ACP-2015-875 (Editor – William Lahoz)

Response to Reviewer 1

The authors thank the reviewer 1 for a thoughtful review of the manuscript. The responses for the reviewer's specific comments are as follows.

**General Comment:**

*Kim et al.'s paper discusses the additional constraints on net biogenic CO2 fluxes in Siberia brought by adding specific regional CO2 observation. The authors add on top of a global ('control') data set (NOAA, WDCGG) additional data that is the Japanese Russian ('JR') network of station in Siberia. The control data set lacks stations over Siberia, a gap that the JR network fills successfully. The inversion set up is the well established CarbonTracker (CT), and inversions of the control and control+JR sites are analysed comparatively. This paper discuss that adding JR observations in the setup, in the vast, poorly-sampled region of Siberia, brings additional information when estimating top-down fluxes. The CT inversion set up used in the present paper was described in two other recent papers (Kim et al. 2014a, b), where the authors applied CarbonTracker with a focus in Asia (including Siberia) to the 'control' data set. Previously, Saeki et al. (2013) already evaluated the impact of adding this same JR data set on the mean biogenic CO2 flux, albeit with a different inversion set-up. Kim et al. find in relative terms a similar reduction in flux uncertainty when adding the JR network in the inversion. The paper lacks sufficient discussion on the ability of their model to reproduce JR and independent observations in Siberia, and rely on high level statistical analysis instead, which limits a deeper understanding of the problem. The paper also lacks distance to the opportunities and limitations associated to inverse modelling in an 'under-documented' region such as Siberia. However the material at hand is very valuable and provides potentially a basis for an in-depth discussion of CO2 fluxes over Siberia. Therefore I suggest rejecting the manuscript to allow its authors to improve it and eventually resubmit.*

**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. Specific responses to the reviewer's comments and revisions are shown below.

**Detailed Comments:**

*1) Abstract Please specify in the abstract the time period over which the study is done. The abstract should be more quantitative about the fluxes to illustrate the improvement brought by the additional data, in terms of control, updated fluxes, and uncertainy reductions. The abstract could state the improvements obtained over Saeki et al. (2013).*

**Author's response**: Following the reviewer's opinion, we have revised the abstract as follows.

"To investigate the effect of additional $CO_2$ observations in the Siberia region on the Asian and global surface $CO_2$ flux analyses, two experiments using different observation dataset were performed for 2000-2009. One experiment was conducted using a data set that includes additional observations of Siberian tower measurements (Japan-Russia Siberian Tall Tower Inland Observation Network: JR-STATION), and the other experiment was conducted using a data set without the above additional observations. The results show that the global balance of the sources and sinks of surface $CO_2$ fluxes was maintained for both experiments with and without the additional observations. While the magnitude of the optimized surface $CO_2$ flux uptake and flux uncertainty in Siberia decreased from -1.17±0.93 Pg C $yr^{-1}$ to -0.77±0.70 Pg C $yr^{-1}$, the magnitude of the optimized surface $CO_2$ flux uptake in the other regions (e.g., Europe) of the Northern Hemisphere (NH) land increased for the experiment with the additional observations, which affect the longitudinal distribution of the total NH sinks. This change was mostly caused by changes in the magnitudes of surface $CO_2$ flux in June and July. ~"

We have not mentioned Saeki et al. (2013) because a reference is not normally stated in the abstract except when the study is a follow-up study of the reference. In addition, we didn't state Saeki et al. (2013) because we have used a different framework (inversion system, transport model, observations, etc.) from Saeki et al. (2013). Instead, we have added verifications using independent observations in Section 3.2.

*2) P2 L6 'useful information': please provide a quantitative estimate for this statement. Last sentence: please also mention the contribution to the estimation of European fluxes.*

**Author's response**: Following the reviewer's opinion, we have revised the abstract as follows.

"The observation impact measured by uncertainty reduction and self-sensitivity tests shows that additional observations provide useful information on the estimated surface $CO_2$ flux. The average uncertainty reduction of the Conifer Forest of EB is 29.1% and the average self-sensitivities at the JR-STATION sites are approximately 60% larger than those at the tower measurements in North America. It is expected that the Siberian observations play an important role in estimating surface $CO_2$ flux in the NH land (e.g., Siberia and Europe) in the future."

*3) Introduction The first paragraph should mention also comparisons with inversion results, e.g. Dolman et al., Biogeosciences, 9, 5323-5340, 2012 The second paragraph (p2 l20-21) should discuss other factors leading to error in inverse modelling results, e.g. model error, representation error etc.: data sparseness is not the only one. P3 l5 after last sentence please discuss results from previous research, including Saeki et al. , 2013 here, as well as Dolman et al. 2012 (see above), and Berchet et al. (Biogeosciences, 12, 5393–5414, 2015 ).*

**Author's response**: Following the reviewer's opinion, we have revised the first paragraph in Section 1 to read, "The terrestrial ecosystem in the Northern Hemisphere (NH) plays an important role in the global carbon balance (Hayes et al., 2011; Le Quéré et al., 2015). Especially, Siberia is considered to be the one of the largest $CO_2$ uptake regions and reservoirs due to its forest area (Schulze et al., 1999; Houghton et al., 2007; Tarnocai et al., 2009; Kurganova et al., 2010; Schepaschenko et al., 2011) and its dynamics and interactions with the climate have global significance (Quegan et al., 2011). Therefore, it is important to accurately estimate the surface $CO_2$ fluxes in this region. For instance, Dolman et al. (2012) estimated terrestrial carbon budget of Russia, Ukraine, Belarus, and Kazakhstan using inventory-based, eddy covariance, and inversion methods and showed that the carbon budgets produced by three methods agree within their uncertainty bounds."

We have revised the second paragraph to read, "To estimate the surface $CO_2$ flux, atmospheric $CO_2$ inversion studies are conducted using atmospheric transport models and atmospheric $CO_2$ observations (Gurney et al., 2002; Peylin et al., 2013). However, prior emission, measurement error of observation, observation operator including model transport, and representative error affect the uncertainty of atmospheric inversion results (Engelen et al., 2002; Berchet et al., 2015a). Along these factors, large uncertainties remain in the estimated surface $CO_2$ fluxes due to the sparseness of current surface $CO_2$ measurements assimilated by inverse models (Peters et al., 2010; Bruhwiler et al., 2011)"

We have revised the sixth paragraph to read, "The Center for Global Environmental Research (CGER) of the National Institute for Environmental Studies (NIES) of Japan with the cooperation of the Russian Academy of Science (RAS) constructed a tower network called the Japan-Russia Siberian Tall Tower Inland Observation Network (JR-STATION) in 2002 to measure the continuous $CO_2$ and $CH_4$ concentrations (eight towers in central Siberia and one tower in eastern Siberia) (Sasakawa et al., 2010, 2013). The vertical profile of $CO_2$ concentrations from the planetary boundary layer (PBL) to the lower free troposphere is also measured by aircraft at one site of the JR-STATION sites (Sasakawa et al., 2010, 2013). Saeki et al. (2013) estimated the monthly surface $CO_2$ flux for 68 subcontinental regions by using the fixed-lag Kalman smoother and NIES-TM transport model with JR-STATION data. They reported that the inclusion of additional Siberian observation data has an impact on the inversion results showing larger interannual variability over northeastern Europe as well as Siberia, and reduces the uncertainty of surface $CO_2$ uptake. Meanwhile, Berchet et al. (2015b) estimated regional $CH_4$ fluxes over Siberia in 2010 by using JR-STATION data."

The results of references suggested by the reviewer are mentioned in appropriate places in Section 1, for a smooth flow of Introduction. Saeki et al. (2013) is already discussed in P3 L32 in the originally submitted manuscript. Doman et al. (2012)'s results are added in first paragraph and Berchet et al. (2015b) is added in sixth paragraph in Section 1.

*4) P4 l22: 'CO2 uptake (. . .) slightly increase': compared to what and by how much? It could be useful for the reader to be reminded if Zhang et al. used (landing/take off) vertical profiles or (cruise altitude) tropopause data.*

**Author's response**: To clarify, we have revised the texts as follows.

"The CONTRAIL measurements include ascending/descending vertical profiles and cruise data below tropopause. The results show that surface $CO_2$ uptake over the Eurasian Boreal (EB) region slightly increases from -0.96 Pg C $yr^{-1}$ to -1.02 Pg C $yr^{-1}$ for the period 2006-2010 when aircraft $CO_2$ measurements were assimilated. However, the surface measurements data over the EB region are still not used in the study by Zhang et al. (2014b)."

*5) Methodology Here the section is written for readers already initiated in CarbonTracker (CT). Many items are not explained or assuming a detailed prior knowledge of CT.*

**Author's response**: The main purpose of this study is to estimate the impact of additional observations (JR-STATION data) in Siberia on the optimized surface $CO_2$ fluxes over Eurasian Boreal region as well as Northern hemisphere. Therefore, the methodology part of the manuscript contains an essential knowledge of CT necessary for understanding inversion results. Many previous studies using CT exist and explain much details about CT framework and methodology (Peters et al. 2007, 2010; Masarie et al. 2011; Kim et al. 2012, 2014a, 2014b; Zhang et al. 2014a, 2014b; Babenhauserheide et al. 2015; van der Laan-Luijkx et al. 2015). Therefore, we have moved the text to read, "The detailed algorithm of inversion method used in this study can be found in Peters et al. (2007) and Kim et al. (2014a)." at the end of Section 2.1.

*6) P5 l9: 'emissions': could these F's be defined as the 'a priori' emissions?*

**Author's response**: As indicated, F's are a priori emissions. We have revised the manuscript as follows.

"where $F_{bio}(x,y,t)$, $F_{ocn}(x,y,t)$, $F_{ff}(x,y,t)$ and $F_{fire}(x,y,t)$ are a priori emissions from the biosphere, the ocean, fossil fuel, and fires. $\lambda_r$ is the scaling factor to be optimized in the data assimilation process,"

*7) P5 l12 What is an 'ecoregion'?*

**Author's response**: According to CarbonTracker documentation, the ecoregions represent large areas of land in a continent, which have similar ecosystem types, and are used to divide continents into smaller pieces for optimization. To avoid the confusion in the original text, we have revised the text to read, "$\lambda_r$ is the scaling factor to be optimized in the data assimilation process, corresponding to 156 regions around the globe ~".

*8) P5 l13: Gurney et al (2002) uses 11 land regions and this research uses 126 land regions. Therefore the reference to Gurney 2002 might not be appropriate, or explanation lacking. Please explain the difference in region definition.*

**Author's response**: Following the reviewer's opinion, we have revised the manuscript for clarification as follows.

"In the land, the ecoregions are defined as the combination of 11 land region of Transcom regions (Gurney et al., 2002) with 19 land-surface characterization based on Olson et al. (1992). Inappropriate combinations of TransCom regions and Olson types are excluded. In the ocean, 30 ocean regions are defined following Jacobson et al. (2007)."

*9) P5 l14-15: scaling factor: how are these (5 weeks, 1 week) durations chosen?*

**Author's response**: The assimilation window (5 weeks, 1 week) used in this study follows previous studies for CarbonTracker (e.g., Peters et al., 2007; 2010, Kim et al., 2012, 2014a, 2014b, Zhang et al., 2014a, 2014b; van der Laan-Luijkx et al., 2015). The previous studies have shown that this configuration is appropriate to estimate the surface $CO_2$ flux using CarbonTracker. We have revised the manuscript as follows.

"The scaling factor spans 5 weeks with 1 week resolution. Several previous studies for CarbonTracker (e.g., Peters et al., 2007; 2010, Kim et al., 2012, 2014a, 2014b, Zhang et al., 2014a, 2014b; van der Laan-Luijkx et al., 2015) showed that 5 weeks of lag and 1-week time resolution are appropriate for optimizing the surface $CO_2$ fluxes.".

*10) P5 l15: What is an assimilation cycle in this context?*

**Author's response**: Assimilation cycle means an analysis step in the inversion process. Optimization of surface $CO_2$ fluxes is performed every assimilation cycle. We have revised the texts to read, "In each assimilation cycle (i.e., analysis step), ~ ".

*11) P5 l15-17 the two sentences ('In each assimilation. . . assimilation cycle.') are unclear, please revise the explanation.*

**Author's response**: Following the reviewer's suggestion, we have revised the text to read, "In each assimilation cycle (i.e., analysis step), the entire scaling factor for 5 weeks is updated by 1 week observations measured most recent week by a time stepping approach. The smoother window moves forward by 1 week at each assimilation cycle. After 5 assimilation cycles, the first part of the scaling factor analyzed by 5 weeks observations is regarded as the optimized scaling factor. The more detailed information of the assimilation process can be found in Kim et al. (2014b). ".

Because a schematic diagram of the assimilation process is already shown in Fig. 1 of Kim et al. (2014b) below, the interested reader is diected to Kim et al. (2014a) for more information about the assimilation process used in CT.

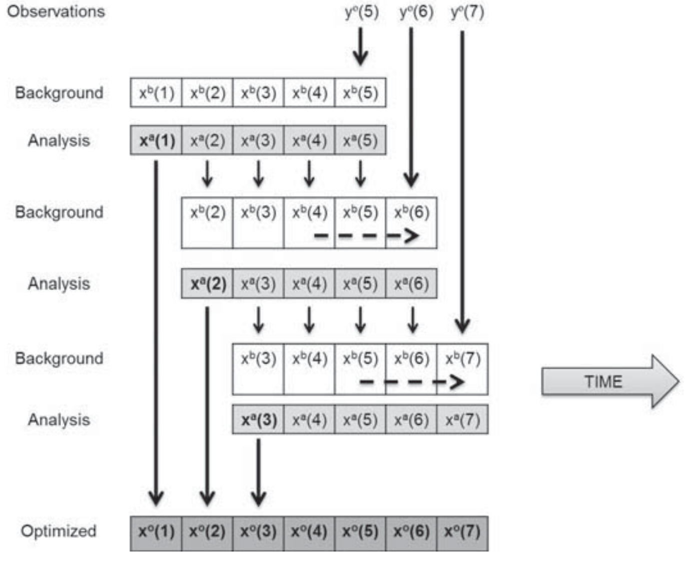
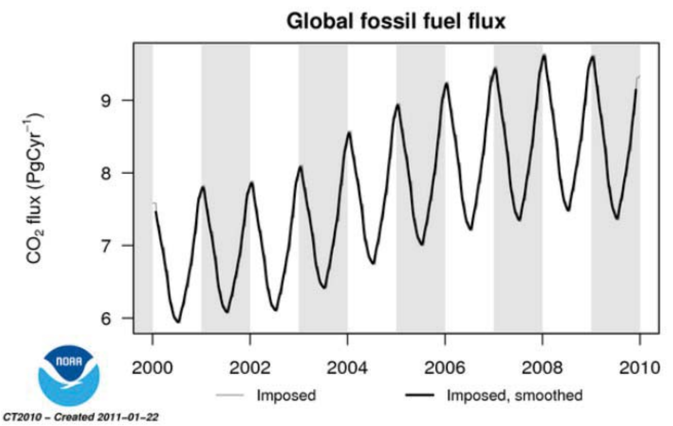



Figure 1. Schematic diagram of the assimilation process employed in CarbonTracker. In each analysis cycle, observations made within one week are used to update the state vectors with a five-week lag. The dashed line indicates how the simple dynamic model uses analysis state vectors from the previous one and two weeks to produce a new

background state vector for the current analysis time. The TM5 model is used as the observation operator to calculate the model $CO_2$ concentration for each corresponding observation location and time (Courtesy of Kim et al. 2014b).

*12) P7 l7 is EDGAR corrected for interannual growth of CO2?*

**Author's response**: In CarbonTrakcer, annual global total fossil fuel $CO_2$ emissions are from the CDIAC. EDGAR provides annual emission estimates at 1°×1° resolution. Fluxes are spatially distributed in two steps: First, the coarse scale flux distribution country totals from CDIAC are mapped onto a 1°x1° grid; next, the country totals within the countries are distributed according to the spatial patterns from the EDGAR inventories (Documentation CT2010). Time series of global fossil fuel emission used in this study is shown in Figure_rev 1.



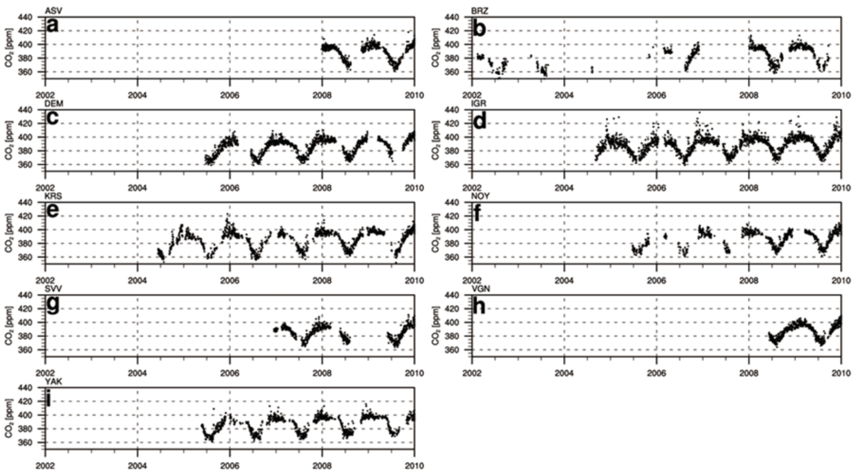

Figure_rev 1. Times series of global fossil fuel emission. (Courtesy of Documentation CT2010 [available online at: http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2010/documentation_CT2010.pdf]).

To clarify, we have revised the texts to read, "~ (4) the prescribed fossil fuel emissions are from the Carbon Dioxide Information and Analysis Center (CDIAC, Boden et al., 2010) and the Emission Database for Global Atmospheric Research (EDGAR, European Commission, 2009) databases. The annual global total fossil fuel emissions are based on

CDIAC. Fluxes at 1°x1° resolution are spatially distributed according to the EDGAR inventories."

*13) P7 l22-24: Is there a correction applied to account for the difference of the NIES scale in the inversion? The paper should mention how does this bias translates into uncertainty (especially when inversion correction modifies the balances Siberia vs Europe)*

**Author's response**: No correction was applied to the NIES scale in the inversion. As explained the manuscript, according to Machida et al. (2011), NIES 09 $CO_2$ scale is lower than the WMO-X2007 $CO_2$ scale by 0.07 ppm at approximately 360 ppm and consistent in the range between 380 and 400 ppm. Most observations used in the assimilation are between 360-420 ppm (Fig_rev. 2). The assigned MDM of JR-STATION data is 3 ppm, which reflects the measurement error of observations and is much larger value than difference between NIES 09 $CO_2$ scale and WMO-X2007 $CO_2$ scale. In this assignment, the JR station data do not constrain the optimized flux more greatly than their confidence. Moreover, $CO_2$ measurements with the NIES scale have been successfully used in the many inversion studies. For example, Zhang et al. (2014b) assimilated Comprehensive Observation Network for Trace gases by Airliner (CONTRAIL) $CO_2$ observations in CarbonTracker. Saeki et al. (2013) used JR-STATION data with NOAA $CO_2$ data in the same inversion framework.



Figure_rev 2. Times series of JR-STATION $CO_2$ data used in this study. The daytime (12-16 LST) averaged data are used in the assimilation.

*14) P8 l4: regarding the notion of having 'the same' MDM: it is not consistent with the fact that MDM is specified above to be determined by Eq. 6 in the paper. How can it be equal to 3 ppm? The authors should also explain why the same confidence is given to the JR-STATION network MDM (3 ppm) as for the US network, given their different tower design (e.g. sampling height) . The ability of models to reproduce the observations needs to be discussed to comfort the chosen value.*

**Author's response**: When new observations are assimilated to CarbonTracker, the MDM is assigned by the site categories of the new observations. After then, innovation $\chi^2$ statistics are gathered during the optimization to evaluate whether they are close to 1. The statistics near 1 implies that the assigned MDM value is appropriate.

We have followed the above process when determining the MDM of JR station data. In CarbonTracker, MDM of continuous tower measurements is assigned 3 ppm. Following the site categories, we assigned 3 ppm MDM for JR-STATION data. After then, we have verified whether the assignment is appropriate by calculating $\chi^2$ statistics which turns to be close to 1. The statistics are from 0.84 to 1.36 (Table 4) and the results are discussed in detail in Section 3.2. The statistics of JR station are closer to 1 compared to the sites in ET and Europe which use the MDM from the original CarbonTracker 2010 release.

Although the tower design of US network and JR stations are different, the same type of site categories use the same MDM because both of them are continuous tower measurements and their $\chi^2$ statistics show appropriate values.

The misleading texts were revised as follows.

"In CarbonTracker, model data mismatch (MDM, **R** in Eq. (7)) is assigned by site categories. The location of each observation site is represented in Fig. 1. The assigned MDM requires innovation $\chi^2$ statistics in Eq. (7) become close to one at each observation site (Peters et al. 2007).

$$\chi^2 = \frac{(y^o - \mathbf{H}x^b)^2}{\mathbf{H}\mathbf{P}^b\mathbf{H}^T + \mathbf{R}}, \quad (7)$$

where $y^o$-$\mathbf{H}x^b$ represent innovation. The site categories and MDM values are assigned the same value as in previous studies (Peters et al., 2007; Kim et al. 2014b; Zhang et al., 2014b): marine boundary layer (0.75 ppm), continental sites (2.5 ppm), mixed land/ocean and mountain sites (1.5 ppm), continuous sites (3.0 ppm), and difficult sites (7.5 ppm). Continuous site category is generally used for observations measured continuously. For the JR-STATION sites that have continuous tower measurements, the MDM is set to 3 ppm, which is the same as tower measurements in North America."

The feasibility of assigned MDM of JR-STATION was evaluated by Eq. (7), using innovation $\chi^2$-statistics, which shows that average value of each site are from 0.84 to 1.36 as explained in Section 3.2.

*15) P9 l4 The difference between the inversions should also include a comparison to the prior fluxes for the sake of further discussion. 'The difference in fluxes . . . distinctive in . . . Siberia': Here it seems from Fig 2 that the fluxes are modified because the CNTL inversion puts an anomalous large sink in Siberia in the absence of local measurements. Therefore the JR run brings back fluxes to a realistic value. The difference is reflecting a particular approach (be it prior fluxes or optimization process) chosen by the inversion.*

**Author's response:** As shown in Fig. 1, there are observations over East Asia although not enough number of observations over Siberia. The CNTL inversion results were produced by assimilating many observations over the globe including East Asia. The observations over East Asia (located partly border of Siberia) affect the optimized fluxes over Siberia by 5-week-lag of the assimilation window. Thus large flux uptakes in Siberia were constrained by atmospheric $CO_2$ measurements that are located remotely. In addition, the large flux uptakes in Siberia have been noticed most of the CarbonTracker results as well as other inversion systems as reported in Peylin et al. (2013) (e.g. Fig. 5 and Fig. S8 in Peylin et al., 2013). Therefore the difference between the two experiments is not reflecting a particular approach used in this study.

In Fig. 2, the direct comparison among the prior, CNTL, and JR are shown. In addition, the aggregated prior and optimized surface $CO_2$ fluxes of CNTL and JR experiments over Eurasian Boreal (Siberia) region are -0.07±1.10 Pg C $yr^{-1}$, -1.17±0.93 Pg C $yr^{-1}$, and -0.77±0.70 Pg C $yr^{-1}$, respectively (Table 2). As seen in the above numbers, the difference of surface $CO_2$ fluxes between prior and JR is still large over Siberia region. Therefore, we have revised the text to read, "The difference in fluxes between the prior and JR experiment is large in EB (Figs. 2a, d) although smaller than that between the prior and CNTL experiment (Figs, 2a, c). The differences in fluxes between the CNTL and JR experiments are distinctive in EB (Siberia) where the new additional observations are assimilated (Fig. 2b)."

*16) P9 l13: How is the 1 sigma standard deviation determined (on which basis: ensembles, . . .)? Does error on prior fluxes intervene in the inversion uncertainty?*

**Author's response**: One sigma standard deviation of surface fluxes was calculated based on ensembles of surface fluxes. To clarify, we have revised the text to read, "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)."

Error on prior fluxes could intervene in the inversion uncertainty in the data assimilation process by means of the ensembles of prior surface fluxes which reflect the prior surface flux uncertainties and errors.

*17) P9 l27: 'uncertainty of the. . . uptake. . . is reduced': this is quite expected and I suggest adding the word 'is expectedly reduced'. However in terms of relative uncertainty (error ratio to estimated fluxes) no progress has been made. This reflects the fact that the CNTL inversion tends to allocate strangely large fluxes to Siberia in the absence of atmospheric measurement able to constrain this region*

**Author's response**: Following the reviewer's opinion, we have revised the texts to read, "The uncertainty of the optimized surface $CO_2$ uptake in the EB in the JR experiment is expectedly reduced by assimilating additional ~".

As shown in Fig. 1, there are observations over East Asia although not enough number of observations over Siberia. The CNTL inversion results were produced by assimilating many observations over the globe including East Asia. The observations over East Asia (located partly border of Siberia) affect the optimized fluxes over Siberia by 5-week-lag of the assimilation window. Thus large flux uptakes in Siberia were constrained by atmospheric measurements located remotely. In addition, the large flux uptakes in

Siberia have been noticed most of the CarbonTracker results. By assimilating additional observations over Siberia, the large flux uptakes in Siberia were reduced as shown in Fig. 7.

*18) P10 l2-3: Since the drought affects Europe to a large extent, and the dataset is not different over Europe for the two runs JR and CNTL, it is not plausible that the drought can be used as an explanation for differences between JR and CNTL runs. Please revise this part.*

**Author's response**: The drought over the northern mid-latitudes and Europe can affect the reduced uptakes in Siberia remotely through 5-week-lag of the assimilation window. Therefore, we think that the drought is associated with the reduced uptakes in EB (Fig. 5a) (Knorr et al., 2005). Because of remote drought effect, the flux uptakes in Siberia were reduced in CNTL. However, by assimilating observations over Siberia in JR, the flux uptakes were slightly increased. Therefore, the previous misleading text 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)"

*19) P10 l5: This difference of number of observation and its impact on the fluxes may partly explain the time pattern of Fig. 4. Please provide some quantified information on the impact of the evolution of observations on the time pattern (e.g. by removing some sites or maintaining a sparse network and comparing with the long term run).*

**Author's response**: The texts "difference of number of observation" is for only JR-STATION data. Since 2002 when the JR-STATION site was started to operate at BRZ, the number of operation site and observations of JR-STATION have been increased.

Therefore, the observation number of JR-STATION in 2003 is relatively small compared to that from 2004 to 2009.

To clarify the text, we have revised the texts to read, “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.”

Following the reviewer’s opinion, we have added a discussion which may explain the time pattern of Fig. 5a. Although comprehensive observation system experiments such as data denial experiment or using different network provide quantitative information on the impact of the observation evolution on the time pattern of $CO_2$ fluxes, it is beyond the scope of this study. Besides, the similar patterns of CNTL and JR experiments in Fig. 4 imply that the impact of the evolution of observations on the time pattern may be small at least global sense. The local impact would be studied as a future work.

*20) Explanations for the trends observed in Fig 4 and 5 should be discussed, see e.g. Sitch et al (2015, Biogeosciences, 12, 653–679)*

**Author’s response**: Following the reviewer’s opinion, we have analyzed the trends observed in Figs. 4 and 5. We have revised the text as follows.

“Figure 4 shows the time series of annual and average prior and optimized surface $CO_2$ fluxes over global total, global land, and global ocean. For global total, the magnitude of optimized fluxes are much greater than that of prior fluxes due to the greater uptake of optimized fluxes than that of prior fluxes over global land (Figs. 4a and b). In contrast, the magnitude of optimized fluxes over global ocean is slightly weaker than that of prior fluxes (Fig. 4c). As shown in Table 2, the differences between annual and average optimized surface $CO_2$ fluxes over the globe are small and the average is almost the same for the two experiments (Fig. 4a) with a similar trend of -0.33 Pg C $yr^{-2}$ and -0.35 Pg C $yr^{-2}$ in CNTL and JR experiment respectively, and the differences in global land and ocean are also small (Figs. 4b, c) with a similar trend of -0.22 Pg C $yr^{-2}$ in global land of both CNTL and JR experiment and -0.11 Pg C $yr^{-2}$ and -0.13 Pg C $yr^{-2}$ in global ocean of CNTL and JR experiment respectively. The optimized surface $CO_2$ fluxes from each experiment show similar interannual variability, which implies that the additional

Siberian observations do not affect the interannual variability of global surface $CO_2$ uptakes.

Figure 5 is the same as Fig. 4 but covers land regions in the NH. Although the optimized surface $CO_2$ fluxes over global total are similar, those over each TransCom region are different in each experiment. The optimized fluxes over each region show greater annual uptake relative to the prior fluxes in both experiment. The difference between the two experiments is largest in the EB as expected (Fig. 5a). The JR experiment exhibits a weaker surface $CO_2$ uptake in the EB than does the CNTL experiment except for 2003 as shown in Fig. 3b, whereas the JR experiment exhibits a greater surface $CO_2$ uptake in the other regions, especially over Europe in 2008 and 2009, than the CNTL experiment (Figs. 5b, c, d, and e). It is driven by the increase of $CO_2$ uptake in Eastern Europe (Figs. 3g and h). Because most of JR-STATION sites are located in the western part of Siberia (Fig. 1), the optimized surface $CO_2$ fluxes over Eastern Europe could be affected by JR-STATION observations. The trend of EB in CNTL experiment is -0.06 Pg C $yr^{-2}$, whereas that in JR experiment is 0.02 Pg C $yr^{-2}$ due to the reduced uptake of $CO_2$ in JR experiment since 2005 (Fig. 5a). As a result, the trends of the surface $CO_2$ uptake of EB and Europe in two experiments show opposite signs. In contrast, the surface $CO_2$ uptake trends of other land regions in NH are similar between the two experiments."

Below, the trends of surface $CO_2$ flux for each region (unit: Pg C $yr^{-2}$) are shown.

| Region | Experiment | |
|---|---|---|
| | CNTL | JR |
| Global total | -0.33 | -0.35 |
| Global land | -0.22 | -0.22 |
| Global ocean | -0.11 | -0.13 |
| Eurasian Boreal | -0.06 | 0.02 |
| Eurasian Temperate | -0.03 | -0.04 |
| North American Boreal | -0.03 | -0.04 |
| North American Temperate | -0.02 | -0.03 |
| Europe | -0.04 | -0.10 |

*21) P11 l16: what are background surface $CO_2$ fluxes?*

**Author's response**: Background surface $CO_2$ fluxes are calculated by multiplying background scaling factor (background state vector in Eq. (2)) to prior biosphere and ocean fluxes as in Eq. (1).

For readability, we have added the text to read, “The background surface $CO_2$ fluxes are calculated by multiplying the background scaling factor to prior biosphere and ocean fluxes as in Eq. (1).”.

*22) P11 l18-20: How are the results of this study sensitive to MDM? Could the authors test this assumption (well prescribed MDM) with different MDM values? Inversely, do poor (different from 1) values of this chi-2 parameter for other stations imply that the MDM is poorly prescribed? (e.g. BAL, MNM, . . .). Is MDM not dependent on sampling height in the JR station network? To support this statement the authors should show and discuss comparison of JR station CO2 observations and model (prior and optimized, in the JR experiment context).*

**Author’s response**: The results are sensitive to MDM. As answered in the reviewer’s question 14 above, we have chosen 3 ppm MDM for JR-STATION data because they are continuous tower measurements same as the US network and their $\chi^2$ statistics showed appropriate values. The MDM of other stations (e.g. BAL, MNM, . . .) follows the specification of CarbonTracker 2010 release. We cannot change the original specification of MDM for observation sites included in the public release of CarbonTracker. We guess that the MDM of other stations (e.g. BAL, MNM, . . .) was assigned that way because of poor model simulation of their observed $CO_2$ as indicated in manuscript. Same as other observation sites in CarbonTracker, the sampling height in the JR station was not considered in determining MDM.

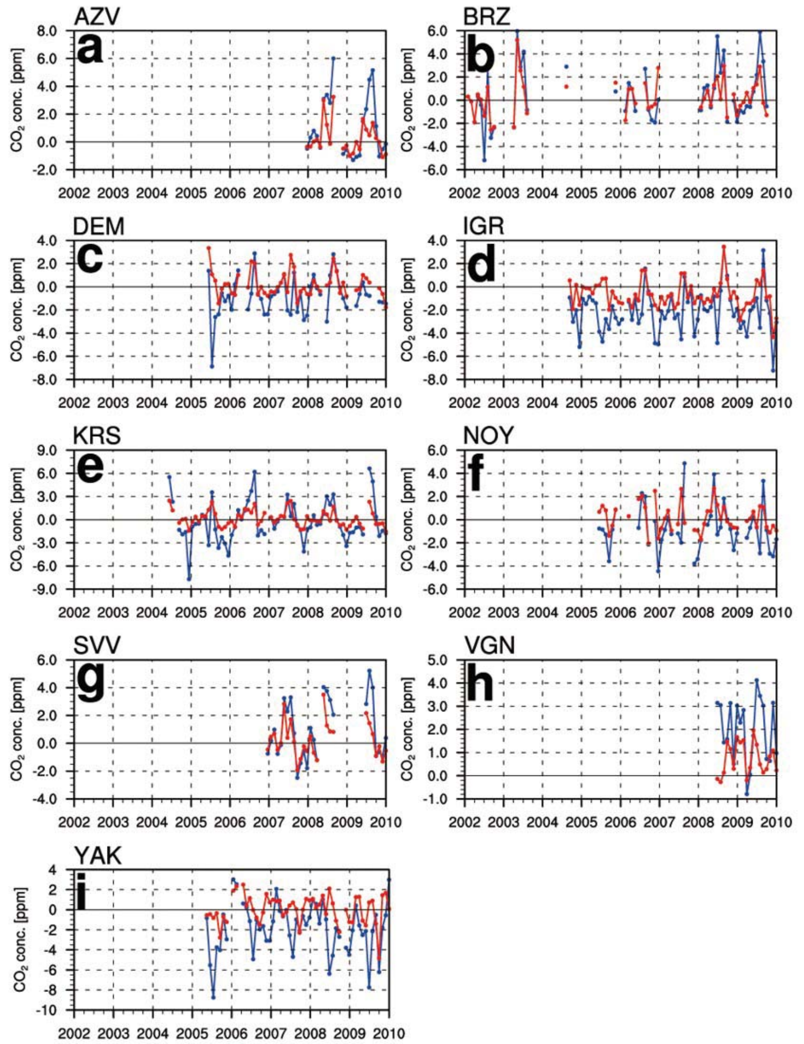
We have shown and discussed the comparison of JR station $CO_2$ observations and model (prior and optimized) in the JR experiment context in Section 3.2 and Table 4. The 6th and 7th columns in Table 4 present the differences of background and optimized model from the observations in the JR experiment. In the JR experiments, the optimized model $CO_2$ concentrations are closer to observations compared to the background $CO_2$ concentrations.

*23) P11 l29. Sites with 7.5 ppm MDM are presented as afflicted by poor model simulation of their observed CO2. However no confidence is given about the JR-STATION sites in terms of the accuracy of model representation of CO2 at these sites, only a mean bias which is a very* *limited measure of modelâ˘A˘Tobservation fit improvement. This should be presented and extensively discussed prior to discussing the result of inverse modelling with a blind approach to the forward simulated CO2 (this is also directly related to the comment above).*

**Author's response**: Peters et al. (2010) mentioned "A second set of observations was deweighted because the large spread in model-minus-observed $CO_2$ suggested that our model regularly missed the model-data-mismatch target. This latter set includes the continuous data from the Cabauw tower (CBW0200_52C3), Westerland (WES_23C0), and Kasprowy Wierch (KAS_53C0) as well as the discrete samples from BAL_01D0, BSC_01D0, HUN_01D0, and OBN_01D0. The first two sites (CBW, WES) are known to be in highly industrialized regions and susceptible to strong fossil fuel burning influences and model representation error. For some of the other sites there was reason to doubt the representivity and/or data quality of parts of the time series.".

Therefore, we have added a reference (Peters et al., 2010) at the end of the texts in P11 l29.

According to reviewer's opinion, we have checked monthly averaged differences of the model $CO_2$ concentration and observed $CO_2$ concentration at JR sites in Fig_rev3. For the assimilation period, the JR experiment consistently shows smaller biases compared to the CNTL experiment, which implies that the model representation of $CO_2$ at JR sites is more accurate in the JR experiment than in the CNTL experiment. We have added the text to read, "In addition to the average bias for the entire period, the time series of monthly averaged bias of the model $CO_2$ concentration from the observed $CO_2$ concentration at JR-STATION sites shows that the JR experiment consistently shows smaller biases compared to the CNTL experiment (not shown), which implies that the model representation of $CO_2$ at JR-STATION sites is more accurate in the JR experiment than in the CNTL experiment.".




Figure_rev 3. Time series of difference between observed and model $CO_2$ concentration simulated using optimized surface fluxes in CNTL experiment (blue), and JR experiment (red) at (a) AZV, (b) BRZ, (c) DEM, (d) IGR, (e) KRS, (f) NOY, (g) SVV, (h) VGN, and (i) YAK site. The differences are calculated by subtracting observed CO2 concentrations from model CO2 concentrations and averaged by month. Units are ppm.

*24) Overall section 3.2 is too limited and lacks a conclusion to support the subsequent analyses, especially in view of demonstrating the value of additional observations offered by JR-STATION.*

**Author's response**: We have revised Section 3.2 by including the comparison with the independent observations of vertical profiles which were not used for assimilation.

We have 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.

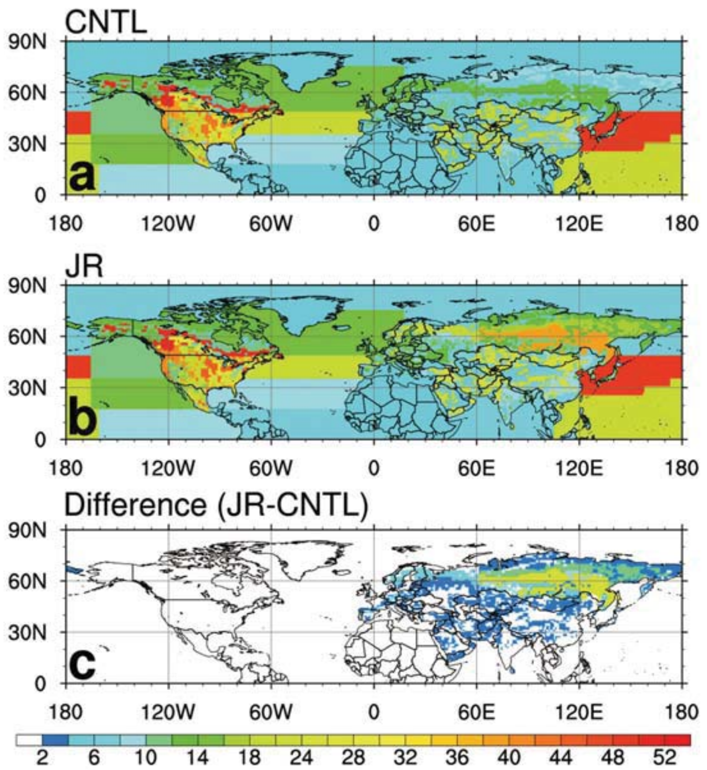
| Altitude (km) | Bias (ppm) | | Root-Mean-Square Difference (ppm) | | Mean Absolute Error (ppm) | | Pearson's Correlation Coefficient | |
|---|---|---|---|---|---|---|---|---|
| | CNTL | JR | CNTL | JR | CNTL | JR | CNTL | JR |
| ~ 0.5 | -0.13±4.81 | 0.20±4.57 | 4.82 | 4.57 | 3.45 | 3.23 | 0.95 | 0.95 |
| 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 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."

*25) In section 3.3. Fig 7 8 and 9 are valuable but not sufficient in themselves to allow the reader to appreciate the contribution of the additional JR observations. A mapping of prior uncertainties, CNTL UR and JR UR would be required to support the discussion.*

**Author's response**: Following the reviewer's opinion, 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 4). 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 4a) and JR (Fig._rev 4b) is readily apparent in Siberia (Fig._rev 4c), 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 4 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); $\sigma_{CNTL}$ or $\sigma_{JR}$ used instead of $\sigma_{JR}$ in Eq. (8)) shows similar values in the NH except in Siberia region (not shown). In addtion, 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 4. 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).

*26) P12 l15: 'additional observations sometimes have a great impact' : Please be more explicit and quantitative about 'sometimes' and 'great impact'.*

**Author's response**: Following the reviewer's opinion in editorial comment 29, this statement and Fig. 7b were removed in the revised manuscript.

*27) P12 l16: The author find stronger UR in summer than in winter. Is this due to a higher uncertainty related to larger net fluxes in summer relative to winter? How is this seasonal UR difference explained over Siberia?*

**Authors's response**: As the reviewer's point, stronger uncertainty reduction of EB in summer than that in winter is due to a higher uncertainty related to larger net fluxes in summer relative to winter. The correction of optimized surface $CO_2$ fluxes from prior fluxes is larger in summer than winter (Fig. 6a in revised manuscript). This is due to that the observations in Siberia exhibited large flux correction and uncertainty reduction in summer than winter.

Therefore, we have revised the texts to read, "The uncertainty reduction of EB in summer is higher than that in winter (Figs. 7b, c) due to a higher uncertainty associated with larger net fluxes in summer compared to winter (Fig. 6a).".

*28) P13 l7-8: please give more details about why high 1-week RMSD and self sensitivities of JR STATION sites is consistent.*

**Author's response**: The information content is a measure of the information extracted from the observations. The average information content is proportional to the average value of self-sensitivity and the number of observations used in the data assimilation. As shown in Kim et al. (2014b), the regions with large average information contents are consistent with the regions with a high RMSD, which implies that observations in that region provide much information. The JR-STATION tower sites have abundant observations and large self-sensitivities. Therefore, large self-sensitivities at JR-STATION is correlated with the large 1-week RMSD. To clarify, we have revised the texts to read, **"**The RMSD of the analyzed surface $CO_2$ fluxes constrained by one week of observations from the background fluxes in JR experiment is greater than that in CNTL experiment (Figs. 9a, b), implying that surface $CO_2$ fluxes in Siberia are analyzed by JR-STATION data in Siberia directly at the first cycle. This is consistent with the high value of self-sensitivities at JR-STATION sites as shown in Fig. 8b. Because JR-

STATION data are abundant and have large self-sensitivities, these observations provide large information on the estimated surface $CO_2$ fluxes over Siberia in the first cycle. ~".

*29) P13 l9: 'it takes 5 weeks to affect the surface $CO_2$ fluxes in Siberia by the transport of $CO_2$ concentrations' : this statement is not supported by the demonstration in Kim et al. (2014, see their Fig 13), who only compared 1 week and 5 weeks, but not other time intervals. Therefore this incorrect interpretation needs to be reformulated. I could suggest a sentence such as 'it takes more than 1 week to affect the surface $CO_2$. . .', which is better supported by the elements provided.*

**Author's response**: We have revised the texts as the reviewer suggested.

*30) However this observation by the authors is important. If the correction of Siberian surface fluxes, in CNTL, is only performed based on air masses between 1 and 5 weeks, it means that Siberia is an underconstrained region in terms of $CO_2$ fluxes (and this is a conservative statement). As a result, comparisons between CNTL and JR should take into account the large 'weakness' of fluxes allocated to Siberia by the CNTL inversion. This is illustrated in Table 2: EB is the region with the strongest increment between a priori and CNTL (from -0.07 to -1.17 PgC/y), but at the same time it is the only region with the least in situ observations. The other regions have smaller increment, and at the same time more 'local' observations are available. This bias needs to be explicated and discussed. The sentence of the abstract (p2, l1) comparing the fluxes calculated with the additional observations to the fluxes calculated without, suggests as such that the two flux values can be compared directly ('uptake. . . decreased'). On the contrary, Siberian fluxes calculated without the additional JR observations are highly sensitive to many assumptions within the inversion, and therefore any direct comparison requires a clear statement that this comparative approach is dependent on the inversion set up. This is also true for the sentence concluding this section (p13 l14-16).*

**Author's response**: Following the reviewer's opinion, we have added the texts to read, "The largest increment between a priori and CNTL is shown in EB with the least in situ observations as shown in Fig. 1. The other regions show smaller increment with more 'local' observations available." in Section 3.1.

The differences between the CNTL and JR are caused by additional JR-STATION data over Siberia, but not caused by the inversion set up because the two experiments use the same inversion modeling setup except JR-STATION data.

*31) Section 3.4. This section should also propose comparison with inversions intercomparison excercises, such as the TRANSCOM intercomparisons, see Gurney et al. (2002) or RECCAP Peylin et al (2013 Biogeosciences, 10, 6699-6720, doi:10.5194/bg-10-6699-2013). Please also compare with the synthesis work of Dolman et al. (2012)*

**Author's response**: Following the reviewer's opinion, the comparison with synthesis work of Dolamn et al. (2012) based on bottom-up and top-down method is included in Table 5 of the revised manuscript.

On the other hand, the other reviewer asked us to choose the same spatial domain (Eurasian Boreal and Europe) and temporal extent with other studies as similar as possible. The analysis period of mean fluxes in Gurney et al. (2002) is from 1992 to 1996 and that in Peylin et al. (2013) is from 2001 to 2004, which does not exactly match with the analysis period (2002-2009) in this study. Therefore, the results of Gurney et al. (2002) and Peylin et al. (2013) were not used in comparison with other studies.

We have revised the texts in Section 3.4 as follows.

"A comparison of the optimized surface $CO_2$ flux in this study with other previous studies is presented in Table 6. In the EB, the land sink from the JR experiment (-0.77±0.70 Pg C $yr^{-1}$) is smaller than those reported by Zhang et al. (2014b) (-1.02±0.91 Pg C $yr^{-1}$), Maki et al. (2010) (-1.46±0.41 Pg C $yr^{-1}$), and the CT2013B (CarbonTracker released on 9 Feburary 2015; documented online at http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2013B/) results (-1.00±3.75 Pg C $yr^{-1}$), but higher than those reported by Saeki et al. (2013) (-0.35±0.61 Pg C $yr^{-1}$; including biomass burning 0.11 Pg C $yr^{-1}$)), and similar with those reported by Dolman et al. (2012) (-0.613 Pg C $yr^{-1}$).

Because CT2013B and Zhang et al. (2014b) use the similar inversion framework as this study, the reduced land sink is caused by assimilating additional observations. The difference in land sink between the JR experiment and Saeki et al. (2013) is caused by a different inversion system framework which includes prior flux information, atmospheric transport model, observation data set, and inversion method. Despite different inversion system framework used in each study, two studies using the JR-STAITON data exhibit similar results in relative terms, reduced uptake of $CO_2$ fluxes and uncertainties over Siberia. Nontherless, the land sink from the JR experiment is somewhat different with other inversion results, its value falls within the flux uncertainty range. Although the land sink in Dolamn et al. (2012) is the average land sink obtained from three methods (inventory-based, eddy covariance, and inversion methods) and estimated not only for Siberia but for Russian territory including Ukraine, Belarus, and Kazakhstan, the land sinks of the JR experiment and Dolman et al. (2012) shows similar values. Overall, the optimized surface $CO_2$ fluxes in EB of JR experiment are comparable to those of other previous studies."

*32) P13 l26 the paragraph is concluded by the importance of the inversion framework used. Therefore the difference with the results of Saeki et al. (2013) needs to be examined in more detail. This paragraph leads the reader to the obvious conclusion that the choice of the inversion setup has as much impact on the posterior fluxes uncertainty of Siberia than the addition of a novel observation network such as JR-STATION.*

*Comparing the study reviewed and Saeki et al. (2013) from the numbers provided in the papers, it is striking that the two studies consistently conclude, in relative terms, both to a Siberian flux that is lower by about one third when adding JR-STATION (-37.5% for Saeki et al., -34.1% for this study), and decrease their uncertainty by about one-quarter (-22.7% and -24.7% respectively). At the same times, when comparing the two studies (being based on similar observation data sets), Kim et al.'s find fluxes consistently two times higher that Saeki et al. with or without the JR-STATION dataset, and report uncertainty that are 15% higher, with or without the JR STATION dataset.*

*Therefore the reported numbers lead to the observations that a change in inversion setup has more impact on the estimated fluxes in Siberia than using or not the only existing dataset in the region. This is stimulating because it means that more research is needed before CO2 budgets calculated using inverse methods over Siberia can be reliably used. It supports the suggestion for extensive comparison of the simulated and measured CO2 at the JR STATION sites in this study.*

*The numbers above also imply that the current set up questions the constraints on CO2 fluxes (in terms of range of likely flux value) over Siberia reported by Saeki et al. 2013, and this requires further comparison with other studies, possibly bottom up allometric or modelling studies. It should be noted also that Maki et al. 2010 reported smaller uncertainty (0.41 PgC/y), even without the JR-STATION network. This requires a detailed comparison of these studies for the sake of coherence.*

**Author's response**: Although both this study and Saeki et al. (2013) used JR station data, prior flux information (e.g. biosphere, ocean, fires, and fossil fuel fluxes), atmospheric transport model, observation data set, and inversion method of two studies are different. Therefore, the different flux values in EB in this study and Saeki et al. (2013) are caused by not only the inversion setup but also most components which constitute the inversion system framework. The term "inversion system framework" used in P3 l26 denotes prior flux information (e.g. biosphere, ocean, fires, and fossil fuel fluxes), atmospheric transport model, observation data set, and inversion method.

Despite several differences in the inversion system frameworks, the optimized surface $CO_2$ fluxes over Siberia in this study and Saeki et al. (2013) show the similar conclusions in relative terms but different magnitudes in terms of fluxes and their uncertainties. These discrepancies of estimated surface fluxes over specific regions among inversion systems are already reported in previous studies. For example, in the intercomparison study using 11 inversion systems, Peylin et al. (2013) demonstrated that: (1) there are more consistencies between inversions for larger scales such as interannual variability of global fluxes; (2) the largest total land sink in the Northern Hemisphere is nearly unanimously located in the Eurasian domain, whereas a large spread among the inversions remains for the specific regions (e.g., North America, Europe, North Asia) in Northern Hemisphere. Consequently, the longitudinal breakdown of the total northern sink appears to be much more variable than the total flux itself. These characteristics are also shown in the comparison between this study and Saeki et al. (2013). The average global total flux is similar between this study (-3.61±1.73 Pg C $yr^{-1}$ ) and Saeki et al. (2013) (-3.51±3.18 Pg C $yr^{-1}$). However, the partition between land and ocean fluxes and fluxes in EB region are different between two studies (note the table below for more information).

| Region | This study<br>(2002-2009) | Saeki et al. (2013)<br>(2000-2009) |
|---|---|---|

| | Without Siberian data | With Siberian data | Without Siberian data | With Siberian data |
|---|---|---|---|---|
| Global total | -3.60±1.85 | -3.61±1.73 | -3.50±3.26 | -3.51±3.18 |
| Global land | -1.68±1.57 | -1.61±1.43 | -1.95±3.08 | -1.90±3.00 |
| Global ocean | -1.91±0.97 | -2.00±0.97 | -1.55±1.06 | -1.61±1.06 |
| Eurasian Boreal | -1.04±0.93 | -0.64±0.70 | -0.56±0.79 | -0.35±0.61 |

*For the land and ocean fluxes, biomass-burning (fire) emissions are included and fossil fuel emissions are not included.

Anyway, flowing the reviewer's opinion, we have added the comparison with other study based on bottom-up and modelling studies (Note detailed comment 31).

The object of this study is to compare between optimized surface $CO_2$ fluxes in CNTL experiment and those in JR experiment within the same inversion system. In this sense, verification of the inversion results using the independent observations would be beneficial. As shown in Fig_rev2, during the assimilation period, the JR experiment consistently shows smaller biases compared to the CNTL experiment, which implies that the model representation of $CO_2$ at JR sites is more accurate in the JR experiment than in the CNTL experiment. In addition, the root-mean-square difference (RMSD) and mean absolute error (MAE) of model $CO_2$ concentration calculated by optimized fluxes in JR experiment exhibits better agreement with independent observation which is not used in the optimization (vertical profile of $CO_2$ concentration measured over BRZ site).

Thus, we have revised the text to reads, "The difference in land sink between the JR experiment and Saeki et al. (2013) is caused by a different inversion system framework which includes prior flux information, atmospheric transport model, observation data set, and inversion method. Despite different inversion system framework used in each study, two studies using the JR-STAITON data exhibit similar results in relative terms, reduced uptake of $CO_2$ fluxes and uncertainties over Siberia."

*33) P14 l2 and 3: what is the uncertainty range of single-year flux values (here 2008 and 2009 are discussed)?*

**Author's response**: Following the reviewer's opinion, we have revised the manuscript as follows.

"The land sinks of the JR experiment in 2008 and 2009 are -0.73±0.41 and -0.76±0.38 Pg C $yr^{-1}$, respectively, whereas much lower uptakes (-0.21±0.49, -0.38±0.43 Pg C $yr^{-1}$) are obtained for the CNTL experiment."

*34) Section 4 Please revise the conclusions according to the discussion above. What are the key challenges identified by the authors before estimating robust $CO_2$ fluxes over Siberia from atmospheric inverse modelling?*

**Author's response**: Following the reviewer's opinion, we have revised the conclusion section as follows. The key challenge is overcoming the sparseness of atmospheric $CO_2$ observing network over Siberia to better estimate the surface $CO_2$ fluxes over Siberia.

"The global balances of the sources and sinks of surface $CO_2$ fluxes were maintained with a similar trend for both experiments, while the distribution of the optimized surface $CO_2$ fluxes changed. The magnitude of the optimized biosphere surface $CO_2$ uptake and its uncertainty in EB (Siberia) was decreased from -1.17±0.93 Pg C $yr^{-1}$ to -0.77±0.70 Pg C $yr^{-1}$, whereas it was increased in other regions of the NH (Eurasian Temperate, Europe, North American Boreal, and North American Temperate). The land sink of Europe increased significantly for 2008 and 2009, which is consistent with the other inversion results inferred by satellite observations. Additional observations are used to correct the surface $CO_2$ uptake in June and July, the active vegetation uptake season, in terms of monthly average optimized surface $CO_2$ fluxes. As a result, the additional observations do not exhibit a change in the magnitude of the global surface $CO_2$ flux balance because they provide detailed information about the Siberian land sink instead of the global land sink magnitude, when they are used in the well-constructed inversion modeling system.

The model $CO_2$ concentration using the background and optimized surface $CO_2$ fluxes in the JR experiment are more consistent with the $CO_2$ observations used in the optimization than those in the CNTL experiment, showing lower biases in the EB region. In contrast, the differences of biases in ET and Europe between the two experiments are not distinguishable. In comparison with vertical profiles of $CO_2$ concentration observations which are not used in the optimization, the model $CO_2$ concentrations in the JR experiment show the smaller RMSD and MAE, and the greater correlation coefficient that those in CNTL experiment.

The new observations provide useful information on the optimized surface $CO_2$ fluxes. The observation impact of the Siberian observation data is investigated by means of uncertainty reduction and self-sensitivity calculated by an influence matrix. Additional observations reduce the uncertainty of the optimized surface $CO_2$ fluxes in Asia and Europe, mainly in the EB (Siberia), where the new observations are used in the assimilation. The average self-sensitivities of the JR-STATION sites are approximately 60% larger than those at other continuous measurements (e.g., tower measurements in North America). The global average self-sensitivity and cumulative impact of the JR experiment are higher than that of the CNTL experiment, which implies that the individual observation impact of JR-STATION data on optimized surface $CO_2$ fluxes is higher than the average values. The RMSD of the analyzed surface $CO_2$ fluxes constrained by one week of observations from the background fluxes also suggests that new Siberian observations provide a larger amount of information on the optimized surface $CO_2$ fluxes."

*35) P15 l9 is the longitudinal redistribution toward Europe a conclusion shared by Saeki et al., 2013?*

**Author's reponse**: Saeki et al. (2013) didn't show the longitudinal redistribution toward Europe. This is a finding of this study. Thus, we have revised the misleading text as follows.

"This study shows that the JR-STATION data affect the longitudinal distribution of the total NH sinks, especially in the EB and Europe, when it is used by atmospheric $CO_2$ inversion modeling."

*36) P32 fig 5 further discussion of the trend in European fluxes and its possible drivers would be valuable.*

**Author's response**: Following the reviewer's opinion, we have added further discussions on the trends in European fluxes as follows.

"Figure 5 is the same as Fig. 4 but covers land regions in the NH. Although the optimized surface $CO_2$ fluxes over global total are similar, those over each TransCom region are different in each experiment. The optimized fluxes over each region show greater annual uptake relative to the prior fluxes in both experiment. The difference between the two experiments is largest in the EB as expected (Fig. 5a). The JR experiment exhibits a weaker surface $CO_2$ uptake in the EB than does the CNTL experiment except for 2003 as shown in Fig. 3b, whereas the JR experiment exhibits a greater surface $CO_2$ uptake in the other regions, especially over Europe in 2008 and 2009, than the CNTL experiment (Figs. 5b, c, d, and e). It is driven by the increase of $CO_2$ uptake in Eastern Europe (Figs. 3g and h). Because most of JR-STATION sites are located in the western part of Siberia (Fig. 1), the optimized surface $CO_2$ fluxes over Eastern Europe could be affected by JR-STATION observations. As a result, the trends of the surface $CO_2$ uptake of EB and Europe in two experiments are different. The trend of EB in CNTL experiment is -0.06 Pg C $yr^{-2}$, whereas that in JR experiment is 0.02 Pg C $yr^{-2}$ due to the reduced uptake of $CO_2$ in JR experiment since 2005 (Fig 5a). In contrast, the surface $CO_2$ uptake trends of other land regions in NH are similar between two experiments.“

*37) P33 fig 6 please add the prior fluxes seasonal cycles to each panel*

**Author’s response**: We have added prior fluxes seasonal cycles in Fig. 6 following the reviewer’s opinion.

**Editorial Comments:**

*1) There are several occurrences of unexplained acronyms; the authors should check this carefully.*

**Author's response**: We have explained acronyms in the revised manuscript.

*2) P2 l13: typo: Schulze et al, not Schuleze et al*

**Author's response**: We have corrected the typo.

*3) P3 l10: 'useful information': please be more specific on the usefulness of this information.*

**Author's response**: Following the reviewer's opinion, we have revised the texts to read, "Though a broad spatial coverage of $XCO_2$ from satellite radiance observations provides useful information for inversion systems in quantifying surface $CO_2$ fluxes at various scales which is not provided by ground-based measurements, the current $XCO_2$ has low accuracy and regional biases of a few tenths of a ppm, which may hamper the accuracy of estimated surface $CO_2$ fluxes (Miller et al., 2007; Chevallier et al., 2007)."

*4) P3 l18: due to the difference in time period the word 'accompany' is not correct, should be e.g. 'preceded'*

**Author's response**: We have revised the word following the reviewer's opinion.

*5) P3 l21: typo: YAK-AEROBO -> YAK-AEROSIB.*

**Author's response**: We have corrected the typo.

*6) P3 l25 : multi-year Zotto measurements can certainly be used for inverse modelling.*

**Author's response:** Following the reviewer's opinion, we have revised the texts as follows.

"However, except Zotino that has multi-year measurements, these data collected during specific seasons or over only a few years do not provide the long-term $CO_2$ concentration data necessary to be used as a constraint in the inverse modeling system."

*7) P4 l11: 'increasing the sites': should be 'increasing the number of sites'*

**Author's response**: We have revised the texts following the reviewer's opinion.

*8) P5 l19: expand EnKF acronym*

**Author's response**: We have expanded the acronym.

*9) P5 l22 (eq. 2) and l26: please be consistent on notation: x (superscript) b or x (subscript)*

**Author's response**: We have revised the notation.

*10) P6 l7-13: ensembles, perturbation, background error, localization, physical distance: these notions have not been introduced before, please provide guidance for the reader to understand*

**Author's response:** Following the reviewer's opinion, we have provided references as follows.

"The detailed algorithm of inversion method used in this study can be found in Peters et al. (2007) and Kim et al. (2014a). "

*11) P6 l15-17: please revise this sentence for clarity and syntax*

**Author's response:** Following the reviewer's opinion, we have revised the manuscript as follows.

"Statistical significance test is performed on the linear correlation coefficient with a cut-off at a 95% significance in a student's T-test. Then the components of Kalman gain with an insignificant statistical value are set to zero."

*12) P7 l7 please give references for CDIAC and EDGAR.*

**Author's response:** Following the reviewer's opinion, we have provided the references.

*13) P7 l12: please provide link for ESRL data set, and give credit consistently to organization operating the measurements (e.g. in Europe).*

**Author's response:** Following the reviewer's opinion, we have provided link for ESRL data set as follows.

"(1) surface $CO_2$ observations distributed by the NOAA ESRL (observation sites operated by NOAA, Environment Canada (EC), the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), the National Center for Atmospheric Research (NCAR), Lawrence Berkeley National Laboratory (LBNL)) (observation data is available at http://www.esrl.noaa.gov/gmd/ccgg/obspack/data.php; Masarie et al., 2014) "

In addition, the organizations operating the measurements are denoted in Table 1 and credited in Acknowledgments.

*14) P7 l29: Is the MDM 'determined' or incremented? It is unclear with this formulation. Please revise accordingly. What is intended by 'innovation' chi-2?*

**Author's response**: The MDM is determined and innovation is $y^o$-$\mathbf{H}x^b$. Therefore innovation $\chi^2$ statistics is $\chi^2$ formulation in Eq. (7). To clarify, we have revised the texts indicated by the reviewer as follows.

"In CarbonTracker, model data mismatch (MDM, **R** in Eq. (7)) is assigned by site categories. The location of each observation site is represented in Fig. 1. The assigned MDM requires innovation $\chi^2$ statistics in Eq. (7) become close to one at each observation site (Peters et al. 2007).

$$\chi^2 = \frac{(y^o\text{-}\mathbf{H}x^b)^2}{\mathbf{H}\mathbf{P}^b\mathbf{H}^T+\mathbf{R}}, \qquad (7),$$

where $y^o$-$\mathbf{H}x^b$ represent innovation."

*15) P8 l17: typo: exists -> exist*

**Author's response**: We have corrected the typo.

*16) P8 l25: 'from two experiments': I suggest to change to a determined form 'from the two experiments'*

**Author's response**: We have revised the texts as the reviewer suggested.

*17) P9 l4 'greater': please quantify in the text*

**Author's response**: Following the reviewer's opinion, we have revised the texts to read, "The optimized biosphere flux uptakes of the CNTL and JR experiments are globally 1.60 ~ 1.61 Pg C $yr^{-1}$ greater than the prior flux uptakes (Figs. 2a, c, d, Table 2).".

*18) P9 l14: global total optimized CO2 fluxes': the wording is problematic because this does not include fossil fuel and forest fire. Should be e.g. 'total biogenic'.*

**Author's response**: Because these fluxes are sum of biosphere and ocean fluxes (fossil fuel and forest fire are not included) over the globe, we have revised the text to read, "The global total biogenic and oceanic optimized CO2 fluxes are ~"

*19) P9 l20: typo 'between two the experiments' -> 'between the two experiments'*

**Author's response**: We have corrected the typo.

*20) P10 l2 please revise and clarify: 'is reduced all years' , I suggest 'is reduced in JR for all years'*

**Author's response**: We have revised the texts as the reviewer suggested.

*21) P10 l9 readability would be improve to write Siberia instead of 'EB'. What is 'ET'?*

**Author's response**: We have revised the texts as the reviewer suggested.

*22) P10 l14 the figure is not a histogram (binned distribution) but a time series. Please correct accordingly.*

**Author's response**: We have corrected the mistake.

*23) P11 l1 'Additional Siberian data": very indeterminate formulation. Please add e.g. 'These additional JR Siberian data'*

**Author's response**: We have revised the texts as the reviewer suggested.

*24) P11 l17 what are background scaling factor? This seemingly important notion should be explained in the section on experimental framework.*

**Author's response**: We have revised the Section 2.1 as follows.

"After one analysis step is completed, the new mean scaling factor that serves as the background scaling factor for next analysis cycle is predicted as

$$\lambda_t^b = \frac{(\lambda_{t-2}^a + \lambda_{t-1}^a + 1)}{3}, \qquad (6)$$

where $\lambda_t^b$ is a prior mean scaling factor of the current analysis cycle, $\lambda_{t-2}^a$ and $\lambda_{t-1}^a$ are posterior mean scaling factors of previous cycles. Eq. (6) propagates information from one step to the next step (Peters et al., 2007)"

*25) P11 l22 ET: explain acronym*

**Author's response**: To answer the question 21) above, we have explained ET earlier in the manuscript.

*26) Section 3.3. : Sect. 3.3. or part thereof should be before 3.1 and 3.2 as these sections 3.1 and 3.2 discuss already on the basis of CNTL vs JR runs. The structure of the paper could be reassessed for the benefit of readability.*

**Author's response**: As the reviewer indicated, the Sections 3.1 and 3.2 discuss already the difference between CNTL and JR runs in terms of carbon fluxes and concentrations. Section 3.3 discusses the difference between CNTL and JR in terms of uncertainty reduction and observation impact on data assimilation. We think the differences on fluxes and concentrations need to be discussed first, and the uncertainty reduction and observation impact can follow. The original title of Section 3.3 does not represent what it deals with appropriately. Therefore, instead of changing the order of Sections, we have retitled the Section 3.3 as 'uncertainty reduction and observation impact' for better readability.

*27) P12 l10: Conifer: typo (confer). Why are only Conifer Forest of EB mentioned with no discussion of other ecosystems? What do they represent vs the rest of the Siberian ecosystems?*

**Author's response**: We have corrected the typo. We only discussed the Conifer Forest of EB because JR stations are mainly located in the Conifer Forest of EB. In addition, ecoregions close to the Conifer Forest of EB show relatively large value of uncertainty reduction as mentioned.

*28) P12 l11 'which has additional information'; I suggest to use a determinate form 'which has the additional information'*

**Author's response**: We have revised the texts as the reviewer suggested.

*29) P12 l14: 'the magnitude of the maximum uncertainty reduction is higher than the average value': this is certainly trivial. Please remove this sentence. I don't see the value of maximum weekly UR at all and I suggest to remove this panel 7b*

**Author's response**: Following the reviewer's opinion, we have removed that sentence and Fig. 7b.

*30) P12 l26 please relate the definition of self sensitivity to the*

**Author's response**: Although, it is hard to recognize what the reviewer intended in this comment, we have revised the manuscript as follows.

"The self-sensitivity is the diagonal element of the influence matrix which measures the impact of individual observations in the observation space on the optimized surface $CO_2$ flux. The large self-sensitivity value implies that the information extracted from observations is large. Figure 8 shows the self-sensitivities of the two experiments averaged from 2002 to 2009. The average self-sensitivities at the JR-STATION sites are approximately 60% larger than those at the towers in North America, i.e., Continuous site category observations in Fig. 1."

*31) P12 l26 what are 'Continuous site category observations'?*

**Author's response**: The observation sites used in CarbonTracker are categorized as marine boundary layer, continental sites, mixed land/ocean and mountain sites, continuous sites, and difficult sites. Continuous site category observations are observations sampled continuously. JR-STATION observations are sampled continuously, thus assigned to continuous site category. To clarify, we have added following texts in the last paragraph of Section 2.3.

"The site categories and MDM values are assigned the same value as in previous studies (Peters et al., 2007; Kim et al. 2014b; Zhang et al., 2014b): marine boundary layer (0.75 ppm), continental sites (2.5 ppm), mixed land/ocean and mountain sites (1.5 ppm), continuous sites (3.0 ppm), and difficult sites (7.5 ppm). Continuous site category is generally used for observations measured continuously. For the JR-STATION sites that have continuous tower measurements, the MDM is set to 3 ppm, which is the same as for tower measurements in North America."

*32) P13 l6-7: 'fluxes. . . are analysed by direct observations at the first cycle': this sentence might not be clear. Please rephrase.*

**Author's response**: Following the reviewer's opinion, we have revised the manuscript as follows.

“The RMSD of the analyzed surface $CO_2$ fluxes constrained by one week of observations from the background fluxes in JR experiment is greater than that in CNTL experiment (Figs. 9a, b), implying that surface $CO_2$ fluxes in Siberia are analyzed by JR-STATION data in Siberia directly at the first cycle.”

*33) P13 l21 What is CT2013B?*

**Author’s response**: CT2013B is the CarbonTraker released by NOAA on 9 Feburary 2015. We have revised the manuscript as follows.

“In the EB, the land sink from the JR experiment (-0.77±0.70 Pg C $yr^{-1}$) is smaller than those reported by Zhang et al. (2014b) (-1.02±0.91 Pg C $yr^{-1}$), Maki et al. (2010) (-1.46±0.41 Pg C $yr^{-1}$), and the CT2013B (CarbonTracker released on 9 Feburary 2015; documented online at http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2013B/) results (-1.00±3.75 Pg C $yr^{-1}$), but higher than those reported by Saeki et al. (2013) (-0.35±0.61 Pg C $yr^{-1}$; including biomass burning 0.11 Pg C $yr^{-1}$) and Dolman et al. (2012) (-0.613 Pg C $yr^{-1}$). ”

*34) P13 l22 Please be careful when reporting numbers. The uncertainty of 0.41 PgC/y is wrong , the correct number is given in your Table 5 (0.61).*

**Author’s response**: We have corrected the typo.

*35) P15 l20. Please add acknowledgments for other observational data providers.*

**Author’s response**: Following the reviewer’s opinion, we have revised the acknowledgments as follows.

“The authors appreciate two reviewers for their valuable comments. This study was funded by the Korea Meteorological Administration Research and Development Program under the Grant KMIPA 2015-2021. The JR-STATION is supported by the Global Environment Research Account for National Institutes of the Ministry of the Environment, Japan and the Russian Foundation for Basic Research (Grant No. 14-05-00590). The authors also acknowledge atmospheric $CO_2$ measurements data providers and cooperating agencies at China Meteorological Administration, Commonwealth Scientific and Industrial Research Organization, Environment Canada, Finnish Meteorological Institute, Hungarian Meteorological Service, Japan Meteorological Agency, Lawrence Berkeley National Laboratory, National Institute of Environmental Research, Norwegian Meteorological Institute, Max Planck Institute for Biogeochemistry, Morski Instytut Rybacki, National Center for Atmospheric Research, National Oceanic and Atmospheric Administration Earth System Research Laboratory, and Romanian Marine Research Institute."

*36) P23 Table 1 the table needs to differentiate altitude and sampling height, which is a potential indicator of how difficult it is to simulate a particular site. Also please make sure the proper credits are given to the providing Laboratories (last 7 lines, in Europe).*

**Author's response**: Following the reviewer's opinion, we have revised Table 1. For sites which have different altitude and sampling height, the sampling height is added. In addition, we have given the proper credits to the providing laboratories.

*37) P24 Table 2 I suggest to add total Northern hemisphere*

**Author's response**: Following the reviewer's opinion, we have added surface fluxes of total Northern hemisphere. In addition, Tropical total and Southern Hemisphere total are also added in Table 2.

*38) P27 CT2013B and CTE2014: please give reference.*

**Author's response**: Following the reviewer's suggestion, we have revised Table 6 to include references of CT2013B and CTE2014.

*39) P32 Fig 5 Panel (a): please correct typo (Euraisan -> Eurasian)*

**Author's response**: We have corrected the typo.

*40) P32 l3 there are no 'ocean' in this figure, please correct Fig 5 caption accordingly.*

**Author's response**: We have revised the caption of Fig. 5.

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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.

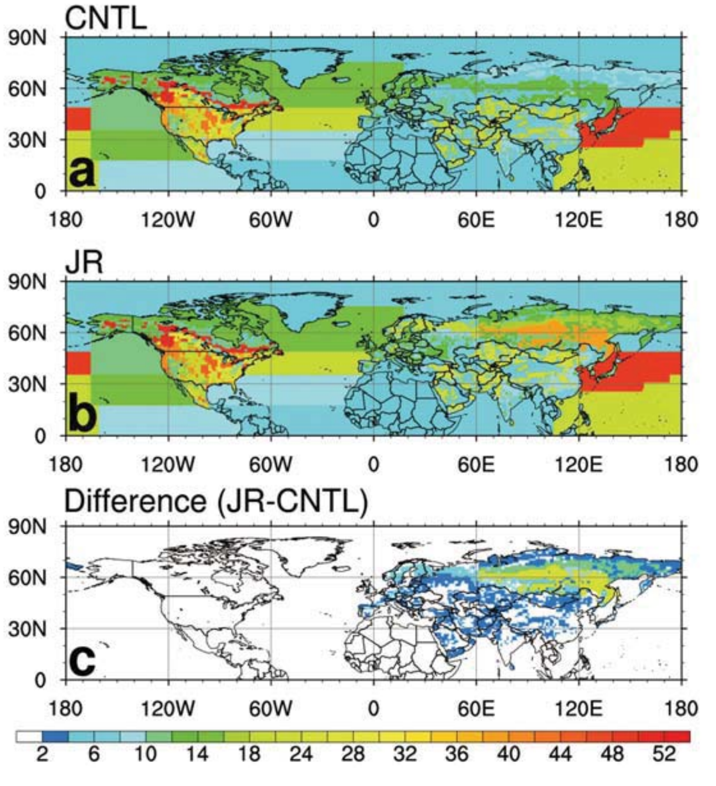
"The uptake of optimized surface $CO_2$ flux in this region is reduced in JR for all years except 2003. In 2003, extreme drought occurred in the northern mid-latitudes (Knorr et al., 2007) and Europe (Ciais et al., 2005), which resulted in increased NEE (i.e. reduced uptake of $CO_2$) in EB in the CNTL 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 | 2002-2009 | JR experiment |
| | | -0.75±0.63 | 2008-2009 | |
| Reuter et al. (2014) | Europe | -1.02±0.30 | 2010 | Using satellite data |
| CTE2014[c] | Europe | -0.07±0.49 | 2002-2009 | |
| | | -0.11±0.38 | 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/).

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# Impact of Siberian observations on the optimization of surface $CO_2$ flux

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## Abstract

To investigate the effect of additional $CO_2$ observations in the Siberia region on the Asian and global surface $CO_2$ flux analyses, two experiments using different observation dataset were performed for 2000-2009. One experiment was conducted using a data set that includes additional observations of Siberian tower measurements (Japan-Russia Siberian Tall Tower Inland Observation Network: JR-STATION), and the other experiment was conducted using a data set without the above additional observations. The results show that the global balance of the sources and sinks of surface $CO_2$ fluxes was maintained for both experiments with and without the additional observations. While the magnitude of the optimized surface $CO_2$ flux

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uptake and flux uncertainty in Siberia decreased from -1.17±0.93 Pg C yr$^{-1}$ to -0.77±0.70 Pg C yr$^{-1}$, the magnitude of the optimized surface $CO_2$ flux uptake in the other regions (e.g., Europe) of the Northern Hemisphere (NH) land increased for the experiment with the additional observations, which affect the longitudinal distribution of the total NH sinks. This change was mostly caused by changes in the magnitudes of surface $CO_2$ flux in June and July. The observation impact measured by uncertainty reduction and self-sensitivity tests shows that additional observations provide useful information on the estimated surface $CO_2$ flux. The average uncertainty reduction of the Conifer Forest of EB is 29.1% and the average self-sensitivities at the JR-STATION sites are approximately 60% larger than those at the towers in North America. It is expected that the Siberian observations play an important role in estimating surface $CO_2$ flux in the NH land (e.g., Siberia and Europe) in the future.

## 1 Introduction

The terrestrial ecosystem in the Northern Hemisphere (NH) plays an important role in the global carbon balance (Hayes et al., 2011; Le Quéré et al., 2015). Especially, Siberia is considered to be the one of the largest $CO_2$ uptake regions and reservoirs due to its forest area (Schuleze et al., 1999; Houghton et al., 2007; Tarnocai et al., 2009; Kurganova et al., 2010; Schepaschenko et al., 2011); and its dynamics and interactions with the climate have global significance (Quegan et al., 2011). Therefore, it is important to accurately estimate the surface $CO_2$ fluxes in this region.

For instance, Dolman et al. (2012) estimated terrestrial carbon budget of Russia, Ukraine, Belarus, and Kazakhstan using inventory-based, eddy covariance, and inversion methods and showed that the carbon budgets produced by three methods agree within their uncertainty bounds.

To estimate the surface $CO_2$ flux, atmospheric $CO_2$ inversion studies are conducted using atmospheric transport models and atmospheric $CO_2$ observations (Gurney et al., 2002; Peylin et al., 2013). However, prior emission, measurement error of observation, observation operator including model transport, and representative error affect the uncertainty of atmospheric inversion results (Engelen et al., 2002; Berchet et al., 2015a). Along these factors, However, large uncertainties remain in the estimated surface $CO_2$ fluxes due to the sparseness of current surface $CO_2$ measurements assimilated by inverse models (Peters et al., 2010;

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서식 있음: 글꼴 색: 검정, 영어(영국)
서식 있음: 들여쓰기: 왼쪽 0 글자, 오른쪽 0 글자, 간격 앞: 6 pt, 단락 뒤: 0 pt, 줄 간격: 1.5줄, 단락의 첫 줄이나 마지막 줄 분리 방지, 한글과 영어 간격을 자동으로 조절, 한글과 숫자 간격을 자동으로 조절
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Bruhwiler et al., 2011). Peylin et al. (2013) performed an intercomparison study of estimated surface $CO_2$ fluxes from 11 different inversion systems. The results showed that the estimated surface $CO_2$ flux uptake in the NH, where the atmospheric $CO_2$ network is dense, is similar across the inversion systems; meanwhile, the established flux is noticeably different across the inversion systems for the tropics and SH, where the atmospheric $CO_2$ network is sparse.

Regionally, however, the longitudinal breakdown of all the NH sinks appears to be much more variable than the total flux itself. Therefore, additional observations in a sparse $CO_2$ observation network region are necessary to reduce uncertainty in estimating the surface $CO_2$ flux. Maksyutov et al. (2003) showed that additional observations in the Asia region show the largest effect and reduce the uncertainty in the estimated regional $CO_2$ fluxes for Siberia during 1992-1996 by time-independent synthesis inversion. Chevallier et al. (2010) also argued that an extension of the observation network toward Eastern Europe and Siberia is necessary to reduce uncertainty in estimated fluxes by inversion methods. Despite the necessity of additional observations in this region, only a few atmospheric $CO_2$ inversion studies have been conducted using observations in this region due to the deficiency of observations (Quegan et al., 2011).

Meanwhile, Reuter et al. (2014) and Feng et al. (2016~~5~~) reported that the European terrestrial $CO_2$ uptake inferred by the satellite-retrieved dry-air column-average model fraction of $CO_2$ ($XCO_2$) is larger than that inferred by a bottom-up inventory approach or inverse modeling systems using surface-based in situ $CO_2$ atmospheric concentrations. Though a broad spatial coverage of $XCO_2$ from satellite radiance observations provides useful information for inversion systems in quantifying surface $CO_2$ fluxes at various scales which is not provided by ground-based measurements, the current $XCO_2$ has low accuracy and regional biases of a few tenths of a ppm, which may hamper the accuracy of estimated surface $CO_2$ fluxes (Miller et al., 2007; Chevallier et al., 2007). Therefore, in situ observations determined by surface measurements~~ in remote regions~~ are necessary to more accurately estimate the surface $CO_2$ flux in the inverse models.

To supply additional observations over Siberia to inverse modeling studies, several efforts to observe the atmospheric $CO_2$ concentrations in Siberia have been conducted. For example, the Max Plank Institute (MPI) operates a tower (since April 2009), ~~accompanied~~preceded by aircraft measurements (from 1998 to 2005 with 12 to 21 day intervals) at Zotino (ZOTTO; 60.75°N, 89.38°E) (Lloyd et al., 2002; Winderlich et al. 2010). In addition, the Airborne

Extensive Regional Observations in Siberia (YAK-AERO~~BO~~SIB) aircraft campaign in 2006 (Paris et al., 2008) and Trans-Siberian Observation Into the Chemistry of the Atmosphere (TROICA) project (Turnbull et al., 2009) have measured $CO_2$ and other chemical species. However, except Zotino that has multi-year measurements, ~~-~~these data collected during specific seasons or over only a few years do not provide the long-term $CO_2$ concentration data necessary to be used as a constraint in the inverse modeling system.

서식 있음: 영어(영국)

The Center for Global Environmental Research (CGER) of the National Institute for Environmental Studies (NIES) of Japan with the cooperation of the Russian Academy of Science (RAS) constructed a tower network called the Japan-Russia Siberian Tall Tower Inland Observation Network (JR-STATION) in 2002 to measure the continuous $CO_2$ and $CH_4$ concentrations (eight towers in central Siberia and one tower in eastern Siberia) (Sasakawa et al., 2010, 2013). The vertical profile of $CO_2$ concentrations from the planetary boundary layer (PBL) to the lower free troposphere is also measured by aircraft at one site of the JR-STATION sites ~~and measure the vertical profile of $CO_2$ from the planetary boundary layer (PBL) to the lower free troposphere by aircraft at one site~~ (Sasakawa et al., 2010~~;~~, ~~-~~2013). Saeki et al. (2013) estimated the monthly surface $CO_2$ flux for 68 subcontinental regions by using the fixed-lag Kalman smoother and NIES-TM transport model with JR-STATION data. They reported that the inclusion of additional Siberian observation data has an impact on the inversion results showing larger interannual variability over northeastern Europe as well as Siberia, and reduces the uncertainty of surface $CO_2$ uptake. Meanwhile, Berchet et al. (2015b) estimated regional $CH_4$ fluxes over Siberia in 2010 by using JR-STATION data.

서식 있음: 아래 첨자

CarbonTracker, developed by the National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA ESRL) (Peters et al., 2007), is an atmospheric $CO_2$ inverse modeling system that estimates optimized weekly surface $CO_2$ flux on a 1°×1° horizontal resolution by using the Ensemble Kalman Filter (EnKF). Since the original CarbonTracker release (Peters et al 2007), a series of improvements have been made with subsequent releases. These include increasing the number of sites from which $CO_2$ data are assimilated, increasing the resolution of atmospheric transport, improving the simulation of atmospheric convection in TM5, and the use of multiple first-guess flux models to estimate dependence on priors. These improvements are documented at http://carbontracker.noaa.gov. Several studies have focused on Asia using CarbonTracker (Kim et al., 2012~~;~~, 2014a,~~; 2014~~ b~~,~~; Zhang et al., 2014a,~~, 2014~~ b). Schneising et al. (2011) showed that SCanning Imaging

Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) retrieval data indicate a stronger North American boreal forest uptake and weaker Russian boreal forest uptake compared to CarbonTracker within their uncertainties. On the other hand, Zhang et al. (2014b) estimated surface $CO_2$ fluxes in Asia by assimilating CONTRAIL (Machida et al., 2008) aircraft $CO_2$ measurements into the CarbonTracker framework. The CONTRAIL measurements include ascending/descending vertical profiles and cruise data below tropopause. The results show that surface $CO_2$ uptake over the Eurasian Boreal (EB) region slightly increases from -0.96 Pg C $yr^{-1}$ to -1.02 Pg C $yr^{-1}$ for the period 20068-2010 when aircraft $CO_2$ measurements were assimilated.. However, the surface measurements data over the EB region are still not used in the study by Zhang et al. (2014b). Using an influence matrix calculation, Kim et al. (2014b) showed that comprehensive coverage of additional observations in an observation sparse region, e.g., Siberia, is necessary to estimate the surface $CO_2$ flux in these areas as accurately as that obtained for North America in the CarbonTracker framework.

서식 있음: 강조 없음

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~~using an influence matrix calculation.~~

In this study, the impact of additional Siberian observations on the optimized surface $CO_2$ flux over the globe and Asian region within CarbonTracker (The version of CarbonTracker used in this study is based on the CarbonTracker 2010 release) are investigated by comparing the results of estimated surface $CO_2$ fluxes from two experiments with and without Siberian observations.  Section 2 presents the methodology including a priori flux data, atmospheric $CO_2$ observations, and experimental framework. Section 3 presents the results, and Section 4 provides a summary and conclusions.

# 2 Methodology

## 2.1 Inversion method

CarbonTracker is an inverse modeling system developed by Peters et al. (2007). Optimized surface $CO_2$ fluxes with a 1°×1° horizontal resolution are calculated as follows:

$$F(x,y,t) = \lambda_r \cdot F_{bio}(x,y,t) + \lambda_r \cdot F_{ocn}(x,y,t) + F_{ff}(x,y,t) + F_{fire}(x,y,t)\,, \qquad (1)$$

where $F_{bio}(x,y,t)$, $F_{ocn}(x,y,t)$, $F_{ff}(x,y,t)$, and $F_{fire}(x,y,t)$ are a priori ~~the~~ emissions from the biosphere, the ocean, fossil fuel, and fires. $\lambda_r$ is the scaling factor to be optimized in the data assimilation process, corresponding to 156 ~~eco~~regions around the globe (126 land and 30 ocean regions). ~~In the land, the ecoregions are defined as following the Transcom regions (Gurney et al., 2002) with ecosystem classification defined Olson et al. (1992).~~ In the land, the ecoregions are defined as the combination of 11 land region of Transcom regions (Gurney et al., 2002) with 19 land-surface characterization based on Olson et al. (1992). Inappropriate combinations of TransCom regions and Olson types are excluded. In the ocean, 30 ocean regions are defined following Jacobson et al. (2007). The scaling factor spans 5 weeks with 1 week resolution. Several previous studies for CarbonTracker (e.g., Peters et al., 2007; 2010, Kim et al., 2012~~,~~; 2014a~~,~~; ~~2014~~b~~,~~; Zhang et al., 2014a, ~~2014~~ b; van der Laan-Luijkx et al., 2015) showed that 5 weeks of lag~~assimilation window~~ and 1-week time resolution are appropriate for optimizing the surface $CO_2$ fluxes. In each assimilation cycle (i.e., analysis step), the entire scaling factor for 5 weeks is updated by 1 week observations measured most recent week by a time stepping approach. The smoother~~assimilation~~ window moves forward by 1 week at each assimilation cycle. After 5 assimilation cycles, the first part of the scaling factor analyzed by 5 weeks observations is regarded as the optimized scaling factor. The more detailed information of the assimilation process can be found in Kim et al. (2014b).

The e~~E~~nsemble Kalman f~~F~~ilter (EnKF) data assimilation method used in CarbonTracker is the ensemble square root filter (EnSRF) suggested by Whitaker and Hamill (2002). The analysis equation for data assimilation is expressed as

$$\mathrm{x}^{a} = \mathbf{K}\mathrm{y}^{o} + (\mathbf{I}_n - \mathbf{KH})\mathrm{x}^{b}, \qquad (2)$$

where $\mathrm{x}^{a}$ is the n-dimensional analysis (posterior) state vector ; $\mathrm{y}^{o}$ is the p-dimensional observation vector (atmospheric $CO_2$ observations); $\mathbf{K}$ is the n × p dimensional Kalman gain; $\mathbf{I}_n$ is the identity matrix; $\mathbf{H}$ is the linearized observation operator, which transforms the information in the model space to the information in the observation space; and $\mathrm{x}^{b}$ is the background state vector. In CarbonTracker, the state vector corresponds to the scaling factor. The Kalman gain $\mathbf{K}$ is defined as

$$\mathbf{K} = \left(\mathbf{P}^{b}\mathbf{H}^{T}\right)\left(\mathbf{H}\mathbf{P}^{b}\mathbf{H}^{T} + \mathbf{R}\right)^{-1}, \qquad (3)$$

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where $\mathbf{P}^b$ is the background error covariance; $\mathbf{R}$ is the observation error covariance or model data mismatch, which is predefined at each observation site. $\mathbf{P}^b\mathbf{H}^T$ and $\mathbf{H}\mathbf{P}^b\mathbf{H}^T$ in Eq. (3) can be calculated as

$$\mathbf{P}\mathbf{H}^T \approx \frac{1}{m-1}\left(x_1', x_2', \ldots, x_m'\right)\cdot\left(\mathbf{H}x_1', \mathbf{H}x_2', \ldots, \mathbf{H}x_m'\right)^T, \quad (4)$$

$$\mathbf{H}\mathbf{P}\mathbf{H}^T \approx \frac{1}{m-1}\left(\mathbf{H}x_1', \mathbf{H}x_2', \ldots, \mathbf{H}x_m'\right)\cdot\left(\mathbf{H}x_1', \mathbf{H}x_2', \ldots, \mathbf{H}x_m'\right)^T, \quad (5)$$

where $m$ is the number of ensembles and $'$ denotes the perturbation of ensemble mean.

To reduce the sampling error and filter divergence due to the underestimation of background error covariance in the EnKF, the covariance localization method is used (Houtekamer and Mitchell, 2001). The localization is not applied to Marine Boundary Layer (MBL) sites (e.g. observation sites in Antarctica), because the MBL sites are considered as including information on large footprints of flux signals (Peters et al., 2007). The physical distance between the scaling factors cannot be defined. Therefore, localization is performed based on the linear correlation coefficient between the ensemble of the scaling factor and the ensemble of the model $CO_2$ concentration (Peters et al., 2007). Statistical significance test is performed on the linear correlation coefficient with a cut-off at a 95% significance in a student's T-test. Then the components of Kalman gain with an insignificant statistical value are set to zero.

~~The Kalman gain with an insignificant statistical value is set to zero after a statistical significance test, 95% significance level in a student's T-test, is performed on the correlations.~~After one analysis step is completed, the new mean scaling factor that serves as the background scaling factor for next analysis cycle is predicted as

$$\lambda_t^b = \frac{(\lambda_{t-2}^a + \lambda_{t-1}^a + 1)}{3}, \quad (6)$$

where $\lambda_t^b$ is a prior mean scaling factor of the current analysis cycle, $\lambda_{t-2}^a$ and $\lambda_{t-1}^a$ are posterior mean scaling factors of previous cycles. Eq. (6) propagates information from one step to the next step (Peters et al., 2007).

The detailed algorithm of inversion method used in this study can be found in Peters et al. (2007) and Kim et al. (2014a).

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## 2.2 A priori flux data

Four types of a priori and imposed $CO_2$ fluxes used in this study are as follows: (1) First guess biosphere flux from the Carnegie–Ames–Stanford Approach Global Fire Emissions Database (CASA GFED) version 3.1 (van der Werf et al., 2010). The 3 hour interval Net Ecosytem Exchange (NEE) is calculated from monthly mean Net Primary Production (NPP) and ecosystem respiration (RE) by using a simple temperature $Q_{10}$[1] relationship and a linear scaling of photosynthesis with solar radiation (Olsen and Randerson, 2004); (2) the prior ocean flux from air-sea partial pressure differences based on Jacobson et al. (2007). Short-term flux variability is derived from the atmospheric model wind speeds via the gas transfer coefficient; (3) biomass burning emissions obtained from GFED v3.1 (van der Werf et al., 2010); (4) the prescribed fossil fuel emission from the Carbon Dioxide Information and Analysis Center (CDIAC, Boden et al., 2010)) and the Emission Database for Global Atmospheric Research (EDGAR, European Commission, 2009)) databases. The annual global total fossil fuel emissions are based on CDIAC. Fluxes at 1°x1° resolution are spatially distributed according to the EDGAR inventories.

## 2.3 Atmospheric $CO_2$ observations

Atmospheric $CO_2$ mole fraction observations measured at surface observation sites are used in this study. Figure 1 shows the observation network and Table 1 presents observation site information for the Asian and European regions. Three sets of atmospheric $CO_2$ observations data are assimilated: (1) surface $CO_2$ observations distributed by the NOAA ESRL (observation sites operated by NOAA, Environment Canada (EC), the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), the National Center for Atmospheric Research (NCAR), and Lawrence Berkeley National Laboratory (LBNL)) (observation data is available at http://www.esrl.noaa.gov/gmd/ccgg/obspack/data.php; Masarie et al., 2014); (2) World Data Centre for Greenhouse Gases (WDCGG, http://ds.data.jma.go.jp/wdcgg/); (3) JR-STATION observation data over Siberia operated by

[1] It is calculated as $Q_{10}(t) = 1.5^{((T_{2m}-T_0)/10.0)}$, where $t$ is time, $T_{2m}$ is temperature (K) at 2 m, and $T_0$ is 273.15 K.

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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 w~~W~~est Siberia, both tower and ~~a light~~ 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 ~~(LFT). Atmospheric air was sampled at four levels on the BRZ tower and at two levels on the other eight towers.~~ vertical profiles are used as independent observations for verification.

Sampled $CO_2$ data were calibrated against the NIES 09 $CO_2$ scale which are lower than the WMO-X2007 $CO_2$ scale by 0.07 ppm at around 360 ppm and consistent in the range between 380 and 400 ppm (Machida et al., 2011). Detailed description of JR-STATION sites can be found in Sasakawa et al. (2010~~;~~, 2013). Daytime averaged $CO_2$ concentrations (1200-1600 LST, representing the time when active vertical mixing occurred in the PBL) for each day from the time series at the highest level of tower measurements are used in the data assimilation.

In CarbonTracker, model data mismatch (MDM, **R** in Eq. (7)) is assigned by site categories. The location of each observation site is represented in Fig. 1. The assigned MDM ~~determined by~~ requires~~ing~~ innovation $\chi^2$ statistics in Eq. (7~~6~~) become close to one at each observation site (Peters et al. 2007).

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$$\chi^2 = \frac{(y^o - \mathbf{H}x^b)^2}{\mathbf{HP}^b\mathbf{H}^T + \mathbf{R}}, \qquad (7~~6~~)$$

where $y^o - \mathbf{H}x^b$ represent innovation.

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The site categories and MDM~~model-data mismatch~~ values are assigned the same value as in previous studies (Peters et al., 2007; Kim et al. 2014b; Zhang et al., 2014b): marine boundary layer (0.75 ppm), continental sites (2.5 ppm), mixed land/ocean and mountain sites (1.5 ppm), continuous sites (3.0 ppm), and difficult sites (7.5 ppm). Continuous site category is generally used for observations measured continuously. ~~.~~ For the JR-STATION sites that have continuous tower measurements, the MDM~~model-data mismatch~~ is set to 3 ppm, which is the same as ~~for~~ tower measurements in North America.

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~~The location of each observation site is represented in Fig. 1.~~

### 2.4 Experimental framework

Two experiments with different set of observations are conducted in this study: one experiment, the CNTL experiment, is conducted by using set of observations without observations in the Siberia region (black color observation sites represented in Fig. 1); the other experiment, the JR experiment, is conducted by using all available observations including the Siberia data (all observation sites represented in Fig. 1). The TM5 model (Krol et al., 2005) which calculates four-dimensional $CO_2$ concentration field runs at global 3°×2° horizontal resolution and a nesting domain centered in Asia with 1°×1° horizontal resolution. The nesting domain is shown in Fig. 1. Meteorological variables for running the TM5 transport model are from the European Centre for Medium-Range Weather Forecasts (ECMWF) forecast model output. The experimental period is from 1 January 2000 to 31 December 2009. The observation data commonly used for CNTL and JR experiments exists from 2000, but the additional Siberia data for the JR experiment exist from 2002. The number of ensembles is 150, and the scaling factor includes 5 weeks of lag, as in previous studies (Peters et al., 2007,; Peters et al., 2010; Peylin et al., 2013; Kim et al., 2012, 2014a , 2014b; Zhang et al., 2014a, 2014b).

## 3 Results

### 3.1 Characteristics of carbon fluxes

In this section, optimized surface $CO_2$ fluxes inferred from the two experiments are examined. The optimized surface $CO_2$ flux in 2000 and 2001 is excluded from this analysis because 2000 is considered a spin-up year similar to previous studies using CarbonTracker, and JR-STATION data are used since 2002. Only the biosphere and ocean fluxes are presented here because fires (biomass burning) and fossil fuel emissions are not optimized in CarbonTracker.

Figure 2 presents the spatial distribution of the averaged prior and optimized biosphere and ocean fluxes of the two experiments and the difference between the CNTL and JR experiments from 2002 to 2009. The optimized biosphere flux uptakes of the CNTL and JR experiments are globally 1.650 ~ 1.661 Pg C $yr^{-1}$ greater than the prior flux uptakes (Figs. 2a, c, d, Table 2). The difference in fluxes between the prior and JR experiment is large in EB (Figs. 2a, d) although smaller than that between the prior and CNTL experiment (Figs. 2a, c). The differences in fluxes between the CNTL and JR experiments are distinctive in EB

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(Siberia) where the new additional observations are assimilated (Fig. 2b). The magnitude of surface $CO_2$ uptakes decreases in that region by assimilating JR-STATION observation data. On the contrary, the average surface $CO_2$ uptakes in other regions, such as North America, Europe, the western North Pacific Ocean, and the Atlantic Ocean, increase by assimilating JR-STATION observation data.

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). Flux uncertainty is calculated as one-sigma standard deviation of the fluxes estimated, assuming Gaussian errors. The global total biogenic and oceanic optimized $CO_2$ fluxes are similar for each experiment at -5.5469±1.845 Pg C $yr^{-1}$ (CNTL experiment) and -5.6055±1.72 Pg C $yr^{-1}$ (JR experiment), compared with the global prior flux of -3.94±2.234 Pg C $yr^{-1}$. The global land sink in the CNTL experiment is larger by 0.07 Pg C $yr^{-1}$ than that of the JR experiment, and the global ocean sink in the CNTL experiment is smaller by 0.08 Pg C $yr^{-1}$ than that of the JR experiment. The additional observations do not make any discrepancy between two the two experiments with respect to the global total sink, and they indicate only a small difference in the land-ocean $CO_2$ flux partitioning. The estimated $CO_2$ flux uncertainty in the land region from the JR experiment is smaller than that of the CNTL experiment because new observations provide additional constraints on the optimized $CO_2$ flux. For specific regions in the NH, a large difference of optimized surface $CO_2$ flux is observed in the EB. T-he largest increment between a priori and CNTL is shown in EB with the least in situ observations as shown in Fig. 1. The other regions show smaller increment with more 'local' observations available. The surface $CO_2$ uptakes in the EB of the CNTL experiment is -1.17±0.93 Pg C $yr^{-1}$ and that of the JR experiment is -0.787±0.70 Pg C $yr^{-1}$, respectively. The uncertainty of the optimized surface $CO_2$ uptake in the EB infrom the JR experiment is expectedly reduced by assimilating additional observations. In contrastOn the other hand, the surface $CO_2$ uptake increases in other regions of the NH.

Figure 3 presents the spatial distribution of the optimized biosphere fluxes difference between the CNTL and JR experiments from 2002 to 2009. The difference of optimized surface $CO_2$ flux is calculated as in Fig. 2b. The largest difference of optimized surface $CO_2$ fluxes

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between the two experiments occurs in Siberia. 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 experimentin 2003 due to the remote effect of drought in Europe. Despite the number of JR-STATION dataobservations 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 increasedreduced uptake of optimized surface $CO_2$ fluxes in 2003 in Siberia (Fig. 3b).

Optimized surface $CO_2$ fluxes averaged from 2002 to 2009 for each ecoregion in the NH are shown in Table 3. In the Siberia (EB (Siberia)), optimized surface $CO_2$ uptake from the JR experiment is smaller (larger) than that of the CNTL experiment in the Conifer Forest and Northern Taiga (in other ecoregions). In the Eurasian Temperate (ET), Europe, North American Boreal (NAB), and North American Temperate (NAT) regions, the optimized surface $CO_2$ uptakes from the JR experiment are larger than those of the CNTL experiment in most ecoregions.

Figure 4 shows the time serieshistogram of annual and average prior and optimized surface $CO_2$ fluxes over global total, global land, and global ocean. For global total, the magnitude of optimized fluxes are much greater than that of prior fluxes due to the greater uptake of optimized fluxes than that of prior fluxes over global land (Figs. 4a and b). In contrast, the magnitude of optimized fluxes over global ocean is slightly weaker than that of prior fluxes (Fig. 4c). As shown in Table 2, the differences between annual and average optimized surface $CO_2$ fluxes over the globe are small and the average is almost the same for the two experiments (Fig. 4a) with a similar trend of -0.33 Pg C $yr^{-2}$ and -0.35 Pg C $yr^{-2}$ in CNTL and JR experiment respectively, and the differences in global land and ocean are also small (Figs. 4b, c) with a similar trend of -0.22 Pg C $yr^{-2}$ in global land of both CNTL and JR experiment and -0.11 Pg C $yr^{-2}$ and -0.13 Pg C $yr^{-2}$ in global ocean of CNTL and JR experiment respectively. The optimized surface $CO_2$ fluxes from each experiment show similar interannual variability, which implies that the additional Siberian observations do not affect the interannual variability of global surface $CO_2$ uptakes.

Figure 5 is the same as Fig. 4 but covers land regions in the NH. Although the optimized surface $CO_2$ fluxes over global total are similar, those over each TransCom region are

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different in each experiment. The optimized fluxes over each region show greater annual uptake relative to the prior fluxes in both experiment. The difference between the two experiments is largest in the EB as expected (Fig. 5a). The JR experiment exhibits a weaker surface $CO_2$ uptake in the EB than does the CNTL experiment except for 2003 as shown in Fig. 3b, whereas the JR experiment exhibits a greater surface $CO_2$ uptake in the other regions, especially over Europe in 2008 and 2009, than the CNTL experiment (Figs. 5b, c, d, and e). It is driven by the increase of $CO_2$ uptake in Eastern Europe (Figs. 3g and h). Because most of JR-STATION sites are located in the western part of Siberia (Fig. 1), the optimized surface $CO_2$ fluxes over Eastern Europe could be affected by JR-STATION observations. ~~As a result, the trends of the surface $CO_2$ uptake of EB and Europe in two experiments are different.~~ The trend of EB in CNTL experiment is -0.06 Pg C $yr^{-2}$, whereas that in JR experiment is 0.02 Pg C $yr^{-2}$ due to the reduced uptake of $CO_2$ in JR experiment since 2005 (Fig 5a). As a result, the trends of the surface $CO_2$ uptake of EB and Europe in two experiments show opposite signs. In contrast, the surface $CO_2$ uptake trends of other land regions in NH~~orthern Hemisphere~~ are similar between the two experiments.

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Figure 6 shows monthly prior and optimized surface $CO_2$ fluxes averaged from 2002 to 2009 with their uncertainties from both experiments. In general, optimized fluxes in both experiments show greater uptake in boreal summer and weaker uptake in other seasons compared to the prior fluxes, which results in greater annual $CO_2$ uptake of optimized fluxes than prior fluxes as shown in Fig. 5. The largest difference in surface $CO_2$ flux between the two experiments occurs in June and July, which represent the active season of the terrestrial ecosystem with a large surface $CO_2$ flux uncertainty. The JR experiment exhibits a weaker surface $CO_2$ summer uptake in the EB (Fig. 6a) and slightly greater uptake in the other regions (Figs. 6b, c, d, and e). These ~~A~~additional JR-STATION~~–Siberian~~ data provides information on the surface $CO_2$ uptake by vegetation activities~~y~~ in the NH summer.

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### 3.2 Comparison with observations

Table 4 presents the average bias of the model $CO_2$ concentrations calculated by the background and optimized fluxes of the two experiments at each observation site located in Asia and Europe from 2002 to 2009. The bias is calculated by subtracting the observed $CO_2$ concentrations from the model $CO_2$ concentrations. Biases of the JR experiment are smaller than those of the CNTL experiment at the JR-STATION sites, which indicates that the optimized surface $CO_2$ flux of the JR experiment is more consistent with the observed $CO_2$

concentrations than that in the CNTL experiment. The negative bias at five JR-STATION sites (DEM, IGR, KRZ, NOY, and YAK) located in the forest area of the EB is reduced compared with those of the CNTL experiment, which indicates that the optimized surface $CO_2$ uptake of the CNTL experiment is overestimated with respect to $CO_2$ concentration observations in Siberia. Otherwise~~Otherwise~~, the reduced surface $CO_2$ uptake of the JR experiment exhibits more consistent model $CO_2$ concentrations in this region. In addition to the average bias for the entire period, the time series of monthly averaged bias of the model $CO_2$ concentration from the observed $CO_2$ concentration at JR-STATION sites shows that the JR experiment consistently shows smaller biases compared to the CNTL experiment (not shown), which implies that the model representation of $CO_2$ at JR-STATION sites is more accurate in the JR experiment than in the CNTL experiment. Model $CO_2$ concentrations calculated by background surface $CO_2$ fluxes in~~from~~ the JR experiment are also more consistent with the observations, implying that background scaling factors of the JR experiment are more accurate than those of the CNTL experiment. The background surface $CO_2$ fluxes are calculated by multiplying the background scaling factor to prior biosphere and ocean fluxes as in Eq. (1). In addition, the average innovation $\chi^2$-statistics at the JR-STATION sites are generally close to 1, implying that the defined MDM is an appropriate value. Therefore, by assimilating JR-STATION observation data, the JR experiments exhibits better results than the CNTL experiment at observation sites in EB.

However, at observation sites in ET and Europe, the difference in biases of the two experiments is relatively small and not significant enough to determine which experiment exhibits better results. This is due to the small difference of optimized surface $CO_2$ fluxes between the two experiments in the ET region. The observation sites in Europe are located far from Eastern Europe and Siberia as shown in Fig. 1 so that they are not sensitive to the change of surface $CO_2$ uptake in those regions. In addition, the MDM at four sites (BAL, BSC, HUN, and OBN) in Europe is assigned as 7.5 ppm, the largest value in CarbonTracker, due to poor representation of the transport model at these sites (Peters et al., 2010).

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

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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.

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## 3.3 Uncertainty reduction and observation impactEffect of additional observations

The effectss of additional observations on the optimized surface $CO_2$ flux and associated uncertainties are investigated. Figure 7 shows the average, maximum, average in summer (June, July, and August) and average in winter (December, January, February) uncertainty reductions from 2002 to 2009. The uncertainty reduction based on the uncertainty of CNTL as the reference is calculated as follows:

$$UR = \frac{\sigma_{CNTL} - \sigma_{JR}}{\sigma_{CNTL}} \times 100(\%), \qquad (87)$$

where $\sigma_{CNTL}$ and $\sigma_{JR}$ are one-sigma standard deviations of the optimized scaling factor for CNTL experiment and JR experiment, respectively, assuming Gaussian errors. The maximum uncertainty reduction is the greatest value in any week in the period 2002 to 2009 in each ecoregion. As expected, the average uncertainty reduction is readily apparent in the Conifer Forest of EB in which JR stations are mainly located, which has the additional observations (Fig. 7a). The uncertainty reduction of Asia and Europe, especially in the forest of Siberia and Eastern Europe, is greater than for other regions. The spatial pattern of the maximum uncertainty reduction is similar to that of the average values, but the magnitude of the maximum uncertainty reduction is higher than the average value, which implies that additional observations sometimes have a great impact on the optimization of surface $CO_2$

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~~flux (Fig. 7b)(삭제).~~ (not shown). The uncertainty reduction of EB in summer is higher than that in winter (Figs. 7b~~e~~, c~~d~~) due to a higher uncertainty associated with larger net fluxes in summer compared to winter (Fig. 6a).~~.~~ For example, the average value of the Conifer Forest of EB is 29.1%, the maximum value is 78.6%, the average value in summer is 36.3% and the average value in winter is 29.7%, respectively. 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); $\sigma_{CNTL}$ or $\sigma_{JR}$ used instead of $\sigma_{JR}$ in Eq. (8)) shows similar values in the NH~~orthern Hemisphere~~ except in Siberia region (not shown). In addition, t~~T~~he 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. Therefore, ~~The result shows that~~ the uncertainties of the optimized surface $CO_2$ fluxes are reduced by the additional observations.

To investigate the impact of individual observations on the optimized surface~~,~~ $CO_2$ flux, the self-sensitivities are calculated by the method demonstrated by Kim et al. (2014b). The self-sensitivity is the diagonal element of the influence matrix which measures the impact of individual observations in the observation space on the optimized surface $CO_2$ flux. The large self-sensitivity value implies that the information extracted from observations is large. Figure 8 shows the self-sensitivities of the two experiments averaged from 2002 to 2009. The average self-sensitivities at the JR-STATION sites are approximately 60% larger than those ~~as large as those~~ at the tower~~s measurements~~ in North America, i.e., c~~C~~ontinuous site category observations in Fig. 1. The global average self-sensitivities are 4.83% (CNTL experiment) and 5.08% (JR experiment), and the cumulative impacts for the 5 weeks assimilation window are 18.79% (CNTL experiment) and 19.33% (JR experiment). 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.

~~To assess the observation impact on the optimized surface $CO_2$ fluxes, T~~The ~~root mean square differences (~~RMSDs~~)~~ between the optimized surface $CO_2$ fluxes and the background fluxes at each assimilation step in summer are calculated (Fig. 9). The RMSD of the analyzed surface $CO_2$ fluxes constrained by one week of observations from the background fluxes in JR

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experiment is greater than that in CNTL experiment (Figs. 9a, b), . The RMSD values in Siberia are as high as those in North America, iimplying that surface $CO_2$ fluxes in Siberia are analyzed by JR-STATION data in Siberia directly direct observations at the first cycle. This is consistent with the high value of self-sensitivities at JR-STATION sites as shown in Fig. 8b. Because JR-STATION data are abundant and have large self-sensitivities, these observations provide large information on the estimated surface $CO_2$ fluxes over Siberia in the first cycle. Kim et al. (2014b) showed that the RMSD in Asia increases after 5 weeks of optimization, which implies that it takes more than 1 week to affect the surface $CO_2$ fluxes in Siberia by the transport of the $CO_2$ concentrations observed in remote regions. However, by assimilating the $CO_2$ concentrations observed at the JR-STATION sites in Siberia, the observation impact on the optimized surface $CO_2$ fluxes in Siberia increases after 1 week of optimization (Fig. 9b). In contrast, On the other hands, the RMSD in the Siberia region increases after 5 weeks of optimization in the CNTL experiment compared to that in the JR experiment (Figs. 9c, d), which corresponds to the reduced uptake of optimized surface $CO_2$ fluxes in JR experiment as shown in Fig. 2b.

## 3.4 Comparison with other results

Kim et al. (2014b) showed that the RMSD in Asia increases after 5 weeks of optimization, which implies that it takes 5 weeks to affect the surface $CO_2$ fluxes in Siberia by the transport of the $CO_2$ concentrations observed in remote regions. However, by assimilating the $CO_2$ concentrations observed at the JR-STATION sites in Siberia, the observation impact on the optimized surface $CO_2$ fluxes in Siberia increases after 1 week of optimization (Fig. 9b).

On the other hands, the RMSD in the Siberia region increases after 5 weeks of optimization in the CNTL experiment compared to that in the JR experiment (Figs. 9c, d), which corresponds to the reduced uptake of optimized surface $CO_2$ fluxes in JR experiment as shown in Fig. 2b.

3.4 Comparison with other results

A comparison of the optimized surface $CO_2$ flux in this study with other previousinversion studies is presented in Table 65. In the EB, the land sink from the JR experiment (-0.778±0.70 Pg C $yr^{-1}$) is smaller than those reported by Zhang et al. (2014b) (-1.02±0.91 Pg C $yr^{-1}$), Maki et al. (2010) (-1.46±0.41 Pg C $yr^{-1}$), and the CT2013B (CarbonTracker released on 9 Feburary 2015; documented online at http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2013B/) results (-1.090±43.0375 Pg C $yr^{-1}$), but higher than those reported by Saeki et al. (2013) (-

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0.35±0.6141 Pg C $yr^{-1}$; including biomass burning 0.11 Pg C $yr^{-1}$)-), and similar with those reported by Dolman et al. (2012) (-0.613 Pg C $yr^{-1}$).

Because CT2013B and Zhang et al. (2014b) use the similarame inversion framework as this study, the reduced land sink is caused by assimilating additional observations. The difference in land sink between the JR experiment and Saeki et al. (2013) is caused by a different inversion system framework which includes –prior flux information, atmospheric transport model, observation data set, and inversion method. Despite different inversion system framework used in each study, two studies using the JR-STAITON data exhibit similar results in relative terms, reduced uptake of $CO_2$ fluxes and uncertainties over Siberia. Nontherless, the land sink from the JR experiment is somewhat differentce with other inversion results, its value falls within the flux uncertainty range. Because the land sink in Dolamn et al. (2012) is the average land sink obtained from three methods (inventory-based, eddy covariance, and inversion methods) and estimated not only for Siberia but for Russian territory including Ukraine, Belarus, and Kazakhstan, the land sinks of the JR experiment and Dolman et al. (2012) are different.Although the land sink in Dolamn et al. (2012) is the average land sink obtained from three methods (inventory-based, eddy covariance, and inversion methods) and estimated not only for Siberia but for Russian territory including Ukraine, Belarus, and Kazakhstan, the land sinks of the JR experiment and Dolman et al. (2012) shows similar values. Overall, the optimized surface $CO_2$ fluxes in EB of JR experiment are comparable to those of other previous studies.

In Europe, though the long-term average land sink from the JR experiment (-0.357±0.654 Pg C $yr^{-1}$) is similar to→higher than that of CTE2014 (-0.0733±0.8049 Pg C $yr^{-1}$), the average land sink from 2008-2009 of the JR experiment (-0.75±0.63 Pg C $yr^{-1}$) is much higher than that of CTE2014 (-0.11±0.38 Pg C $yr^{-1}$). The land sinks of the JR experiment in 2008 and 2009 are -0.73±0.41 and -0.76±0.38 Pg C $yr^{-1}$, respectively, whereas much lower uptakes (-0.21±0.49, -0.38±0.44 Pg C $yr^{-1}$) are obtained for the CNTL experiment. According to Reuter et al. (2014), despite the different experiment period, the land sink of Europe in 2010 (-1.02±0.30 Pg C $yr^{-1}$) estimated by using satellite observations is much higher than previous inversion studies (e.g., Peylin et al. 2013) using only surface observations. The land sinks of the JR experiment in 2008 and 2009 are -0.67±0.49 and -0.75±0.44 and -0.75 Pg C $yr^{-1}$, respectively, whereas much lower uptakes (-0.21±0.41, -0.39±0.38 0.21, -0.39 Pg C $yr^{-1}$) are obtained for the CNTL experiment.

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~~Overall, the optimized surface $CO_2$ fluxes of JR experiment are comparable to those of other previous studies.~~

## 4 Summary and conclusions

In this study, to investigate the effect of the Siberian observations, which are not used in the previous studies using CarbonTracker, on the optimization of surface $CO_2$ fluxes, two experiments, named CNTL and JR, with different sets of observations from 2000 to 2009 were conducted and optimized surface $CO_2$ fluxes from 2002 to 2009 were analyzed.

The global balances of the sources and sinks of surface $CO_2$ fluxes were maintained with a similar trend for both experiments, while the distribution of the optimized surface $CO_2$ fluxes changed. The magnitude of the optimized biosphere surface $CO_2$ uptake ~~in EB (Siberia) was decreased,~~ and its uncertainty in EB (Siberia) was decreased from -1.17±0.93 Pg C $yr^{-1}$ to -0.77±0.70 Pg C $yr^{-1}$, whereas it was increased in other regions of the NH (Eurasian Temperate, Europe, North American Boreal, and North American Temperate). The land sink of Europe increased significantly for 2008 and 2009, which is consistent with the other inversion results inferred by satellite observations. Additional observations are used to correct the surface $CO_2$ uptake in June and July, the active vegetation uptake season, in terms of monthly average optimized surface $CO_2$ fluxes. As a result, the additional observations do not exhibit a change in the magnitude of the global surface $CO_2$ flux balance because they provide detailed information about the Siberian land sink instead of the global land sink magnitude, when they are used in the well-constructed inversion modeling system.

The model $CO_2$ concentration using the background and optimized surface $CO_2$ fluxes in the JR experiment are more consistent with the $CO_2$ observations used in the optimization than those in the CNTL experiment, showing lower biases in the EB region. In contrast~~On the other hand~~, the differences of biases in ET and Europe between the two experiments are not distinguishable. In comparison with vertical profiles of $CO_2$ concentration observations which are not used in the optimization, the model $CO_2$ concentrations in the JR experiment show the smaller RMSD and MAE, and the greater correlation coefficient that those in CNTL experiment.

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The new observations provide useful information on the optimized surface $CO_2$ fluxes. The observation impact of the Siberian observation data is investigated by means of uncertainty reduction and self-sensitivity calculated by an influence matrix. Additional observations reduce the uncertainty of the optimized surface $CO_2$ fluxes in Asia and Europe, mainly in the EB (Siberia), where the new observations are used in the assimilation. The average self-sensitivities of the JR-STATION sites are approximately 60% larger than those at ~~as large as~~ other continuous measurements (e.g., tower measurements in North America). The global average self-sensitivity and cumulative impact of the JR experiment are higher than that of the CNTL experiment, which implies that the individual observation impact of JR-STATION data on optimized surface $CO_2$ fluxes is higher than the average values. The RMSD of the analyzed surface $CO_2$ fluxes constrained by one week of observations from the background fluxes also suggests that new Siberian observations provide a larger amount of information on the optimized surface $CO_2$ fluxes.

This study shows~~reaffirms~~ that the JR-STATION data affect the longitudinal distribution of the total NH sinks, especially in the EB and Europe, when it is used by atmospheric $CO_2$ inversion modeling. In the future, it is expected that Siberian observations will be used as an important constraint for estimating surface $CO_2$ fluxes over the NH with various $CO_2$ observations (e.g. satellite and aircraft measurements) simultaneously.

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Table 1. Information on observation sites located in the Asia and Europe region. MDM represents the model-data mismatch which is the observation error.

| Site | Location | Latitude | Longitude | Height (Sampling height) (m) | Laboratory (Cooperating agency) | MDM (ppm) |
|---|---|---|---|---|---|---|
| AZV | Azovo, Russia | 54.71°N | 73.03°E | 110(50)~~110~~ | NIES | 3 |
| BRZ | Berezorechka, Russia | 56.15°N | 84.33°E | 168(80)~~168~~ | NIES | 3 |
| DEM | Demyanskoe, Russia | 59.79°N | 70.87°E | 63(63)~~63~~ | NIES | 3 |
| IGR | Igrim, Russia | 63.19°N | 64.41°E | 9(47)~~9~~ | NIES | 3 |
| KRS | Karasevoe, Russia | 58.25°N | 82.42°E | 76(67)~~76~~ | NIES | 3 |
| NOY | Noyabrsk, Russia | 63.43°N | 75.78°E | 108(43)~~108~~ | NIES | 3 |
| SVV | Savvushka, Russia | 51.33°N | 82.13°E | 495(52)~~495~~ | NIES | 3 |
| VGN | Vaganovo, Russia | 54.50°N | 62.32°E | 192(85)~~192~~ | NIES | 3 |
| YAK | Yakutsk, Russia | 62.09°N | 129.36°E | 264(77)~~264~~ | NIES | 3 |
| WLG | Mt. Waliguan, China | 36.29°N | 100.9°E | 3810 | CMA/ESRL | 1.5 |
| BKT | Bukit Kototabang, Indonesia | 0.20°S | 100.3~~1~~2°E | 864 | ESRL | 7.5 |
| WIS | Sede Boker, Israelr, | 31.13°N | 34.88°E | 400 | ESRL | 2.5 |
| KZD | Sary Taukum, Kazakhstan | 44.45°N | 77.57°E | 412 | ESRL | 2.5 |
| KZM | Plateau Assy, Kazakhstan | 43.25°N | 77.88°E | 2519 | ESRL | 2.5 |
| TAP | Tae-ahn Peninsula, South Korea | 36.73°N | 126.13°E | 20 | ESRL | 5 |
| UUM | Ulaan Uul, Mongolia | 44.45°N | 111.10°E | 914 | ESRL | 2.5 |
| CRI | Cape Rama, India | 15.08°N | 73.83°E | 60 | CSIRO | 3 |
| LLN | Lulin, Taiwan | 23.47°N | 120.87°E | 2862 | ESRL | 7.5 |
| SDZ | Shangdianzi, China | 40.39°N | 117.07°E | 287 | CMA/ESRL | 3 |
| MNM | Minamitorishima, Japan | 24.29°N | 153.98°E | 8 | JMA | 3 |
| RYO | Ryori, Japan | 39.03°N | 141.82°E | 260 | JMA | 3 |
| YON | Yonagunijima, Japan | 24.47°N | 123.02°E | 30 | JMA | 3 |
| GSN | Gosan, South Korea | 33.15°N | 126.12°E | 72 | NIER | 3 |
| BAL | Baltic Sea, Poland | 55.35°N | 17.22°E | 3 | ESRL (MIR*)~~ESRL~~ | 7.5 |
| BSC | Black Sea, Constanta, Romania | 44.17°N | 28.68°E | 3 | ESRL (RMRI*)~~ESRL~~ | 7.5 |
| HUN | Hegyhatsal, Hungary | 46.95°N | 16.65°E | 248 | ESRL (HMS*)~~ESRL~~ | 7.5 |
| OBN | Obninsk, Russia | 55.11°N | 36.60°E | 183 | ESRL~~ESRL~~ | 7.5 |
| OXK | Ochsenkopf, Germany | 50.03°N | 11.80°E | 1022 | ESRL (MPI-BGC*)~~ESRL~~ | 2,5 |
| PAL | Pallas-Sammaltunturi, GaW Station, Finland | 67.97°N | 24.12°E | 560 | ESRL (FMI*)~~ESRL~~ | 2.5 |
| STM | Ocean Station M, Norway | 66.00°N | 2.00°E | 0 | ESRL (MET Norway*)~~ESRL~~ | 1.5 |

* Cooperating agencies of observation sites in Euope: Morski Instytut Rybacki (MIR), Romanian Marine Research Institute (RMRI), Hungarian Meteorological Service (HMS), Max Plnack Institute for Biogeochemistry (MPI-BGC), Finnish Meteorological Institute (FMI), Norwegian Meteorological Institute



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**서식 있음:** 들여쓰기: 왼쪽 1 글자, 오른쪽 1 글자, 지정한 문자 수와 상관없이 오른쪽 들여쓰기 하지 않음, 간격 앞: 0 pt, 단락 뒤: 10 pt, 줄 간격: 배수 1.15 줄, 단락의 첫 줄이나 마지막 줄 분리 허용, 한글과 영어 간격을 자동으로 조절하지 않음, 한글과 숫자 간격을 자동으로 조절하지 않음

Table 2. A prior and optimized surface $CO_2$ fluxes and their one-sigma uncertainties (Pg C $yr^{-1}$ $Region^{-1}$) of global total, land, ~~and~~ ocean, and other regions averaged spatially from 2002 to 2009.

| Region | A priori | CNTL | JR. |
|---|---|---|---|
| Eurasian Boreal | -0.07±1.10 | -1.17±0.93 | -0.77±0.70 |
| Eurasian Temperate | -0.05±0.49 | -0.3~~2~~1±0.41 | -0.3~~7~~6±0.40 |
| Europe | -0.0~~2~~1±-0.76 | -0.2~~2~~0±0.67 | -0.3~~8~~7±0.64 |
| North American Boreal | -0.04±0.61 | -0.30±0.38 | -0.36±0.38 |
| North American Temperate | -0.0~~3~~2±0.66 | -0.5~~6~~5±0.41 | -0.~~60~~59±0.41 |
| Northern Hemisphere total | -1.42±1.85 | -3.21±1.49 | -3.21±1.34 |
| Tropical total | 0.0~~5~~6±0.80 | 0.12±0.74 | 0.11±0.74 |
| Southern Hemisphere total | -2.57±0.97 | -2.46±0.81 | -2.45±0.81 |
| Global total | -3.94±2.2~~3~~4 | -5.5~~9~~4±1.85~~4~~ | -5.~~60~~55±1.72 |
| Global land | -1.3~~6~~3±1.90 | -3.~~64~~59±1.57 | -3.5~~7~~2±1.43 |
| Global ocean | -2.~~58~~61±1.1~~8~~9 | -1.95±0.97 | -2.03±0.96 |

서식 있음: 강조 없음

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Table 3. The optimized surface $CO_2$ fluxes (Pg C $yr^{-1}$ $Region^{-1}$) of ecosystem types at Eurasian Boreal, Eurasian Temperate, Europe, North American Boreal, and North American Temperate region averaged over 2002 - 2009.

| Ecosystem type | Eurasian Boreal | | Eurasian Temperate | | Europe | | North American Boreal | | North American Temperate | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CNTL | JR | CNTL | JR | CNTL | JR | CNTL | JR | CNTL | JR |
| Conifer Forest | -0.8165 | -0.3378 | -0.005 | -0.005 | -0.0678 | -0.06971 | -0.107 | -0.121 | -0.0554 | -0.06970 |
| Broadleaf Forest | -0.006 | -0.0134 | -0.004 | -0.005 | -0.005 | -0.005 | 0.000 | 0.000 | -0.002 | -0.002 |
| Mixed Forest | -0.04950 | -0.090 | -0.02930 | -0.0345 | -0.0256 | -0.063 | -0.053 | -0.054 | -0.01920 | -0.021 |
| Grass/Shrub | -0.0355 | -0.056 | -0.24748 | -0.2857 | -0.0167 | -0.032 | 0.000 | -0.001 | -0.077 | -0.081 |
| Tropical Forest | 0.000 | 0.000 | -0.001 | -0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Scrub/Woods | 0.000 | 0.000 | -0.002 | -0.002 | -0.001 | -0.001 | 0.000 | 0.000 | -0.013 | -0.013 |
| Semitundra | -0.1456 | -0.1889 | -0.0078 | -0.00910 | -0.008 | -0.009 | -0.057 | -0.0867 | -0.010 | -0.011 |
| Fields/Woods/Savanna | -0.0123 | -0.0212 | -0.005 | -0.0056 | 0.003 | -0.00910 | -0.004 | -0.004 | -0.149 | -0.1534 |
| Northern Taiga | -0.094 | -0.02930 | 0.000 | 0.000 | -0.006 | -0.007 | -0.066 | -0.0778 | 0.000 | 0.000 |
| Forest/Field | -0.003 | -0.008 | 0.006 | 0.0065 | -0.0867 | -0.1056 | -0.001 | -0.001 | -0.0123 | -0.0167 |
| Wetland | -0.002 | -0.014 | 0.000 | -0.000 | -0.001 | -0.002 | -0.003 | -0.006 | -0.002 | -0.003 |
| Shrub/Tree/Suc | 0.000 | 0.000 | -0.001 | -0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Crops | -0.002 | -0.008 | -0.019 | -0.022 | -0.00711 | -0.0758 | 0.000 | 0.000 | -0.216 | -0.227 |
| Wooded tundra | -0.003 | -0.005 | 0.000 | 0.000 | 0.003 | 0.003 | -0.003 | -0.0023 | 0.000 | 0.000 |
| Water | 0.000 | 0.000 | -0.000 | -0.000 | -0.0010 | -0.0010 | -0.001 | -0.001 | -0.001 | -0.001 |

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Table 4. Average differences between: model $CO_2$ concentrations (ppm) simulated using the background and the observed $CO_2$ concentration (ppm) (fourth and sixth columns), model $CO_2$ concentrations (ppm) simulated using the optimized surface $CO_2$ flux and the observed $CO_2$ concentration (ppm) (fifth and seventh columns), and average innovation $\chi^2$ from 2002 to 2009 at observation sites located in Asia and Europe (eighth column).

| Region | Site | MDM [ppm] | CNTL | | JR | | |
|---|---|---|---|---|---|---|---|
| | | | Bias (background) | Bias (optimized) | Bias (background) | Bias (optimized) | Innovation $\chi2$ |
| Eurasian Boreal | AZV | 3 | 1.68 | 1.04 | 0.77 | 0.19 | 0.85 |
| | BRZ | 3 | 1.41 | 0.68 | 0.67 | 0.39 | 1.17 |
| | DEM | 3 | 0.15 | -0.84 | 0.32 | 0.11 | 0.84 |
| | IGR | 3 | -1.58 | -2.71 | -0.52 | -1.26 | 1.15 |
| | KRS | 3 | 0.57 | -0.22 | 0.27 | 0.12 | 1.22 |
| | NOY | 3 | -0.02 | -1.06 | 0.16 | 0.00 | 0.86 |
| | SVV | 3 | 1.25 | 0.71 | 0.63 | 0.09 | 0.96 |
| | VGN | 3 | 2.55 | 2.11 | 1.50 | 0.84 | 1.18 |
| | YAK | 3 | 0.23 | -2.18 | 0.87 | 0.03 | 1.36 |
| Eurasian Temperate | WLG | 1.5 | 0.17 | 0.19 | 0.15 | 0.16 | 1.09 |
| | BKT | 7.5 | 4.12 | 4.06 | 4.13 | 4.05 | 0.57 |
| | WIS | 2.5 | 0.27 | 0.12 | 0.22 | 0.07 | 0.72 |
| | KZD | 2.5 | 1.79 | 0.98 | 1.42 | 1.14 | 1.26 |
| | KZM | 2.5 | 1.17 | 0.96 | 1.13 | 0.93 | 1.26 |
| | TAP | 5 | 0.50 | 0.55 | 0.58 | 0.71 | 0.58 |
| | UUM | 2.5 | 0.24 | -0.07 | 0.20 | 0.12 | 1.05 |
| | CRI | 3 | -1.95 | -1.57 | -1.94 | -1.56 | 0.66 |
| | LLN | 7.5 | 4.42 | 3.09 | 4.42 | 3.09 | 0.47 |
| | SDZ | 3 | -3.02 | -5.26 | -3.09 | -5.28 | 2.08 |
| | MNM | 3 | 0.56 | 0.52 | 0.59 | 0.56 | 0.17 |
| | RYO | 3 | 1.26 | 1.16 | 1.32 | 1.32 | 1.07 |
| | YON | 3 | 1.10 | 0.98 | 1.14 | 1.07 | 0.56 |
| | GSN | 3 | -1.92 | -1.71 | -1.92 | -1.70 | 1.83 |
| Europe | BAL | 7.5 | -1.23 | -1.32 | -1.31 | -1.45 | 0.37 |
| | BSC | 7.5 | -4.12 | -4.97 | -4.12 | -5.13 | 1.01 |
| | HUN | 7.5 | 0.93 | 0.53 | 0.86 | 0.36 | 0.46 |
| | OBN | 7.5 | 0.70 | -0.71 | 0.59 | -0.89 | 0.44 |
| | OXK | 2.5 | 0.50 | 0.02 | 0.43 | -0.09 | 1.52 |
| | PAL | 2.5 | 0.47 | 0.07 | 0.58 | 0.16 | 0.76 |
| | STM | 1.5 | 0.54 | 0.42 | 0.55 | 0.42 | 0.76 |

**서식 있음:** 들여쓰기: 왼쪽 0 글자, 오른쪽 0 글자

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 |

**서식 있음:** 글꼴 색: 자동, 영어(영국), 강조 없음
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Table 6~~5~~. 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~~-1.09±4.03~~ | 2002-2009~~2001-2012~~ | |
| This study | Europe | -0.38±0.64<br>-0.75±0.63~~-0.38±0.64~~<br>~~-0.75±0.63~~ | 2002-2009<br>2008-2009~~2002-2009~~<br>~~2008-2009~~ | JR experiment |
| Reuter et al. (2014) | Europe | -1.02±0.30~~-1.02±0.30~~ | 2010~~2010~~ | Using satellite data |
| CTE2014[c] | Europe | -0.07~~5~~±0.~~37~~49<br>-0.11~~04~~±0.38~~2~~~~-0.33±0.80~~<br>~~-0.11±0.38~~ | 2002-2009<br>2008-2009~~2001-2013~~<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~~, Le Quéré et al. 2015)~~, Peters et al., 2010) were derived from (ftp://ftp.wur.nl/carbontracker/data/fluxes/).

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서식 있음: 들여쓰기: 왼쪽 0 글자, 오른쪽 0 글자
서식 있음: 영어(미국)

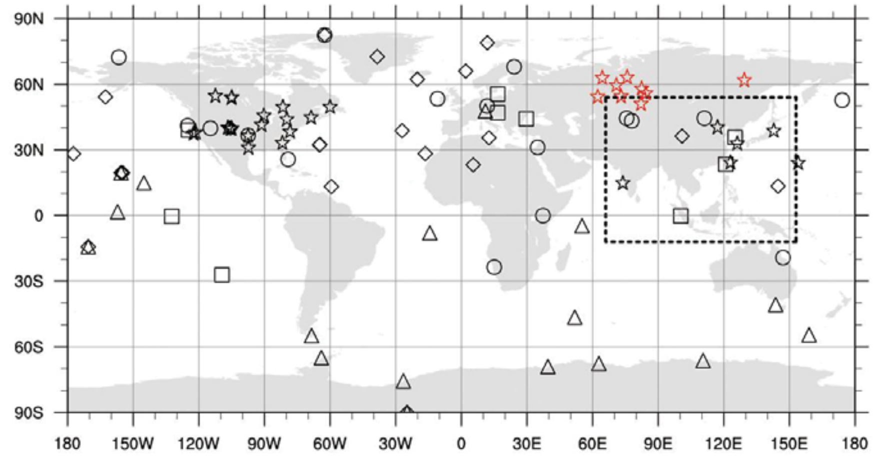


Figure 1. Observation networks of $CO_2$ concentrations around the globe and the nested domain of the TM5 transport model over Asia (dashed box). Each observation site is assigned to different categories (△: MBL; ○: Continental; ◇: Mixed land/ocean and mountain; ☆: Continuous; □: Difficult). JR-STATION observation sites are represented in red color.

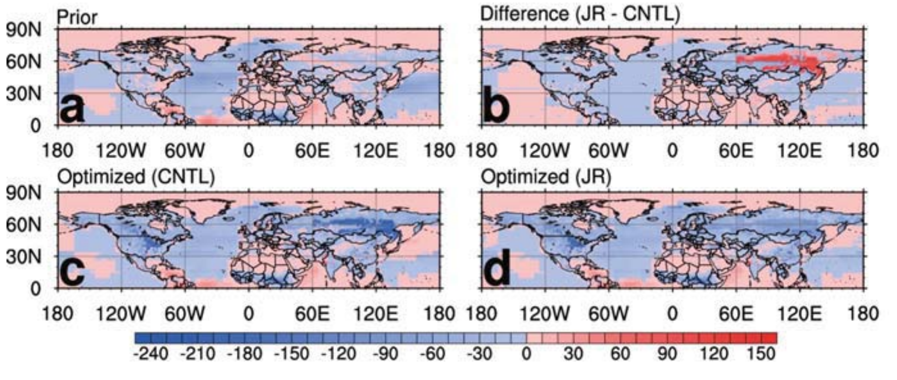


Figure 2. Average biosphere and ocean fluxes (gC $m^{-2}$ $yr^{-1}$) from 2002 to 2009 of (a) the prior flux, (b) the difference between the optimized fluxes in the JR and CNTL experiments, (c) the optimized flux in the CNTL experiment, and (d) the optimized flux in the JR experiment. Blue colors (negative) denote net $CO_2$ flux uptake while red colors (positive) denote net $CO_2$ release to the atmosphere. The difference is calculated by subtracting surface $CO_2$ flux of CNTL experiment from that of JR experiment.

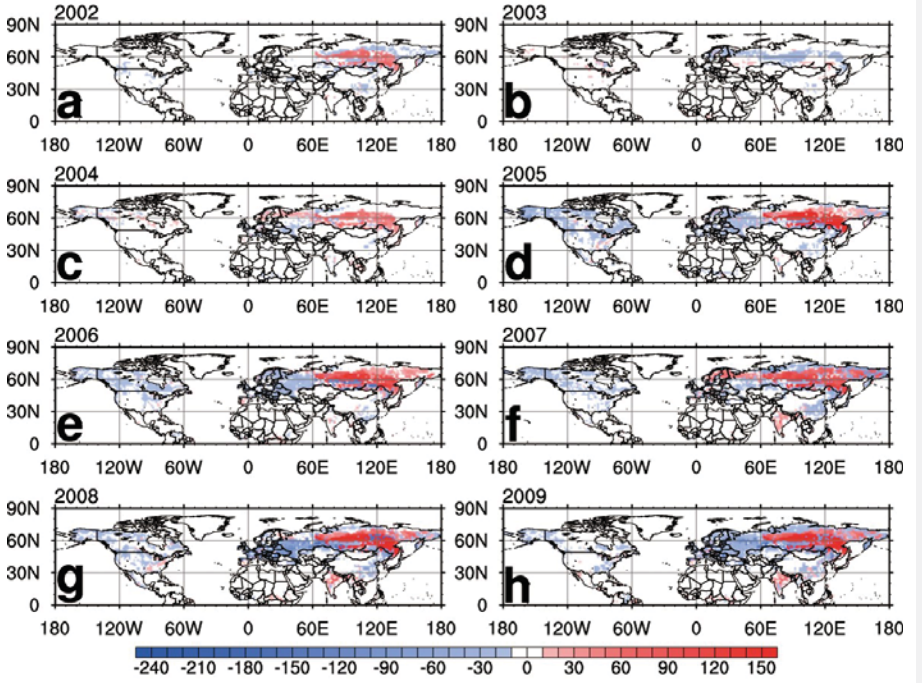


Figure 3. The difference between the optimized biosphere fluxes from the JR and CNTL experiment (g C m$^{-2}$ yr$^{-1}$) of (a) 2002, (b) 2003, (c) 2004, (d) 2005, (e) 2006, (f) 2007, (g) 2008, and (h) 2009. Blue colors (negative) denote net $CO_2$ flux uptake while red colors (positive) denote net $CO_2$ release to the atmosphere. The difference is calculated by subtracting surface $CO_2$ flux of CNTL experiment from that of JR experiment.

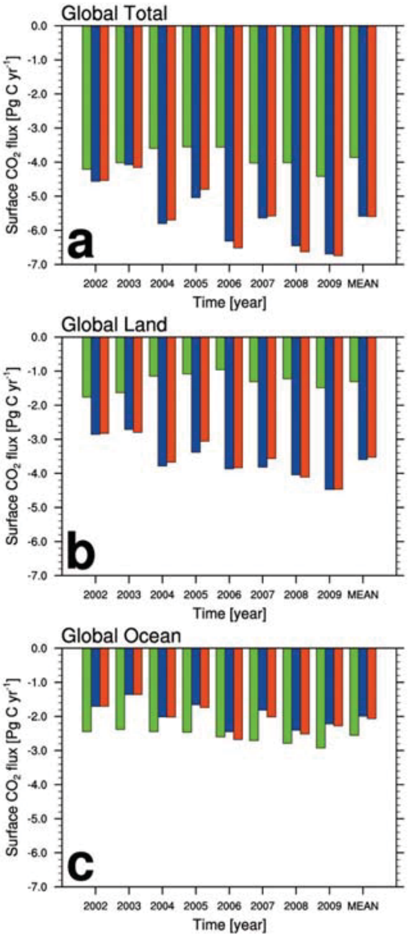


Figure 4. Annual and average biosphere and ocean fluxes (Pg C $yr^{-1}$) from the prior (green bar), CNTL (blue bar) and JR (red bar) experiment aggregated over the (a) whole globe, (b) land, and (c) ocean.

**서식 있음**

**서식 있음:** 들여쓰기: 왼쪽 0 글자, 오른쪽 0 글자, 간격 앞: 6 pt, 단락 뒤: 0 pt, 줄 간격: 1.5줄, 단락의 첫 줄이나 마지막 줄 분리 방지, 단어 잘림 방지, 한글과 영어 간격을 자동으로 조절, 한글과 숫자 간격을 자동으로 조절

**서식 있음:** 위 첨자

**서식 있음**

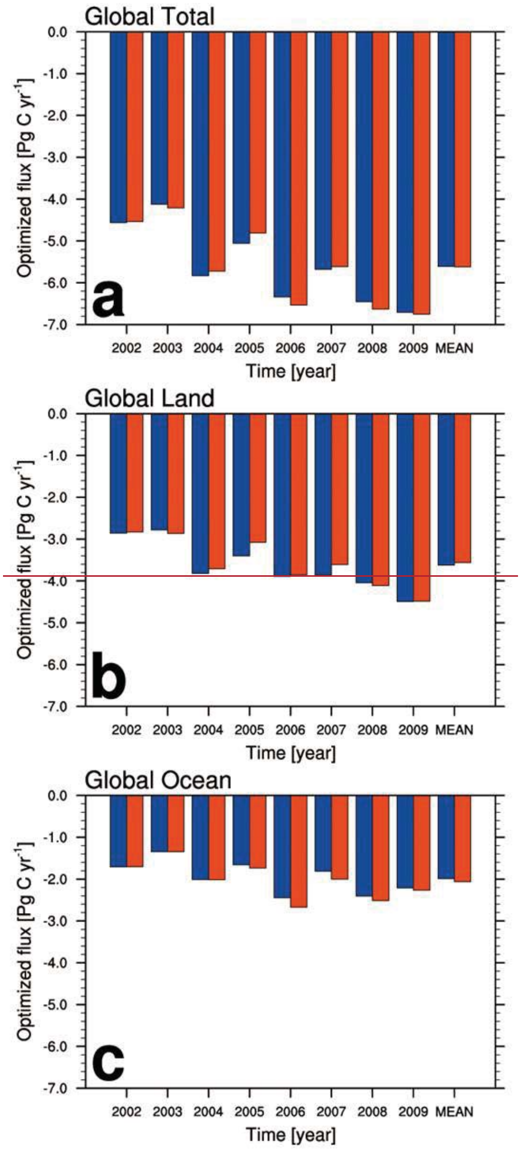


Figure 4. Annual and average biosphere and ocean fluxes (Pg C $yr^{-1}$) from the CNTL (blue bar) and JR (red bar) experiment aggregated over the (a) whole globe, (b) land, and (c) ocean.

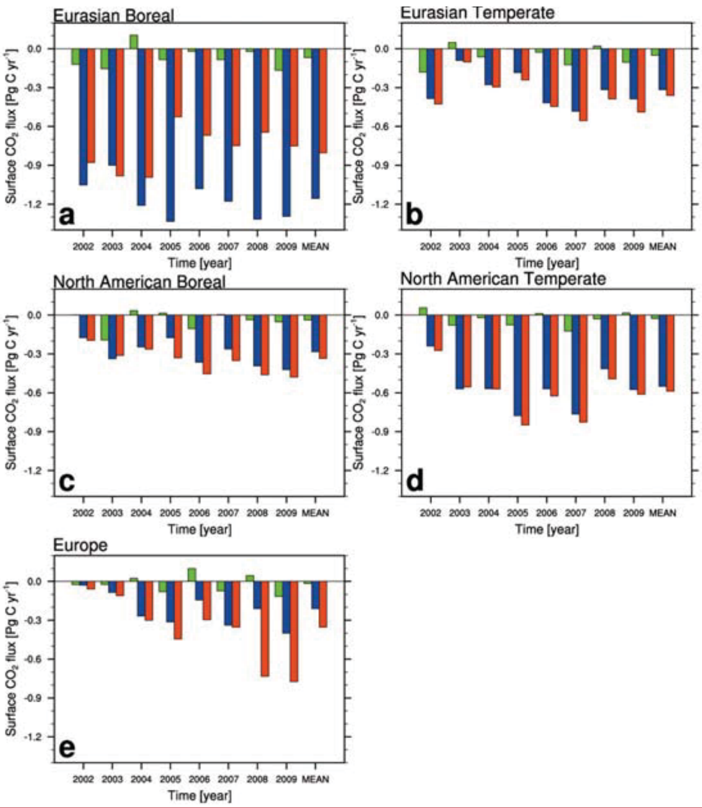


Figure 5. Annual and average biosphere fluxes (Pg C yr[-1]) from the prior (green bar), CNTL (blue bar) and JR (red bar) experiment aggregated over the (a) Eurasian Boreal, (b) Eurasia Temperate, (c) North American Boreal, (d) North American Temperate, and (e) Europe.

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**서식 있음:** 들여쓰기: 왼쪽 0 글자, 오른쪽 0 글자, 간격 앞: 6 pt, 단락 뒤: 0 pt, 줄 간격: 1.5줄, 단락의 첫 줄이나 마지막 줄 분리 방지, 단어 잘림 방지, 한글과 영어 간격을 자동으로 조절, 한글과 숫자 간격을 자동으로 조절

**서식 있음:** 위 첨자

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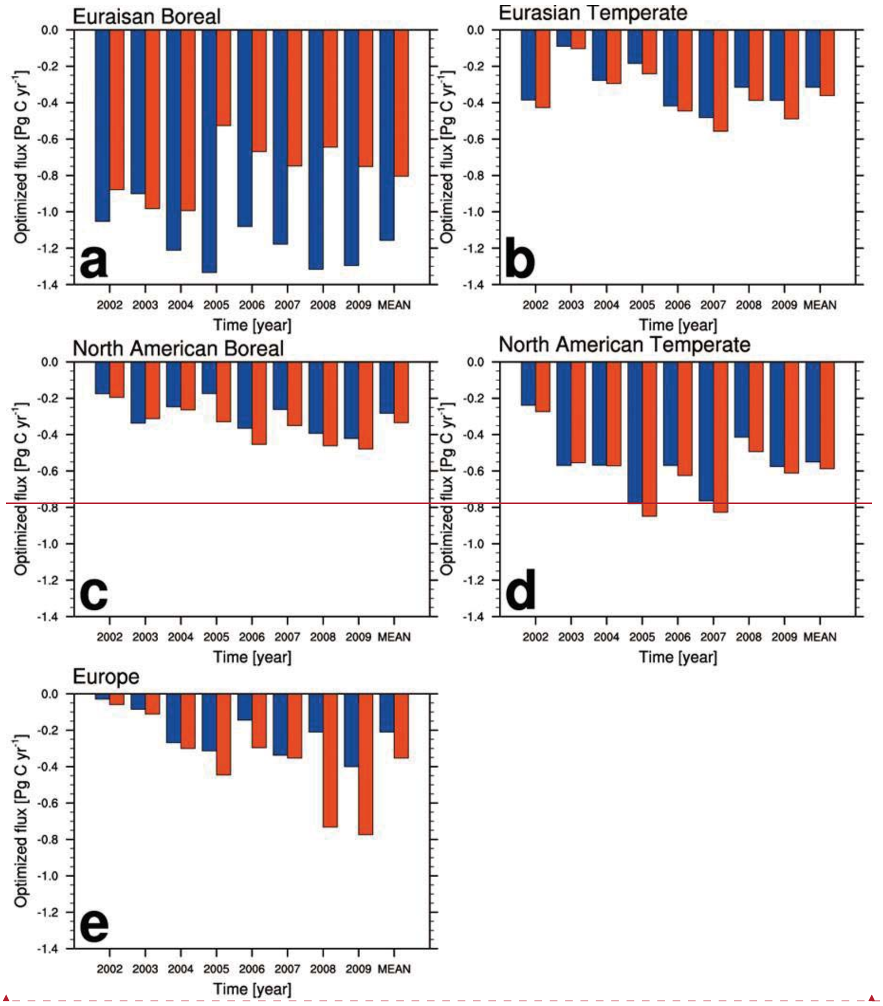


Figure 5. Annual and average biosphere and ocean fluxes (Pg C $yr^{-1}$) from the CNTL (blue bar) and JR (red bar) experiment aggregated over the (a) Eurasian Boreal, (b) Eurasia Temperate, (c) North American Boreal, (d) North American Temperate, and (e) Europe.

**서식 있음:** 글꼴 색: 자동, 맞춤법 및 문법 검사

**서식 있음:** 양쪽

**서식 있음:** 글꼴 색: 자동, 영어(미국)

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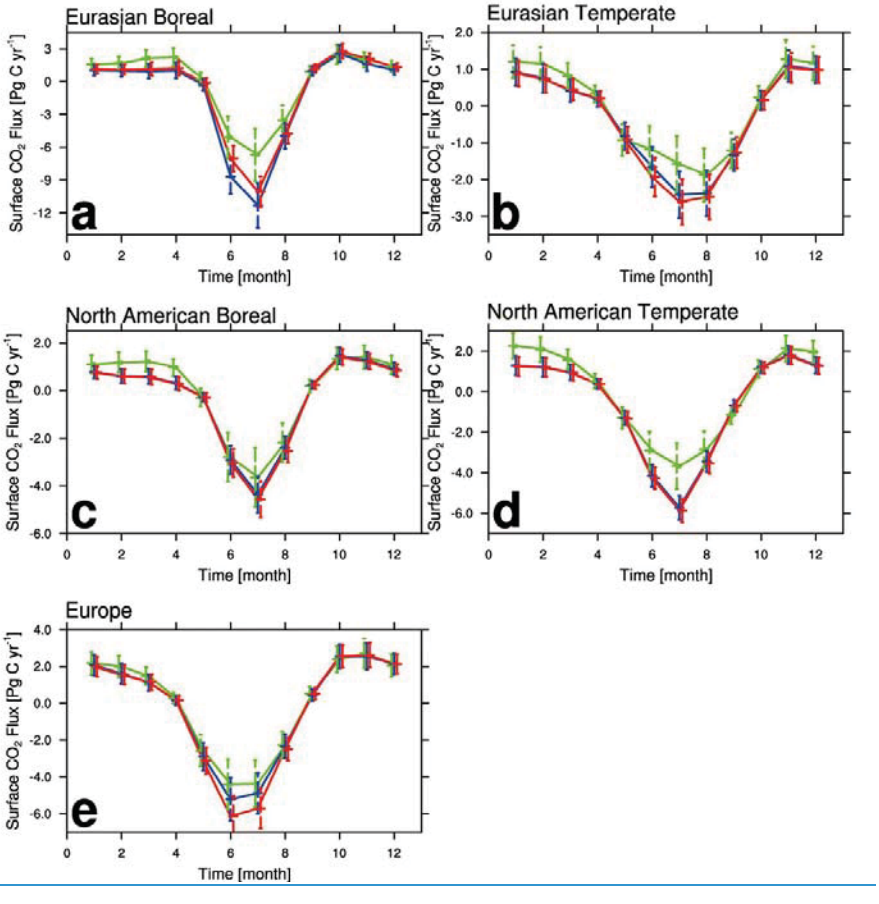

Eurasian Boreal
Surface CO2 Flux [Pg C yr-1]
Time [month]
a
Eurasian Temperate
b
North American Boreal
c
North American Temperate
d
Europe
e

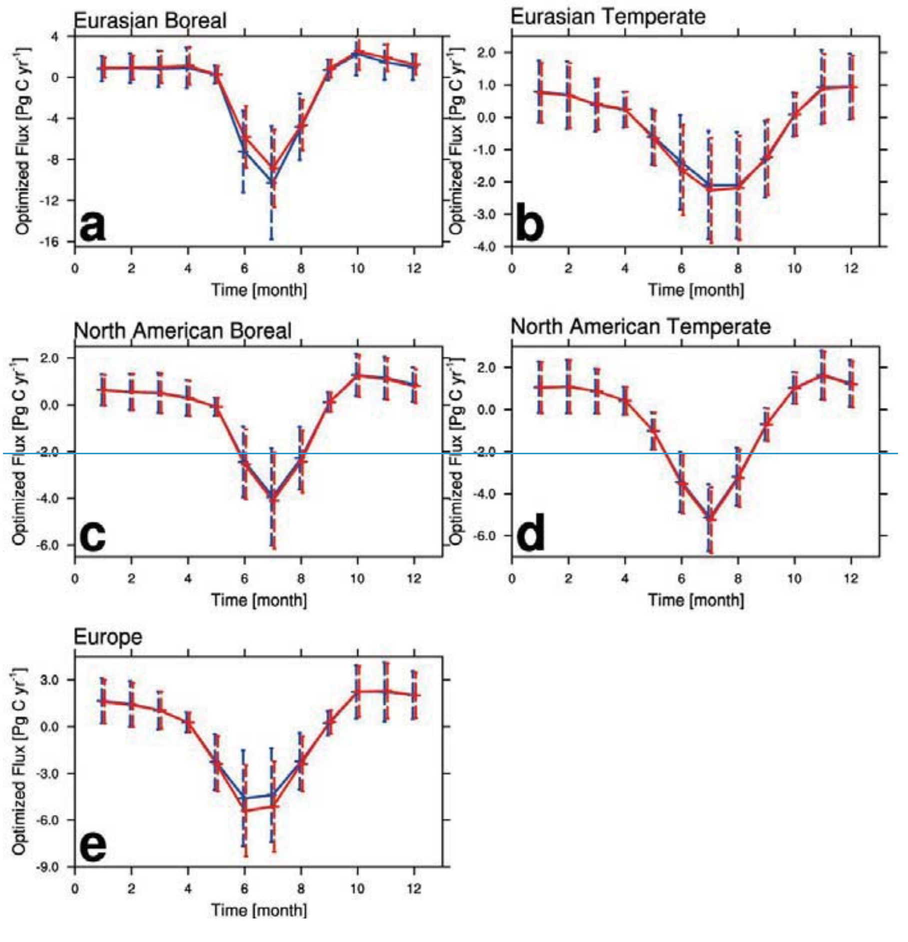


Figure 6. The monthly prior (green) and optimized biosphere fluxes averaged from 2002 to 2009 of CNTL (blue) and JR (red) experiment with their uncertainties over the (a) Eurasian Boreal, (b) Eurasian Temperate, (c) North American Boreal, (d) North American Temperate, and (e) Europe.

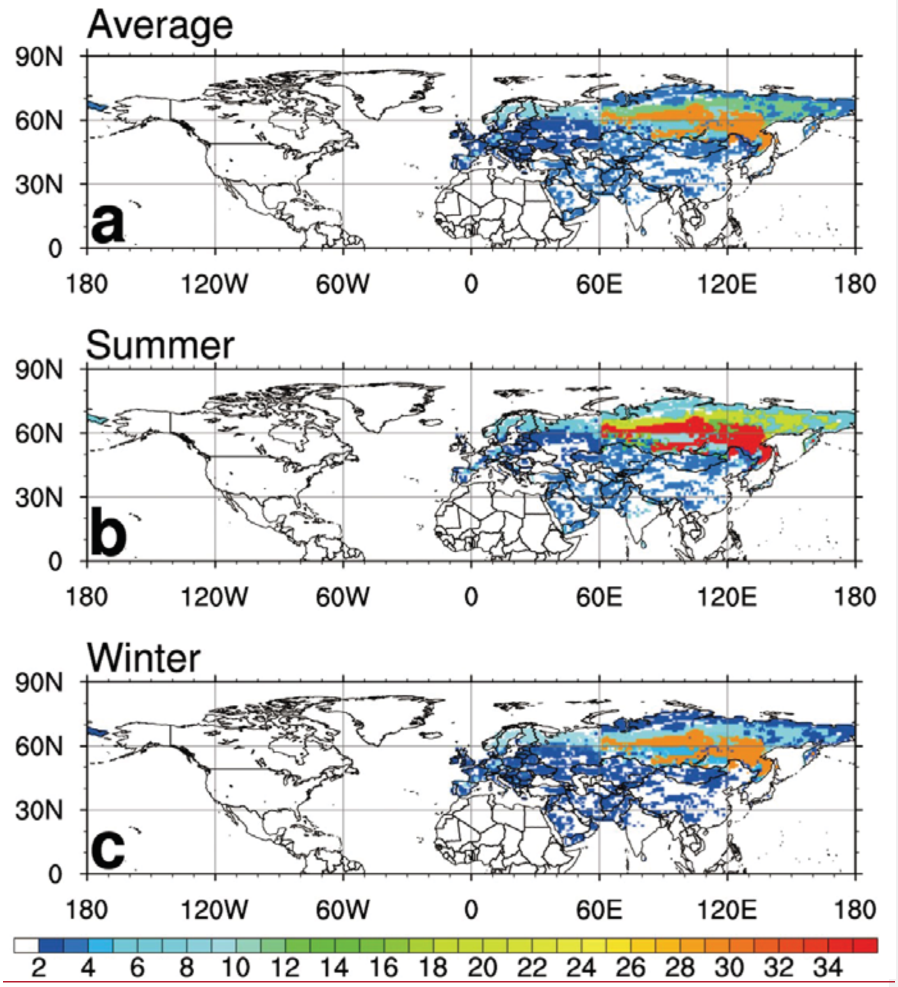


Figure 7. (a) Average uncertainty reduction (%) from 2002 to 2009, average uncertainty reduction (%) in (b) summer, and (c) winter for the estimated uncertainty of the JR experiment relative to that of the CNTL experiment. Red (blue) denotes relatively high (low) value of uncertainty reduction.

**서식 있음:** 들여쓰기: 첫 줄: 0 글자

**서식 있음:** 강조 없음

**서식 있음:** 들여쓰기: 첫 줄: 0 글자, 지정한 문자 수에 맞춰 오른쪽 들여쓰기 자동 조정, 간격 앞: 6 pt, 단락 뒤: 0 pt, 줄 간격: 1.5줄, 단락의 첫 줄이나 마지막 줄 분리 방지, 한글과 영어 간격을 자동으로 조절, 한글과 숫자 간격을 자동으로 조절

Figure 7. (a) Average uncertainty reduction (%) from 2002 to 2009, and (b) maximum uncertainty reduction (%) in any week from 2002 to 2009, average uncertainty reduction (%) in (c) summer, and (d) winter for the estimated uncertainty of the JR experiment relative to that of the CNTL experiment. Red (blue) denotes relatively high (low) value of uncertainty reduction.

**서식 있음:** 글꼴: (영어) Times New Roman, 글꼴 색: 자동, 맞춤법 및 문법 검사

**서식 있음:** 글꼴: (영어) Times New Roman, 글꼴 색: 자동, 맞춤법 및 문법 검사

**서식 있음:** 글꼴 색: 자동, (한글) 한국어, (언어2) 영어(미국)

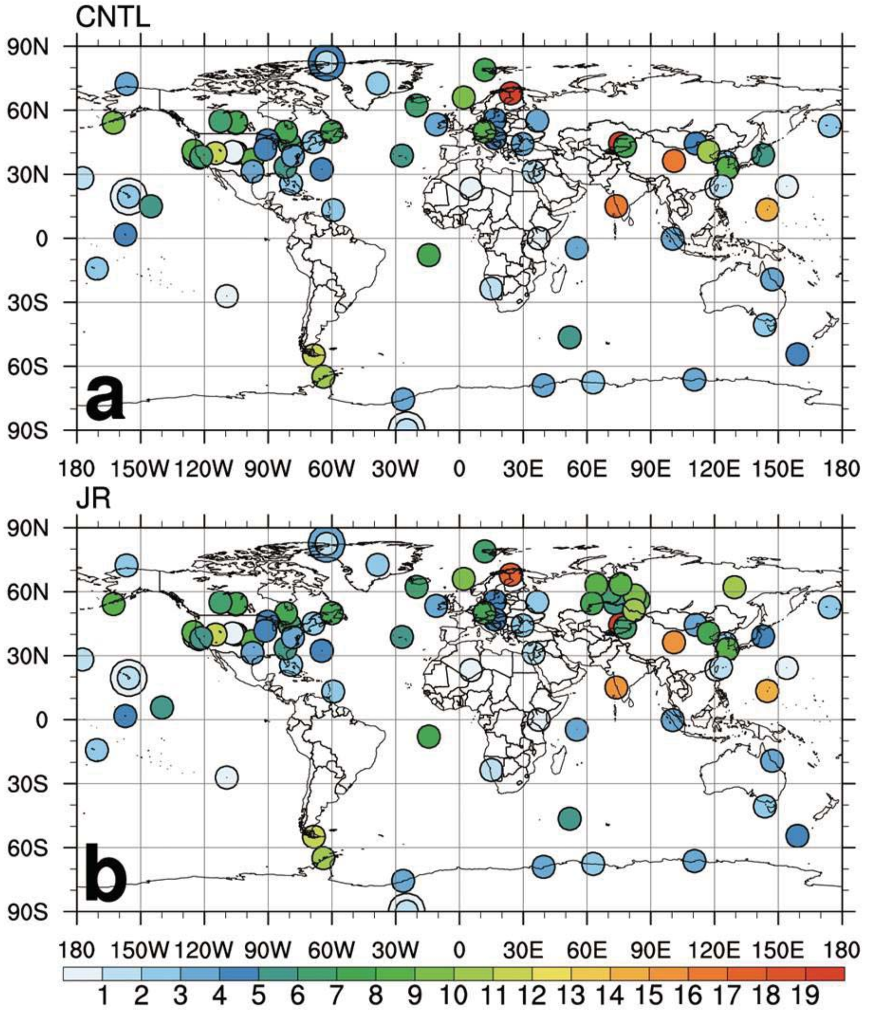


Figure 8. Self-sensitivity at each observation site averaged from 2002 to 2009 of (a) CNTL experiment and (b) JR experiment. The overlapping observation sites at the same locations or at close locations are distinguished by different sizes of circles. Red (blue) denotes relatively high (low) value of self-sensitivity.

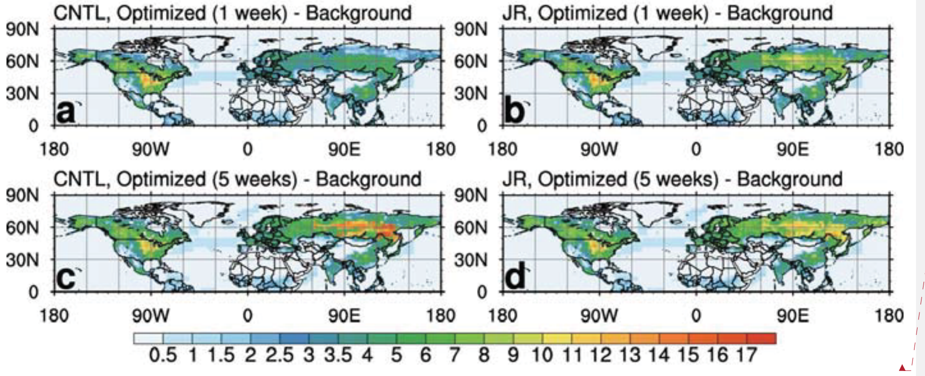


Figure 9. RMSD averaged from 2002 to 2009 between the background flux and posterior flux optimized in Northern Hemisphere summer by 1 week of observations ~~in Northern Hemisphere summer~~ of (a) CNTL ~~experiment~~ and (b) JR experiment; and ~~RMSD averaged from 2002 to 2009 between the background flux and posterior flux optimized~~ by 5 weeks of observations ~~in Northern Hemisphere summer~~ of (c) CNTL ~~experiment~~ and (d) JR experiment. The units are g C m$^{-2}$ week$^{-1}$. Red (blue) denotes relatively high (low) value of RMSD.

**서식 있음:** 글꼴 색: 자동, 맞춤법 및 문법 검사