

First of all, we appreciate the reviewer's comments. In response to the reviewer's comments, we have made relevant revisions in the manuscript. Listed below are our answers and the changes made to the manuscript according to the questions and suggestions given by the reviewer. Each comment of the reviewer (in black) is listed and followed by our response (in blue).

Interactive comment on "Effects of model resolution and parameterizations on the simulations of clouds, precipitation, and their interactions with aerosols" by Seoung Soo Lee et al.

Anonymous Referee #1

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This manuscript is a bit of a mixed bag. I really like the analysis of the difference between the bin and bulk microphysics. The analysis of resolution dependence of the clouds and cloud-aerosol interactions is not so clear, as too little information is provided regarding the representation of deep convection at coarse resolution.

The illustrations are generally helpful, and the writing is mostly quite clear.

Lines 35-38. Is the comparison done at the same scale? We certainly wouldn't expect a coarse resolution simulation to produce the same updraft intensity as a fine resolution simulation if they aren't compared at the same scale. So I'm withholding judgement on this conclusion until I know more. Perhaps need to clarify this in the text.

As described in Section 4.2, an identical domain for each of the Seoul and Houston cases is applied to both the CSRM and GFS simulations. Stated differently, the spatial scale or the extent of the analysis area is identical between the CSRM and GFS simulations, although the number of grid points in the area or the domain is different between the CSRM and GFS simulations due to differences in resolutions between those simulations. To clarify the point here, the following is added:

(LL235-238 on p12)

Stated differently, the spatial scale or the extent of the analysis area is identical between the CSRM simulations and the GFS simulations, although the number of grid points in the area or the domain is different between the CSRM simulations and the GFS simulations due to differences in resolution between those simulations.

Line 68. Not clear what is meant by "scale-aware schemes". Does this refer to microphysics? Please provide citations.

Note that the traditional cumulus parameterizations are limited by the issue of scale separation (Yano, 2012). Due to this limitation, the traditional cumulus parameterizations can only be used in coarse

resolutions which are coarser than ~ 50 km and cannot be used in finer resolutions which are finer than ~ 50 km. Nowadays, as mentioned in text, many NWP models start to adopt resolutions finer than ~ 50 km and due to this, to replace the traditional cumulus parameterizations, the scale-aware or scale-free schemes which can be used for any resolutions whether they are coarser than ~ 50 km or not have been developed. Since the scale-aware schemes are designed to replace the traditional cumulus parameterizations, the scale-aware schemes basically represent sub-grid-scale convective dynamic processes (e.g., cloud-scale updrafts and downdrafts) like the traditional cumulus parameterizations.

To clarify the point here, the following is added:

(LL62-65 on p3-4)

These scale-aware schemes, which represent sub-grid-scale dynamic processes (e.g., cloud-scale updrafts and downdrafts) that are associated with cloud convection as the traditional cumulus parameterizations do, are designed to be applied to the increased resolution in the NWP models.

We already provided citations about the scale-aware schemes in LL59-62 on p3 as follows:

Motivated by this, scale-aware cumulus parameterization schemes (e.g., Bogenschutz and Krueger, 2013; Thayer-Calder et al., 2015; Griffin and Larson, 2016) are being implemented into these models of different resolutions for better representation of clouds and precipitation.

Reference:

Yano, 2012, What is Scale Separation?: A Theoretical Reflection, obtainable at http://convection.zmaw.de/fileadmin/user_upload/convection/Convection/COST_Documents/Basic_Parameterization_Concepts_and_Issues/What_is_Scale_Separation___A_Theoretical_Reflection.pdf

Line 100-102. Not clear what is meant by “RRTMG considers the effects of aerosols on the effective sizes of hydrometeors”. RRTMG accounts for radiative effects of both aerosols and hydrometeors, but not the effects of aerosols on hydrometeors. That is handled elsewhere, typically in the microphysics code.

We checked the code and found that the effective size of hydrometeors is calculated in the microphysics scheme adopted and then the calculated size is transferred to the RRTMG scheme for the calculation of the effects of clouds on radiation with the consideration of the effective size. To clarify this, the corresponding text is revised as follows:

(LL101-104 on p5-6)

The effective sizes of hydrometeors, which vary with varying aerosol properties, are calculated in a microphysics scheme that is adopted by this study and described below and the calculated sizes are transferred to the RRTMG. Then, the effects of the effective sizes of hydrometeors on radiation are calculated in the RRTMG.

Line 136. Before “less”, insert “At pressures”.

Done.

Line 141. Not clear what is meant by “cloud mass”. Is it liquid water content?

Cloud mass in the scheme of Moorthi et al. (2001) is represented by cloud liquid content or cloud ice content in g m^{-3} , depending on temperature. Here, cloud liquid represents droplets and cloud ice represents ice crystals. To clarify this, the following is added:

(LL156-158 on p8)

Here, cloud mass is represented by cloud liquid content (CLC) or cloud ice content (CIC), depending on temperature, and cloud liquid (cloud ice) represents droplets (ice crystals).

Line 192. More description is needed here. The description of the model never discusses how turbulence or convection are represented.

The CSRМ explicitly resolves the cloud-scale convection and thus we do not use parameterizations (e.g., cumulus parameterizations) to represent the cloud-scale convection as described in text. To clarify this better, the relevant text is revised as follows:

(LL215-216 on p11)

Note that the cumulus parameterization scheme is not used in this domain where cloud-scale convection and associated convective rainfall generation are assumed to be explicitly resolved.

To indicate how the turbulence is represented, the following is added:

(LL104-106 on p6)

The ARW model considers the sub-grid-scale turbulence by adopting 1.5-order turbulence kinetic energy closure (Basu et al., 1998).

Lines 227-230. Much more description is needed here. Surely more was changed than resolution. The 15 km and 35 km configurations must parameterize convection. How is that done?

Here, for those 15-km and 35-km configurations or the repeated simulations with the 15-km and 35-km resolutions, we do not parameterize convection using schemes such as “cumulus parameterizations”. We just want to identify the pure effects of resolutions on the simulations of clouds, precipitation, and their interactions with aerosol or we simply want to identify the pure errors caused by the use of the coarse resolutions via comparisons between the CSRМ simulations with the 500-m or fine resolutions and the repeated simulations with the 15-km and 35-km resolutions or coarse resolutions. This is why we repeat the standard CSRМ runs only by varying the resolutions. In case we apply the convection parameterization (which is not applied to the CSRМ simulations with the 500-m resolution) to the repeated simulations with the 15-km and 35-km resolutions, comparisons between the CSRМ simulations and repeated simulations are not able to isolate the effects of resolutions due to the fact

that not only resolutions but also the convection parameterization contributes to differences among those simulations.

By only varying the resolutions among the simulations and not applying the convection parameterizations to the repeated simulations with the coarse resolutions, we can say that differences between the CSRMs (with fine resolutions) and the repeated simulations (with coarse resolutions) are the errors in the simulations of clouds, precipitation, and their interactions with aerosol by taking the CSRMs as benchmark simulations, and the varying resolutions or the coarse resolutions are the only factor that produces the errors in the repeated simulations. To clarify the point here, the following is added:

(LL257-266 on p13-14)

To isolate the effects of resolution on the simulations of clouds, precipitation, and their interactions with aerosols, only resolution varies among the CSRMs at the fine resolution and the repeated runs at the coarse resolutions here and these runs have an identical model setup except for resolution. For the identical setup, as an example, we do not apply the convection parameterizations (e.g., cumulus parameterizations) to the repeated runs, since the convection parameterizations are not applied to the CSRMs. Hence, cloud variables (e.g., the updraft speed) are not diagnosed by convection parameterizations but predicted in both the CSRMs and the repeated runs. With the identical setup except for resolution, the comparisons between the CSRMs and the repeated simulations can isolate the pure effects of the use of coarse resolution on clouds, precipitation, and their interactions with aerosol.

Note that the GFS simulation uses not only resolutions similar to those in the repeated simulations but also the convection parameterizations or cumulus parameterizations to represent the sub-grid convection. Interestingly, the GFS simulation produces results which are similar to those in the repeated simulations with the 15-km and 35-km resolutions and are very different from those in the CSRMs simulations with the 500-m resolutions despite the use of the convection parameterizations. This indicates that the use of the convection parameterizations, whose purpose is to correct the errors caused by the use of coarse resolutions and then to produce results similar to those in the simulations with the fine resolutions such as the CSRMs simulations, does not correct the errors well. This problem with the convection parameterizations is discussed in text.

Lines 247-248. “substantial decreases in the cloud mass at the 15- and 35-km resolutions compared to the cloud mass in the simulations at the 500-m resolution”. Since you refer to decreases, that suggests changes with aerosol, but I’m not sure if that is what you mean. You could mean there is less cloud mass at coarse resolution than at fine resolution. If you mean the latter, replace “are substantial decreases in the” with “is substantially less”.

Done.

Line 267. As above, change “are decreases in” to “is less”.

Done.

Line 271. At fine resolution?

As described in Section 4.1 and in text in other sections such as that in LL 227-228 (in the old manuscript), the CSRMs simulations are by definition those performed with the 500-m resolution or the fine resolution. To clarify this, the corresponding text is revised as follows:

(LL301-304 on p15-16)

In Figures 5 and 6, satellite-observed LWP and IWP for both cases follow reasonably well their CSRMs-simulated counterparts for the polluted scenario. This shows that the CSRMs simulations, which are performed with the 500-m resolution, perform well and can thus represent benchmark simulations.

Line 280. More discussion is needed here. At coarser resolution the updrafts are not resolved, so aerosol activation is poorly represented. If there is a cumulus parameterization, it probably lacks aerosol-aware microphysics.

As mentioned in our response to the comment for the Lines 227-230, in the repeated simulations with the coarse resolutions, we do not use cumulus parameterizations for the reasons detailed in the response to the comment for the Lines 227-330. As detailed in the response, by not using cumulus parameterizations, we can isolate the pure effects of the use of the coarse resolutions on clouds, precipitation, and their interactions with aerosol. Here, these pure effects include the effects of updrafts not resolved by the coarse resolutions on clouds, precipitation, and their interactions with aerosol via microphysical processes such as activation. As detailed in our response to the comment for the Lines 227-330, these pure effects are none other than the differences in results between the CSRMs simulations with the fine resolution and the repeated simulations with the coarse resolutions; note that these differences represent the pure errors caused by the use of the coarse resolutions (as detailed in our response to the comment for the Lines 227-330) and for example, associated updrafts not resolved and poorly represented activation. These differences are compared to differences between the CSRMs simulations and the GFS simulation to evaluate how the cumulus parameterization in GFS works to minimize the errors. Here, the differences between the CSRMs simulations and the repeated simulations with the coarse resolutions should act as a maximum extent of the errors when the cumulus parameterizations to correct the errors are not used. As the differences between the CSRMs simulations and the GFS simulation become closer to those between the CSRMs simulations and the repeated simulations, the cumulus parameterization used in the GFS simulation is considered to be working worse. Stated differently, if there are no differences in results between the CSRMs simulations and the GFS simulation, the cumulus parameterization in the GFS simulation is considered to work perfect. Here, as mentioned in text, the CSRMs simulations act as benchmark simulations and this is proven by comparisons between the CSRMs simulations and observations.

In summary, here, the pure errors include those caused by updrafts not resolved and poorly represented activation as exemplified by the reviewer here and we quantify these errors via the comparisons

between simulations as described above and based on quantification, we provide a guideline by which the parameterizations in GFS can be developed in an efficient way; see our discussion related to this in the last five paragraphs of “summary and discussion”

Lines 283-285. If the GFS model lacks aerosol-aware physics then there would be little sensitivity to aerosol. The description of the GFS does not indicate any dependence on aerosol.

It is true that there is no “aerosol-aware physics” in the current GFS. However, in the text pointed out here, it is meant that even though aerosol-aware physics is implemented into GFS, it is likely that GFS shows the weak sensitivity (to increasing aerosol concentration) as shown in the ARW simulations at the coarse resolution.

The cumulus parameterization in the current GFS is not able to correct errors in variables such as updrafts to result in the similarity between the GFS simulation and the ARW simulations at the coarse resolutions. The ARW simulations which are equipped with the aerosol-aware physics and at the coarse resolutions demonstrate that when those errors are not corrected or updrafts are underestimated (as compared to the CSRMs simulations), even the presence of “aerosol-aware physics” does not prevent the weak sensitivity to increasing aerosol concentrations. Hence, the current GFS, which does not correct errors in updrafts well or underestimates updrafts as discussed in “summary and discussion”, is likely to show the weak sensitivity even though “aerosol-aware physics” is implemented into GFS.

To clarify the point here, the following is added:

(LL363-374 on p19)

Taking the sensitivity of updraft mass fluxes to increasing aerosol concentrations in the CSRMs simulations as the benchmark sensitivity, the GFS simulations likely also underestimate the sensitivity, considering the similarity in results between the ARW simulations at the 15- and 35-km resolutions and the GFS simulations. Since the current GFS model does not consider pathways through which increasing aerosol concentrations interact with updraft mass fluxes, this probable underestimation of the sensitivity is even more likely. Note that the ARW simulations which are at the 15- and 35-km resolutions and underestimate updrafts themselves, even with the consideration of those pathways, result in the much weaker sensitivity at the coarse resolutions as compared to that in the CSRMs simulations. Hence, even though those pathways are implemented into the GFS model, the underestimated updrafts in the GFS simulations are likely to result in the weak sensitivity, unless the cumulus parameterization which represents updrafts in the GFS model is further developed to prevent the underestimation of updrafts.

Line 291. Need discussion of how convection is represented in ARW at different resolutions. I assume the updraft mass flux in the coarse simulations is diagnosed from the convection scheme.

The convection scheme such as the cumulus parameterization is not used in the ARW simulations at all of the different resolutions due to the reasons which are elaborated in our response to the comment for the Lines 227-230. The discussion of how convection is presented in the ARW simulations at different resolutions is given as follows:

(LL257-266 on p13-14)

To isolate the effects of resolution on the simulations of clouds, precipitation, and their interactions with aerosols, only resolution varies among the CSRMs runs at the fine resolution and the repeated runs at the coarse resolutions here and these runs have an identical model setup except for resolution. For the identical setup, as an example, we do not apply the convection parameterizations (e.g., cumulus parameterizations) to the repeated runs, since the convection parameterizations are not applied to the CSRMs runs. Hence, cloud variables (e.g., the updraft speed) are not diagnosed by convection parameterizations but predicted in both the CSRMs runs and the repeated runs. With the identical setup except for resolution, the comparisons between the CSRMs simulations and the repeated simulations can isolate the pure effects of the use of coarse resolution on clouds, precipitation, and their interactions with aerosol.

Lines 307-310. The difference could be due to poor parameterization of convection in both models. More information is needed.

See our responses to the comments on Line 280 and Lines 283-285.

Lines 311-312. Even if the GFS simulated the updraft mass flux correctly, it would likely still underestimate the sensitivity to the aerosol because it lacks the physics that drives the sensitivity.

See our responses to the comment on Lines 283-285. Based on them and the fact that the CSRMs simulations act as benchmark simulations that predict updrafts correctly and show the benchmark sensitivity to the aerosol, it is believed that in case the GFS simulation predicts the updraft mass flux correctly and is equipped with "aerosol-aware physics" like the CSRMs simulations, the GFS simulation is likely to produce a correct sensitivity.

Line 313. How do you get updraft speed from updraft mass flux? Cumulus parameterizations produce mass flux, but additional assumptions are needed to diagnose updraft speed. More detail is needed here.

In the ARW simulations at any resolutions, as explained in our responses above, cumulus parameterizations are not used. Instead, in those ARW simulations, the updraft speed itself is predicted by the ARW model. Then the updraft mass flux is obtained simply by multiplying the updraft speed with air density. To clarify the point here, the following is added:

(LL262-264 on p13-14)

Hence, cloud variables (e.g., the updraft speed) are not diagnosed by convection parameterizations but predicted in both the CSRMs runs and the repeated runs.

(LL324-325 on p17)

Updraft mass fluxes are obtained by multiplying the predicted updraft speed by air density.

Lines 323-339. Do the convection schemes in the models have any physics that would cause the updrafts to depend on aerosol?

As elaborated in our responses above, the convection schemes are not used in the ARW simulations at any resolutions in this paper. Instead, based on results from those simulations, the discussion about the convection schemes with the dependence on aerosol is given in “summary and discussion”; see the last paragraph in the paper for the discussion.

Section 5.2. Excellent work and presentation!

Lines 468-473. Some discussion of the microphysics in the convection schemes used in the coarse resolution simulations would be helpful.

As elaborated in our responses above, the convection schemes are not used in the ARW simulations at any resolutions in this paper.

Lines 519-520. It should be noted here that in saturation adjustment schemes the condensed water does not depend on updraft velocity. And the coarse resolution models lack dependence of cumulus microphysics on supersaturation.

We believe that saturation adjustment calculates the amount of water vapor that should be condensed based on the predicted or diagnosed updrafts and the associated level of saturation. Even in saturation adjustment, stronger updrafts produce a lower level of saturation for a given amount of water vapor to result in more condensed water vapor that affects associated microphysical processes, as in schemes that predict supersaturation. However, in saturation adjustment, the entire amount of water vapor that is determined to be condensed is removed from the atmosphere within one time step, which is different from those schemes that predict supersaturation or the supersaturation prediction; Tao et al. (1989) is one of classic papers on saturation adjustment and see this paper for the details of saturation adjustment. Hence, in saturation adjustment, condensed water depends on updrafts or updraft speed. Stated differently, even in saturation adjustment, the underestimation of the updraft intensity leads to the underestimation of condensed water and thus cloud mass. Based on this, whether the NWP models adopt saturation adjustment (and its impacts on microphysics) or supersaturation prediction (and its impacts on microphysics), the use of coarse resolutions in the NWP models, which results in the underestimation of updrafts, induces the underestimation of condensed water and cloud mass. As detailed in our responses to some of the comments above, whether the NWP models adopt “aerosol-aware physics (that considers the effect of updrafts and supersaturation (or the saturation level) on cumulus microphysics and aerosol impacts on the effect)” as phrased by the reviewer above, the NWP models are likely to underestimate cloud variables (e.g., updrafts, condensed water and cloud mass) and the sensitivity of cloud variables to increasing aerosol concentrations based on the ARW simulations.

Text pointed out here is revised as follows to remove impression that the statement in this text is only applicable to the supersaturation prediction but not the saturation adjustment:

(LL577-579 on p29)

This study shows that the use of coarse resolution can cause an underestimation of the updraft intensity and thus condensation and deposition, which leads to an underestimation of the cloud mass.

Reference:

Tao, W. K., J. Simpson, and M. McCumber, 1989, An ice-water saturation adjustment, *J. Appl. Meteor.*, 117, 231-235.

Lines 555-570. This is great discussion. Perhaps note that global models designed to represent cloud-aerosol interactions do use a subgrid updraft velocity for activation in stratiform clouds, so they would exhibit less resolution dependence of clouds than the ARW model. See, e.g, Ghan et al. JGR 1997.

As detailed in our discussion (LL540-554 in the old manuscript), although the GFS model is coupled to the sub-grid parameterizations or the convection scheme such as cumulus parameterizations that diagnose the subgrid variables such as the subgrid updraft speed, the GFS model produces the results similar to those in the ARW simulations at the coarse resolution. As detailed in our discussion (LL540-554 in the old manuscript), this means that the diagnosis of the subgrid variables (by the convection scheme) and the calculation of their impacts on microphysical processes such as activation do not work well in the GFS model. Associated with this, as detailed in our responses to some of the reviewer's comments above, although "aerosol-aware physics" as phrased by the reviewer here is implemented into GFS, GFS is likely to show the weak sensitivity (to increasing aerosol concentration) as shown in the ARW simulations at the coarse resolution. Stated differently, the GFS model (representing global models) which considers cloud-aerosol interactions is likely to produce the weak sensitivity or the underestimation of the sensitivity, unless the convection scheme is improved to remove the errors that are caused by the use of the coarse resolution and the subsequent incorrect diagnosis of the subgrid variables. This discussion about the GFS model (representing global models) is all about the GFS model at the coarse resolution. In this study, we assume that in case GFS model adopts the resolution as fine as in the CSRMs simulations, the GFS model does not have to use the convective schemes as in the CSRMs simulations, since cloud variables such as updrafts are considered to be explicitly resolved at the fine resolution. Considering that the dependence of model results on microphysics parameterizations is very small as compared to that on resolutions as discussed in Section 5.3, we assume that the GFS model (representing the global models) produce results (including the sensitivity) similar to those in the CSRMs as long as the GFS model uses the resolution as fine as in the CSRMs and thus explicitly resolves updrafts as in the CSRMs, although there can be differences in physics parameterizations between the GFS and the CSRMs. Based on this assumption and the fact that at the coarse resolution, results are similar between the GFS model and the ARW model, we believe that the variation of results (including the sensitivity) among the ARW simulations with a transition from a fine resolution to a coarse resolution is likely to be similar to that variation among the GFS simulations with that transition.