

## Response to referee comments on “Technical note: 12-km resolution capability for the global GEOS-Chem model of atmospheric composition”

### Response to Anonymous Referee #1:

The authors extend the existing GEOS-Chem Classic modelling framework to double the spatial resolution relative to previous implementations, yielding a regional simulation with a resolution of  $0.125^\circ \times 0.15625^\circ$  (roughly  $12 \times 12$  km<sup>2</sup>). They show that the effects of some processes manifest differently in this new configuration, most notably a strengthening in vertical transport.

The central advance is incremental, but useful. Being able to perform higher-resolution regional simulations with GEOS-Chem provides a new and relevant capability for the user community. The announcement of new data archives is particularly welcome, and the authors provide some excellent insights into the new results which can be developed. However, I have one concern which I would argue is not well addressed by the current manuscript but which is important to interpreting its results. I have also listed some minor errors.

We sincerely thank the reviewer for the constructive and insightful comments. Our replies are shown in blue and *revised text is shown in italic blue*. Line numbers in our responses refer to the revised manuscript version with marked revisions.

My major concern is the question of whether the results the authors are seeing are specifically because of better resolving the meteorology, or just that an increase in resolution allows for gradients to be better preserved. This concern is raised in part due to the question below regarding "native" resolution, and I recognize that this may be beyond the scope that the authors intended for a technical note. However, the abstract specifically argues that the different results are due to better resolution of transport variables (line 21), but do not provide evidence of this. I would recommend that the authors consider running a simulation in which their input meteorology is degraded to 25 km resolution, but their simulation grid remains at 12 km. This would allow them to directly assess how much of the benefit comes from the meteorology being better resolved compared to from the ability to better resolve emissions and chemical gradients.

Thank you for this insightful comment. We added a sensitivity TransportTracers simulation at 12-km resolution driven by the 25-km advection archive. The differences between this sensitivity simulation and the standard 12-km simulation are shown in the newly added right columns of Figures 1–3. We find that both better resolved horizontal convergence and finer resolution of concentration gradients at 12-km contribute to the differences between resolutions. We have added a discussion of this sensitivity test in the main text.

[Lines 199–204]: *“Differences between the 12-km and 25-km simulations could reflect stronger vertical winds at 12-km due to better resolved horizontal convergence (Yu et al., 2018) and better resolution of concentration gradients leading to stronger tracer convergence for the same winds.*

*To separate these two effects, we conducted a 12-km sensitivity simulation driven by the 3-hourly 25-km advection archive regridded to 12-km resolution during runtime (right columns of Figures 1-3). We find that both effects contribute.”*

My more minor issue concerns the way that the grids are described. The authors state that GC-Classic can operate on native GEOS grid resolutions (line 63), but this is not true. To my knowledge, GC-Classic cannot directly ingest cubed-sphere data and it does not use a cubed sphere grid. As it stands, the paper risks misleading the reader by implying that there has been no regridding (i.e. information loss) between the GEOS and GC-Classic grids, which is not true. Based on section 2 (specifically lines 91-92) it appears that the data has already been regridded from C720 to  $0.125^{\circ} \times 0.15625^{\circ}$ ; such an operation will have introduced spurious resolution at the poles, and will have greatly degraded the resolution at the equator where the C720 grid is actually finer. Furthermore the misalignment of grid edges likely means that, even where the C720 and  $0.125^{\circ} \times 0.15625^{\circ}$  grids are roughly the same size, the data will have been "smoothed out" by the regridding process. This is inevitable in a cubed sphere to rectilinear regrid, and does not detract from the idea that the use of a higher resolution rectilinear grid should still yield benefit. However, the manuscript currently flips between describing the GC-Classic simulation as being at  $0.125^{\circ} \times 0.15625^{\circ}$  (presumably correct), "native" (likely incorrect unless the architecture has changed to allow C720 simulation), and 12-km (definitely incorrect as even C720 has some variation in grid cell area - albeit much less than at  $0.125^{\circ} \times 0.15625^{\circ}$ ). I would recommend that the authors revise the manuscript to precisely describe exactly what grid resolution is being used where (e.g. are the pre-calculated archives, listed as "12 km", actually at C720 or at  $0.125^{\circ} \times 0.15625^{\circ}$ ?), and to be clear about where lossy regridding is or is not being applied. I would also request that claims such as "[t]he 12-km simulation has no spatial averaging of winds relative to the parent GEOS ESM" (lines 166-167) be removed, as this is not true unless GC-Classic is now running on a cubed sphere at C720.

Thank you for pointing out this lack of clarity. We have revised the manuscript throughout to use consistent terminology for the different grids and to clarify where regridding is applied and its effects. We now use "native" to refer only to the GEOS-FP cubed-sphere C720 archive, while " $0.125^{\circ} \times 0.15625^{\circ}$ " refers to the GC-Classic nested grid simulation. For convenience, we continue to refer to GC-Classic simulation at  $0.125^{\circ} \times 0.15625^{\circ}$  as the 12-km capability and have revised the text to clearly define this. Relevant revisions are now included in the Abstract, Sections 1 and 2, and Table 1, including the following:

[Abstract, lines 14–19]: *“This capability can be applied to simulations for any user-selected domain worldwide from March 2021 onward by accessing a new hourly cubed-sphere C720 (approximately 12 km  $\times$  12 km resolution) global wind archive from the NASA GEOS-FP meteorological data assimilation system. We regridded the archive to support rectilinear GEOS-Chem Classic nested grid simulations worldwide at  $0.125^{\circ} \times 0.15625^{\circ}$  resolution and denote this as the 12-km GEOS-Chem capability.”*

[Section 1, lines 41–47]: *“Here we introduce the capability to conduct GEOS-Chem simulations at  $0.125^\circ \times 0.15625^\circ$  ( $\approx 12 \text{ km} \times 12 \text{ km}$ ) resolution by... In what follows we will refer to it as the 12-km capability in GEOS-Chem.”*

[Section 1, lines 62–64]: *“GEOS-FP operates at native C720 resolution (approximately  $12 \text{ km} \times 12 \text{ km}$ ) but the data archive was previously made available only at  $0.25^\circ \times 0.3125^\circ$  resolution.”*

[Introduction, lines 83–84]: *“The one-way nested GC-Classic capability at GEOS-FP  $0.25^\circ \times 0.3125^\circ$  (referred to as 25-km) resolution is widely used for...”*

We have clarified that the 12-km advection archive is generated by regridding the hourly global C720 GEOS-FP archive to the rectilinear  $0.125^\circ \times 0.15625^\circ$  grid, which can introduce information loss.

[Section 2, lines 102–112]: *“Here we use the new global C720 GEOS-FP hourly advection archive, regridded to  $0.125^\circ \times 0.15625^\circ$ , to produce the 12-km advection archive that enables GC-Classic nested-grid simulations at  $0.125^\circ \times 0.15625^\circ$  resolution. ... The regridding from cubed-sphere C720 to the rectilinear  $0.125^\circ \times 0.15625^\circ$  grid yields an approximately  $12 \text{ km} \times 12 \text{ km}$  horizontal scale over midlatitudes, slightly coarser toward the equator and finer toward the poles.”*

We have removed the misleading discussion that “the 12-km simulation has no spatial averaging of winds relative to the parent GEOS ESM” as suggested.

Finally, my understanding is that GEOS-Chem is usually referred to as “GEOS-Chem X.Y.Z” rather than “GEOS-Chem version X.Y.Z” (line 79), although I would defer to the senior authors on this manuscript in that regard given their leadership in the community.”

Thank you for catching this. We have revised it to “GEOS-Chem 14.6.0”.

## **Response to referee comments on “Technical note: 12-km resolution capability for the global GEOS-Chem model of atmospheric composition”**

### **Response to Anonymous Referee #2:**

The manuscript “Technical note: 12-km resolution capability for the global GEOS-Chem model of atmospheric composition” by Xiaolin Wang et al. presents the new option to apply a 12 km nest in GEOS-Chem simulations using the global wind archive from NASA GEOS\_FP meteorological data assimilation system at 12 km resolution. 12 km nested simulations are evaluated against simulations at 25 km resolution and observations.

This 12 km resolution nested capability of GEOS-Chem is a great advance and very helpful for the atmospheric chemistry and composition modelling community. I think the manuscript would better fit the scope of GMD than ACP. I would suggest transferring it and the review to GMD. Independent of the journal, some points should be addressed before publication.

We thank the reviewer for the positive assessment and the helpful suggestions. Below we provide a point-by-point response to the reviewer’s comments and have revised the manuscript accordingly. Our replies are shown in blue and *revised text is shown in italic blue*. Line numbers refer to the revised manuscript with marked revisions. We believe ACP remains an appropriate venue for this work, as the focus is on the scientific implications and broad applications of the model 12-km capability rather than on major model development.

### **Major comments**

The manuscript is lacking of conclusions. This is kind of surprising because the first chapters of the manuscript are well structured. A small summary is provided at the end of chapter 5, but only the last sentence of the summary is related to chapter 5 itself. I would suggest to move this summary into a proper conclusion chapter, which also should include an outlook.

Thank you for this suggestion. We have revised the previous summary into a conclusion section and added an outlook at the end.

[Section 6, lines 319–323]: *“Overall, this 12-km capability further extends the application of GEOS-Chem in regional atmospheric chemistry and in the use of high-resolution satellite observations to quantify emissions of air pollutants and greenhouse gases at fine spatial scales. Higher model resolution improves the representation of finer concentration gradients and inverse model sensitivity through improved transport and chemistry.”*

Related to the missing conclusions: The manuscript describes the model development well, but lacks in highlighting the scientific impact of these developments.

This has been addressed in our response to the previous comment.

## Minor comments

In general:

Please check for a uniform presentation, i.e. “ $0.125^\circ \times 0.15625^\circ$ ” (line 16) and “ $0.125^\circ \times 0.15625^\circ$ ” (line 35) or “ $\approx 12 \times 12 \text{ km}^2$ ” (line 35), “” and “ $\approx 25\text{-km}$ ” (line 73).

Thank you for pointing this out. We have revised the manuscript for consistency.

[Abstract, lines 16–21]: “...from March 2021 onward by accessing a new hourly cubed-sphere C720 (approximately  $12 \text{ km} \times 12 \text{ km}$  resolution)... We evaluate this 12-km configuration of GEOS-Chem by comparison with the standard 25-km ( $0.25^\circ \times 0.3125^\circ$  resolution)... ”

[Section1, lines 41–43]: “Here we introduce the capability to conduct offline GEOS-Chem simulations at  $0.125^\circ \times 0.15625^\circ$  ( $\approx 12 \text{ km} \times 12 \text{ km}$ ) resolution...”

[Section1, lines 83–84]: “The one-way nested GC-Classic capability at GEOS-FP  $0.25^\circ \times 0.3125^\circ$  (referred to as 25-km) resolution...”

The date of latest access is missing for most of the links.

Thank you. We have checked the manuscript and added the latest access dates throughout.

Line 32-33: For my understanding, does that mean that the chemistry and meteorology are not coupled, i.e. the chemistry has no feedback on the meteorology?

Yes, we have clarified this in lines 36–41:

“The standard offline configuration of GEOS-Chem is driven by archived Goddard Earth Observing System (GEOS) meteorological data from the NASA Global Modeling and Assimilation Office (GMAO), with no feedback of chemistry on meteorology. GEOS-Chem can also operate online in dynamical coupling with Earth system models (Fritz et al., 2022; Hu et al., 2018; Lu et al., 2020) or the WRF regional model (Lin et al., 2020).”

Line 38: It might be good to include already here, why the simulations are possible from March 2021 and not from an earlier date.

We have revised the sentence to clarify that the simulations begin in March 2021 because the GEOS-FP C720 advection archive is only available from that date onward.

[Lines 41–44]: “Here we introduce the capability to conduct offline GEOS-Chem simulations at  $0.125^\circ \times 0.15625^\circ$  ( $\approx 12 \text{ km} \times 12 \text{ km}$ ) resolution by exploiting a new GEOS advection data archive (grid-scale winds) available from March 2021 onward.”

Line 38: What does onward mean? Until when are the NASA GEOS-FP data available?

Thank you for this question. This has been clarified in our response to the previous comment.

Line 99 and 100: Is ‘online’ meant by “on the fly”?

Yes, we have revised the text to clarify this. Lines 119–121 now read:

*“Other non-advection meteorological inputs including convective mass fluxes and vertical mixing depths are from the standard GEOS-FP archive at  $0.25^\circ \times 0.3125^\circ$  resolution and are dynamically regridded to  $0.125^\circ \times 0.15625^\circ$  at runtime.”*

Line 115: ‘7 times’ instead of “7×”.

Corrected.

Line 116: See remark to line 115.

Corrected.

Line 225 and following: It would be helpful to include one or two sentences about the basics of analytical inversion of satellite data for readers, who are not familiar with this topic.

Thank you for the helpful suggestion. We have added a brief description of the IMI inversion framework in lines 264–270:

*“It uses Bayesian inference to minimize the mismatch between the TROPOMI methane column observations and the corresponding concentrations simulated by GEOS-Chem, regularized by prior information on emissions. GEOS-Chem is applied to construct the Jacobian matrix describing the sensitivity of TROPOMI observations to emissions as simulated by the model transport. This is then used together with the TROPOMI observations, prior emission estimates, and prior and observational error statistics to derive optimized (posterior) emissions.”*

Figure 2:

Out of curiosity: Can you explain, what causes the stratospheric negative delta  $^{222}\text{Rn}$  difference between  $20^\circ\text{N}$  and  $30^\circ\text{N}$  in June?

Thank you for this question. We have added a brief discussion in the revised manuscript:

[Lines 183–187]: *“The lower  $^{222}\text{Rn}$  concentrations in the tropical stratosphere in June, combined with the lower  $^7\text{Be}$  concentrations below the tropopause, may reflect greater restriction of transport across the tropopause at higher resolution (Stanevich et al., 2020) but would require further investigation because the absolute changes are very small.”*

Do you know, what causes the enhanced  $^7\text{Be}$  at 12 km resolution compared to 25 km resolution in the troposphere between  $20^\circ\text{N}$  and  $30^\circ\text{N}$  in June?

Thank you for this question. We have added a brief explanation in the revised manuscript:

[Lines 216–217]: *“The  $^7\text{Be}$  lifetime against deposition is 3% higher at 25-km resolution, explaining the slightly higher overall tropospheric concentrations.”*

It would be great to see for reference how vertical winds for the two different resolutions look like.

Thank you for raising this point. Vertical winds are not directly used in GEOS-Chem, and vertical advection is derived from horizontal mass flux convergence. For this reason, we use the TransportTracers simulation as a benchmark for model vertical transport. We have clarified this in the revised manuscript:

[Lines 165–167]: *“These tracers are particularly useful for evaluating model vertical transport, whereas grid-scale vertical winds are calculated from horizontal mass flux convergence and is not directly available in the model.”*