach used to calculate the uncertainty? What is the basis for this approach?*

**Author's response**: The uncertainty estimation in this study is not based on ad-hoc method but based on uncertainty estimation method used in previous studies using CarbonTracker (Peters et al., 2007, 2010; Zhang et al., 2014a, 2014b). As mentioned by the reviewer, in Ensemble Kalman Filter system, the posterior uncertainty can be estimated directly from the ensembles. One sigma standard deviation of surface fluxes was calculated based on ensembles of prior and optimized surface fluxes. To clarify the uncertainty estimation method, we have revised the manuscript as follows.

“The difference in the optimized $CO_2$ flux between the two experiments is analyzed. Table 2 presents prior and optimized fluxes with their uncertainties for global total, global land, global ocean, NH total, Tropics total, Southern Hemisphere total, and TransCom regions in the NH. Flux uncertainties are calculated from the ensembles of prior and optimized surface fluxes assuming Gaussian errors, following previous method used in Peters et al. (2007, 2010).”

*3) Reduced uptake estimated in EB between 2002-2009 – Possibly the real significant finding from the additional JR-STATION tower observations are that the overall magnitude of the uptake reduced in Eurasian boreal region during NH summer. This is a reasonable conclusion for the summer of 2003 (anomalous drought for this year) but the authors claim a consistent reduction averaged out over the entire 2002-2009 period. The authors do not address any underlying mechanism for this difference in uptake from the two experiments. Is this simply an artifact of the inverse modeling setup, interplay between data density, error covariances, etc.? Or are there changes in vegetative activity that took place during this period in the Eurasian Boreal region and the JR-STATION tower observations were able to observe those local changes. The authors need to provide some form of mechanistic understanding for their inverse modeling results.*

**Author’s response:** In 2003, the uptake in EB in the JR experiment was not reduced, but increased. The reason is that the drought in Europe affected the reduced uptake in EB in the CNTL experiment whereas the uptake in EB is actually not that much reduced.

The CNTL and JR experiments have the same inversion modeling setup except the observation data set (with or without JR-STATION data). Therefore, the differences in flux uptakes over Northern Hemisphere were from the additional JR-STATION data used in the inversion. The JR-STATION tower observations are able to observe those local vegetation activities in boreal summer appropriately as shown in Fig. 6. Without JR-STATION data, the surface flux uptakes are determined mostly by the transport model and remote observations. By adding JR-STATION data, the surface flux uptakes in Siberia are constrained both the model and JR-STATION observations. The differences between observed and model $CO_2$ concentrations simulated using optimized surface fluxes in JR experiment are much smaller than those in CNTL experiment at JR-STAION sites, which implies that an appropriate agreement between observed and optimized surface $CO_2$ concentrations over Siberia in JR experiment.

Therefore, the previous misleading texts in Section 3.1 was revised as follows.

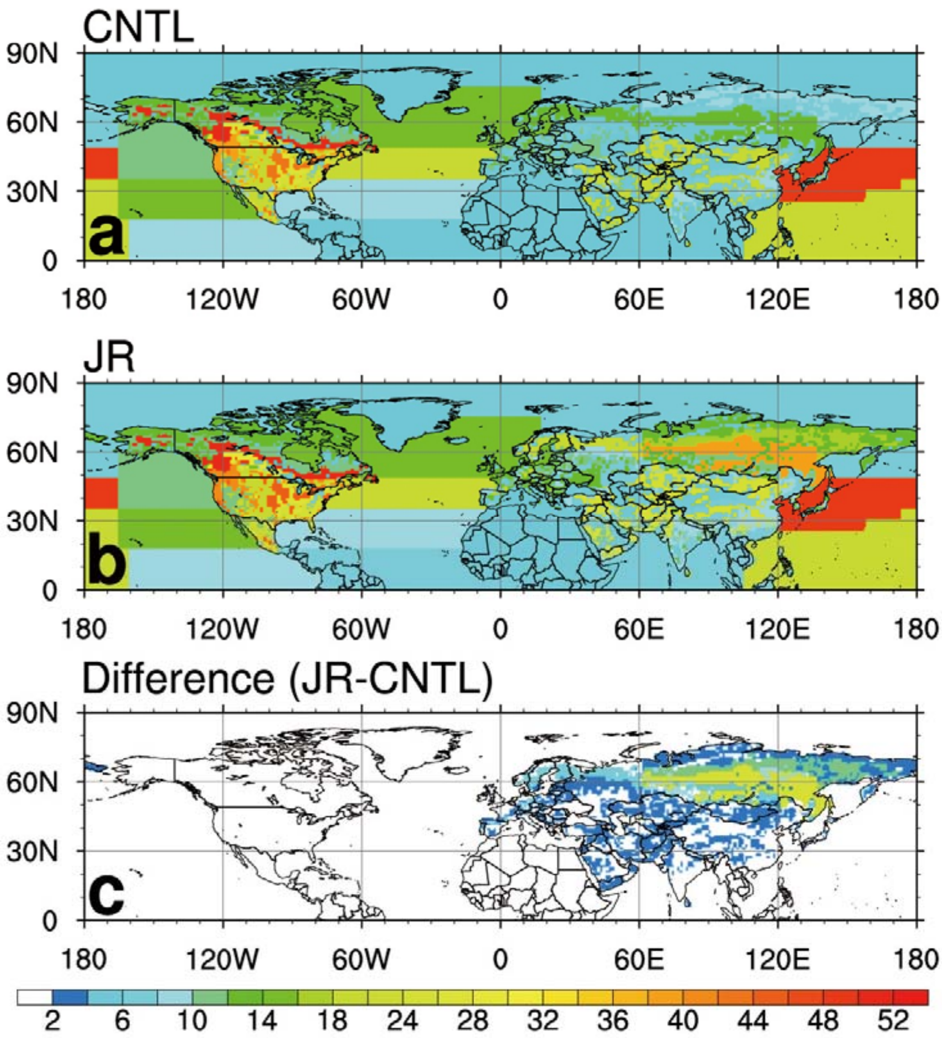
“The uptake of optimized surface $CO_2$ flux in this region is reduced in JR for all years except 2003. In 2003, extreme drought occurred in the northern mid-latitudes (Knorr et al., 2007) and Europe (Ciais et al., 2005), which resulted in increased NEE (i.e. reduced uptake of $CO_2$) in EB in the CNTL experiment. The uptake of optimized surface $CO_2$ fluxes in Siberia in 2003 is reduced in the CNTL experiment due to the remote effect of drought in Europe. Despite the number of JR-STATION data used in the optimization in 2003 being relatively smaller than that in the later experiment period, new observations in the JR experiment provide information on the increased uptake of optimized surface $CO_2$ fluxes in 2003 in Siberia (Fig. 3b)"

*4) Prior flux estimates and associated uncertainty used throughout the study – For Figures 4,5 and 6 the authors should add the prior flux estimates (say green or gray bars/lines) to the figures. For the uncertainty reduction reported in Section 3.3, the authors should use the prior uncertainties as a baseline and compare the posterior uncertainties from their two experiments.*

**Author's response**: Following the reviewer's opinion, prior fluxes are added in Figs. 4, 5, and 6 in the revised manuscript. In addition, we have added explanations and comparisons of prior and posterior fluxes accordingly in the revised manuscript.

We have plotted the uncertainty reductions (UR) of CNTL experiment and JR experiment from their prior uncertainties and the difference of two URs (Fig_rev 1). A mapping of prior uncertainties is not shown because the prior uncertainties do not show the contribution of the additional observations. Except the EB region (i.e. Siberia), the average URs of two experiments show similar patterns in the Northern Hemisphere. The difference between the URs of CNTL (Fig._rev 1a) and JR (Fig._rev 1b) is readily apparent in Siberia (Fig._rev 1c), which is very similar result with the UR using Eq. (7) shown in Fig. 7c. Because the Fig. 7 in the manuscript already shows the contribution of the additional JR observations clearly and the URs of CNTL and JR from the prior uncertainties do not provide additional information on the impact of Siberian observations, we did not insert Fig._rev 1 in the revised manuscript. Instead, we have added the texts to read,

"The uncertainty reduction of CNTL and JR experiments based on the prior uncertainty as the reference ($\sigma_{prior}$ used instead of $\sigma_{CNTL}$ in Eq. (8); or $\sigma_{CNTL}$ used instead of $\sigma_{JR}$ in Eq. (8)) shows similar values in the NH except in Siberia region (not shown). In addition, the difference between average uncertainty reduction of CNTL and JR experiments based on the prior unceatinty as the reference (not shown) is very similar to the average of uncertainty reduction in Eq. (8) shown in Fig.7a."




Figure_rev 1. Average uncertainty reduction (%), based on the prior uncertainty as a reference, of (a) CNTL experiment and (b) JR experiment. (c) The difference between (a) and (b).

*5) Section 3.3 self-sensitivity calculation – It is slightly counter-intuitive that the single JR-STATION tower that is located at 60N, 130E provides the same influence on the analyses as all the other set of JR-STATION towers that are clumped together between 60-90E. As per previous studies (Cardinali et al. 2004, Liu et al. 2009, Kim et al. 2014), typically there is a negative correlation between the self-sensitivities and the spatial density of the observations. Can the authors comment on why that one single tower observation does not provide higher influence than a cluster of towers together?*

**Author's response**: The average self-sensitivity of YAK site located in east Siberia is 10.8% which is the largest sensitivity value among the JR-STATION sites. The average of the self-sensitivities for other eight sites located between 60°E and 90°E is 8.4%. Therefore, YAK site provides greater impacts than a cluster of Siberian towers. This is intuitive result. To clarify, we have revise text to read, “The average self-sensitivities of additional observations are higher than those of other sites, providing much information for estimating surface $CO_2$ fluxes. In particular, YAK site located in east Siberia provides greater impacts than other JR-STATION sites located in 60 ~ 90°E.”

**Minor Comment:**

*(a) Kindly check the spelling of ‘Eurasian Boreal’ in Figure 5A.*

**Author’s response**: Following the reviewer’s opinion, we have revised the manuscript.

*(b) The color scale for Figure 7 should be modified – either a linear increase or use something analogous to a log scale. Currently it jumps from a scale of 34-36 to 70-75.*

**Author’s response**: Following the reviewer’s opinion, the color scale for Fig. 7 was modified. In addition, following the other reviewer’s opinion, Fig. 7b was removed in the revised manuscript.

*(c) For Section 3.4 and Table 5, the authors should choose a set of studies spanning the same spatial domain, temporal extent, space-time resolution at which fluxes are estimated and then compare to their estimates from the CNTL and the JR experiments. This would help out bring out the main message in this section.*

**Author’s response**: We agree with the reviewer’s opinion, choosing a set of studies spanning the same spatial domain, temporal extent, space-time resolution is important in comparing this study with other studies. We have chosen the same spatial domain (Eurasian Boreal and Europe) with other studies. However, it is difficult to match the same temporal extent because each study use different experimental period. For example, Saeki et al. (2013; Table 6) and Zhang et al, (2014b; Table 7) compared their estimated fluxes with those of other studies for different time periods.

We have tried to match the temporal period between this study and other CT framework results that are provided in each CarbonTracker’s homepage. Therefore, Table 6 is partially revised as follows.

Table 6. Optimized surface $CO_2$ fluxes (Pg C $yr^{-1}$) from this study and other inversion studies.

| Citation | Area | Estimate surface $CO_2$ flux | Period | Remarks |
|---|---|---|---|---|
| This study | Eurasian Boreal | -0.77±0.70 | 2002-2009 | JR experiment |
| Saeki et al. (2013) | Eurasian Boreal | -0.35±0.61 | 2000-2009 | Including biomass burning (0.11Pg C $yr^{-1}$), Using JR-STATION observations |
| Zhang et al. (2014b) | Eurasian Boreal | -1.02±0.91 | 2006-2010 | Using CONTRAL observations |
| Maki et al. (2010) | Eurasian Boreal | -1.46±0.41 | 2001-2007 | |
| Dolman et al. (2012) | Russia[a] | -0.613 | | Average of inventory-based, eddy covariance, and inversion methods |
| CT2013B[b] | Eurasian Boreal | -1.00±3.75 | 2002-2009 | |
| This study | Europe | -0.38±0.64<br>-0.75±0.63 | 2002-2009<br>2008-2009 | JR experiment |
| Reuter et al. (2014) | Europe | -1.02±0.30 | 2010 | Using satellite data |
| CTE2014[c] | Europe | -0.07±0.49<br>-0.11±0.38 | 2002-2009<br>2008-2009 | |

[a]Including Ukraine, Belarus and Kazakhstan (total area is $17.1\times10^{12}$ $m^2$)

[b]The results of CT2013B (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2013B/) were derived from (ftp://aftp.cmdl.noaa.gov/products/carbontracker/co2/fluxes/).

[c]The results of CTE2014 (CarbonTracker Europe, Peters et al., 2010) were derived from (ftp://ftp.wur.nl/carbontracker/data/fluxes/).

## References

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, Chr., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M. J., Schulze, E. D., Vesala, T., and Valentini, R.: Europe-wide reduction in primary productivity caused by the heat and drought in 2003, Nature, 529-533, doi:10.1038/natures03972, 2005.

Knorr, W., Gobron, N., Scholze, M., Kaminski, T., Schnur, R., and Pinty, B.: Impact of terrestrial biosphere carbon exchanges on the anomalous $CO_2$ increase in 2002-2003, Geophys. Res. Lett., 34, L09703, doi:10.1029/2006GL029019, 2007.

Peters, W., Jacobson, A. R., Sweeney, C., Andrews, A. E., Conway, T. J., Masarie, K., Miller, J. B., Bruhwiler, L. M. P., Petron, G., Hirsch, A. I., Worthy, D. E. J., van der Werf, G. R., Randerson, J. T., Wennberg, P. O., Krol, M. C., Tans, P. P.: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, Proc. Nat. Acd. Sci. U.S.A., 104, 18925-18930, 2007.

Peters, W., Krol, M. C., van der Werf, G. R., Houweling, S., Jones, C. D., Hughes, J., Schaefer, K., Masarie, K. A., Jacobson, A. R. Miller, J. B., Cho, C. H., Ramonet, M., Schmidt, M., Ciattaglia, L., Apadula, F., Heltai, D., Meinhardt, F., di Sarra, A. G., Piacentino, S., Sferlazzo, D., Aalto, T., Hatakka, J., Ström, J., Haszpra, L., Meijer, H. A. J., van der Laan, S., Neubert, R. E. M., Jordan, A., Rodó, X., Morguí, J. A., Vermeulen, A. T., Popa, E., Rozanski, K., Zimnoch, M., Manning, A. C., Leuenberger, M., Uglietti, C., Dolman, A. J., Ciais, P. Heimann, M., and Tans, P. P.: Seven years of recent European net terrestrial carbon dioxide exchange constrained by atmospheric observations, Global Change Biol., 16, 1317-1337, doi:10.1111/j.1365-2486.2009.02078.x, 2010.

Saeki, T., Maksyutov, S., Sasakawa, M., Machida, T., Arshinov, M., Tans, P. P., Conway, T. J., Saito, M., Valsala, V., Oda, T., Andres, R. J., and Belikov, D.: Carbon flux estimation for Siberia by inverse modeling constrained by aircraft and tower $CO_2$ measurements, J. Geophys. Res. Atmos., 118, 1100-1122, doi:10.1002/jgrd.50127, 2013.

Sasakawa, M., Shimoyama, K., Machida, T., Tsuda, N., Suto, H., Arshinov, M., Davydov, D., Fofonov, A., Krasnov, O., Saeki, T., Koyama, Y., and Maksyutov, S.: Continuous measurements of methane from a tower network over Siberia, Tellus, 62B, 403-416, doi:10.1111/j.1600-0889.2010.00494.x, 2010.

Sasakawa, M., Machida, T., Tsuda, N., Arshinov, M., Davydov, D., Fofonov, A., and Krasnov, O.: Aircraft and tower measurements of $CO_2$ concentration in the planetary boundary layer and the lower free troposphere over southern taiga in West Siberia: Long-term records from 2002 to 2011, J. Geophys. Res. Atmos., 118, 9489-9498, doi:10.1002/jgrd.50755, 2013.

Zhang, H. F., Chen, B. Z., van der Laan-Luijkx, I. T., Chen, J., Xu, G., Yan, J. W., Zhou, L. X., Fukuyama, Y., Tans, P. P., and Peters, W.: Net terrestrial $CO_2$ exchange over China during 2001–2010 estimated with an ensemble data assimilation system for atmospheric $CO_2$. J. Geophys. Res. Atmos., 119, 2013JD021297, doi:10.1002/2013JD021297, 2014a.

Zhang, H. F, Chen, B. Z., van der Laan-Luijkx, Machida, T., Matsueda, H., Sawa, Y, Fukuyama, Y., Labuschange, C., Langenfelds, R., van der Schoot, M., Xu, G., Yan, J. W., Zhou, L. X., Tans, P. P., and Peters, W.: Estimating Asian terrestrial carbon fluxes from CONTRAIL aircraft and surface $CO_2$ observations for the period 2006 to 2010, Atmos. Chem. Phys., 14, 5807-5824, doi:10.5194/acp-14-7807-2014, 2014b.