

Author's comments in reply to the anonymous referee for "Evaluation of a multi-model, multi-constituent assimilation framework for tropospheric chemical reanalysis" by K. Miyazaki et al.

We want to thank the referees for the helpful comments. We have revised the manuscript according to the comments, and hope that the revised version is now suitable for publication. Below are the referee comments in italics with our replies in normal font.

Reply to Referee #1

This study presents an unprecedented work consisting in applying the same data assimilation framework to different Chemical Transport Models. This allows to treat the different flavor of model error terms such as chemistry, transport and deposition schemes in a consistent manner. The study is well written and presents a comprehensive work. The evaluation against independent measurements is greatly appreciated. The discussion on the model error is quite interesting, this could be further compared to the observations error, which has been effectively used in the analysis procedure. It is stated that the analysis error can be overestimated, which is not common in EnKFs where the spread in the ensemble is usually too small. The ensemble spread and the analysis error of the model mean against TES can be as low as 1 ppb (Fig. 6). One can expect that the use of a multi-model estimate (inter-model differences in the spread) of the model error fits nicely the observation error. In general, throughout the paper, error bars can be added to the observations.

Thank you for the helpful comments. We have added the following comments about the relationship between the observation error and the obtained results. Since the detailed observation error information are not provided for most of the independent observations, we have not added error bars in the figures.

In Section 2.4.1

“The observation error is 5-10 % between the surface and 30 km (Smit et al., 2007).”

In Section 4.1.2

“The obtained mean errors and multi-model spreads of the data assimilation analysis are comparable to or smaller than the ozonesonde observation errors (5-10 %).”

In Section 4.1.1

“The mean retrieval uncertainty of the TES measurements is typically between 5-10 ppb in the SH and 10-15 ppb in the NH, which are larger than the multi-model spread and the mean model errors after data assimilation.”

In Section 4.2

“The OMI NO₂ super-observation error is typically about 20-50 % of the tropospheric NO₂ columns over polluted areas, which are comparable to or larger than the analysis error.”

P9L25: “The state vector includes the chemical concentrations of various species as well as the surface sources of NO_x and CO and LNO_x sources”. And P10L6: “We also applied covariance localization for different variables in the state vector (Kang et al., 2011), by setting the covariance among non- or weakly related variables to be zero.” Could you be more specific and describe which observations are used to estimate which state variable? In particular in the case of the Ozone responses to NO_x perturbation, it would be interesting to know which state variables are optimized while assimilating ozone.

The following sentences have been added:

“Concentrations of NO_y species and ozone were optimized from TES ozone, OMI and SCIAMACHY NO₂, and MLS ozone and HNO₃ observations.”

Minor comments: For future work, you could look at the impact of assimilation on the O₃-CO correlations and dO₃/dCO enhancement ratios (Zhang et al. 2006).

Thanks for the suggestions. I agree that ozone-CO correlations would be another interesting model response that could be measured using the MOMO-Chem framework. In the current data assimilation setting, we didn't optimize CO concentrations using ozone observations to avoid sampling errors (c.f., Section 2.6). To note the future possibility, the following sentences have been added:

“In addition, tropospheric ozone shows strong correlations with other species such as CO (Zhang et al., 2006) over regions such as continental outflow regions. The relationship can be included in the state vector to improve the tropospheric ozone analysis. The uncertainty information in the CO response to ozone obtained from the MOMO-Chem can be expected to provide useful information on model diagnostics and future predictions.”

*P5L4: the family name of the author is “Olivier” not “Oliver” according
<https://themasites.pbl.nl/tridion/en/themasites/edgar/publications/index-2.html>*

Corrected.

P9L24: The data assimilation settings were almost same among the systems as follows. Should it be a “the” before same? this sentence can be improved.

Rewritten as

"Almost the same data assimilation settings were used for the four systems as follows."

P12L26 "lowover", is there a space missing ?

Added.

P15L12: "the large multi-model spreads (25–55%) suggest that individual models have large uncertainty in representing strong ozone productions, for instance, associated with VOCs emissions and chemistry." Is it really an uncertainty or is it just because the chemical regime is not in favor of a clear and linear relationship between Ozone and NOx emissions.

It is possible that the chemical regime differs among the models because of, for instance, different level of VOCs. Also, chemical and transport mechanisms affecting ozone formation can differ among the models. To clarify it the sentence has been rewritten as follow:

"the large multi-model spreads (25–55%) suggest that individual models have large uncertainty in representing strong ozone productions, for instance, associated with VOCs emissions and chemistry that could results in different chemical regimes."

P15L16: "the mean of the individual model estimates (solid while lines)". I guess you mean 'white line' instead of 'while line'.

Corrected

P21 L34: "Fig.13 compares the global distributions of annual and tropospheric mean OH concentrations." How do you define tropospheric? – also in legend of Fig. 13.

The tropospheric mean OH concentrations were calculating by averaging OH from the surface to 300 hPa, which is explained in the revised manuscript. Note that the averages between the surface to 300 hPa and between the surface to the tropopause made only small differences.

Figure 3: You should define what the dashed lines are in legend.

Defined.

Figure 5: you could replace 'model' by 'control'

In all the figures, we labeled “Model” rather than “Control”. Although either is fine, we would like to keep the consistent labeling (Model).

Figure 6: “(a) Standard Deviation among the models”

Collected.

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Reply to Referee #2

General comments:

The paper provides a consistent inter-comparison of state-of-the-art EnK chemical DA systems. Exploring the importance of the modelling approach, the authors show (i) that the analyses are an improved (compared to the models) representation of the atmospheric concentration for the assimilated variables and (ii) the limitation of current EnK approaches to come to consistent, i.e. model independent, posterior estimate of the emissions. The later point is of particular interest to the community and needs to be more emphasised.

Thank you for the helpful comments. We have endeavored to address your helpful concerns and comments in the revised manuscript. Please see additional replies to your comments below.

Presenting the calculation of the weighted mean of the four analyses ("integrated reanalysis") as "Multi-mOdel Multi-cOnstituent Chemical data assimilation (MOMO- Chem) framework" sounds like an inflation of terms. But more importantly, it is mis-leading because the term framework implies to me that the four EnK DA system runs were connected in any way. After reading the paper carefully, I came to the conclusion that this seems not the case. (I hope it did not miss anything). I believe the averaging procedure could be carried for any set of KF DA analysis even without the need to use the same EnKF software. I strongly recommend changing the title and modify the abstract accordingly .

While we agree that the averaging procedure could in principle be applied to any reanalysis, we disagree that these analyses are disconnected. Modern assimilation systems consist of: (1) model, (2) data, and (3) an estimation algorithm that integrates the two. With the MOMO-Chem framework, components 2 and 3 are the same leaving only component 1 to vary. Consequently, by applying the same data assimilation scheme and assimilating the same sets of observations into the four systems, analysis uncertainty of

individual analyses can be evaluated consistently among models, which have enabled us to provide integrated analysis fields and to quantify forecast model performance on the data assimilation analysis. For typical reanalysis intercomparisons, it is very difficult to disentangle the relative contributions of these components to system performance. To the best of our knowledge, MOMO-Chem provides a unique framework.

There is another way to integrate multi-models in EnKF data assimilation, that combines multi-model forecasts during data assimilation by including them in background error covariances. In this approach, ensembles of models are used to construct flow-dependent analysis system. In the revised manuscript, the following paragraph has been added to explain the possible approaches and the uniqueness of the proposed approach more clearly:

“Data assimilation that relies on a single model may lead to biased estimation and underestimate model uncertainty by under-sampling of the relevant model space. The limitations with a single model could be overcome by integrating multi-model information in data assimilation in various ways. First, ensembles of models can be used to construct a flow-dependent analysis system. For instance, Xue and Zhang (2014) extended data assimilation to the multi-model Bayesian model averaging analysis framework, in which the posterior model weight for each model is determined through Bayes' theorem reflecting the prior probability of each model and the analysis consistency with the observations. This approach requires a framework to execute and update multiple-model states continuously, which is difficult with multiple state-of-the-art CTMs that have been optimized using different platforms. Another way to integrate multiple-model information is to apply a common data assimilation framework with multiple models. By assimilating the same sets of observations, this framework can be used to demonstrate the importance of forecast model performance on data assimilation analysis, while uncertainty information of individual analyses can be evaluated consistently by using a same data assimilation framework. Uncertainty-weighted multi-model integrated analysis fields would provide unique information that are less dependent on individual model performance and are fundamentally different from averages of individual data assimilation analyses. Quantifying model performance with a multi-model integration is difficult when using different data assimilation frameworks.”

With this explanation and the new evaluation results of the multi-model integrated fields (please see our reply below), we think that the current title is appropriate. Meanwhile, the relevant sentences in the abstract and the conclusion have been rewritten to more properly explain our approach as follows:

Abstract:

“We introduce a Multi-mOdel Multi-cOnstituent Chemical data assimilation (MOMO-Chem) framework that directly accounts for model error in transport and chemistry and integrate a portfolio of data assimilation analyses obtained using multiple forward chemical transport models in a state-of-the-art ensemble Kalman filter data assimilation system. The data assimilation simultaneously optimizes both concentrations and emissions of multiple species through ingestion of a suite of measurements (ozone, NO₂, CO, HNO₃) from multiple satellite sensors.”

Conclusion:

“We developed the MOMO-Chem framework to integrate a portfolio of data assimilation analyses obtained using forward CTMs (GEOS-Chem, AGCM-CHASER, MIROC-Chem, MIROC-Chem-H) in a state-of-the-art ensemble Kalman filter data assimilation system.”

Furthermore, Fig.1 has been added to explain the general idea of our multi-model data assimilation integration approach using in this study.

Combining four analysis using their standard deviation estimate as weights, is of course an advantage of the analyses compared to model runs for which this uncertainty information is not available. On the other hand, the analysis error standard deviation is a derived quantity (from P and R) and not estimated using independent observations. Therefore, it would be beneficial to show that the weighted mean approach leads to better results than an unweighted mean (“multi model”), or perhaps even other approaches to represent ensembles such as the median or the choice of best performing system.

Thanks for this valuable comment. The comparisons of the uncertainty-weighted and non-weighted multi-model mean have been added in Table 2 and Table 6 in the revised manuscript. The following sentences have been added to explain the results in Section 4.1.2 and Section 4.4. As discussed in the manuscript, the multi-model integration was not applied to CO and NO_x concentrations because the analysis spreads of near surface NO_x and CO concentrations tend to be similar among the models.

Section 4.1.2:

“The uncertainty-weighted multi-model integrated fields (Eq. 10) show a closer agreement with the ozonesonde observations than the (non-weighted) multi-model means for the lower troposphere, except at SH high latitudes, as summarized in Table 2. The annual and regional mean bias is smaller by 15-40 % in the uncertainty-weighted fields from the SH mid to NH high latitudes, reflecting the larger analysis biases and larger analysis uncertainties in AGCM-CHASER and MIROC-Chem for most cases. The closer agreements suggest improved estimates of ozone in the multi-model integrated fields. In the extratropical

middle and upper troposphere, GEOS-Chem revealed smallest analysis uncertainty and largest analysis errors against the ozonesonde observations, likely associated with the less complex stratospheric chemistry (i.e., smaller spread growth). This model dominated the uncertainty-weighted integrated fields and led to a degradation of the integrated fields. These results suggest a requirement to optimize the analysis uncertainty in some of the systems, considering the fundamental differences in the model framework such as model complexity and resolution, as discussed above. Increasing the number of models would also help to provide more robust statistics.”

Section 4.4:

“The integrated analysis shows slightly higher OH concentrations than the multi-model means for most regions, mainly reflecting largest OH spreads and smallest OH concentrations in MIROC-Chem-H among the models. The analysis spread of OH is determined by analysis spreads in various species such as ozone (c.f., Section 3.2) during model forecasts. Because of the different chemical mechanisms and model responses to given perturbations (c.f., Section 5), OH spreads differed by factor of up to 2.5 among the models for the regional means. The integrated uncertainty is smaller than the multi-model spreads by 20-50 % for most regions.”

The validation section (4) only discusses the errors against independent observations of the 4 individual analyses and their unweighted mean (“multi-model”) but not the weighted mean (“integrated”). This seems not consistent with the intension of the paper and all the discussion before, which focuses on the merits of the weighted-mean (“integrated”) analysis. A comparison of unweighted (“multi-model”) vs. weighted (“in- tegrated”) would be an important aspect of the paper, which is missing. Tables 3 to 6 should also include the respective figures for the weighted (“integrated”) means. Further, moving the validation section 4 (Validation results) before section 3 (Data assimilation statistics) seems advisable because having established trust in the data set by the validation could make the discussion on emission response more convincing.

For the uncertainty-weighted results, please see our reply above.

Because the multi-model integration used in Section 4 is based on the analysis uncertainty shown in Section 3, we think it is straightforward to keep the order. On the other hand, as suggested by the reviewer, it would be better to show the emission response results (Section 3.4) after the validation results (Section 4), because the model response results can benefit from the validation results. Thus, we have moved the emission response section (Section 3.4) to Section 5 (as a new section). Furthermore, the

following sentences have been added to explain the evaluation results of the uncertainty-weighted integrated fields in Section 5 corresponding to the reviewer's comment above:

“Meanwhile, the uncertainty-weighted multi-model integrated ozone fields showed closer agreements with independent observations than the multi-model averages in the lower troposphere (c.f., Section 4.1.2). This suggests that the MOMO-Chem framework provides improved estimates of the atmospheric states for many cases.”

The authors use the standard deviation to represent the variation between the four analyses. Given that 4 is a relatively small number and Gaussianity can not be assumed, using a different measure such as the range should be considered.

The limitation of this study using the small number of models is discussed as follows in the revised manuscript:

“Given the small number of models ($j=1-4$) used in this study, the multi-model integration would suffer from sampling biases. With increasing the number of models in future study, this approach would provide more robust statistics.”

Any other quantities such as ranges are not added to avoid additional confusions.

The paper is quite long. Presenting the four reanalysis for concentrations and emission response would be one very valid paper. Comparing the different approaches to combine the reanalyses could be a second paper.

We think that describing the proposed methodology and presenting the overall performance in a single paper benefits readers. We expect that those readers only interested in specific results, e.g., NO_x emissions, will focus on the relevant sections. For the emission response analysis, we plan to conduct a more detailed analysis in a separate paper. Nevertheless, demonstrating the general idea and initial results of the emission response combining in the presented paper is essential to demonstrate the capability of the developed framework.

Specific comments

Abstract:

p1 l14. Please consider not to introduce a complex acronym for an averaging procedure of independent data sets.

Removed the acronyms from the abstract.

p1 l21. The sentence starting “ These improvements ..” is difficult to understand. Improvement would imply a reduction in uncertainty of the emissions but this seems no the case. Please make a quantitative statement on the global or regional total of the prior and posterior emissions.

The sentence has been rewritten as follow:

“The uncertainty ranges in the a posteriori emissions due to model errors were quantified in 4–31% for NO_x and 13–35% for CO regional emissions.”

Because of the word limit, we cannot add other information in the abstract. A more quantitative statement is given in the main text.

p1 l25. The last sentence is not a consequence of the statement before, but quite the opposite. It only shows how difficult the estimation of emissions is because of the complexities of atmospheric chemistry.

The sentence has been rewritten. Please see our reply below.

p1 l26. Please clarify “emerging constraints” in the abstract. Also why specifically the “integrated” reanalyses are better suited for this than the single re-analysis or the “multi-model” mean reanalysis.

The sentence has been replaced as follows to avoid the confusion:

“A systematic investigation of model ozone response and analysis increment in MOMO-Chem could benefit evaluation of future prediction of chemistry-climate system as a hierarchical emergent constraint.”

Because there is no space in the abstract and the words “emergent constraints” is becoming well-known, we have added the following sentence in the main text (Section 3.4.1):

“as a hierarchical emergent constraint that uses relationships between future and current climate states to constrain projections of climate response with observations (Bowman et al., 2018). They could also be useful for making effective ozone control strategies.”

For the multi-model integrated fields, please see our replies above.

p2 l20 These are climate runs over several years. In the data assimilation context, model errors are the errors in the forecast over the short assimilation window started from previous analysis. It is not clear that long-term errors are a predictor for the short-range forecast errors of the model. Inconsistencies between the analysis and the model equilibrium state and inadequate background error statistics (inflation factors etc.) may play a large role too, but do not affect the multi-year runs.

Data assimilation increments can be used to suggest systematic model biases such as in emissions, chemical reaction rate, and deposition rate. These model biases could be regarded as inherent and persistent model errors that could affect long-term model errors. They could partly be measured during a short data assimilation window because of the fast model chemistry and transport processes. By applying data assimilation corrections to these factors, we expect that both short-term and long-term model simulations and data assimilation analyses can be improved to some extent. Note that the relevant discussion is already given in Section 3.4.1 as follows:

“While these simulations describe relatively slow, equilibrium responses, data assimilation incremental updates provide statistics on “fast” responses within the short data assimilation windows. By simultaneously updating ozone and NO_x emissions, multi-constituent data assimilation can yield insight into this fundamental quantity.”

p3 l3 “a common data assimilation framework “ , see my general comments. I think it is not a common data assimilation framework because the information from the error statistics (P) of each system is not used to come up with a better common analysis. Running different chemistry scheme as part of the ensemble would have been a common framework. The four systems are completely independent. You compare and average different analysis and emissions/concentration responses.

Please see our replies above.

p3 l8 Please mention that the assimilated observations are not the same for all 4 reanalyses.

The sentence has been rewritten as

“Using the same data assimilation settings and assimilating almost the same multi-constituent observations from multiple satellite sensors...”

p4 l3 Please provide more details on the quantitative value of the inflation factors and any differences between the four applications.

The sentence has been replaced by

“A covariance inflation factor (Δ , 6% in this study for all the models, following the setting in Miyazaki et al (2015))...”

P4 l19 “a common data assimilation framework to four CTM frameworks” better “the same data assimilating system using 4 different CTM”.

Rewritten as:

“We applied the same data assimilation system to four CTM frameworks”

p4 l20 Please include a general statement that the CTMs differ in emissions, chemistry scheme, resolution etc.

“The major differences among the models are the meteorological input data, the complexity of the chemical mechanisms (simplest in AGCM-CHASER for the troposphere), emission inventories (oldest in GEOS-Chem), vertical coordinate (sigma in AGCM-CHASER only), and spatial resolution (highest in MIROC-CHem-H).”

p4l 23 - p5 l24 The model descriptions vary to much in detail. In particular section 2.2.4 (MIROC-Chem) seems shorter than the others and does not have detailed information about the emissions. Please avoid too much duplication of information included in the text and provided in table 1. I recommend including the facts in the table and discuss specifics in the text.

Since the emission data in MIROC-Chem are same as in the AGCM-CHASER, the model description is shorter. Some of the text have been removed to avoid duplicates with the table.

p7 l3 S and A should be in a bold font as in the formula below

Corrected.

p7 l10 Please clarify this sentence. Biases in the observations, in particular if the instrument biases in NO₂ and Ozone are not consistent, may severely degrade the performance. I would even speculate the a

potential inconsistency between the NO₂ and Ozone retrievals are a major reason for problems with the performance of chemical DA systems.

To explain the importance of bias correction, the sentences have been rewritten as follows:

“Biases in the assimilated satellite retrievals can degrade data assimilation performance. The ozone analysis bias is not solely determined by bias in the assimilated ozone measurements in the multi-constituent data assimilation approach. Miyazaki et al. (2015) demonstrated that the assimilation of measurements other than TES measurements led to corrections in the lower and middle tropospheric ozone. Application of a bias correction procedure for multiple measurements could improve the data assimilation analysis quality. However, we did not apply any bias correction because of the difficulty in estimating the bias structure that could vary temporally and spatially. Meanwhile, since the data is the same for all comparisons with different models, the differences with respect to independent observations are relatively independent of those biases. ”

p8 l11 Please make a comment on the differences between the two MOPITT versions.

The following sentence has been added:

“The version 7 products have been improved from the version 6 products with respect to overall retrieval biases, bias variability and bias drift uncertainty (Deeter et al., 2017).”

p9 l2 “We construct integrated data assimilation analysis using multiple models combined with multiple-species measurements.” I am not sure if the word “integrated” implies what you do. You calculate a mean of 4 analyses, which were produced with the same DA system using each a different modelling approach. This is not integration or data assimilation as such but simply a weighted average. Please consider replacing the word (“integrated”) throughout the text. Please make clear a distinction between the weighted and unweighted mean.

As discussed in our replies above, we attempted to "integrate" the multi-model data assimilation analyses while considering the analysis uncertainty of individual data assimilation analyses. This provides integrated information on the tropospheric chemistry system. Using the common data assimilation framework and assimilating the same sets of the measurements, this method has enabled us to integrate the multi-model data assimilation analysis fields in a consistent way, which provided fundamentally different information from multi-model means, as demonstrated in the revised manuscript as per the reviewer's comments.

p9 l4 Please provide more details on the standard deviation field σ_j . It would be helpful to include a formula in section 2.1 Also say if σ_j is a field of the same time-space dimension as the analysis.

The following sentence has been added:

"The analysis uncertainties are estimated from the root mean square of the analysis ensemble perturbation matrix (see Eq. (8)) that is obtained by transforming the background ensemble using the local analysis error covariance (see Eq. (5))."

p9 l5 Please clarify what the spatial resolution of mean reanalysis is, given that the for re-analysis are carried out at different resolutions (table 5)

The following sentence has been added:

"The multi-model integrated analysis fields were produced at the highest horizontal resolution of the models (1.1°x1.1°) after linearly interpolation."

p9 l16 Please discuss here (or elsewhere) quantitatively the standard deviations to give an indication which model dominates the weighted-mean analysis.

The quantitative description of the standard deviations (i.e., analysis uncertainty) is more clearly discussed in the revised manuscript.

p9 l13 Please clarify why this is not "meaningful"

The sentence has been rewritten as follow:

"Because of the predefined minimum values of the standard deviations applied to surface emissions of CO and NO₂ to prevent covariance underestimation during data assimilation (c.f., Section 2.6), the analysis spreads of near surface NO_x and CO concentrations tend to be similar among the models due to the artificial adjustments and are not fully meaningful."

p9 l26 The longer assimilation window for GEOS-Chem could have implications for the assimilation of NO₂ and CO because their life time can be short and the diurnal cycle of the NO_x emissions is very pronounced.

This is already discussed in the manuscript as follow:

“The data assimilation cycle was set to be two hours for the AGCM-CHASER, MIROC-Chem, and MIROC-Chem-H systems, and six hours for the GEOS-Chem system because of the limitation associated with meteorological data input in GEOS-Chem. The emission and concentration fields were analyzed and updated at each analysis step in all the systems. We have confirmed that the results of data assimilation can differ when the data assimilation cycle is changed from two hours to six hours using the AGCM-CHASER system. This occurs, in particular, for the analysis of short-lived species with strong diurnal variability and NO_x emission estimates. The performance of the GEOS-Chem data assimilation can thus be expected to differ with the use of a two-hour data assimilation cycle and meteorological data inputs with higher temporal frequency for short-lived species. ”

p11 l20 Please provide evidence for the fact that TES plays the largest role.

The following sentences have been added:

“Using observing system experiments (OSEs), our previous studies (Miyazaki et al., 2012b, 2015, 2019) revealed that the TES ozone data assimilation dominate the corrections in the tropospheric ozone analysis, whereas the use of measurements other than TES measurements (mainly NO₂ measurements) led to corrections in the lower and middle tropospheric ozone during the forecast.”

p12 l24 instead of “integration” use “mean”

Please see our replies above.

p12 l31 The smaller standard deviation seems “trivial” given the formula of its calculation. Only the comparison with independent observation can demonstrate that the mean is a more reliable representation of the field.

The results of the multi-model integrated analysis are compared with independent observations in the revised manuscript. Please also see our replies above.

p13 l16 Please provide more detail how the regression coefficients are calculated. Do they represent the mean over regions, month and all hours of the day? Please explain how the response is calculated for the weighted mean (“integrated”) analysis.

The sentence has been rewritten as follows:

“By applying linear regressions to the multi-model integrated fields (c.f., Section 3.3), we evaluated model responses of surface ozone and NO₂ concentrations to NO_x emissions. We first produced the daily multi-model integrated fields at 1.1° x 1.1° resolution and then applied linear regressions.”

p13 l29 Please clarify that sentence. The study comes up with a different response functions for each model but gives no guidance which is the correct one. Given the non-linearities a mean over conflicting responses might not be the most suited approach.

Because there is no truth information (i.e., observational estimates) on the responses, we cannot provide such guidance. The sentence addresses that the MOMO-Chem provides a framework to quantify the response of forward models and its multi-model differences, without making any sensitivity calculations. So, its principal value is a diagnostic quantity. Future research can further assess whether one or more of these responses is more valid—and their implications for assessing the impact of emission changes.

p14 l17 I would think “conflicting” is a better description than “unique” for the difference in the response

The MOMO-Chem multi-model integrated fields provides different estimates of the responses from the individual models. Thus, “unique” is a reasonable statement.

p15 l13 Please clarify” inter-model correlations”

Rewritten as “The correlations of delta ENO_x and delta ozone among the models estimated at each point at each day...”

p15 l29 Please clarify if the only difference between “mean” and “integrated” (formula 10) is the weighting with the analysis error standard deviations. If this is larger than the unweighted mean, this means a model with a larger “ozone response” had a smaller analysis error standard deviation. In this sense the standard deviation of the analysis error is also used as an indicator for the reliability of the “ozone response”. Is this true an how can this be justified?

We estimated the response using the multi-model integrated fields (integrated) and compared them with the averages of the individual response estimates (mean). These can be different because of the non-Gaussian distributions of the individual model fields. The procedure is more clearly described in the revised manuscript as follows:

“We first produced the daily multi-model integrated fields at $1.1^\circ \times 1.1^\circ$ resolution and then applied them to linear regressions.”

“Finally, the model responses differ significantly between the MOMO-Chem integrated fields (solid blue and red lines) and the mean of the individual model estimates obtained by averaging the model responses from individual model fields”

p11-p18 Please discuss also the errors of the weighted mean (“integrated”) analysis and update the tables

Tables 3 and 6 have been updated to include uncertainty-weighted integrated values and its uncertainty. Please also see our replies above.

p18 l10 Please clarify this sentence. What are the estimated mean errors (the biases?) and how do they relate to the analysis uncertainty, which is expressed as (bias corrected) standard deviation

Thank you for the comment. I agree with the reviewer. The sentence has been rewritten as “The estimated RMSEs (2.5-9.0 ppbv at the SH high latitudes, 3.0-4.3 ppbv at the SH mid latitudes, 2.5-5.3 ppbv in the tropics, 0.7-3.8 ppbv at the NH mid latitudes, and 2.6-6.3 ppbv at the NH high latitudes for 850-500 hPa) are significantly smaller than the analysis uncertainty (Fig. 1b) in AGCM-CHASER and MIROC-Chem (10–16 ppb) and is comparable to that in GEOS-Chem and MIROC-Chem-H.”

p18 l13. Are you suggesting the AGCM-CHASER and MIROC-Chem should be given more weight in the weighted (“integrated”) analysis.

Yes. Note that changes to analysis uncertainty should affect analysis mean.

p22 l22 The reduced multi-model spread for OH is an important finding and should presented more prominently. It shows that the assimilation of O3, NO2 and CO can improve the OH field because different models come to the similar results even without assimilation of OH observations.

To emphasize the results, the following sentence has been added:

“The obtained OH fields, which are less dependent on individual model performance due to reduced model errors in relevant species, demonstrate the potential of the multi-constituent (ozone, CO, and NO₂) data assimilation for various atmospheric chemistry studies including emission inversion and methane budget analyses.”

p23 l11 Please give here also the respective numbers for the prior emissions.

Added.

p23 l20 The comparison seems not quite correct. The prior emissions are biased against each other, which will also strongly influence the posteriori spread.

To discuss the a priori and a posteriori emission spread relationship more carefully, the sentence has been rewritten as follows:

“The multi-model spread of the a posteriori regional NO_x emissions is smaller than the assumed a priori emission uncertainty (i.e., by 40 %) for all the polluted areas (Table 8), while the a priori emission spreads could influence the obtained a posteriori emission spreads. From sensitivity calculations, we confirmed that the daily emission updates greatly reduce the dependence of the a priori emissions for many regions (now shown).”

p25 l5 Could these rather large and diverse correction of the CO emission indicate that the important impact of the VOC emissions on CO concentrations is not considered with the setup of EnKF DA system?

That is possible. To discuss its possibility more clearly, the relevant sentence has been rewritten as follows:

“Also, differences in the chemical production of CO from the oxidation of NMHCs and the chemical lifetime of CO, which were not optimized by the data assimilation, could lead to large multi-model discrepancies in CO simulations and emission estimates, as similarly discussed by Gaubert et al. (2016).”

p28 l2 Please mention that these results were obtained by a regression approach.

Added.

p27118 Please clarify uncertainty ranges in this context. Does it included that the biases or is it just the standard deviation. You should mention that the prior emissions had smaller differences between each other than a posteriori emissions.

The sentence has been rewritten as

“...which are quantified in 4–31% for NO_x and 13–35% for CO regional emissions from a multi-model spread of the a posteriori emissions.”

The prior emissions do not show smaller differences for some cases, which are clearly shown in Table 8 in the revised manuscript. Please also see our reply above.

p28 15 “The obtained results also suggest that the multi-model integrated fields could provide fundamentally different chemical relationships than those in the individual models” I find this statement not convincing. A divergent response of the different model shows predominately that a robust conclusion can not be drawn from this multi-model approach. If only, it means we need more research to find more realistic chemical relationships.

To emphasize the importance of further research, the following sentence has been added:

“Meanwhile, more research is needed to comprehend detailed chemical mechanisms.”

Meanwhile, the given sentence is reasonable because the multi-model integrated fields clearly provide fundamentally different information from individual models.

Table 8 Please include multi-model mean and spread for prior emissions Caption: Please indicate what the number in brackets are

Added.

Figure 3: Indicate what the dashed lines represent Figure 8: Correct spelling of “deveation”

Indicated.

Figure 15: The differences between the different a posteriori and prior estimates between the models could be shown better.

The multi-model spread of the a posteriori emissions are already shown in Figure 17. Detailed spatial patterns for the a priori emissions do not provide any useful information.

Evaluation of a multi-model, multi-constituent assimilation framework for tropospheric chemical reanalysis

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Abstract. We introduce a Multi-mOdel Multi-cOnstituent Chemical data assimilation (MOMO-Chem) framework that directly accounts for model error in transport and chemistry [and integrate a portfolio of data assimilation analyses obtained using multiple forward chemical transport models in a state-of-the-art ensemble Kalman filter data assimilation system. The](#)

15 [data assimilation](#), simultaneously optimizes both concentrations and emissions of multiple species through ingestion of a suite of measurements (ozone, NO₂, CO, HNO₃) from multiple satellite sensors. In spite of substantial model differences, the observational density and accuracy was sufficient for the assimilation to reduce the multi-model spread by 20–85% for ozone, and annual mean bias by 39–97% for ozone in the middle troposphere, while simultaneously reducing the tropospheric NO₂ column biases by more than 40%, and the negative biases of surface CO in the Northern Hemisphere by

20 41–94%. For tropospheric mean OH, the multi-model mean meridional hemispheric gradient was reduced from 1.32±0.03 to 1.19±0.03, while the multi-model spread was reduced by 24–58% over polluted areas. The [uncertainty ranges in the a posteriori emissions due to model errors were quantified in 4–31% for NO_x and 13–35% for CO regional emissions. Harnessing assimilation increments in both NO_x and ozone, we show that the sensitivity of ozone and NO₂ surface concentrations to NO_x emissions varied by a factor of 2 for end-member models revealing fundamental differences in the](#)

25 [representation of fast chemical and dynamical processes. A systematic investigation of model ozone response and analysis increment in MOMO-Chem could benefit evaluation of future prediction of chemistry-climate system as a hierarchical emergent constraint.](#)

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Deleted: by integrating a portfolio of forward chemical transport models (GEOS-Chem, AGCM-CHASER, MIROC-Chem, MIROC-Chem-H) into a state-of-the-art ensemble Kalman filter data assimilation system that

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1 Introduction

Data assimilation is a technique for combining different observational data sets with a model, taking into consideration of the characteristics of individual measurements and model dynamics (e.g., Kalnay, 2003; Lahoz and Schneider, 2014). Atmospheric composition and chemical data assimilation using advanced data assimilation techniques such as four-dimensional variational data assimilation (4D-VAR) and ensemble Kalman filter (EnKF) allow the propagation of observational information in time and space from a limited number of observed species to a wide range of chemical components (e.g., Lahoz et al, 2007; Sandu et al., 2011; Bocquet et al., 2015). Data assimilation provides global fields that are statistically consistent with individual observations. Various studies have demonstrated the capabilities of chemical data assimilation systems in the analysis of chemical species in the troposphere and stratosphere (e.g. Parrington et al., 2009; Kiesewetter et al., 2010; Flemming et al., 2011; Coman et al., 2012; Emili et al., 2014; Miyazaki et al., 2012a, 2012b, 2015, 2019; van der A et al., 2015), emissions optimization (e.g., Miyazaki et al., 2012a, 2013, 2014; Stavrou et al. 2013; Streets et al., 2013; Inness et al., 2015; Jiang et al., 2018), and chemical reanalyses to provide long-term data assimilation products (Inness et al., 2013; Gaubert et al., 2016; Miyazaki et al., 2015; Flemming et al., 2017). Chemical data assimilation frameworks have also been used to evaluate observing system impacts through observation system simulation experiments (OSSEs) (Yumimoto, 2013; Lahoz and Schneider, 2014; Bocquet et al., 2015; Abida et al., 2017; Liu et al., 2017) and evaluate chemistry-climate model simulations (Miyazaki and Bowman, 2017; Kuai et al., 2019).

Developments of advanced data assimilation techniques and satellite retrievals have contributed to improving data assimilation analysis and prediction of atmospheric composition (e.g., Singh et al., 2012; Skachko et al., 2016; Boersma et al., 2018). However, a limiting factor in the accuracy of these systems is the performance of forecast models, that have limited fidelity in the representation of atmospheric dynamics and chemistry. For example, intercomparison studies of the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) (Bowman et al., 2013; Young et al., 2013; Stevenson et al., 2013) and the Chemistry-Climate Model Initiative (CCMI) (Morgenstern et al., 2018; Kuai et al., 2019) revealed a large diversity in simulations of tropospheric composition owing to differences in model processes and input data. The choice of forecast model, thus, largely influences the a priori uncertainty in chemical data assimilation and the a posteriori data assimilation analysis.

As opposed to 4D-Variational techniques that requires a model adjoint, EnKF systems are independent from forecast model code and therefore can readily integrate multiple models into a multi-model data assimilation framework (Houtekamer and Zhang, 2016). EnKF techniques have been successfully applied to multiple different chemical transport models (CTMs) in our previous studies (e.g., Miyazaki et al., 2012, 2015, 2017, 2019), which have been used to assimilate multi-constituent composition measurements from multiple sensors where both the chemical states and emissions of various species were simultaneously optimized. However, the sensitivity of concentrations to emissions, such as ozone response to NO_x emissions, is strongly model dependent and therefore has a first-order impact on the performance in multi-constituent data assimilation framework. Consequently, quantification of this impact is important not only for analysis but also for Observing

System Simulation Experiments (OSSEs) used to assess and design new observing systems. Nevertheless, the importance of forecast model performance on chemical data assimilation has not been demonstrated using a common data assimilation framework for tropospheric chemistry analysis. A multi-model framework can also be used to provide multi-model integrated analysis fields, which are less dependent on individual model performance.

5 [Data assimilation that relies on a single model may lead to biased estimation and underestimate model uncertainty by under-sampling of the relevant model space. The limitations with a single model could be overcome by integrating multi-model information in data assimilation in various ways. First, ensembles of models can be used to construct a flow-dependent analysis system. For instance, Xue and Zhang \(2014\) extended data assimilation to the multi-model Bayesian model averaging analysis framework, in which the posterior model weight for each model is determined through Bayes' theorem](#)
10 [reflecting the prior probability of each model and the analysis consistency with the observations. This approach requires a framework to execute and update multiple-model states continuously, which is difficult with multiple state-of-the-art CTMs that have been optimized using different platforms. Another way to integrate multiple-model information is to apply a common data assimilation framework with multiple models. By assimilating the same sets of observations, this framework can be used to demonstrate the importance of forecast model performance on data assimilation analysis, while uncertainty](#)
15 [information of individual analyses can be evaluated consistently by using a same data assimilation framework. Uncertainty-weighted multi-model integrated analysis fields would provide unique information that are less dependent on individual model performance and are fundamentally different from averages of individual data assimilation analyses. Quantifying model performance with a multi-model integration is difficult when using different data assimilation frameworks.](#)

20 [This study demonstrates, for the first time, the importance of forecast model performance on data assimilation analysis of tropospheric composition and emissions, by utilizing four different CTM frameworks and applying a common EnKF approach. As illustrated in Fig. 1, an EnKF data assimilation system based on the GEOS-Chem model is newly developed in this study. Using the same data assimilation settings and assimilating almost the same multi-constituent observations from multiple satellite sensors, we examine how model bias affects tropospheric chemistry data assimilation performance, including emission estimation, and provide integrated data assimilation analysis fields from an ensemble of analyses that](#)
25 ingested multiple models and multi-constituent measurements.

2 Methodology

2.1 Data assimilation module

The data assimilation technique is based upon on a Local Ensemble Transform Kalman Filter (LETKF) approach developed by Hunt et al. (2007). The LETKF uses an ensemble forecast to estimate the background error covariance matrix
30 and generates an analysis ensemble mean and covariance that satisfy the Kalman filter equations for linear models. In the forecast step, a background ensemble, \mathbf{x}_i^b ($i=1,\dots,k$), is obtained from the evolution of an ensemble model forecast. Here, \mathbf{x}

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represents the model variable, b indicates the background state, and k is the ensemble size (32 in this study). The background ensemble mean $\bar{\mathbf{x}}^b$ and its perturbation \mathbf{X}^b are then estimated as follows:

$$\bar{\mathbf{x}}^b = \frac{1}{k} \sum_{i=1}^k \mathbf{x}_i^b \quad (1)$$

$$\mathbf{X}_i^b = \mathbf{x}_i^b - \bar{\mathbf{x}}^b \quad (2)$$

5 The background error covariance is then estimated at each time step at each grid point as follows:

$$\mathbf{P}^b = \mathbf{X}^b (\mathbf{X}^b)^T \quad (3)$$

The background ensemble is converted into the observation space, $\mathbf{y}_i^b = H(\mathbf{x}_i^b)$, using the observation operator H , which is the composite of a spatial interpolation operator and a satellite retrieval operator (c.f., Section 2.3). An ensemble of background perturbation is defined as $\mathbf{Y}_i^b = \mathbf{y}_i^b - \bar{\mathbf{y}}^b$.

10 Using the covariance matrices of observation and background error, the data assimilation determines the relative weights of the observation and background, and subsequently transforms a background ensemble into an analysis ensemble, \mathbf{x}_i^a ($i=1, \dots, k$). The analysis ensemble mean $\bar{\mathbf{x}}^a$ is obtained by updating the background ensemble mean as follows:

$$\bar{\mathbf{x}}^a = \bar{\mathbf{x}}^b + \mathbf{X}^b \tilde{\mathbf{P}}^a (\mathbf{Y}^b)^T \mathbf{R}^{-1} (\mathbf{y}^o - \bar{\mathbf{y}}^b) \quad (4)$$

$$\tilde{\mathbf{P}}^a = \left[\frac{(k-1)}{1+\Delta} \mathbf{I} + (\mathbf{Y}^b)^T \mathbf{R}^{-1} \mathbf{Y}^b \right]^{-1} \quad (5)$$

15 where $\tilde{\mathbf{P}}^a$ is the $k \times k$ local analysis error covariance in the ensemble space, \mathbf{y}^o is the observation vector, and \mathbf{R} is the observation error covariance. A covariance inflation factor (Δ , [6% in this study for all the models, following the setting in Miyazaki et al \(2015\)](#)) is applied to inflate the forecast error covariance.

The observation-minus-forecast (OmF), that is known as the observational increment, is defined as:

$$\mathbf{y}^o - \bar{\mathbf{y}}^b \quad (6)$$

20 The analysis increment is defined as the correction made by data assimilation as follows:

$$\bar{\mathbf{x}}^a - \bar{\mathbf{x}}^b \quad (7)$$

The analysis ensemble perturbation matrix in the model space (\mathbf{X}^a) is obtained by transforming the background ensemble as follows and used in the subsequent forecast step as initial condition:

$$\mathbf{X}^a = \mathbf{X}^b [(k-1)\tilde{\mathbf{P}}^a]^{1/2} \quad (8)$$

25 In the data assimilation analysis, covariance localization is applied so that the covariance among unrelated or weakly related variables is neglected. This removes the influence of spurious correlations resulting from the limited size of the ensemble. Further, it removes the influence of remote observations that may cause sampling errors. The data assimilation settings such as localization length used in this study are given Section 2.6. Estimation of emissions is based on a state augmentation technique that uses the background error correlations for each grid point to determine the relationship between
30 the concentrations and emissions of various species (Miyazaki et al., 2012a). More detailed description of the basic data assimilation framework is available in Miyazaki et al. (2017).

2.2 Forecast models

We applied the same data assimilation system to four CTM frameworks: GEOS-Chem, AGCM-CHASER, MIROC-Chem, and MIROC-Chem-H. The specifications of these systems are summarized in Table 1. The major differences among the models are the meteorological input data, the complexity of the chemical mechanisms (simplest in AGCM-CHASER for the troposphere), emission inventories (oldest in GEOS-Chem), vertical coordinate (sigma in AGCM-CHASER only), and spatial resolution (highest in MIROC-Chem-H).

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2.2.1 GEOS-Chem

The GEOS-Chem model is driven by assimilated meteorological data from the Goddard Earth Observing System (GEOS-5) of the NASA Global Modeling and Assimilation Office (GMAO). The adjoint model version 35 (Henze et al., 2007), which corresponds to version 9 of the forward model, with a horizontal resolution of $2^\circ \times 2.5^\circ$ and 47 vertical levels extending from the surface to 0.1 hPa was used as a forward forecast model (i.e., without adjoint calculations) in this study. Although newer and improved versions of the forward model are available, we chose this version (the latest version of the adjoint model) so that an intercomparison study of 4D-VAR and EnKF using the same modelling system can be conducted in a separate study.

The core of GEOS-Chem computes the local changes in atmospheric concentrations due to emissions, chemical reactions, and deposition. Further, it can simulate coupled aerosol-oxidant chemistry in the troposphere and stratosphere. This model uses the advection algorithm developed by Lin and Rood (1996) on the rectilinear grid. Convective transport is computed from the convective mass fluxes available in the meteorological archive. The application of the EnKF chemical data assimilation system based to the GEOS-Chem model is newly developed in this manuscript.

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The a priori emission data for NO_x and CO were obtained from the Emission Database for Global Atmospheric Research (EDGAR) version 3 inventory (Olivier et al., 2001) for global anthropogenic emissions and from the monthly Global Fire Emissions Database (GFED) version 2 inventory (van der Werf, 2006) for biomass burning emissions. Volatile organic compound (VOC) emission data were obtained from the RETRO inventory (Schultz et al., 2008). Emission data for North America were replaced with the 2008 National Emissions Inventory (NEI).

2.2.2 AGCM-CHASER

The chemical atmospheric general circulation model for the study of atmospheric environment and radiative forcing (CHASER, Sudo et al., 2002) simulates tracer transport, wet and dry deposition, and emissions. It has a horizontal resolution of T42 ($2.8^\circ \times 2.8^\circ$) and 32 sigma levels from the surface to 4 hPa. This model is coupled to the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES) atmospheric general circulation model (AGCM) version 5.7b. The AGCM fields in this model are nudged towards the National Centers for Environmental Prediction/Department of Energy Atmospheric Model Intercomparison Project II (NCEP-DOE/AMIP-II) reanalyses (Kanamitsu et al., 2002) at each time step of the AGCM (i.e. every 20 min) to reproduce past meteorological conditions. The

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data assimilation system based on the AGCM-CHASER model (Miyazaki et al., 2012a, 2012b; Miyazaki and Eskes, 2013) was used to conduct our first chemical reanalysis calculation for 2005-2012 (TCR-1, Miyazaki et al., 2015) and elucidate the 3-D structures of lightning-induced NO_x (LNO_x) source (Miyazaki et al., 2014).

The anthropogenic NO_x and CO emissions were obtained from the EDGAR version 4.2. Emissions from biomass burning are based on the GFED version 3.1 (van der Werf et al., 2010), while those from soils are based on the monthly Global Emissions Inventory Activity (GEIA) (Graedel et al., 1993). Using the settings reported by Lotos-Euros (Schaap et al., 2008) and Boersma et al. (2008), a diurnal variability scheme developed by Miyazaki et al. (2012a) was applied for surface NO_x emissions depending on the dominant category for each area (anthropogenic, biogenic, and soil emissions). LNO_x sources were determined based on the relationship between lightning activity and cloud top height (Price and Rind, 1992) and using the convection scheme of the AGCM. Biogenic emissions from vegetation are considered for non-methane hydrocarbons (NMHCs) based on Guenther et al. (2006). Oxidations of ethane, propane, ethene, propene, isoprene, and terpenes were included explicitly.

2.2.3 MIROC-Chem

MIROC-Chem is the chemistry component of the MIROC-Earth system model (ESM) and is coupled to the MIROC-AGCM version 4 (Watanabe et al., 2011). It has a horizontal resolution of T42 (2.8° x 2.8°) and 32 eta vertical levels from the surface to 4.4 hPa. Its tropospheric chemistry was developed based on the CHASER model with updates related to chemical reactions and emissions. MIROC-Chem considers the fundamental chemical cycle of Ox-NO_x-HO_x-CH₄-CO along with oxidation of non-methane VOCs (NMVOCs) to accurately represent ozone chemistry in the troposphere. Its stratospheric chemistry simulates chlorine and bromine containing compounds, chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), carbonyl sulfide (OCS), and N₂O. Further, it simulates the formation of polar stratospheric clouds (PSCs) and the associated heterogeneous reactions on their surfaces. The simulated meteorological fields were nudged towards the six-hourly ERA-Interim reanalysis (Dee et al., 2011). An EnKF system that is based on MIROC-Chem has been used to study decadal changes in NO_x emissions (Miyazaki et al., 2017; Jiang et al., 2018). The emission data and LNO_x scheme for this model are same as in the AGCM-CHASER.

2.2.4 MIROC-Chem-H

A high-resolution (1.1° x 1.1°) version of the MIROC-Chem model, MIROC-Chem-H (Sekiya et al., 2018), was also used. This model utilizes the same chemical and transport module as the MIROC-Chem (c.f., Section 2.2.3) and has been used to study processes controlling air quality in east Asia during the KORUS-AQ aircraft campaign (Miyazaki et al., 2019; Thompson et al., 2019) and conduct the second tropospheric chemical reanalysis (TCR-2, Miyazaki et al., in prep) for 2005-2018. Kanaya et al. (2019) demonstrated the overall good performance of the ozone and CO analyses in TCR-2 over remote oceans using observations from research vessels.

Deleted: It considers 92 chemical species and 262 chemical reactions (58 photolytic, 183 kinetic, and 21 heterogeneous reactions) in the troposphere and stratosphere.

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Data for anthropogenic emissions of NO_x and CO were obtained from the HTAP version 2 inventory for 2010 (Janssens-Maenhout et al., 2015). This inventory combines nationally reported emissions data with data from regional scientific inventories of the European Monitoring and Evaluation Programme (EMEP), Environmental Protection Agency (EPA), Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS), and Regional Emission Inventory in Asia (REAS). Emissions from biomass burning were based on the monthly GFED version 4.2 inventory (Randerson et al., 2018) for NO_x and CO, while those from soils were based on the monthly GEIA inventory (Graedel et al., 1993) for NO_x. Emission data for other compounds were taken from the HTAP version 2 and GFED version 4 inventories.

As summarized in Table 1 and described in Section 2.3, the satellite products used in MIROC-Chem-H were more recent than those used in the other three models. Diversity among the data assimilation systems was enhanced by the use of different assimilated data. Although the effects of varying assimilated measurements need careful evaluation, the recently developed retrievals products reveal rather similar characteristics in general. We thus expect that the forecast model performance has a greater influence on data assimilation analysis.

2.3 Assimilated measurements

To assimilate satellite measurements, we have developed an observation operator (H) for individual assimilated measurements. This operator includes the spatial interpolation operator (S), a priori profile for the satellite retrievals ($x_{\text{a priori}}$), and averaging kernel (A), which maps the model fields (x_i^b) into the retrieval space (y^b), as follows:

$$y_i^b = H(x_i^b) = x_{\text{a priori}} + A(S(x_i^b) - x_{\text{a priori}}) \quad (9)$$

The averaging kernel captures the vertical sensitivity profiles of the retrievals (e.g., Eskes and Boersam, 2003; Jones et al., 2003; Migliorini et al., 2008). Even though the retrieval y^o and the model equivalent y^b depend on the a priori profile, using the averaging kernel removes the dependence of the analysis on model–retrieval comparison.

Biases in the assimilated satellite retrievals can degrade data assimilation performance. The ozone analysis bias is not solely determined by bias in the assimilated ozone measurements in the multi-constituent data assimilation approach. Miyazaki et al. (2015) demonstrated that the assimilation of measurements other than TES measurements led to corrections in the lower and middle tropospheric ozone. Application of a bias correction procedure for multiple measurements could improve the data assimilation analysis quality. However, we did not apply any bias correction because of the difficulty in estimating the bias structure that could vary temporally and spatially. Meanwhile, since the data is the same for all comparisons with different models, the differences with respect to independent observations are relatively independent of those biases.

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2.3.1 OMI and SCIAMACHY NO₂

The tropospheric NO₂ column retrievals from the DOMINO version 2 for Ozone Monitoring Instrument (OMI) and Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) (Boersma et al., 2011),

obtained from the Tropospheric Emission Monitoring Internet Service (TEMIS) website (www.temis.nl), were used for the GEOS-Chem, AGCM-CHASER, and MIROC-Chem systems. For MIROC-Chem-H, retrievals from the QA4ECV version 1.1 level 2 (L2) product for OMI (Boersma et al., 2017a) and SCIAMACHY (Boersma et al., 2017b) were used. Low-quality data were excluded following the published recommendations (Boersma et al., 2011; Boersma et al., 2018b).

5 We employed a super-observation approach to produce representative data with the horizontal resolution of each forecast model, following the approach of Miyazaki et al. (2012a). Super-observation error was estimated using the provided retrieval uncertainty and considering an error correlation of 15 % among the individual satellite observations within a model grid cell and representativeness errors in all the systems.

2.3.2 TES ozone

10 The Tropospheric Emission Spectrometer (TES) ozone retrievals used are the version 5 level 2 nadir data obtained from the global survey mode (Bowman et al, 2006; Herman and Kulawik, 2013) for the GEOS-Chem, AGCM-CHASER, and MIROC-Chem systems. The version 6 level 2 nadir data were used for the MIROC-Chem-H system. This data set consists of 16 daily orbits with a spatial resolution of 5–8 km along the orbit track. The standard quality flags were used to exclude low-quality data. The data assimilation of the TES ozone retrievals was performed based on the logarithm of the mixing ratio
15 following the retrieval product specification (Bowman et al., 2006).

2.3.3 MLS ozone and HNO₃

The Microwave Limb Sounder (MLS) data used were the version 3.3 ozone and HNO₃ L2 products (Livesey et al., 2011) for all models except MIROC-Chem-H, which used the version 4.2 data. We used MLS data for pressures of less than 215 hPa for ozone and less than 150 hPa for HNO₃, while tropical-cloud-induced outliers were excluded. The provided accuracy
20 and precision of the measurement error were included as the diagonal element of the observation error covariance matrix.

2.3.4 MOPITT CO

The version 6 level 2 thermal infrared (TIR) products (Deeter et al., 2013) of the Measurement of Pollution in the Troposphere (MOPITT) were used for all models except the MIROC-Chem-H, for which the version 7 level 2 TIR/near infrared (NIR) total column CO data were used (Deeter et al., 2017). The version 7 products have been improved from the
25 version 6 products with respect to overall retrieval biases, bias variability and bias drift uncertainty (Deeter et al., 2017). Owing to data quality problems, we excluded data poleward of 65° and night-time data. For the version 6 TIR products, data at 700 hPa were used for constraining surface CO emissions. For the version 7 TIR/NIR products, the total column averaging kernel was used in the observation operator to estimate simulated total columns. The uncertainty information provided in the retrievals was used in the observation error. Like in the case of NO₂ measurements, the super-observation approach was
30 applied for MOPITT measurements as well.

2.4 Validation data

2.4.1 WOUDC ozonesonde data

All available ozonesonde observations taken from the World Ozone and Ultraviolet Radiation Data Center (WOUDC) database (available at <http://www.woudc.org>) were used as validation data. All ozonesonde profiles have been interpolated to a common vertical pressure grid, with a bin of 25 hPa. The ozone fields from the control and data assimilation calculations were linearly interpolated to the time and location of each measurement, with a bin of 25 hPa, and then compared with the measurements at 4° x 4° grid points. The observation error is 5-10 % between the surface and 30 km (Smit et al., 2007).

2.4.3 WDCGG surface carbon monoxide

Surface CO concentration observations were obtained from the World Data Centre for Greenhouse Gases (WDCGG) operated by the World Meteorological Organization (WMO) Global Atmospheric Watch programme (<http://ds.data.jma.go.jp/gmd/wdccc/>). Hourly and event observations from 59 stations were used to validate surface CO concentrations from the control and data assimilation runs at 5° x 5° grid points.

2.5 Multi-model analysis

We construct integrated data assimilation analysis using multiple models combined with multiple-species measurements (Fig. 1). The multi-model integrated analysis \bar{x}_m are obtained by combining data assimilation analyses (x_j^a) weighted by analysis uncertainties (σ_j^2) of individual models (j=1-4) as follows:

$$\bar{x}_m = \frac{\sum(x_j^a / \sigma_j^2)}{\sum(1/\sigma_j^2)} \quad (10)$$

The analysis uncertainties (σ_j^2) are estimated from the root mean square of the analysis ensemble perturbation matrix (X^a , see Eq. (8)) that is obtained by transforming the background ensemble using the local analysis error covariance (see Eq. (5)). The integrated analysis (\bar{x}_m) provide unique information on atmospheric states, which are less dependent on the characteristics of individual models used for data assimilation, and consider the uncertainty of individual data assimilation analyses. The uncertainty of the integrated analysis ($\overline{\sigma_m^2}$) is defined as follow:

$$\overline{\sigma_m^2} = \frac{1}{\sum(1/\sigma_j^2)} \quad (11)$$

We apply this approach for estimating multi-model mean ozone fields in this study. Because of the predefined minimum values of the standard deviations applied to surface emissions of CO and NO₂ to prevent covariance underestimation during data assimilation (c.f., Section 2.6), the analysis spreads of near surface NO_x and CO concentrations tend to be similar among the models due to the artificial adjustments and are not fully meaningful. For the concentrations and emissions of CO

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and NO_x, therefore, its multi-model mean and uncertainty were estimated as a standard ensemble mean and spread, without using the analysis uncertainty of individual models. The multi-model integrated analysis fields were produced at the highest horizontal resolution of the models (1.1°x1.1°) after linearly interpolation. Given the small number of models (j=1-4) used in this study, the multi-model integration would suffer from sampling biases. With increasing the number of models in future study, this approach would provide more robust statistics.

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2.6 Experimental setting

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We conducted one year of data assimilation calculations and forward model simulations (i.e., control run) from January 1, 2007, with a two-month spin up from November 1, 2006, using the four systems. This assimilation period was chosen to provide comprehensive constraints by OMI measurements while avoiding the influences of OMI row anomalies (December 2009 onwards) (Schenkeveld et al., 2017) and reduced numbers of the TES measurements (2010 onwards). A control run was performed in each system using the same model settings as the data assimilation run but without performing data assimilation. The validation results for the control and data assimilation runs were compared to measure the improvements achieved through data assimilation in each system.

Almost the same data assimilation settings were used for the four systems as follows. The state vector includes the chemical concentrations of various species as well as the surface sources of NO_x and CO and LNO_x sources. The LNO_x source optimization is based on the scheme developed by Miyazaki et al. (2014). For the MIROC-Chem-H system, the state vector also includes surface SO₂ emissions, as implemented in Miyazaki et al. (2019). The state vectors for the MIROC-Chem and MIROC-Chem-H systems include a correction factor for emission diurnal variability to improve the representation of diurnal emission variability using the OMI and SCIAMACHY retrievals obtained at different overpass time, based on the scheme developed by Miyazaki et al. (2017).

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Covariance inflation was applied to analyses of both concentrations and emissions to prevent underestimation of background error covariance and filter divergence caused by sampling errors associated with the limited ensemble size and by model errors, following the settings used by Miyazaki et al. (2015). Further, localization was applied to avoid the influence of remote observations that may cause sampling errors, with a cut-off radius of approximately 1650 km for NO_x emissions and 2000 km for CO emissions, LNO_x sources, and chemical concentrations, as in Miyazaki et al. (2015). We also applied covariance localization for different variables in the state vector (Kang et al., 2011), by setting the covariance among non- or weakly related variables to be zero. The analysis of surface emissions of NO_x and CO allowed for error correlations with NO₂ and CO concentrations only, respectively. For LNO_x sources, covariances with CO data were neglected.

Assimilation of MOPITT CO data was used to constrain surface CO emissions only. Concentrations of NO_y species and ozone were optimized from TES ozone, OMI and SCIAMACHY NO₂, and MLS ozone and HNO₃ observations.

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The a priori error was set to 40% for surface emissions of NO_x and CO and 60 % for LNO_x sources, which are comparable to the reported emission uncertainty (e.g., Schumann and Huntrieser, 2007; Kaiser et al., 2012; Li et al., 2017). To prevent covariance underestimation and maintain emission variability during the long-term assimilation calculation, we applied covariance inflation to the emission source factors in the analysis step. The standard deviation of the emission source factors was artificially inflated to a minimum predefined value (30% of the initial standard deviation) at each analysis step.

The data assimilation cycle was set to be two hours for the AGCM-CHASER, MIROC-Chem, and MIROC-Chem-H systems, and six hours for the GEOS-Chem system because of the limitation associated with meteorological data input in GEOS-Chem. The emission and concentration fields were analyzed and updated at each analysis step in all the systems. We have confirmed that the results of data assimilation can differ when the data assimilation cycle is changed from two hours to six hours using the AGCM-CHASER system. This occurs, in particular, for the analysis of short-lived species with strong diurnal variability and NO_x emission estimates. The performance of the GEOS-Chem data assimilation can thus be expected to differ with the use of a two-hour data assimilation cycle and meteorological data inputs with higher temporal frequency for short-lived species.

In summary, there are differences in the assimilated measurements (updated retrievals were used in MIROC-Chem-H), diurnal emission variability (data assimilation corrections were made in the MIROC-Chem and MIROC-Chem-H systems only), and data assimilation cycle (six hours in GEOS-Chem) of the four systems. These differences will lead to discrepancies in the data assimilation analyses of the four systems attributable to assimilation system configuration rather than the forward models themselves. While impact of these configurations can be further refined in future studies, the major discrepancies in the data assimilation analyses are still primarily attributable to the models themselves.

3 Data assimilation statistics

3.1 Analysis increment

The analysis increment (Eq. 7) information is a measure of the adjustment made in the analysis step, which is estimated from the differences between the forecast and the analysis after each analysis step. As shown in Fig 2a, the annual mean analysis increments are largely different among the models, reflecting different systematic model biases. For individual systems, the analysis increments are in good agreements with the OmF (Eq. (6)). This confirms that the model errors were effectively reduced using data assimilation.

In the ozone concentration field at 500 hPa, the AGCM-CHASER system gives large positive increments in the extratropics of both hemispheres, with annual mean values in the range of 1–3 ppb/day, whereas the increments are negative at low latitudes (up to -1.5 ppbv/day). The standard deviations of the analysis increment are 0.8–1.7 ppb/day in the extratropics and 0.2–0.4 ppb/day at low latitudes. The analysis increments are relatively low in GEOS-Chem (up to -1.8 ppbv/day) and MIROC-Chem (up to 1.4 ppbv/day) in the NH extratropics; in GEOS-Chem (-0.5–1.5 ppbv/day) and MIROC-Chem-H (up to -1.0 ppbv/day) in the tropics; and in MIROC-Chem (up to 1.4 ppbv/day) in the SH extratropics. GEOS-Chem exhibits

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negative increments except over central Africa and northern South America, with large negative increments (up to 2 ppbv/day) over the Southern Ocean and the U.S. west coast in the strong westerlies and Aleutian Low regions, respectively. The positive increments over central Africa and northern South America could imply underestimated ozone productions due to biomass burning or VOCs emissions.

5 The analysis increments differed significantly between the lower and upper troposphere as well as among seasons in all the systems (figure not shown). GEOS-Chem shows large positive increments (0.5–2.2 ppbv/day) in the extratropics at 700 hPa, in contrast to negative increments (up to -2.0 ppbv/day) at low and mid latitudes at 350 hPa. In AGCM-CHASER and MIROC-Chem, the increments changed from positive at 700 hPa (up to 2.2 ppbv/day in AGCM-CHASER and 0.5 ppbv/day in MIROC-Chem) to negative at 350 hPa (up to -2.5 ppbv/day and -1.2 ppbv/day, respectively) in the extratropics of both
10 hemispheres. The positive increments in MIROC-Chem-H decreased with height in the extratropical troposphere. As the increments in the troposphere are mainly introduced by the TES assimilation, the vertical structures suggest that the assimilated TES ozone measurements have independent information regarding the lower- and upper-tropospheric ozone. Using observing system experiments (OSEs), our previous studies (Miyazaki et al., 2012b, 2015, 2019) revealed that the TES ozone data assimilation dominate the corrections in the tropospheric ozone analysis, whereas the use of measurements
15 other than TES measurements (mainly NO₂ measurements) led to corrections in the lower- and middle- tropospheric ozone during the forecast. Jourdain et al. (2007) showed that the TES retrievals have 1–2 DOFs in the troposphere, with the highest number of DOFs for the clear-sky tropics and subtropics. The seasonal changes in the analysis increment reflect variations in the short-term systematic model errors and observational constraints, which also differed significantly among the models.

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3.2 Analysis uncertainty

20 The analysis uncertainty, which is estimated as the standard deviation of the analyzed concentrations across the ensemble (Eq. 8) in individual systems, can be used as a measure of the uncertainty of each data assimilation analysis. The analysis uncertainty is due to errors in the model input data, model processes, and assimilated measurements and is reduced as the analyses converges to the true state. Because the model input data and assimilated measurements are almost same among the models, differences in model processes such as response of ozone to perturbed emissions and chemical lifetimes should be
25 primarily responsible for the analysis spreads among the models through the forecast step. Detailed investigation on the impact of different model processes for each region and season would be helpful to interpret the results but is beyond the scope of this paper. The simultaneous emissions and concentration optimization were important in producing appropriate ensemble perturbations in ozone, especially in the lower and middle troposphere.

30 The ozone analysis uncertainty at 500 hPa shown in Fig. 2b is generally smaller in the tropics than in the extratropics likely a consequence of the higher sensitivities in the TES ozone retrievals in the tropics. Because common settings were applied to the ensemble size and covariance inflation, the obtained inter-model differences in the spread reflect different systematic model errors related to the assimilation window size. The annual mean analysis uncertainty is generally larger in AGCM-CHASER and MIROC-Chem than in GEOS-Chem and MIROC-Chem-H. In the tropics, the analysis uncertainty is

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approximately 2–5 ppb in GEOS-Chem and MIROC-Chem-H and approximately 5–11 ppb in AGCM-CHASER and MIROC-Chem. In the extratropics, the analysis spread is approximately 6–10 ppb in GEOS-Chem and MIROC-Chem-H and 10–16 ppb in AGCM-CHASER and MIROC-Chem. The analysis increments are generally similar among the models (c.f., Fig. 2a). These results suggest that the model forecasts tended to diverge more quickly in AGCM-CHASER and MIROC-Chem, likely as a result of larger differences in the equilibrium state between the model and assimilation. In the UTLS region, the analysis uncertainty is relatively smaller in the extratropics than in the tropics, because of the high accuracy of the MLS measurements. The spatial pattern in GEOS-Chem and MIROC-Chem-H are remarkably similar whereas the CHASER and MIROC patterns are much more similar.

The multi-model standard deviation of the ozone analyses (typically <5 ppb for the globe, Fig. 3c) is significantly lower than the analysis uncertainty in AGCM-CHASER and MIROC-Chem (Fig. 2b). As will be discussed in Section 4.1, mean errors against independent observations are also significantly smaller than the analysis uncertainty in these models. These results indicate that the analysis uncertainty depends on the choice of forward model and was possibly overestimated in AGCM-CHASER and MIROC-Chem because of a large diversity in forecast trajectories. The overestimated analysis error covariance was also confirmed by smaller chi squares (e.g., Ménard, R. and Chang, 2000) in these models (not shown). To measure the analysis spread corresponding to the actual analysis uncertainties, additional observational information and optimizing the covariance inflation to the forecast error covariance would be required.

3.3 Multi-model integrations

Fig. 3a shows the integrated ozone analysis fields, $\overline{x_m}$ defined in Eq. (10), that were created using MOMO-Chem. The annual and multi-model mean ozone concentrations at 500 hPa are high in the NH extratropics (55–70 ppbv) and low over the Maritime continent and the tropical western Pacific (22–35 ppbv). Because the analyses from the GEOS-Chem and MIROC-Chem-H systems exhibit smaller analysis spreads (c.f., Section 3.2), they exert a strong control on the integrated fields. At 500 hPa, the estimated uncertainty of the integrated fields, $\overline{\sigma_m^2}$ defined in Eq. (11), is 2–4.5 ppbv in the NH, 0.5–2 ppbv in the tropics, and 3–5.5 ppbv in the SH (Fig. 3b). These values are smaller than the uncertainties of the individual model analyses (Fig. 2b), demonstrating that the integrated fields can provide more reliable and unique information. The multi-model spread of individual data assimilation analysis (Fig. 3c) is typically smaller than the multi-model mean integrated uncertainty (Fig. 3b). Again, with the multi-model spread (Fig. 3c) and the differences with the ozonesonde measurements (Section 4.1) being smaller than the multi-model mean uncertainty (Fig. 3b), the comparisons suggest that the analysis uncertainty might be overestimated in some of the analyses.

Over the northern South America, the larger multi-model spread compared to the multi-model mean uncertainty suggests that the background errors might have been underestimated, as rapid error growths due to deep convection and biomass burning might have not been accounted for properly. Differences in isoprene emissions and chemistry could also enhance the multi-model spread over the region (Archibald et al., 2010). Techniques such as adaptive inflation for background error covariance (e.g., Anderson, 2007) would be helpful to represent rapid changes in background errors in the individual models.

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4. Validation results

4.1 Ozone profiles

4.1.1 Comparisons against TES observations

Fig. 4 compares the annual zonal mean ozone from the lower to upper troposphere. In comparison with the TES measurements, at 750 hPa, all the control runs underestimate the mean ozone in the NH extratropics (by -4.4 to -3.2 ppb at 50°N). At low latitudes, the mean ozone in MIROC-Chem-H is underestimated by -6 to -3 ppbv. In the SH extratropics, all the models reproduced the lower tropospheric ozone well. At 510 hPa, the zonal mean biases differ obviously among the models, with multi-model standard deviations of 1.5–4 ppv in the SH, 3.2–5 ppb in the tropics, and 3–6.6 ppb in the NH. The biases are largely negative in GEOS-Chem (-7.4 ppb at 50°N) and AGCM-CHASER (-5.3 ppb) in the NH extratropics; they are negative in MIROC-Chem-H (-11 to -6 ppb) at low latitudes, and positive in the models except GEOS-Chem (3.2 to 5.1 ppb at 50°S) in the SH extratropics. Similarly, at 316 hPa, the biases obtained using the models are quite different, with large positive biases in MIROC-Chem and MIROC-Chem-H in the extratropics of both hemispheres and large negative biases in MIROC-Chem-H in the tropics. Global total budgets and the production rates of tropospheric ozone can also differ, as suggested by multi-model inter-comparison studies including GEOS-Chem and MIROC-Chem (Young et al., 2013; 2018; Hu et al., 2017). Sekiya et al (2018) demonstrated that the ozone chemical productions are smaller in MIROC-Chem-H (4647 Tgyr⁻¹ for 2008) than in MIROC-Chem (4809 Tgyr⁻¹).

After the data assimilation, all the models are in good agreement with the assimilated TES measurements as expected, and demonstrate improved inter-model consistency. In the NH, the mean bias at 750 hPa is reduced by 19–73% to between -4.1 and -0.4 ppb (at 50°N) in all the models. At 510hPa, the large negative model biases in GEOS-Chem and AGCM-CHASER are reduced by 76% and 92% at 50°N, respectively. In the SH, most of the large model biases in MIROC-Chem-H are removed throughout the troposphere.

Fig. 5 shows the spatial distributions of the annual mean ozone concentrations at 510 hPa. The general structure of tropospheric ozone is well reproduced by the control runs, such as the low ozone concentrations over the tropical western Pacific and the high over the Middle East. The annual and zonal mean model biases are negative in the tropics in all the models, with large negative biases over the southern Atlantic; the bias is largest in MIROC-Chem-H (by up to 20 ppbv). After data assimilation, most of the model biases are removed for the globe. In the extratropical UTLS (figure not shown), the remaining mean bias was close to the mean observational error of the MLS ozone measurements in all the systems.

As shown in Fig. 6a, the multi-model standard deviation of the annual mean ozone at 510 hPa obtained from the control runs, with applying the TES averaging kernels (AKs), are typically 5–10 ppb from the tropics to the NH high latitudes and 1–5 ppb in the SH extratropics. After the data assimilation, the standard deviation mostly becomes smaller than 5 ppb and 3 ppb for these regions, respectively, with reductions for the zonal mean values by 20–60% in the NH and 30–85% in the SH. The results demonstrate that the assimilation framework provides highly consistent analysis fields among the systems, less dependent on the performance of the individual models. The obtained multi-model standard deviation after data assimilation

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3.4.1 Multi-model comparisons

From a system analysis perspective, one of the fundamental questions in atmospheric chemistry is the sensitivity of a constituent like ozone to changes in surface emissions such as NO_x emissions. With recent advances in estimating preindustrial ozone (Yeung et al., 2019), model sensitivities are the primary drivers of chemistry-climate estimates of quantities such as ozone radiative forcing (Bowman et al., 2013, Myhre et al., 2013). While these simulations describe relatively slow, equilibrium responses, data assimilation incremental updates provide statistics on “fast” responses within the short data assimilation windows. By simultaneously updating ozone and NO_x emissions, multi-constituent data assimilation can yield insight into this fundamental quantity. We explore this potential by regressing both the ozone and NO₂ increments with respect to the NO_x emission analysis increments.

As summarized in Table 2, the response of ozone and NO₂ analysis to emission perturbations (i.e., data assimilation increments) is largely different among the models. The NO₂ surface response to NO_x emissions is well-correlated (correlation ≥ 0.93 for all models) but the response differs by almost a factor of 2 between GEOS-Chem and MIROC-Chem-H. Globally, this diversity holds between surface ozone concentration and NO_x emission increments ($\frac{\Delta O_3}{\Delta NO_x}$) for these two models. However, the AGCM-CHASER ozone-NO_x emissions response (1.5 ppb/(10¹¹ kgNm⁻²s⁻¹)) is the largest among all the models. On the other hand, the correlation between surface ozone and NO_x emissions is relatively weak (correlation < 0.43) reflecting the much more complicated chemical and dynamical relationship. For polluted areas (greater than 3×10^{11} kgNm⁻²s⁻¹, as shown in the brackets in Table 2), the largest response is AGCM-CHASER and MIROC-Chem, which is greater than the other two models by 40–180 %, with similar intercepts and correlations. The multi-model diversity reflects the different representation of NO_x and VOC as well as dynamics, leading to different ozone production efficiencies. In the case of GEOS-Chem and MIROC-Chem-H, there appears to be a clearer relationship between $\frac{\Delta NO_2}{\Delta NO_x}$ and $\frac{\Delta O_3}{\Delta NO_x}$, suggesting that NO_x chemistry plays a more dominant role in ozone formation than other factors. By separating these two responses, MOMO-Chem is able to quantify the responses of forward models with unique diagnostics, without making any sensitivity calculations.

Different model responses would directly impact the Kalman gain in Eq. 4, leading to a more efficient model error reduction. Given the same predefined minimum values for the surface NO_x emission perturbation (c.f., Section 2.4), a larger ozone analysis uncertainty (through a larger forecast model spread) would be obtained in models with a stronger ozone response to NO_x emissions. In fact, stronger ozone response (Table 2) and larger analysis uncertainty (Fig. 1b) are consistently found in AGCM-CHASER and MIROC-Chem. Meanwhile, the ozone response to a given perturbation is dependent on the background condition because of the non-linear O₃-NO_x chemistry (e.g., Zaveri et al., 2003). The multi-constituent framework allows to evaluate model ozone response in a realistic condition while considering possible error ranges in precursor's emissions using emissions analysis increments (c.f., Section 5). The ozone analysis increments became substantially smaller in all the models for most cases by including the emission optimization, and the increments could be regarded as inherent and persistent model biases of individual models. Therefore, a systematic investigation of model ozone response and analysis increment in the multi-constituent data

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(Fig. 6b) is comparable to the mean model errors relative to the TES measurements for most regions, which could thus be used as an estimate of the mean data assimilation uncertainty. The mean retrieval uncertainty of the TES measurements is typically between 5-10 ppb in the SH and 10-15 ppb in the NH, which are larger than the multi-model spread and the mean model errors after data assimilation.

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5 4.1.2 Comparisons against ozonesonde observations

The current ozonesonde network is heterogeneously distributed globally with a sampling interval typically a week or longer. Model errors are also expected to vary greatly in time and space at various scales. As a consequence, the ozonesonde measurements suffer from significant sampling bias. Miyazaki and Bowman (2017) demonstrated that this ozonesonde sampling bias in the evaluated model bias for the seasonal mean concentration relative to global coverage reaches 80 % for the global tropics. Nevertheless, the ozonesonde network provides a critical independent validation of the data assimilation products, while the data assimilation products are advantageous for evaluating actual regionally and seasonally representative model performance, which are required for model improvements. The synergy of the two provides a mechanism to characterize chemical reanalysis evaluation of chemistry-climate models (Miyazaki and Bowman, 2017).

Fig. 7 compares the seasonal variation of ozone with the WOUDC global ozonesonde measurements from the lower troposphere to the lower stratosphere. In the lower troposphere (850–500 hPa), all the models mostly underestimate ozone at NH mid and high latitudes, except for GEOS-Chem at NH mid latitudes in boreal summer. The negative model biases are large at NH high latitudes in boreal spring, with an annual mean bias of -4.7 to -2.6 ppbv (as summarized in Table 2) and large multi-model spreads. In the tropical lower troposphere, the models, other than MIROC-Chem-H, mostly overestimate ozone except in September–October, whereas MIROC-Chem-H underestimates the annual mean ozone by 5.8 ppbv. In the SH, all the models underestimate ozone throughout the year, with an annual mean bias of -6.2 to -0.7 ppbv at mid latitudes and -4.6 to -2.2 ppbv at high latitudes. The negative model biases in the SH have been found in most of the chemistry-climate models in the ACCMIP project (Bowman et al., 2013; Young et al., 2013).

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In the middle and upper troposphere (500–200 hPa), the model biases reveal a large diversity at NH high latitudes. The enhanced multi-model spread in spring could be associated with the different representations of the stratosphere-troposphere exchange (STE) processes. At NH mid latitudes, MIROC-Chem and MIROC-Chem-H overestimate annual mean ozone by 16.1 and 4.1 ppbv, respectively. In the tropics, the models, other than MIROC-Chem-H, overestimate ozone in boreal winter and underestimate it in boreal autumn, thus underestimating the seasonal amplitudes. In the SH, all the models overestimate ozone with an annual mean bias of 2.8–20.5 ppbv at mid latitudes and 8.7–29.9 ppbv at high latitudes. In the upper troposphere and lower stratosphere (UTLS, 200–80 hPa), the large multi-model spread can primarily be due to the different representations of the stratospheric chemistry, STE, as well as convective transport in the tropics. Large positive model biases exist in MIROC-Chem and MIROC-Chem-H in the NH extratropics, MIROC-Chem and GEOS-Chem in the tropics, and all the models in the SH extratropics.

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Because of data assimilation, the large negative model biases in the lower troposphere are largely reduced in the NH lower troposphere in boreal spring. Nevertheless, the annual mean concentrations in all the systems become too high in the NH lower troposphere, with an annual mean bias of from 1.7 to 4.3 ppb at high latitudes and from 1.9 to 5.2 ppb at mid latitudes, while the underestimation in the seasonal amplitude is reduced in all the models. The weak sensitivity of the assimilated measurements and the changes made to the precursor emissions (c.f., Section 4) could be responsible for the overestimations. In the tropics, the negative model bias in boreal autumn is reduced via data assimilation, thus enhancing the seasonal amplitudes in all the system, whereas the analyzed concentrations become too high in AGCM-CHASER and MIROC-Chem-H in boreal summer. In the SH, the data assimilation reduced the negative model biases of MIROC-Chem-H at mid latitudes (from -6.2 ppb to 1.0 ppbv annual mean bias) and MIROC-Chem and MIROC-Chem-H at high latitudes (from -4.6 to -4.5 ppbv to 0.9 to 3.6 ppbv). The observed rapid increases during August–October at SH mid latitudes are well reproduced after data assimilation in all the systems. At high latitudes of both hemispheres, some of the models exhibit too high concentrations after data assimilation. An inaccurate balance between the mid and high latitude in model transport and the lack of direct observational constraints could limit the effectiveness of data assimilation at high latitudes. Conducting observational impact analysis would help suggesting a framework to obtain a better global tropospheric ozone analysis.

Both the agreements against the observation and the multi-model consistency are greatly improved via data assimilation from the middle troposphere to the lower stratosphere for the globe, with annual mean bias reductions from -29.9 to 29.7 ppbv to -9.2 to -6.2 ppbv (i.e., by 53–81%) at NH high latitudes, from -4.0 to 16.1 ppbv to -2.5 to -0.2 ppbv (by 39–76% except for AGCM-CHASER) at NH mid latitudes, from -11.8 to 1.3 ppbv to -0.3 to 3.0 ppbv (by 50–91%) in the tropics, from 2.8 to 20.5 ppbv to -1.9 to 3.0 ppbv (by 71–94%) at SH mid latitudes, and from 8.7 to 29.9 ppbv to 1.0 to 4.7 ppbv (by 46–97%) at SH high latitudes for 500–200 hPa. The estimated RMSEs (2.5-9.0 ppbv at the SH high latitudes, 3.0-4.3 ppbv at the SH mid latitudes, 2.5-5.3 ppbv in the tropics, 0.7-3.8 ppbv at the NH mid latitudes, and 2.6-6.3 ppbv at the NH high latitudes for 850-500 hPa) are significantly smaller than the analysis uncertainty (Fig. 2b) in AGCM-CHASER and MIROC-Chem (10–16 ppb) and is comparable to that in GEOS-Chem and MIROC-Chem-H. These results suggest overestimated analysis uncertainty in AGCM-CHASER and MIROC-Chem.

The uncertainty-weighted multi-model integrated fields (Eq. 10) show a closer agreement with the ozonesonde observations than the (non-weighted) multi-model means for the lower troposphere, except at SH high latitudes, as summarized in Table 2. The annual and regional mean bias is smaller by 15-40 % in the uncertainty-weighted fields from the SH mid to NH high latitudes, reflecting the larger analysis biases and larger analysis uncertainties in AGCM-CHASER and MIROC-Chem for most cases. The closer agreements suggest improved estimates of ozone in the multi-model integrated fields. In the extratropical middle and upper troposphere, GEOS-Chem revealed smallest analysis uncertainty and largest analysis errors against the ozonesonde observations and dominated the uncertainty-weighted integrated fields, likely associated with the less complex stratospheric chemistry (i.e., smaller spread growth). This model dominated the uncertainty-weighted integrated fields and led to a degradation of the integrated fields. These results suggest a requirement to optimize the analysis uncertainty in some of the systems, considering the fundamental differences in the model framework such as model

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complexity and resolution, as discussed above. Increasing the number of models would also help to provide more robust statistics.

Fig. 8 shows that the data assimilation introduces similar changes to the seasonal amplitudes of ozone (defined as the difference between the maximum and minimum concentrations) in the four models, such as the increases in the lower and middle troposphere and the decreases in the extratropical upper troposphere and lower stratosphere. Between 850 and 500 hPa, the control runs underestimated the seasonal amplitude in the extratropics of both hemispheres compared with the ozonesonde measurements (e.g., by up to -29 % at the NH mid latitudes). The model underestimates are largely reduced by data assimilation in all the models. Between 500 and 200 hPa, data assimilation mostly removed the negative bias in GEOS-Chem (-8 %) and AGCM-CHASER (-5 %) and the positive bias of the seasonal amplitude in MIROC-Chem-H (47 %) against the ozonesonde measurements in the NH, and the large positive bias in MIROC-Chem (22%) in the SH. Between 200 and 90 hPa, positive biases are reduced in all the models globally. In the NH, the range in the bias from 13 to 40% is reduced to a range from -12 to 3%, with the largest reduction observed in MIROC-Chem-H (from 40 to 2 %). In the tropics, the range in the bias is reduced from 20 to 148% to from 10 and 25%, with the largest reduction observed in GEOS-Chem (from 148 to 10%). In the SH, the range in bias is reduced from 15 to 92% to from -1 and 19%, with the largest reduction observed in MIROC-Chem (from 92 to 10%).

4.2 Tropospheric NO₂ columns

For the comparisons with the OMI NO₂ retrievals, the OMI NO₂ AKs from the DOMINO2 products were applied to GEOS-Chem, AGCM-CHASER, and MIROC-Chem, whereas those from QA4ECV were applied to MIROC-Chem-H, corresponding to the assimilated measurements for each system. In Fig. 9, the converted tropospheric NO₂ columns from the control and assimilation runs are then compared with the assimilated OMI retrievals: the DOMINO2 product for GEOS-Chem, AGCM-CHASER, and MIROC-Chem (black line vs blue, red, and green lines in Fig. 9) and the QA4ECV product for MIROC-Chem-H (gray line vs yellow line).

As summarized in Table 3, the model bias in tropospheric NO₂ column differed largely among the models, because of the different model configurations (e.g., chemical lifetime of NO_x) and input data (e.g., NO_x emissions). The models, other than GEOS-Chem, mostly underestimate tropospheric NO₂ columns over polluted areas, same as in most other CTMs (van Noije et al., 2006), with an annual mean bias ranging from -2.07 to -0.37×10^{15} molecules cm⁻² over eastern China, -0.51 to -0.26×10^{15} molecules cm⁻² over the United States, and -0.82 to -0.32×10^{15} molecules cm⁻² over Europe. GEOS-Chem overestimates tropospheric NO₂ columns over some parts of China (with annual and regional mean bias of 0.13×10^{15} molecules cm⁻² over eastern China), Europe (0.60×10^{15} molecules cm⁻²), and the United States (0.29×10^{15} molecules cm⁻²). The model biases in tropospheric NO₂ columns can vary with changing the model configurations. For instance, important NO_x sink pathway determining NO₂ simulation uncertainties include the NO₂+OH reaction and the formation of HNO₃ in the NO+HO₂ reaction (Lin et al., 2012; Stavrou et al., 2013), which are represented differently in the models. The columns simulated from MIROC-Chem-H are higher than that from MIROC-Chem, with the same AKs applied over some parts of

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the polluted areas such as eastern China; these differences are attributable to the increased model resolution, which suppresses the dilution effects (Sekiya et al, 2018).

Fig. 9 compares the seasonal variation of tropospheric NO₂. The models, other than GEOS-Chem, underestimate tropospheric NO₂ columns throughout the year over eastern China, the United States, and Europe, with the largest negative biases in boreal winter. Over India, GEOS-Chem reproduced the peak observed in April and the rapid decrease from May to July, whereas the other models underpredicted the seasonal variations. The retrieved tropospheric NO₂ columns are generally lower in the QA4ECV products than in the DOMINO-2 products over most of major polluted areas. The different retrieved columns can largely be attributed to differences in the a priori profiles and does not influence directly the model-observation differences after applying the AKs (Boersma et al. 2018a). Over Southeast Asia, the models, except for GEOS-Chem, underestimate the peak observed in March, which is associated with biomass burning, by 11–55%, whereas the models overestimate the peak over South America in September by 18–31%.

Over northern, central, and southern Africa, all the models underestimate tropospheric NO₂ columns throughout the year, with an annual mean bias ranging from -0.32 to -0.11×10^{15} molecules cm⁻², -0.39 to -0.11×10^{15} molecules cm⁻², and -1.05 to -0.89×10^{15} molecules cm⁻², respectively. Over southern Africa, the negative model bias is maximized in austral winter (by 43–63 %), with MIROC-Chem-H giving the smallest bias. The higher spatial resolution of MIROC-Chem-H is considered essential in resolving individual polluted areas in the Highveld region and in accurately simulating the non-linear effects on NO₂ loss rate.

The tropospheric NO₂ column retrievals from OMI and SCIAMACHY were assimilated to optimize NO_x emissions, and the assimilation of non-NO₂ measurements influence the chemical lifetime of NO_x through changes made to OH. Data assimilation reduced the negative model biases in the models, other than GEOS-Chem, over eastern China (from -2.07 – -0.37×10^{15} molecules cm⁻² to -0.69 – -0.39×10^{15} molecules cm⁻²) and the United States (from -0.51 to -0.26×10^{15} molecules cm⁻² to -0.18 to -0.13×10^{15} molecules cm⁻²), and over western Europe (from -0.82 to -0.32×10^{15} molecules cm⁻² to -0.41 to -0.24×10^{15} molecules cm⁻²). The annual mean positive model biases in GEOS-Chem are reduced by 72% over the United States and by 65% over Europe. The temporal correlations are also improved in all the models.

Over India, the data assimilation increases tropospheric NO₂ columns in boreal winter-spring and reproduced the observed local maximum in May and minimum in July in all the models. Consequently, the seasonal amplitude is enhanced, leading to improved temporal correlations (from 0.20–0.87 to 0.94–0.99) while reducing the annual mean bias (from -0.27 to -0.14×10^{15} molecules cm⁻² to 0.12 to -0.02×10^{15} molecules cm⁻², by 40–86%). Over Southeast Asia, the persistent model negative biases are reduced (from -0.56 to -0.15×10^{15} molecules cm⁻² to -0.18 to 0.05×10^{15} molecules cm⁻², by 40–77%) with improved temporal correlations (from 0.86–0.96 to 0.97–1.00) in all the models. Over South America, data assimilation decreases tropospheric NO₂ columns by up to 25% in the biomass burning season in all the models, while the negative model biases in the biomass-burning off-season are mostly removed. The OMI NO₂ super-observation error is typically about 20–50 % of the tropospheric NO₂ columns over polluted areas, which are comparable to or larger than the analysis error.

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Over Africa, the annual mean negative model biases are reduced from -0.32 to -0.11×10^{15} molecules cm^{-2} to -0.08 to 0.03×10^{15} molecules cm^{-2} (by 75–100%) over northern Africa, from -0.20 to -0.02×10^{15} molecules cm^{-2} to -0.03 to 0.02×10^{15} molecules cm^{-2} (by 77–100%) over central Africa, and from -1.05 to -0.89×10^{15} molecules cm^{-2} to -0.47 to 0.45×10^{15} molecules cm^{-2} (by 48–63%) over southern Africa. The bias reductions over central and southern Africa are large in austral winter-spring. Some of the model negative biases (14–50 %, with a standard deviation of 12 %) remain over southern Africa in austral winter. The inadequate corrections of tropospheric NO_2 columns could be attributed to the insufficient model resolution, short chemical lifetime of NO_x , and biases in the simulated chemical equilibrium state. Spatial resolutions higher than the MIROC-Chem-H resolution ($1.1^\circ \times 1.1^\circ$) would be useful to represent emissions and pollutants over individual sources.

10 4.3 CO

Fig. 10 compares the latitudinal variations of surface CO concentration against the WDCGG observations from 59 stations. All the models underestimate the zonal and annual mean CO concentrations by 25–70 ppb in the NH extratropics and by 10–60 ppb in the tropics (except for MIROC-Chem-Chem-H), as in most of other CTMs (Shindell et al., 2006). In the SH extratropics, GEOS-Chem underestimates surface CO by 8–15 ppb, whereas MIROC-Chem and MIROC-Chem-H overestimate it by 5–20 ppb. Data assimilation reduced most of the model biases for the globe, except for the remaining negative model biases in the tropics in GEOS-Chem and AGCM-CHASER. The different analysis results of CO at high latitudes could mainly reflect differences in atmospheric transport from mid latitudes among the model. The effect of data assimilation is limited because of the lack of measurements at high latitudes.

Fig. 11 compares the seasonal variation of surface CO for the selected stations. All the models well captured the observed seasonal variations, except for relatively low temporal correlations (Table 4) over Barbados ($r=0.58$ – 0.85) and Ascension ($r=0.72$ – 0.94). In the NH extratropics, for most stations, all the models reveal too low CO throughout the year, with larger biases in boreal winter than in summer in the models. The summertime negative biases are largest in GEOS-Chem. In the tropics, the rapid increases in CO associated with biomass burning, e.g., in October over Barbados and in September over Ascension, are underestimated by all the models. In the SH extratropics, a large multi-model spread in the simulated CO exists in austral winter-spring, likely due to the different representation of poleward transport.

The reductions in the model negative bias in the NH owing to data assimilation can be found throughout the year, with annual mean bias reductions of 65–76% for Barrow, 41–74% for Cold Bay, and 57–94% for Iceland, with MIROC-Chem-H exhibiting smaller reductions. The insufficient corrections in MIROC-Chem-H suggest the need to optimize the settings for the assimilation of total column retrievals for the higher resolution system. Further efforts are clearly needed for improving the CO analyses in MIROC-Chem-H. The negative model biases are also reduced at NH low latitudes, i.e., by 68–94% for Bermuda, 48–97% for Midway, and 22–63% for Mauna Loa. Over Barbados, data assimilation corrects the timing of the maximum (in March) and minimum (in August) concentrations and improved the temporal correlation from 0.58–0.85 to 0.75–0.85 in all the models, whereas the observed peak in October is not represented by all the systems. In the SH, the multi-

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model spread is greatly reduced by data assimilation, while showing improved agreements with the observations except for excessively high concentrations over Ascension in June-July in MIROC-Chem-H.

The vertical gradients of CO differ largely among the models (Fig. 12a), with the largest decrease in the annual tropical mean concentrations with height in GEOS-Chem from the lower to upper troposphere. The sharp decrease could be associated with weaker deep convection. In addition, the larger OH concentrations in GEOS-Chem (Fig. 12b) suggest stronger chemical destruction in the middle and upper troposphere. In models other than GEOS-Chem, the tropical mean concentrations of CO show a clear maximum around 200 hPa. After data assimilation, the CO gradient became even larger in GEOS-Chem, in association with a large increase of OH in the upper troposphere. In other models, the data assimilation introduced sharper decreases in CO from about 850 to 600 hPa, as a consequence of the enhanced chemical destructions (i.e., the increased OH) at those levels. The increase in OH by data assimilation is largest in MIROC-Chem-H than in other models in the middle and upper troposphere, which have influenced the vertical profile of CO substantially.

In summary, the tropical annual mean CO gradient between the surface and 400 hPa is decreased by 1–7%, whereas the annual mean OH concentration is increased by 7–20% in the lower troposphere and 15–120% in the middle and upper troposphere in all the models. Therefore, the multi-constituent data assimilation provides strong constraints on the vertical profiles of CO and other species mainly through substantial changes in OH. Changes in OH are further discussed in Section 4.4. It is also suggested that, even after the multi-constituent data assimilation, the representations of the vertical profiles can differ among the models, reflecting both the different model configurations, e.g., in terms of deep convection and chemical reaction rates, and the lack of direct observational constraints on the vertical profiles.

4.4 OH

Because of the simultaneous assimilation of multiple-species data, the global distribution of various species, including OH, is modified considerably in the assimilation systems. The concentration of OH is directly related to the concentrations of species determining the primary production (ozone and H₂O), removal (CO and CH₄), and regeneration of OH (NO_x). Fig. 13 compares the global distributions of annual and tropospheric mean OH concentrations (averaged between the surface and 300 hPa). The multi-model comparisons reveal common characteristics such as higher concentrations in the tropics than in the extratropics and enhanced concentrations over central Africa, Indian Ocean, south and Southeast Asia, and tropical Atlantic. As summarized in Table 5, the simulated OH is higher in GEOS-Chem and AGCM-CHASER than other models over most of the major polluted areas such as eastern China, India, western Europe, India, Southeast Asia, and Africa. The multi-model standard deviation of OH is large over central Africa, northern India and around the Himalayas, Malay peninsula, western United States, Brazil, and over the southern tropics such as over the eastern Pacific and northern Australia (right-top figure in Fig. 13). The zonal mean OH from the tropics to subtropics is lower in MIROC-Chem-H than in other models by approximately 30–45% (Fig. 14). The zonal mean OH shows a strong latitudinal gradient around the subtropics. The ratio of OH in the NH tropics–subtropics (Equator–30°N) to the NH mid-latitudes (30°N–60°N) ranges from 1.42 (GEOS-Chem) to 1.71 (MIROC-Chem).

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Data assimilation largely modified global OH distributions in all the systems. The analyzed OH fields and data assimilation increments are often regionally localized, which demonstrates the importance of accurately representing different chemical regimes and local emissions for each region, for estimation of both regional and global OH distributions. The annual mean OH is increased in the SH extratropics by 10–25% in GEOS-Chem and AGCM-CHASER and by 30–50% in MIROC-Chem and MIROC-Chem-H, probably because of the increased ozone. MIROC-Chem-H shows large increases in OH by 20–40% over Africa, Southeast Asia, tropical Pacific, and central and South America, associated with the increased ozone and decreased CO. The NH exhibits large inter-model differences in OH increments, decreasing in GEOS-Chem by 10–40% with large increments over east Asia, the United States, and Europe and increasing in MIROC-Chem and MIROC-Chem-H by 15–30 % and by 20–40 % over the continents, respectively. The negative increments in GEOS-Chem are likely associated with the increased CO and decreased NO_x, whereas the positive increments in MIROC-Chem and MIROC-Chem-H could be attributed to the increased ozone and increased NO_x. The NH tropics–subtropics (Equator–30°N) to mid-latitudes (30°N–60°N) ratio of OH is increased in all the models by 1–15%, with a largest increase in GEOS-Chem (from 1.42 to 1.64).

Because of the data assimilation, the multi-model spread of OH is reduced by 24–58% over the major polluted areas of the globe such as over Europe (44%), China (31%), the United States (41%), and central Africa (50%) and South America (58%). At local scale, the multi-model spread is reduced largely over central eastern Africa (up to 55%), associated with adjustments made to biomass burning plumes, and over Indonesia (up to 40%) and the western US (up to 55%), corresponding to large changes in local NO_x and CO emissions and consequently in ozone productions. The improved multi-model consistency suggests that the multi-constituent data assimilation provides a more similar representation of the tropospheric chemistry system, by removing model errors in the relevant species in the individual systems. The obtained OH fields, which are less dependent on individual model performance due to reduced model errors in relevant species, demonstrate the potential of the multi-constituent (ozone, CO, and NO_x) data assimilation for various atmospheric chemistry studies including emission inversion and methane budget analyses. Because the chemical lifetimes of NO_x and CO are affected by the amount of OH, these changes once more suggest the importance of the simultaneous optimisation of the concentration and emissions on the entire tropospheric chemical system and the emission estimates.

The integrated analysis $\overline{x_m}$ shows slightly higher OH concentrations than the multi-model means for most regions, mainly reflecting largest OH spreads and smallest OH concentrations in MIROC-Chem-H among the models. The analysis spread of OH is determined by analysis spreads in various species such as ozone (c.f., Section 3.2) during model forecasts. Because of the different chemical mechanisms and model responses to given perturbations (c.f., Section 5), OH spreads differed by factor of up to 2.5 among the models for the regional means. The integrated uncertainty $\overline{\sigma_m^2}$ is smaller than the multi-model spreads by 20-50 % for most regions.

As summarized in Table 6, the north-to-south gradient of the tropospheric OH (averaged below 300 hPa) decreased owing to data assimilation in all the models, i.e., from 1.29–1.36 (1.32 ± 0.03) to 1.17–1.23 (1.19 ± 0.03), as similarly suggested by our previous analysis (Miyazaki et al., 2015). The simulated NH/SH ratio of OH simulated from the four models is in the

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range of 1.28 ± 0.10 in the ACCMIP multi-model estimates (Naik et al., 2013), whereas the values from the data assimilation runs are significantly lower. The data assimilation estimates are in better agreements with an observational estimate (0.97 ± 0.12) obtained using methyl chloroform observations (Patra et al., 2014). The significant changes in the global OH distributions, which are common to all the models, are important in propagating the observational information between various species and modulating the chemical lifetimes of many species, thus improving emission inversion. The simultaneous optimization of emissions and concentrations was essential to modify the global OH distributions. The increases (by 1–32 %) in the global mean OH concentrations by data assimilation in all the models, with the multi-model mean values of $1.12 \pm 0.18 \times 10^6$ mol/cm³ in the control runs and $1.26 \pm 0.10 \times 10^6$ mol/cm³ in the data assimilation as summarized in Table 6, suggest overestimated CH₄ lifetimes in the model simulations.

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5 Ozone and NO₂ response to NOx emissions

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5.1 Multi-model comparisons

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From a system analysis perspective, one of the fundamental questions in atmospheric chemistry is the sensitivity of a constituent like ozone to changes in surface emissions such as NOx emissions. With recent advances in estimating preindustrial ozone (Yeung et al, 2019), model sensitivities are the primary drivers of chemistry-climate estimates of quantities such as ozone radiative forcing (Bowman et al, 2013, Myhre et al., 2013). While these simulations describe relatively slow, equilibrium responses, data assimilation incremental updates provide statistics on “fast” responses within the short data assimilation windows. By simultaneously updating ozone and NOx emissions, multi-constituent data assimilation can yield insight into this fundamental quantity. We explore this potential by regressing both the ozone and NO₂ increments with respect to the NOx emission analysis increments [using the daily mean data assimilation outputs at each grid point](#).

As summarized in Table 7, the response of ozone and NO₂ analysis to emission perturbations (i.e., data assimilation increments) is largely different among the models. The NO₂ surface response to NOx emissions is well-correlated (correlation ≥ 0.93 for all models) but the response differs by almost a factor of 2 between GEOS-Chem and MIROC-Chem-H. Globally, this diversity holds between surface ozone concentration and NOx emission increments ($\frac{\Delta O_3}{\Delta ENOx}$) for these two models. However, the AGCM-CHASER ozone-NOx emissions response ($1.5 \text{ ppb}/(10^{-11} \text{ kgNm}^{-2}\text{s}^{-1})$) is the largest among all the models. On the other hand, the correlation between surface ozone and NOx emissions is relatively weak (correlation < 0.43) reflecting the much more complicated chemical and dynamical relationship. For polluted areas (greater than $3 \times 10^{-11} \text{ kgNm}^{-2}\text{s}^{-1}$, as shown in the brackets in Table 7), the largest response is AGCM-CHASER and MIROC-Chem, which is greater than the other two models by 40–180 %, with similar intercepts and correlations. The multi-model diversity reflects the different representation of NOx and VOC as well as dynamics, leading to different ozone production efficiencies. In the case of GEOS-Chem and MIROC-Chem-H, there appears to be a clearer relationship between $\frac{\Delta NO_2}{\Delta ENOx}$ and $\frac{\Delta O_3}{\Delta ENOx}$, suggesting that NOx chemistry plays a more dominant role in ozone formation than other factors. By separating these two responses,

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MOMO-Chem is able to quantify the responses of forward models with unique diagnostics, without making any sensitivity calculations.

Different model responses would directly impact the Kalman gain in Eq. 4, leading to a more efficient model error reduction.

Given the same predefined minimum values for the surface NO_x emission perturbation (c.f., Section 2.6), a larger ozone analysis uncertainty (through a larger forecast model spread) would be obtained in models with a stronger ozone response to NO_x emissions. In fact, stronger ozone response (Table 7) and larger analysis uncertainty (Fig. 2b) are consistently found in AGCM-CHASER and MIROC-Chem. Meanwhile, the ozone response to a given perturbation is dependent on the background condition because of the non-linear O₃-NO_x chemistry (e.g., Zaveri et al., 2003). The multi-constituent framework allows to evaluate model ozone response in a realistic condition while considering possible error ranges in precursor's emissions using emissions analysis increments (c.f., Section 6). The ozone analysis increments became substantially smaller in all the models for most cases by including the emission optimization, and the increments could be regarded as inherent and persistent model biases of individual models. Therefore, a systematic investigation of model ozone response and analysis increment in the multi-constituent data assimilation framework could benefit evaluation of future prediction of chemistry-climate system as a hierarchical emergent constraint that uses relationships between future and current climate states to constrain projections of climate response with observations (Bowman et al., 2018). They could also be useful for making effective ozone control strategies.

In addition, tropospheric ozone shows strong correlations with other species such as CO (Zhang et al., 2006) over regions such as continental outflow regions. The relationship can be included in the state vector to improve the tropospheric ozone analysis. The uncertainty information in the CO response to ozone obtained from the MOMO-Chem can be expected to provide useful information on model diagnostics and future predictions.

5.2 Implications for chemistry model predictions

By applying linear regressions to the multi-model integrated fields (c.f., Section 3.3), we evaluated model responses of surface ozone and NO₂ concentrations to NO_x emissions. We first produced the daily multi-model integrated fields at 1.1° x 1.1° resolution and then applied them to linear regressions. As shown by Fig. 15, the estimated model responses from the MOMO-Chem integrated fields provide unique information on fast responses to NO_x emissions. The surface NO₂ response exhibits a large seasonal variation in the NH, with a maximum value of about 2 ppb/(10⁻¹¹ kgNm⁻²s⁻¹) in January, reflecting the longer chemical lifetime of NO_x in winter. The rapid increases from September to December and decreases from January to March can be associated primarily with variations in temperature, OH, and NO₂ photolysis. The annual mean slope is about 40 % smaller in the tropics than in the NH (0.70 vs. 1.15 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)), because of the shorter chemical lifetime of NO_x in the tropics. The surface NO₂ and NO_x emissions in the integrated fields are well-correlated (coefficients>0.9) throughout the year both in the NH and the tropics. The inter-model differences (red shade) increase in

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winter in the NH, with a maximum standard deviation of 35 % in January, implying strong model-dependence of surface NO₂ given same NO_x emissions.

The ozone response shows an opposite seasonal cycle to the NO₂ response in the NH. It gradually increased from January to August by about 0.4 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)/month. It reaches 2.4 ppb/(10⁻¹¹ kgNm⁻²s⁻¹) in August with relatively large coefficients (0.3–0.6) in May–September. The large ozone response implies substantial photochemical productions of surface ozone over polluted areas in summer. Then, the slope decreases rapidly from August to October by about 1.1 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)/month, and it becomes negative in winter but with low coefficients (-0.3–0.2). The negative slopes, with a minimum value of -0.6 ppb/(10⁻¹¹ kgNm⁻²s⁻¹) in January, could be driven by the dilution effects over highly polluted areas.

In the tropics, the ozone response is stronger than in the NH (3.1 vs. 0.6 ppb/(10⁻¹¹ kgNm⁻²s⁻¹) for annual mean), with strongest responses of about 4.3 ppb/(10⁻¹¹ kgNm⁻²s⁻¹) in March and October. The different ozone production efficiency implies that any latitudinal shifts in NO_x emissions from the extratropics to the tropics would lead to increases in global tropospheric ozone, as suggested by Zhang et al. (2016), while showing strong seasonality. Our analysis indicates that the mean ozone response is comparable between the NH and the tropics in August and September. The seasonal variation in the tropics is likely associated with biomass burning events (e.g., Bowman et al., 2009; Jones et al., 2009; Parrington et al., 2012), with enhanced ozone responses over Southeast Asia during February–June (2.3–3.7 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)), over central America and tropical South America during April–July (2.8–5.3 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)), over central Africa in March (5.5 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)) and October (7.1 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)), and over India in March and October (5.1 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)). Although the surface ozone and NO_x emissions are well correlated in the multi-model integrated analysis throughout the year (coefficients>0.5), the large multi-model spreads (25–55%) suggest that individual models have large uncertainty in representing strong ozone productions, for instance, associated with VOCs emissions and chemistry that could result in different chemical regimes. The correlations of ΔENO_x and ΔO_3 among the models estimated at each point at each day were strongly dependent on season and location (not shown), which also provide information on the robustness (i.e., multi-model diversity) of the estimated ozone and NO₂ responses for each location and season.

Finally, the model responses differ significantly between the MOMO-Chem integrated fields (solid blue and red lines) and the mean of the individual model estimates obtained by averaging the model responses from individual model fields (solid white lines), especially when the model responses are strong. The multi-model integrated fields exhibit about 20 % larger NO₂ response in December and about 70 % larger ozone response in August than the mean of the individual model estimates in the NH. In the tropics the monthly ozone response is up to about 60 % larger in the multi-model integrated analysis. The different responses reflect non-Gaussian distributions of the individual model fields. The results imply that the observationally constrained, multi-model integrated fields provide fundamentally different fast chemical processes than those in the individual models. Meanwhile, the uncertainty-weighted multi-model integrated ozone fields showed closer agreements with independent observations than the multi-model averages in the lower troposphere (c.f., Section 4.1.2). This suggests that the MOMO-Chem framework provides improved estimates of the atmospheric states for many cases. With

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further investigations of the chemical relationships in the integrated fields, the MOMO-Chem framework would provide insights into ozone production processes to inform chemical predictions through relationships such as emergent constraints (Bowman et al., 2018). This example demonstrates the unique capability of the MOMO-Chem framework for various applications.

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4. Estimated emissions

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4.1 NOx emissions

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As summarized in Table 8 and shown in Fig. 16, the global total NOx emissions are increased by 12% in GEOS-Chem, 40% in AGCM-CHASER, 25% in MIROC-Chem, and 30% in MIROC-Chem-H due to data assimilation. The a posteriori global total emissions vary from 39.1 TgN (GEOS-Chem) to 51.9 TgN (AGCM-CHASER) with the multi-model mean of 47.6±5.8 TgN, in contrast to the a posteriori global total emissions varying from 37.1 TgN (GEOS-Chem) to 42.4 TgN (MIROC-Chem-H).

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The regional NOx emissions are increased in the models other than GEOS-Chem over the United States (with annual regional total emission increases of 10–22%), eastern China (2–34%) and over western Europe (7–23%). The a posteriori emissions over eastern China in these models (5.8–6.4 TgN) are closer to the HTAP-v2 2010 inventory (5.7 TgN) than those from EDGAR v4.2 (4.2 TgN). The emissions over Europe are largely increased in MIROC-Chem-H (by 23%) and AGCM-CHASER (by 24%). In GEOS-Chem, the emissions are decreased over most parts of eastern China (by 21% for regional total emissions), the United States (by 9%), and western Europe (by 21%), where the a posteriori emissions are obviously lower than the other estimates. As shown in Fig. 17, the multi-model mean of the a posteriori emissions shows strong NOx emissions over major polluted areas, while the multi-model spread is large for eastern China, the eastern United States, around Mexico city, western Europe, and South Africa.

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The multi-model spread of the a posteriori regional NOx emissions is smaller than the assumed a priori emission uncertainty (i.e., by 40 %) for all the polluted areas (Table 8), while the a priori emission spreads could influence the obtained a posteriori emission spreads. From sensitivity calculations, we confirmed that the daily emission updates greatly reduce the dependence of the a priori emissions for many regions (now shown).

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For biomass burning areas, the emissions are increased in the all the models by 17–25% over southeast Asia, by 13–30% over northern Africa, and by 4–39% over central Africa. The positive increments over northern and central Africa are smallest in MIROC-Chem-H, likely due to the use of updated biomass burning emission inventories (GFED v4) as well as updated NO₂ retrievals. The a posteriori emissions for the biomass burning areas are similar between the four systems: 0.6–0.8 TgN (16% standard deviation) for southeast Asia, 2.9–3.2 TgN (4%) for northern Africa, and 2.2–2.8 TgN (10%) for central Africa. Over South Africa, the emissions are increased by 29–50% in all the systems, with a large multi-model spread of the a posteriori emissions (0.4–0.9 TgN, 31% standard deviation).

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The seasonal variations in NO_x emissions are largely modified by data assimilation for many regions, with common features for all of the four systems (Fig. 18). Over eastern China, the emissions in early summer (June) and winter (November–January) are enhanced in all the systems, which could be associated with emissions from soils and the use of wintertime heating, respectively. The magnitude of the summertime enhancement differs among the models, which could reflect the different chemical lifetime of NO_x under strong photolysis conditions. Over the United States and Europe, large enhancements in late spring and early summer and subsequently in the seasonal amplitude are commonly found in all the systems. Also, the timing of maximum emissions in summer moves forward by a few months (from one to two months over eastern China and Europe and from two to three months over the United States) due to data assimilation in all the systems, likely due to underestimated soil emissions in early summer, which has also been suggested by Oikawa et al. (2015).

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Over India, the a posteriori emissions reveal strong increases from April to June in all the systems, which is likely associated with open biomass burning that is not represented by the bottom-up inventories (Venkataraman et al., 2006). Over Southeast Asia, the emissions are mostly increased throughout the year in all the systems, with large increases in the biomass burning season (boreal spring), except in MIROC-Chem-H. Over South America, the emissions in the biomass-burning season (August–September) are decreased by 30–50 % due to data assimilation in all the systems. The negative increments suggest an overestimation of emissions by forest fires in dry conditions in the GFED v2, v3, and v4 inventories, as similarly suggested by Castellanos et al. (2014) for the GFED v3 inventory. In contrast, the emissions are increased in the biomass-burning off-season by 30–60% in all the systems.

Over northern Africa, in the biomass burning season (boreal winter), fire-related emission factors in the GFED v3 inventory (AGCM-CHASER, MIROC-Chem) are suggested to be too low by 20–30%, whereas those in the GFED v2 (GEOS-Chem) and v4 (MIROC-Chem-H) inventories are too high by 50% and by 10%, respectively. The multi-model consistency is high throughout the year over northern Africa. Over central Africa, the emissions in the biomass burning season (July–September) are increased by 30–45 % from the GFED v2 and v3 inventories and decreased by 20 % from the GFED v4 inventory.

The differences in the a posteriori emissions could be explained by the different model configurations, such as the chemical lifetime of NO_x, vertical mixing, lightning NO_x sources, and model resolutions for many regions. The obtained inter-model differences are generally larger for industrialized areas (12–31%) than biomass burning areas (4–21%), suggesting the substantial influences of different urban chemistry configurations and/or model settings for anthropogenic NO_x emissions (e.g., NO₂:NO ratio). Large uncertainties in chemical NO_x loss have the strong effects on the simulated NO_x lifetime and the accuracy of top-down NO_x source inversion (Lin et al., 2012; Stavrakou et al., 2013).

As discussed in Section 5, the NO₂ response to NO_x emissions ($\frac{\Delta \text{NO}_2}{\Delta \text{NO}_x}$) is stronger in GEOS-Chem than in other models probably associated with a weaker chemical NO_x loss. This suggests that the same levels of tropospheric NO₂ columns can be explained by smaller amounts of NO_x emissions, and this could explain the lower a posteriori NO_x emissions evaluated in this model with respect to other models. The multi-model differences in simulated NO_x levels could also explain parts of the diversity in model ozone response to NO_x emissions (Section 5). In addition, processes such as vertical mixing and lightning

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NO_x productions are strongly model-dependent and influence the responses of NO₂ to NO_x emissions. Meanwhile, the updated NO₂ retrievals were assimilated only in MIROC-Chem-H, whereas the diurnal emission variability was optimized from data assimilation in MIROC-Chem and MIROC-Chem-H. These differences could also lead to model dependence on emission estimates and model responses to the updated emissions. To fully understand the inter-model differences of the a posteriori emissions, their influence needs to be explored.

6.2 CO emissions

The global total CO emissions are increased by 50% in GEOS-Chem, 51% in AGCM-CHASER, 12% in MIROC-Chem, and 25% in MIROC-Chem-H due to data assimilation, with a large diversity in the estimated global total emissions (943.3–1376.9 TgCO, with 16% multi-model standard deviation), as summarized in Table 8. The CO emissions are increased by 18–119% over eastern China, 9–122% over the United States, and 37–146% over Europe in all the models, suggesting significant underestimations of anthropogenic CO emissions in the bottom-up inventories used as a priori emissions. Using the same a priori emission data sets, the positive increments are larger in AGCM-CHASER than in MIROC-Chem over eastern China, western Europe, and the United States, likely associated with underestimated (or overestimated) chemical production (destruction), as similarly discussed by Jiang et al. (2015). In fact, AGCM-CHASER reveals relatively high OH concentrations corresponding to large CO emissions (c.f., Table 5) over these regions. The multi-model spread of the a posteriori emissions is large over these industrialized regions (13–32%), with largest spreads over central eastern China (Fig. 17).

The a posteriori emissions exhibit a wintertime peak over eastern China in the models other than MIROC-Chem and over Europe other than GEOS-Chem (Fig. 19). Stein et al. (2014) commonly found that large corrections are needed for CO emissions in winter–spring seasons for industrialized areas. Because the chemical destructions are weak in these seasons, the results suggest underestimations in the bottom-up inventories rather than model errors in OH. Meanwhile, the distinct differences in the seasonality as well as mean strength of the a posteriori emissions highlight strong model dependence of CO emission estimations for the anthropogenic emission regions.

Over India, a pronounced peak in boreal spring is commonly introduced, and the a posteriori emissions show similar seasonality between NO_x and CO in all the systems. Over southeast Asia, the annual total emissions are decreased by 3–11% in all the models, with an enhanced multi-model discrepancy in the biomass burning season. Over South America, the annual total emissions are decreased by 27–41% in the models except for MIROC-Chem-H, with large reductions in the biomass burning season. The results suggest a common overestimation problem in fire-related emission factors for both CO and NO_x (c.f., Section 6.1) in GFED v2 and v3 over South America. In African regions, although the analyzed seasonal variations are similar, the annual total emissions reveal large discrepancies among the models (20–35%). In comparison with the averaged values in other models, the estimated emissions are larger by 28% in GEOC-Chem over northern Africa, by 27% in MIROC-Chem-H over central Africa, and by 40% in GEOS-Chem over southern Africa. The multi-model spread of the a posteriori emissions is large over major biomass burning regions, such as eastern Central Africa, northern Thailand, and Amazon (Fig.

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17). The substantial inter-model differences highlight the importance of chemistry and dynamics in understanding the carbon budget over these regions.

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The inter-model differences in data assimilation adjustments and a posteriori emissions are generally larger for CO than for NO_x, which can be associated with different representations of atmospheric transports such as convective transport and vertical mixing (e.g., Jiang et al., 2015) because of the longer chemical lifetime of CO. Also, differences in the chemical production of CO from the oxidation of NMHCs and the chemical lifetime of CO, which were not optimized by the data assimilation, could lead to large multi-model discrepancies in CO simulations and emission estimates, as similarly discussed by Gaubert et al. (2016). Thus, the differences in various factors can enhance the multi-model discrepancies in the a posteriori CO emissions.

Our results suggest requirements for further development of the CO emission optimization framework to obtain more consistent estimates, for instance, by using a longer assimilation window and a larger ensemble size. The data assimilation windows employed (2–6 hours) are clearly insufficient to optimize surface CO emissions using remote measurements with considering the influence of atmospheric transports. The estimated CO emissions were also sensitive to the choice of other parameters such as localization length and covariance inflation factor, while optimal values of these parameters are expected to differ among the models mainly associated with different representations of atmospheric transport among the models. Optimizing these parameters for individual models would thus also be important. Meanwhile, adding observational constraints, for instance, on NMHCs emissions from formaldehyde measurements (e.g., Stavrou et al., 2009), and considering inter-species correlations (e.g., between NO_x and CO) would help to improve the data assimilation analysis and multi-model consistency. Some of the increments seem to be inadequate in MIROC-Chem-H, which could suggest different optimal settings requirements for the assimilation of total column retrievals and for higher resolution models.

7. Conclusions and discussion

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We developed the MOMO-Chem framework to integrate a portfolio of data assimilation analyses obtained using forward CTMs (GEOS-Chem, AGCM-CHASER, MIROC-Chem, MIROC-Chem-H) in a state-of-the-art ensemble Kalman filter data assimilation system. The data assimilation was used to simultaneously optimize both chemical concentrations and emissions of multiple species through ingestion of a suite of measurements (ozone, NO₂, CO, HNO₃) from multiple satellite sensors. The framework was used to demonstrate the importance of the performance of forecast models for tropospheric chemistry data assimilation and to provide multi-model integrated information on the tropospheric chemistry system.

The forecast performance of the models differed for many species because of the different model configurations. In the absence of data assimilation, the multi-model discrepancies and forecast model errors for ozone against the ozonesonde observations were obvious, with annual mean biases ranging from -5.1 to 1.4 ppbv (from -6.2 to -0.7 ppbv) in the lower troposphere and from -4.0 to 16.1 ppbv (from 2.8 to 20.5 ppbv) in the middle and upper troposphere at NH (SH) mid latitudes. Tropospheric NO₂ columns are largely underestimated by the models other than GEOS-Chem over major polluted

areas, whereas the simulated column peaks in over biomass burning areas are largely biased. For CO, all the models underestimated surface concentrations in the NH by 20–80 ppb.

Multi-constituent assimilation greatly improved the multi-model consistency and the level of agreements with independent measurements. In comparison with the ozonesonde measurements, the annual mean bias is reduced by about 40–80% in the NH, by 50–90% in the tropics, and 45–95% in the SH in the middle and upper troposphere, while reducing the multi-model spread of annual mean ozone by 20–60% in the NH and 30–85% in the SH. Data assimilation also reduced the model biases in tropospheric NO₂ columns by more than 40% for both major industrialized and biomass burning areas while improving the seasonal variations. The model negative biases of CO in the NH are also reduced by about 40–95% in all the models. These results demonstrate that harnessing the current observing system provides sufficient constraints to greatly reduce the influences of model errors and to provide the consistent concentration analysis.

The multi-model comparisons of tropospheric OH reveal common features of global distributions but with obvious differences in mean concentration levels among the models. Data assimilation increments for OH differ largely among the models, decreasing in GEOS-Chem by 10–40% over east Asia, the United States, and Europe and increasing in MIROC-Chem and MIROC-Chem-H over most parts of the NH by 15–40%. In spite of the different increments, the multi-constituent data assimilation reduced the multi-model spread by about 25–60% over major polluted areas, while the north-to-south hemispheric ratio is reduced in all the models from 1.32 ± 0.03 to 1.19 ± 0.03 . These results suggest that the multi-constituent data assimilation framework can be used to provide a common representation of the tropospheric chemistry system that is less dependent on individual model performance.

The MOMO-Chem framework provides possible uncertainty ranges in the a posteriori emissions in the current data assimilation framework due to model errors, which are quantified in 4–31% for NO_x and 13–35% for CO regional emissions from a multi-model spread of the a posteriori emissions. Meanwhile, the multi-model analysis commonly suggests potential problems in the bottom-up emission inventories, such as underestimation of soil NO_x emissions in early summer at NH mid-latitudes, underestimations of open biomass burning emissions in spring over India, and overestimation of emissions by forest fires in dry conditions over South America. For NO_x emissions, the large inter-model discrepancies are attributable to the chemical lifetime of NO_x, vertical mixing, lightning NO_x sources, and model resolution. For CO emissions, the a posteriori emission differences are largely attributable to different representations of atmospheric transport, such as convective transport and vertical mixing, as well as chemical destruction and production and the use of a short assimilation window. The larger discrepancy for CO emissions than for NO_x emissions suggest the need to further develop the CO emission optimization framework, for instance, by using a longer assimilation window and a larger ensemble size.

The response of surface NO₂ and ozone concentrations to NO_x emission perturbations is largely different among the models. A stronger ozone response could help to reduce model errors more efficiently through changes in the model ozone equilibrium state from the emission optimization. The multi-constituent framework allows us to evaluate model ozone responses in a realistic condition while considering possible error ranges in precursor's emissions. The ozone and emission analysis increment information obtained using the optimized emissions can be used as a diagnostic to quantify model

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sensitivities related to chemistry and transport. Thus, a systematic investigation of model ozone response and analysis increment in the multi-constituent data assimilation framework could benefit evaluation of future prediction of chemistry-climate system as a hierarchical emergent constraint (Bowman et al., 2018). By using the multi-model integrated fields from MOMO-Chem [and applying the linear regressions](#), we estimated the surface concentration responses to NO_x emissions in the NH to be largest in January for NO₂ (2.0 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)) and in August for ozone (2.4 ppb/(10⁻¹¹ kgNm⁻²s⁻¹)). The estimated ozone response was larger in the tropics than in the NH, implying that any latitudinal shifts in NO_x emissions from the extratropics to the tropics would lead to increases in global tropospheric ozone. The obtained results also suggest that the multi-model integrated fields could provide fundamentally different chemical relationships than those in the individual models, which would inform chemical predictions through relationships such as emergent constraints. [Meanwhile, more research is needed to comprehend detailed chemical mechanisms](#). This example demonstrates the unique capability of MOMO-Chem for various applications.

In summary, the MOMO-Chem framework can be used to generate an ensemble of data assimilation analyses, and to provide integrated unique information on the tropospheric chemistry system including precursor's emissions, while directly accounting for structural uncertainty. Meanwhile, the framework provides uncertainty ranges in data assimilation analyses including the a posteriori emissions due to model errors. The information on the uncertainty obtained from the multi-model framework could be used to suggest requirements for the development of the individual models and observations. To obtain highly consistent data assimilation fields, increasing observational constraints and/or optimization of model parameters, such as VOCs emissions, would be needed. Also, improving background error information (e.g., by using multi-model ensembles), considering inter-species emission correlations, and increasing the ensemble size would be useful to improve the performance of the individual data assimilation systems. Comparing different data assimilation methods, such as EnKF vs 4D-VAR, would also be important to investigate whether we are able to produce a consistent data assimilation analysis that is independent of both the data assimilation scheme and forecast model performance.

Author contributions

KM and KWB designed the study. KM, TW, and KY developed the data assimilation code and set up the data assimilation experiments. KS developed the model code. KM performed the model simulations and data assimilation experiments. KM and KWB prepared the manuscript with contributions from all co-authors.

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Table 1: Summary of the forecast models used in this study

| | GEOS-Chem | AGCM-CHASER (TRC-1) | MIROC-Chem | MIROC-Chem-H (TCR-2) | |
|----------------------------|---|---|---|--|------------------------|
| Horizontal resolution | 2°x2.5° | 2.8°x2.8° | 2.8°x2.8° | 1.1°x1.1° | |
| Vertical resolution | 47 layers to 0.1 hPa (hybrid) | 32 layers to 4 hPa (sigma) | 32 layers to 4 hPa (hybrid) | 32 layers to 4 hPa (hybrid) | |
| Forecast model | GEOS-Chem v9 (adjoint v35) | CCSR/NIES/FRCGC AGCM-CHASER | MIROC-Chem | MIROC-Chem | |
| Chemistry | 43 species, 318 reactions | 47 species, 88 reactions | 92 species, 262 reactions | 92 species, 262 reactions | |
| Meteorological data | GEOS-5 | Nudged to NCEP- DOE/AMIP-2 | Nudged to ERA-Interim | Nudged to ERA-Interim | |
| Assimilated data | OMI NO ₂ (DOMINO2), SCIAMACHY NO ₂ (DOMINO2), TES ozone (v5) MOPITT CO (v6 NIR) MLS ozone & HNO ₃ (v3.3) | OMI NO ₂ (DOMINO2), SCIAMACHY NO ₂ (DOMINO2), TES ozone (v5) MOPITT CO (v6 NIR) MLS ozone & HNO ₃ (v3.3) | OMI NO ₂ (DOMINO2), SCIAMACHY NO ₂ (DOMINO2), TES ozone (v5) MOPITT CO (v6 NIR) MLS ozone & HNO ₃ (v3.3) | OMI NO ₂ (QA4ECV), SCIAMACHY NO ₂ (QA4ECV), TES ozone (v6) MOPITT CO (v7J) MLS ozone & HNO ₃ (v3.3) | |
| A priori emissions | EDGAR_3, NEI2008, RETRO, GFED2 | EDGAR 4.2 GFED 3.1, GEIA | EDGAR 4.2, GFED 3.1, GEIA | HTAP v2, GFED 4, GEIA | |
| State vector | Concentrations of 43 species + emissions (NO _x , CO, LNO _x) | Concentrations of 35 species + emissions (NO _x , diurnal variability, CO, LNO _x) | Concentrations of 35 species + emissions (NO _x , diurnal variability, CO, LNO _x) | Concentrations of 35 species + emissions (NO _x , diurnal variability, CO, SO ₂ , LNO _x) | |
| Reference model) | (Forecast model) | Henze et al. (2007) | Sudo et al. (2002) | Watanabe et al. (2011) | Sekiya et al. (2018) |
| Reference assimilation) | (Data) | This study | Miyazaki et al. (2012a, 2012b, 2014, 2015) | Miyazaki et al. (2017) | Miyazaki et al. (2019) |

Deleted: Table 2 Linear regression of changes in surface NOx emissions (in 10^{11} kgNm⁻²s⁻¹) and surface concentrations of ozone and NO₂ (in ppb) by data assimilation in May 2007 over areas with NOx emission changes greater than 5×10^{-13} kgNm⁻²s⁻¹ in the four models. The results for regions without strong NOx emission changes (greater than 3×10^{11} kgNm⁻²s⁻¹, that could suffer from dilution effects) are shown in brackets.¶

¶ ... [2]

Table 2: Annual mean bias of the mean ozone concentrations (in ppbv) between the data assimilation or control run (in brackets) and the ozonesonde observations from the WUOUC network for 850–500 hPa and 500–200 hPa in ppb for five latitudinal bands, SH high latitudes (55°S–90°S), SH mid-latitudes (15°S–55°S), tropics (15°S–15°N), NH mid-latitudes (15°N–55°N), and NH high latitudes (55°N–90°N). The results are shown for individual models, multi-model mean (mean±1 sigma), and integrated analysis ($\bar{x}_m \pm \sigma_m^2$).

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| | | 90°S–55°S | 55°S–15°S | 15°S–15°N | 15°N–55°N | 55°N–90°N |
|--------------------------------|--------------------------------|-------------------------------|-------------------------------|-------------------------------|---------------------------------|-------------------------------|
| 850–500 hPa | GEOS-Chem | (-2.3) 7.4 | (-0.7) 2.2 | (-1.2) 0.0 | (1.4) 3.4 | (-2.6) 2.3 |
| | AGCM- CHASER | (-2.2) 2.4 | (-2.0) 2.7 | (-1.0) 3.6 | (-2.0) 5.2 | (-4.7) 4.3 |
| | MIROC-Chem | (-4.6) 0.9 | (-1.5) 1.9 | (2.2) 4.6 | (-1.3) 2.6 | (-4.7) 1.7 |
| | MIROC-Chem- H | (-4.5) 3.6 | (-6.2) 1.0 | (-5.8) 2.3 | (-5.1) 1.9 | (-3.6) 3.2 |
| | <u>Multi-model mean</u> | <u>(-3.4±2.0) 3.6±2.5</u> | <u>(-2.5±2.5) 1.9±1.1</u> | <u>(-1.4±3.1) 2.7±1.8</u> | <u>(1.8±2.7) 3.3±1.6</u> | <u>(-3.9±1.4) 2.9±1.7</u> |
| | <u>Integrated analysis</u> | <u>4.0±3.7</u> | <u>1.6±2.6</u> | <u>1.6±1.1</u> | <u>2.8±2.7</u> | <u>2.2±3.0</u> |
| | GEOS-Chem | (8.7) 4.7 | (10.5) 3.0 | (1.3) -0.3 | (-4.0) -0.9 | (-29.9) -9.2 |
| | AGCM- CHASER | (29.9) 1.6 | (8.6) -1.9 | (-3.2) 0.3 | (0.3) -1.9 | (-13.5) -6.2 |
| | MIROC-Chem | (28.7) 1.0 | (20.5) -1.3 | (0.4) -0.2 | (16.1) -0.2 | (12.9) -6.1 |
| | MIROC-Chem- H | (24.8) 1.4 | (2.8) 0.3 | (-11.8) 3.0 | (4.1) -2.5 | (29.7) -5.5 |
| <u>Multi-model mean</u> | <u>(23.0±10.7) 2.2±2.6</u> | <u>(10.6±7.2) 0.3±2.4</u> | <u>(-3.3±5.3) 0.7±1.5</u> | <u>(4.1±8.6) -1.4±2.1</u> | <u>(-0.2±24.0) -6.7±3.0</u> | |
| <u>Integrated analysis</u> | <u>3.4±6.7</u> | <u>1.1±4.0</u> | <u>1.7±1.7</u> | <u>-1.5±4.8</u> | <u>-8.4±8.0</u> | |

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Table 3: Annual mean bias and temporal correlation of regional mean tropospheric NO₂ columns: the data assimilation minus the satellite retrievals from OMI in 10¹⁵ molecules cm⁻². The results of the control run are also shown in brackets. The results are shown for eastern China (110–123°E, 30–40°N), Europe (10°W–30°E, 35–60°N), USA (70–125°W, 28–50°N), South America (50–70°W, 20°S–Equator), northern Africa (20°W–40°E, Equator–20°N), central Africa (10–40°E, Equator–20°S), and southern Africa (25–34°E, 22–31°S). The results are shown for individual models and multi-model mean (mean±1 sigma).

| | E China | E USA | Europe | India | SE Asia | S America | N Africa | C Africa | S Africa | |
|--------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Bias | GEOS-Chem | (0.13) | (0.29) | (0.60) | (-0.20) | (-0.15) | (-0.02) | (-0.11) | (-0.11) | (-0.89) |
| | | -0.16 | 0.11 | 0.21 | -0.05 | 0.05 | 0.02 | 0.00 | 0.00 | -0.46 |
| | AGCM-CHASER | (-2.07) | (-0.51) | (-0.82) | (-0.27) | (-0.44) | (-0.06) | (-0.32) | (-0.39) | (-1.05) |
| | | -0.69 | -0.18 | -0.41 | -0.12 | -0.18 | -0.02 | -0.08 | -0.09 | -0.45 |
| | MIROC-Chem | (-1.59) | (-0.26) | (-0.32) | (-0.15) | (-0.30) | (-0.11) | (-0.30) | (-0.39) | (-0.93) |
| | | -0.60 | -0.14 | -0.35 | -0.09 | -0.18 | -0.03 | -0.07 | -0.09 | -0.34 |
| | MIROC-Chem-H | (-0.37) | (-0.31) | (-0.56) | (-0.14) | (-0.56) | (-0.19) | (-0.23) | (-0.23) | (-0.96) |
| | | -0.39 | -0.13 | -0.24 | -0.02 | -0.13 | 0.01 | 0.03 | 0.01 | -0.47 |
| | Multi-Model | (-1.04±0.94) | (-0.34±0.11) | (-0.58±0.20) | (-0.18±0.06) | (-0.36±0.18) | (-0.10±0.07) | (-0.24±0.09) | (-0.28±0.14) | (-0.96±0.07) |
| | | -0.46±0.23 | -0.09±0.13 | -0.20±0.28 | -0.07±0.04 | -0.11±0.11 | -0.01±0.02 | -0.03±0.05 | -0.04±0.05 | -0.43±0.06 |
| T-Corr | GEOS-Chem | (0.97) | (0.70) | (0.95) | (0.87) | (0.96) | (0.97) | (0.90) | (0.96) | (0.38) |
| | | 1.00 | 0.86 | 0.97 | 0.94 | 0.99 | 1.00 | 0.98 | 0.99 | 0.92 |
| | AGCM-CHASER | (0.95) | (0.83) | (0.95) | (0.66) | (0.95) | (0.94) | (0.94) | (0.96) | (0.96) |
| | | 1.00 | 0.97 | 0.97 | 0.98 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 |
| | MIROC-Chem | (0.96) | (0.80) | (0.94) | (0.20) | (0.92) | (0.91) | (0.96) | (0.96) | (0.98) |
| | | 0.99 | 0.97 | 0.97 | 0.99 | 1.00 | 0.99 | 0.99 | 1.00 | 1.00 |
| | MIROC-Chem-H | (0.98) | (0.58) | (0.90) | (0.86) | (0.86) | (0.98) | (0.99) | (0.99) | (0.98) |
| | | 1.00 | 0.94 | 0.98 | 0.98 | 0.97 | 0.99 | 0.99 | 1.00 | 0.98 |
| | Multi-Model | (0.97±0.01) | (0.73±0.11) | (0.94±0.02) | (0.64±0.31) | (0.92±0.05) | (0.95±0.03) | (0.95±0.04) | (0.97±0.02) | (0.83±0.30) |
| | | 1.00±0.01 | 0.94±0.05 | 0.97±0.01 | 0.97±0.02 | 0.99±0.01 | 1.00±0.01 | 0.99±0.01 | 1.00±0.01 | 0.98±0.04 |

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Table 4: Annual mean bias and temporal correlation of surface CO. Units are ppb. The observations used are the WDCGG observations. The results of the control run are also shown in brackets. The results are shown for individual models and multi-model mean (mean±1 sigma).

| | Barrow | Cold Bay | Iceland | Bermuda | Midway | Mauna Loa | Barbados | Ascension | Cape Grim | Showa | South Pole | |
|------|---------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Bias | GEOS-Chem | (-47) -11 | (-48) -12 | (-40) -3 | (-34) 7 | (-44) -22 | (-33) -13 | (-30) -13 | (-12) -7 | (-11) -6 | (-10) -6 | (-6) -3 |
| | AGCM-CHASER | (-43) -14 | (-50) -21 | (-45) -12 | (-32) -2 | (-35) -1 | (-28) -16 | (-19) -16 | (-19) -18 | (-2) -1 | (-5) -5 | (-1) 3 |
| | MIROC-Chem | (-23) -8 | (-41) -24 | (-30) -13 | (-19) -6 | (-19) -1 | (-23) -18 | (-17) -17 | (-4) -12 | (6) -2 | (5) -4 | (10) 14 |
| | MIROC-Chem-H | (-35) -34 | (-30) -28 | (-23) -23 | (-13) -13 | (-18) -20 | (-6) -9 | (-2) -9 | (10) 4 | (18) 7 | (17) 3 | (23) 9 |
| | Multi-Model | (-37±11) -17±12 | (-42±9) -21±7 | (-35±10) -13±8 | (-25±13) -3±12 | (-29±12) -11±9 | (-23±12) -14±4 | (-17±12) -14±4 | (-11±6) -8±9 | (-9±7) -1±5 | (-9±6) -3±4 | (-10±9) 6±7 |
| | GEOS-Chem | (0.94) 0.90 | (0.99) 0.85 | (0.99) 0.95 | (0.95) 0.95 | (0.99) 0.94 | (0.99) 0.96 | (0.85) 0.75 | (0.72) 0.90 | (0.96) 0.96 | (0.97) 0.96 | (-0.24) 0.20 |
| | AGCM-CHASER | (0.80) 0.97 | (0.54) 0.84 | (0.74) 0.94 | (0.89) 0.97 | (0.70) 0.96 | (0.85) 0.92 | (0.58) 0.85 | (0.94) 0.96 | (0.75) 0.75 | (0.99) 0.99 | (0.44) -0.13 |
| | MIROC-Chem | (0.74) 0.80 | (0.71) 0.77 | (0.89) 0.95 | (0.97) 0.96 | (0.88) 0.94 | (0.88) 0.96 | (0.64) 0.83 | (0.89) 0.90 | (0.96) 0.96 | (0.97) 0.97 | (0.35) 0.27 |
| | MIROC-Chem-H | (0.88) 0.90 | (0.95) 0.90 | (0.98) 0.96 | (0.95) 0.92 | (0.96) 0.94 | (0.96) 0.96 | (0.80) 0.81 | (0.78) 0.71 | (0.98) 0.95 | (0.98) 0.99 | (0.47) 0.69 |
| | Multi-Model | (0.84±0.09) 0.89±0.07 | (0.80±0.21) 0.84±0.05 | (0.90±0.12) 0.95±0.01 | (0.94±0.03) 0.95±0.02 | (0.88±0.13) 0.95±0.01 | (0.92±0.07) 0.95±0.02 | (0.72±0.13) 0.81±0.04 | (0.83±0.10) 0.86±0.11 | (0.91±0.10) 0.91±0.10 | (0.98±0.01) 0.98±0.01 | (0.26±0.33) 0.26±0.34 |

Table 5: Annual and regional mean OH concentration at 700 hPa, Units are 10^6 mol/cm^3 . The results of the control run are also shown in brackets. The results are shown for individual models, multi-model mean (mean \pm 1 sigma), and integrated analysis ($\bar{x}_m \pm \sigma_m^2$). Changes in the multi-model spread due to data assimilation (Aspread, in %) are also shown.

| | E China | E USA | Europe | India | SE Asia | S America | N Africa | C Africa | S Africa |
|------------------------------------|--|--|--|--|--|--|--|--|--|
| GEOS-Chem | 1.9 (2.2) | 1.5 (1.8) | 1.2 (1.5) | 2.5 (2.5) | 2.3 (2.2) | 1.2 (1.1) | 2.1 (2.1) | 2.1 (2.1) | 2.2 (2.1) |
| AGCM-CHASER | 2.4 (2.5) | 1.7 (1.7) | 1.4 (1.4) | 2.6 (2.6) | 2.2 (2.0) | 1.2 (1.2) | 2.3 (2.1) | 1.9 (1.6) | 2.4 (2.1) |
| MIROC-Chem | 2.1 (1.9) | 1.5 (1.3) | 1.3 (1.1) | 2.4 (2.1) | 2.1 (1.8) | 1.3 (1.1) | 2.4 (2.0) | 1.9 (1.5) | 2.1 (1.7) |
| MIROC-Chem-H | 1.6 (1.4) | 1.3 (1.1) | 1.1 (1.0) | 1.9 (1.7) | 1.6 (1.3) | 1.1 (0.7) | 1.8 (1.4) | 1.7 (1.3) | 1.7 (1.1) |
| Multi-model mean | 2.0 \pm 0.3 (2.0 \pm 0.4) | 1.5 \pm 0.2 (1.5 \pm 0.3) | 1.3 \pm 0.1 (1.3 \pm 0.2) | 2.3 \pm 0.3 (2.2 \pm 0.3) | 2.0 \pm 0.3 (1.8 \pm 0.3) | 1.2 \pm 0.1 (1.0 \pm 0.2) | 2.1 \pm 0.2 (1.9 \pm 0.3) | 1.9 \pm 0.2 (1.6 \pm 0.3) | 2.1 \pm 0.3 (1.8 \pm 0.4) |
| Δ spread [%] | -31 | -41 | -44 | -25 | -27 | -58 | -16 | -50 | -24 |
| Integrate analysis | 2.0\pm0.2 | 1.5\pm0.1 | 1.3\pm0.1 | 2.5\pm0.2 | 2.2\pm0.2 | 1.2\pm0.1 | 2.1\pm0.1 | 2.0\pm0.2 | 2.3\pm0.2 |

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Table 6: Interhemispheric gradient (NH/SH) and global mean (with area weight) concentration (in 10^6 mol/cm³) of tropospheric mean OH (averaged between the surface and 300 hPa) from the control and data assimilation runs. The results are shown for individual models and multi-model mean (mean \pm 1 sigma).

| | | GEOS-Chem | AGCM-CHASER | MIROC-Chem | MIROC-Chem-H | Multi-model |
|-------------|--------------|-----------|-------------|------------|--------------|-----------------|
| NH/SH ratio | Model | 1.30 | 1.36 | 1.29 | 1.31 | 1.29 \pm 0.03 |
| | Assimilation | 1.17 | 1.23 | 1.18 | 1.21 | 1.18 \pm 0.03 |
| Global mean | Model | 1.31 | 1.23 | 1.13 | 0.82 | 1.12 \pm 0.18 |
| | Assimilation | 1.31 | 1.31 | 1.34 | 1.09 | 1.26 \pm 0.10 |

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Table 7: Linear regression of changes in surface NOx emissions (in 10^{-11} kgNm⁻²s⁻¹) and surface concentrations of ozone and NO₂ (in ppb) by data assimilation in May 2007 over areas with NOx emission changes greater than 5×10^{-13} kgNm⁻²s⁻¹ in the four models. The results for regions without strong NOx emission changes (greater than 3×10^{-11} kgNm⁻²s⁻¹, that could suffer from dilution effects) are shown in brackets.

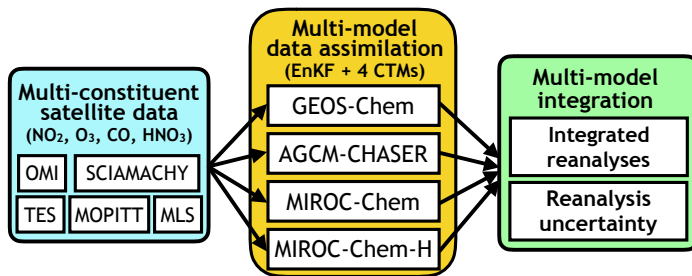
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| | | <u>Slope</u> (ppb/(10^{-11} kgNm ² s ⁻¹)) | <u>Intercept</u> (ppb) | <u>Correlation</u> |
|-----------------------|---------------------|--|---------------------------|-----------------------|
| <u>Ozone</u> | <u>GEOS-Chem</u> | <u>1.2</u> (1.8) | <u>2.2</u> (2.2) | <u>0.34</u> (0.34) |
| | <u>AGCM-CHASER</u> | <u>1.5</u> (3.6) | <u>3.6</u> (3.0) | <u>0.42</u> (0.45) |
| | <u>MIROC-Chem</u> | <u>1.0</u> (2.5) | <u>3.0</u> (2.7) | <u>0.35</u> (0.42) |
| | <u>MIROC-Chem-H</u> | <u>0.6</u> (1.3) | <u>4.1</u> (3.9) | <u>0.25</u> (0.42) |
| | | | | |
| <u>NO₂</u> | <u>GEOS-Chem</u> | <u>0.80</u> | <u>0.01</u> | <u>0.93</u> |
| | <u>AGCM-CHASER</u> | <u>0.56</u> | <u>0.01</u> | <u>0.96</u> |
| | <u>MIROC-Chem</u> | <u>0.54</u> | <u>0.01</u> | <u>0.94</u> |
| | <u>MIROC-Chem-H</u> | <u>0.44</u> | <u>0.04</u> | <u>0.94</u> |

Table 8: Annual regional total NOx emissions of NOx (in TgNyr⁻¹) and CO (in TgCOyr⁻¹) obtained from the a priori emissions (in brackets) and a posteriori emissions for 2007. The multi-model mean and standard deviation (“spread”) of the a posteriori emissions among the four systems (in %) is also shown.

| | E China | USA | W Europe | India | SE Asia | S America | N Africa | C Africa | S Africa | Globe | |
|-----|------------------------|-------------------------|------------------------|------------------------|-----------------------|------------------------|------------------------|-------------------------|------------------------|-----------------------|--------------------------|
| NOx | GEOS-Chem | 3.8 (4.6) | 4.7 (5.1) | 3.7 (4.5) | 2.3 (2.1) | 0.6 (0.5) | 1.1 (1.1) | 3.1 (2.7) | 2.2 (1.6) | 0.4 (0.2) | 39.1 (37.2) |
| | AGCM-CHASER | 6.4 (4.2) | 7.2 (5.6) | 5.1 (4.1) | 3.0 (2.6) | 0.8 (0.6) | 0.9 (1.3) | 2.9 (2.1) | 2.4 (1.6) | 0.9 (0.5) | 51.9 (39.2) |
| | MIROC-Chem | 5.8 (4.2) | 6.3 (5.6) | 4.4 (4.1) | 3.0 (2.6) | 0.8 (0.6) | 1.2 (1.3) | 3.0 (2.1) | 2.6 (1.6) | 0.8 (0.5) | 49.1 (39.2) |
| | MIROC-Chem-H | 5.8 (5.7) | 6.1 (5.5) | 4.8 (3.7) | 2.9 (3.1) | 0.6 (0.5) | 1.5 (1.5) | 3.2 (2.8) | 2.8 (2.7) | 0.7 (0.5) | 50.4 (42.4) |
| | Multi model spread [%] | 5.5±21% (4.7±15%) | 6.1±17% (5.5±4%) | 4.5±13% (4.1±8%) | 2.8±12% (2.6±16%) | 0.7±16% (0.6±%10) | 1.2±21% (1.3±13%) | 3.0±4% (2.4±16%) | 2.5±10% (1.9±29%) | 0.7±31% (0.4±35%) | 47.6±12% (39.5±5%) |
| CO | GEOS-Chem | 146.0 (123.6) | 149.4 (67.3) | 81.1 (35.0) | 84.1 (67.9) | 23.1 (23.8) | 63.8 (87.2) | 131.9 (123.4) | 117.9 (82.4) | 14.0 (4.5) | 1376.9 (916.1) |
| | AGCM-CHASER | 152.9 (69.7) | 123.9 (59.0) | 74.5 (30.3) | 67.3 (63.9) | 26.8 (29.1) | 42.9 (73.3) | 110.2 (88.4) | 95.2 (87.1) | 11.9 (5.8) | 1275.9 (843.5) |
| | MIROC-Chem | 128.6 (69.7) | 97.0 (59.0) | 54.9 (30.3) | 53.8 (63.9) | 24.5 (29.1) | 51.1 (73.3) | 66.7 (88.4) | 96.7 (87.1) | 6.5 (5.8) | 943.3 (843.5) |
| | MIROC-Chem-H | 177.5 (130.0) | 71.2 (65.2) | 37.4 (27.3) | 76.8 (67.4) | 16.7 (18.8) | 68.2 (64.1) | 102.1 (98.6) | 142.8 (93.2) | 7.7 (6.7) | 1108.8 (888.0) |
| | Multi model spread [%] | 151.3±13% (98.3±34%) | 110.4±31% (62.6±7%) | 62.0±32% (30.7±10%) | 70.5±19% (66.8±3%) | 22.8±19% (25.2±20%) | 56.5±21% (74.5±13%) | 102.7±26% (99.7±17%) | 113.2±20% (87.5±5%) | 10.0±35% (5.7±16%) | 1176.2±16% (872.8±4%) |

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Figure 1: Schematic diagram of the MOMO-Chem framework. The MOMO-Chem utilizes four different CTMs and applies a common EnKF approach to investigate the importance of forecast model performance and model sensitivities on data assimilation analysis. This framework also provides multi-model integrated analysis fields and its uncertainty ranges.

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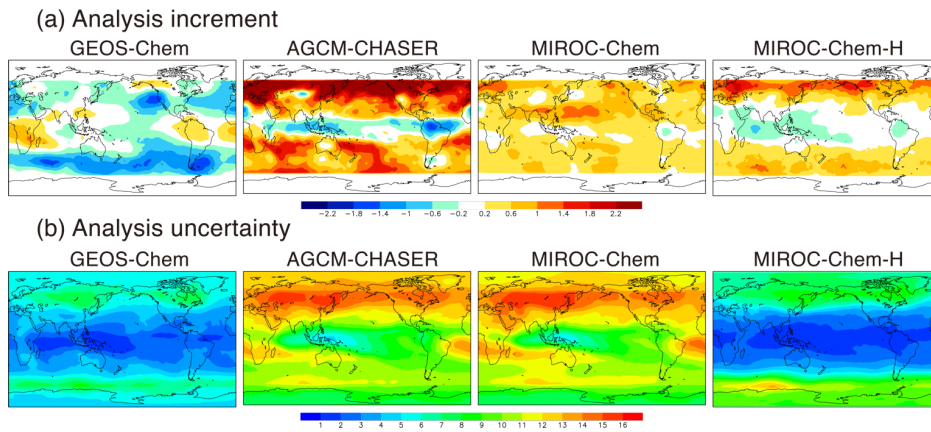


Figure 2: Spatial distributions of (a) analysis increment (in ppbv/day) and (b) analysis uncertainty (in ppb) of ozone at 500 hPa averaged over 2007 from the four systems.

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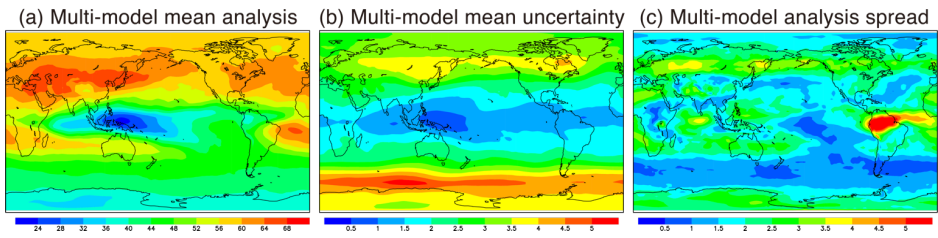


Figure 3: Spatial distributions of the multi-model mean values of (a) data assimilation analysis and (b) its uncertainty of annual mean ozone at 500 hPa estimated using Eqs. (10) and (11), respectively. (c) shows the standard deviation (i.e., multi-model spread) of the annual mean ozone analysis among the four models.

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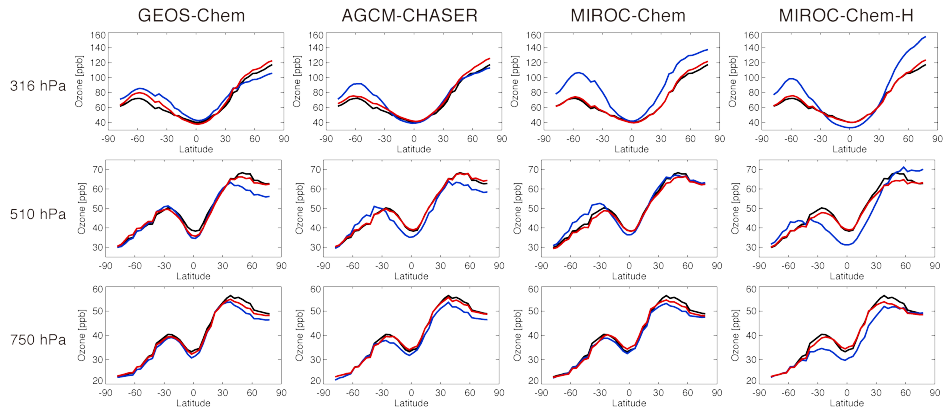


Figure 4: Comparisons of latitudinal distributions of annual and zonal mean ozone concentrations between the TES measurements (black line), control runs (blue line), and data assimilation analyses (red line) at 316 hPa (upper panels), 510 hPa (middle panels), and 750 hPa (lower panels) in 2007 for the four systems.

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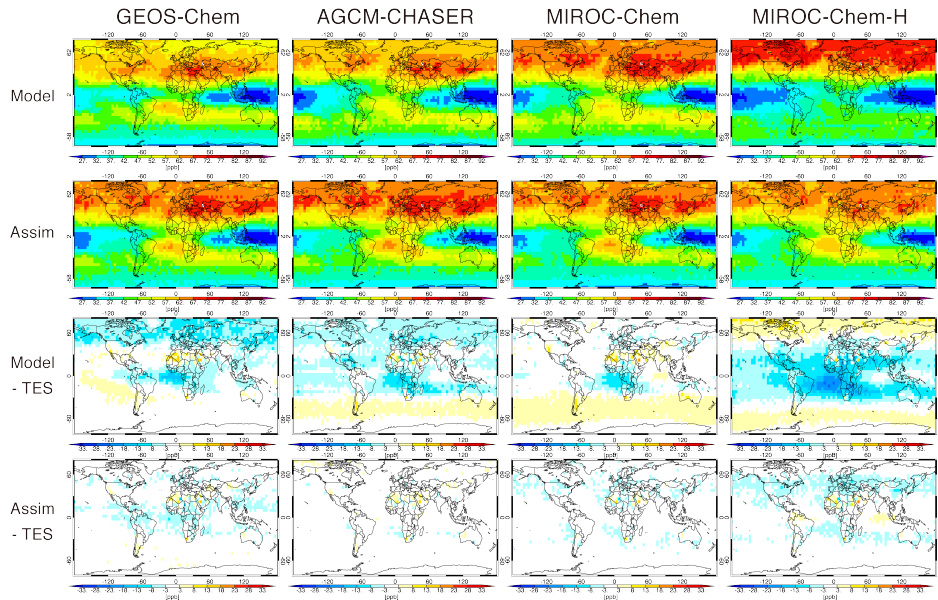


Figure 5: Comparisons of the spatial distributions of annual mean ozone concentrations between the TES measurements, control runs, and data assimilation analyses at 510 hPa in 2007. Units are ppbv.

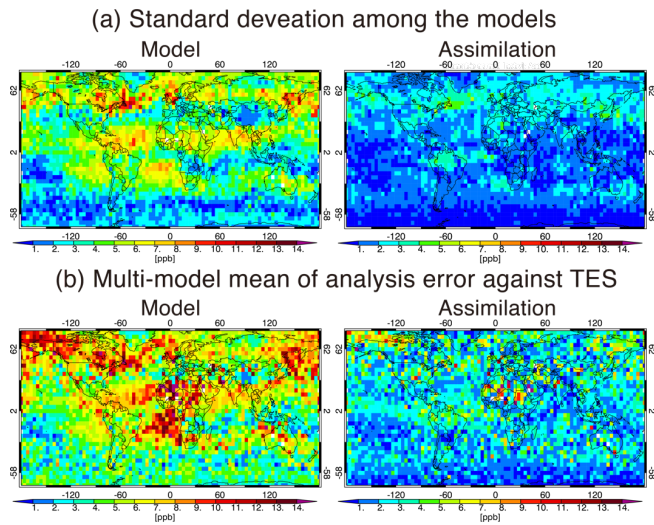


Figure 6: (a) Standard deviation among the models for the data assimilation analysis with applying the TES AK at 510 hPa. (b) Spatial distributions of multi-model mean (root-mean-square) values of error against TES measurements for the control runs (left) and data assimilation analyses (right) at 510 hPa.

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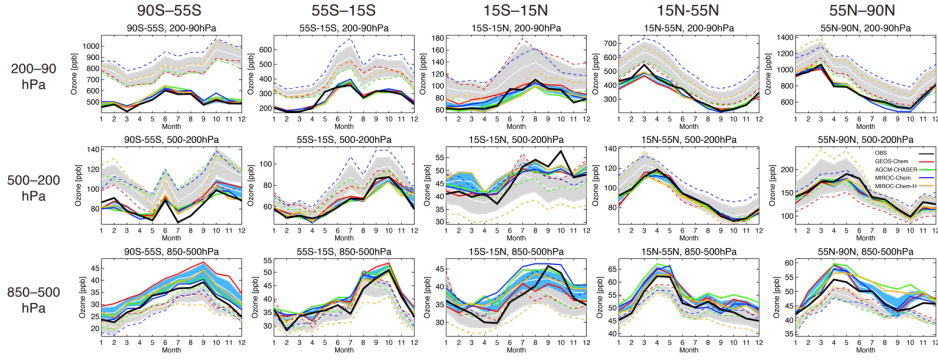


Figure 7: Comparison of seasonal variation of ozone concentration between the ozonesonde observations (black solid line), model simulations (colored dotted lines), and data assimilation (colored solid lines) averaged between 90°S–55°S, 55°S–15°S, 15°S–15°N, 15°N–55°N, and 55°N–90°N for 2007. From top to bottom, results are shown for concentrations averaged over 80–200 hPa, 200–500 hPa, and 500–850 hPa. The $\pm 1\sigma$ deviation among the four models (i.e., model spread) is shown in grey for the control runs and in light blue for the data assimilation results.

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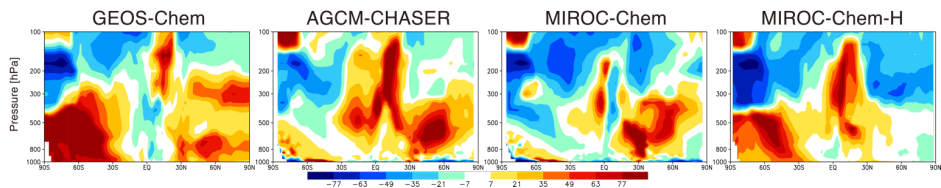
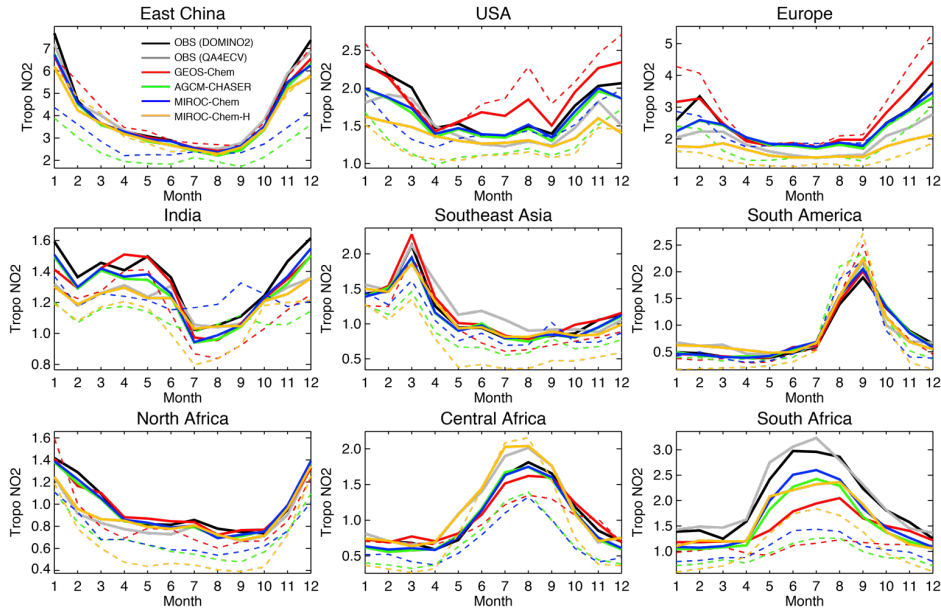


Figure 8: Latitude-pressure cross section of changes in seasonal amplitude of zonal mean ozone concentrations (in ppbv) due to data assimilation (data assimilation minus control runs), as estimated from the maximum minus minimum values of the monthly mean ozone concentrations.

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5 **Figure 9:** Time series of regional monthly mean tropospheric NO₂ columns (in 10¹⁵ molecules cm⁻²) from the satellite retrievals (black for OMI QA4ECV and gray for OMI DOMINO v2), control runs (colored dotted lines), and data assimilation analysis (colored solid lines) for 2007. The model simulation and data assimilation results are obtained at the local overpass time of the retrievals by applying the averaging kernel of OMI DOMINO v2 for GEOS-Chem, CHASER, and MIROC, and of OMI QA4ECV for MIROC-H, respectively, corresponding to the assimilated measurements. The multi-model standard deviations are not shown because of the use of different assimilated measurements in the individual systems.

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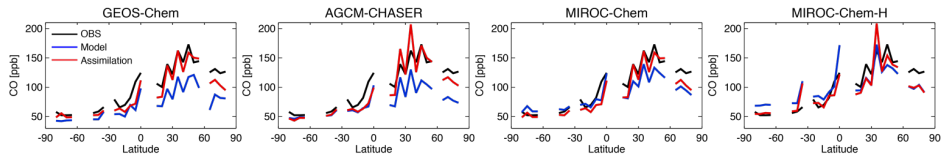


Figure 10: Latitudinal distributions of zonal mean surface CO concentrations (in ppbv) averaged over the WDCGG surface measurement sites from the observations (black), control runs (blue), and data assimilation analyses (red).

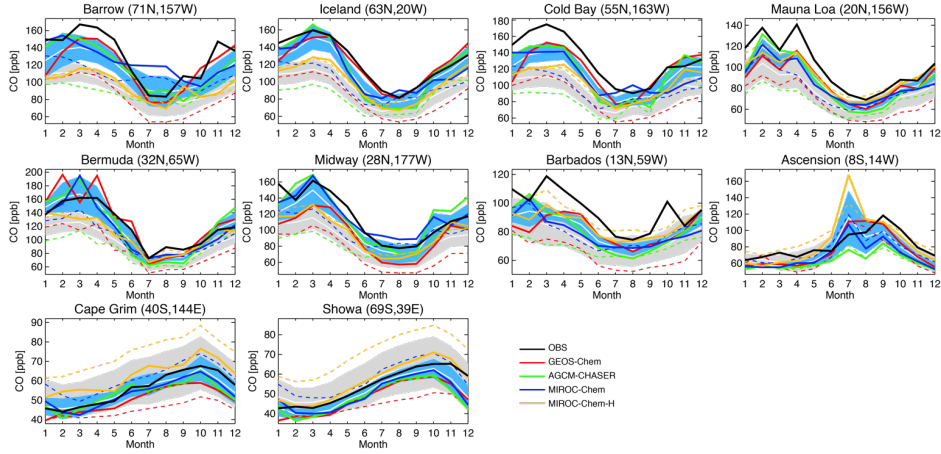


Figure 11: Time series of monthly mean surface CO concentrations (in ppbv) from the WDCGG observations (black solid line), control runs (colored dotted lines), and data assimilation analyses (colored solid lines). The $\pm 1\sigma$ deviation among the four models (i.e., model spread) is shown in grey for the control runs and in light blue for the data assimilation results.

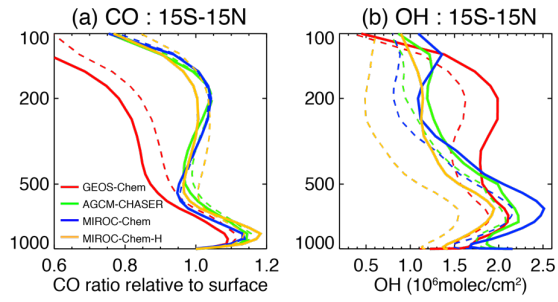
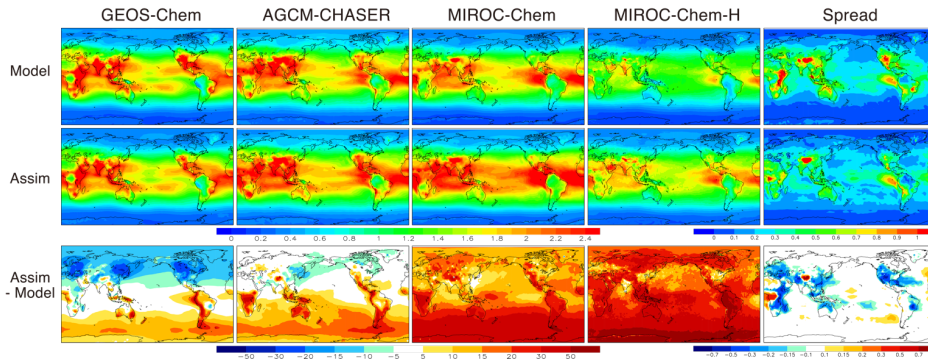


Figure 12: Vertical profiles of (a) annual mean CO concentrations and (b) annual mean OH concentrations averaged between 15°S–15°N, obtained from the control runs (dotted lines) and data assimilation analysis (solid line). For CO (a), the relative ratio to the mean surface concentrations is shown. For OH (b), the unit is 10^6 mol/cm^3 .

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5 Figure 13: Global distributions of annual mean OH concentrations (in 10^6 mol/cm^3) averaged over the troposphere (from the surface to 300 hPa) from the control runs (upper panels), data assimilation analyses (middle panels), and differences between the data assimilation analyses and the control runs (bottom panels, in %). The figures on the right shows the standard deviation among the four systems for the control runs (right top) and data assimilation analyses (right middle). The right bottom figure shows the difference in the multi-model standard deviation between the data assimilation analyses and the control runs (in 10^6 mol/cm^3).

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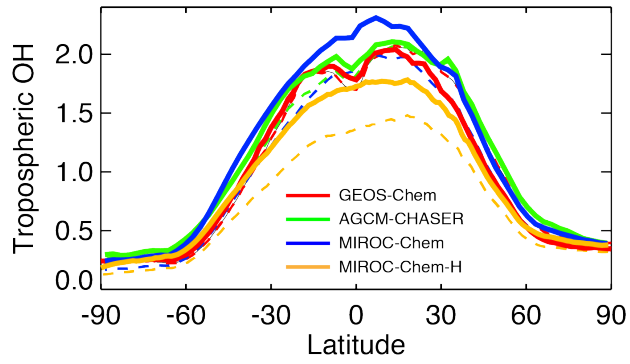


Figure 14: Latitudinal distributions of annual and zonal mean OH concentrations (in 10^6 mol/cm^3) averaged over the troposphere obtained from the control runs (dotted lines) and data assimilation analyses (solid lines) for the four systems.

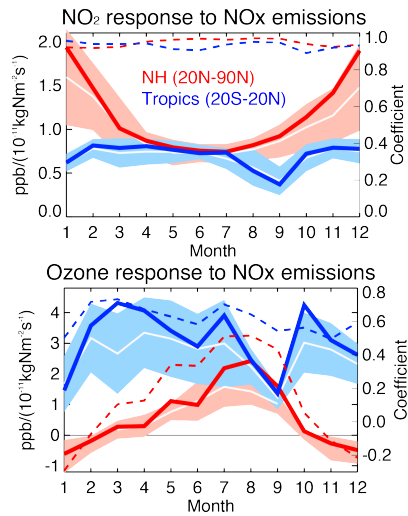


Fig. 15: Time series of model response of surface ozone and NO₂ concentrations to NO_x emissions estimated from linear regressions using the multi-model integrated fields in 2007 over areas with NO_x emission changes greater than $5 \times 10^{-13} \text{ kgNm}^{-2}\text{s}^{-1}$ for the Northern hemisphere (20°N–60°N, red line) and the tropics (20°S–20°N, blue line). The $\pm 1\sigma$ deviation among the four models (i.e., model spread) is shown in light red for the NH and in light blue for the tropics. The multi-model mean value (i.e., an average of individual estimates) is shown by white lines. The correlation is shown by dashed lines.

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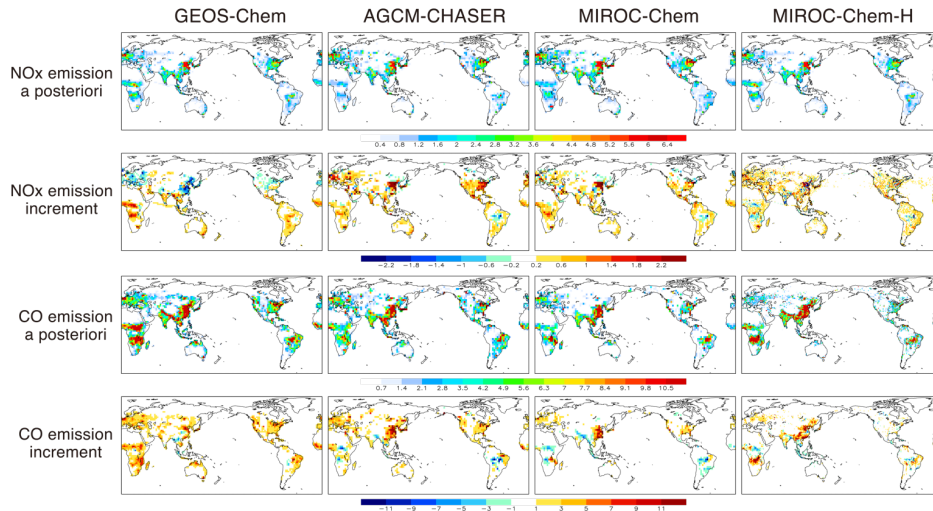


Figure 16: Global distributions of annual mean surface NO_x emissions (in 10^{-11} kgN m⁻²s⁻¹) and surface CO emissions (in 10^{-10} kgCO m⁻²s⁻¹) for 2007. The a posteriori emissions and analysis increment (a posteriori minus a priori emissions) are shown.

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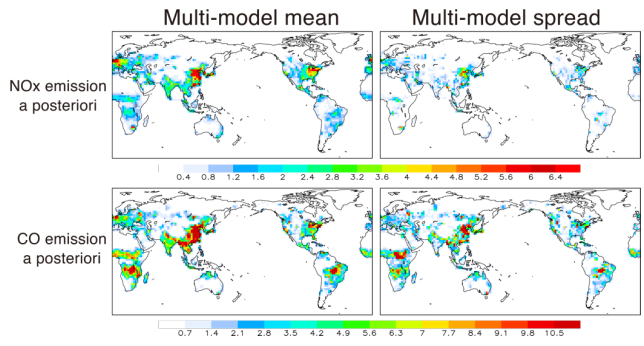


Figure 17: Same as Fig. 16, but for the multi-model mean and spread.

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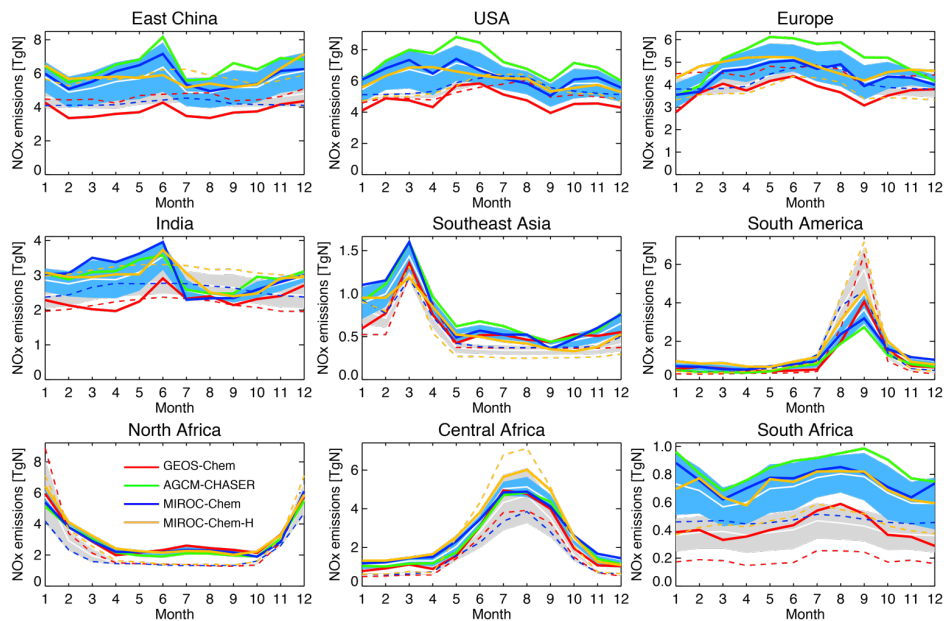


Figure 18: Time series of monthly total regional surface NO_x emissions (in TgNyr⁻¹) obtained from the a priori emissions (dotted lines) and the a posteriori emissions (solid lines) for 2007 for the four systems. AGCM-CHASER and MIROC-Chem use the same a priori emissions. The $\pm 1\sigma$ deviation among the four models (i.e., model spread) is shown in grey for the control runs and in light blue for the data assimilation results.

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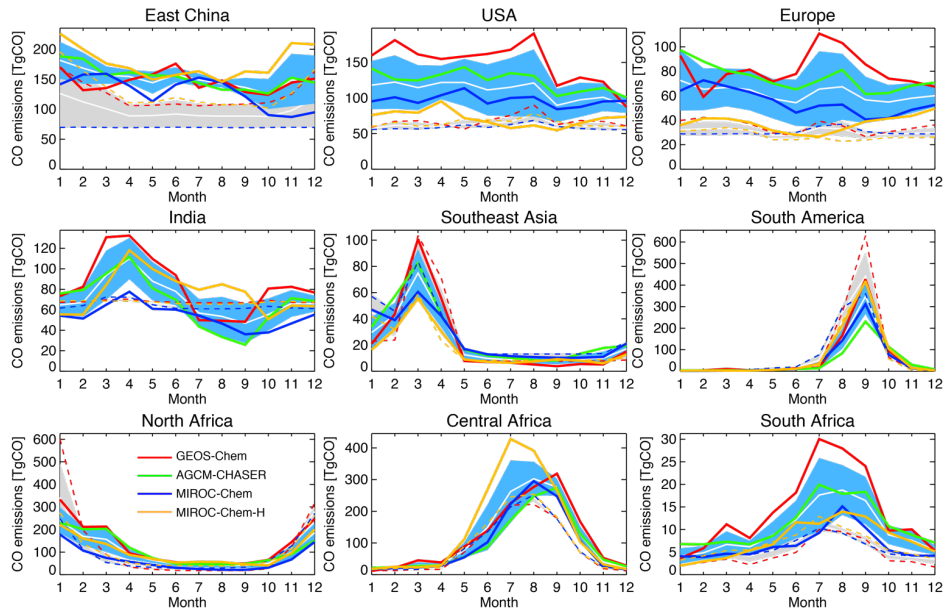


Figure 19: Same as in Fig. 18, but for monthly total regional surface CO emissions (in TgCOyr⁻¹).

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