Authors’ response to the review comments #1

Title: Evaluation of modeled surface ozone biases as function of cloud cover fraction (gmd-2015-42)

Authors: Hyun Cheol Kim, Pius Lee, Fong Ngan, Youhua Tang, Hye Lim You, and Li Pan

Anonymous Referee #1

General response: First of all, the authors express their appreciation to the two reviewers and the editor. We believe that their comments are very productive and substantially contributed to improve the manuscript. We offer point-by-point responses to the issues and comments addressed by reviewers. Reviews’ comments are shown in italics. Figures 1-4 indicate figures in the new manuscript, and Figures R1-R5 indicates figures in this reply.

We thank to both reviewers for mentioning the statistical significance of current analysis. We agree that current analysis including all site data can be limited due to geographical and local characteristics of individual sites. In order to supplement current analysis, we present the geographical distribution of cloud-fraction (CF)-O3 correlation (Figure R1, Figure 4 in the revised manuscript) for each AQS monitoring site. Examples from several selected monitoring sites are shown in Figure R2. Hopefully, this analysis can provide additional information for the issues that reviewers have commented.

As the reviewer #1 mentioned, this manuscript tries to raise a question on the CF handling which hasn’t been addressed much after the early stage of air quality model development. The estimation of CF impact to ozone bias from this manuscript is intended to provide an estimated range of impact. We do not claim this guess is a finalized quantitative interpretation. We do understand more accurate quantity can be reached by further investigating individual site’s behavior after removing other local uncertainties (e.g. emission variation). Hopefully, we can pursue it in the following studies.

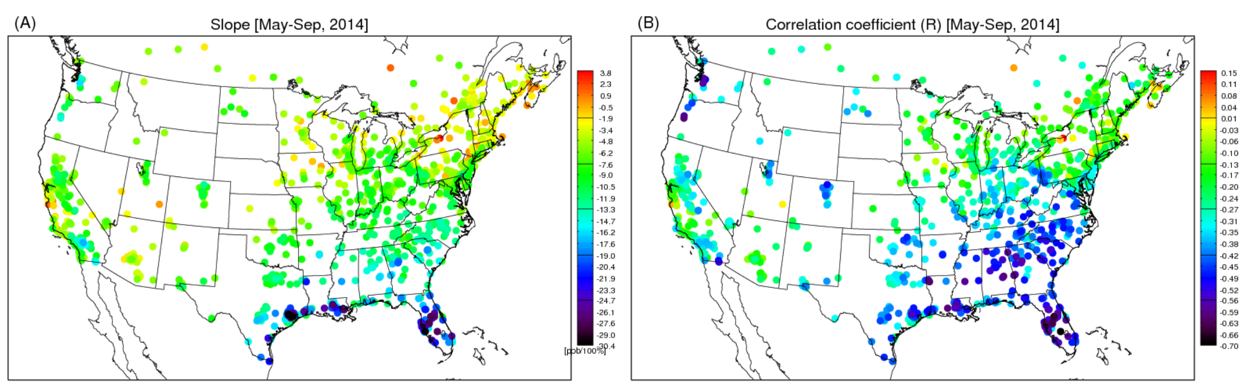

Figure R1. Spatial distributions of (a) slope and (b) correlation coefficient of linear regress between MODIS CF and MDA8 ozone.

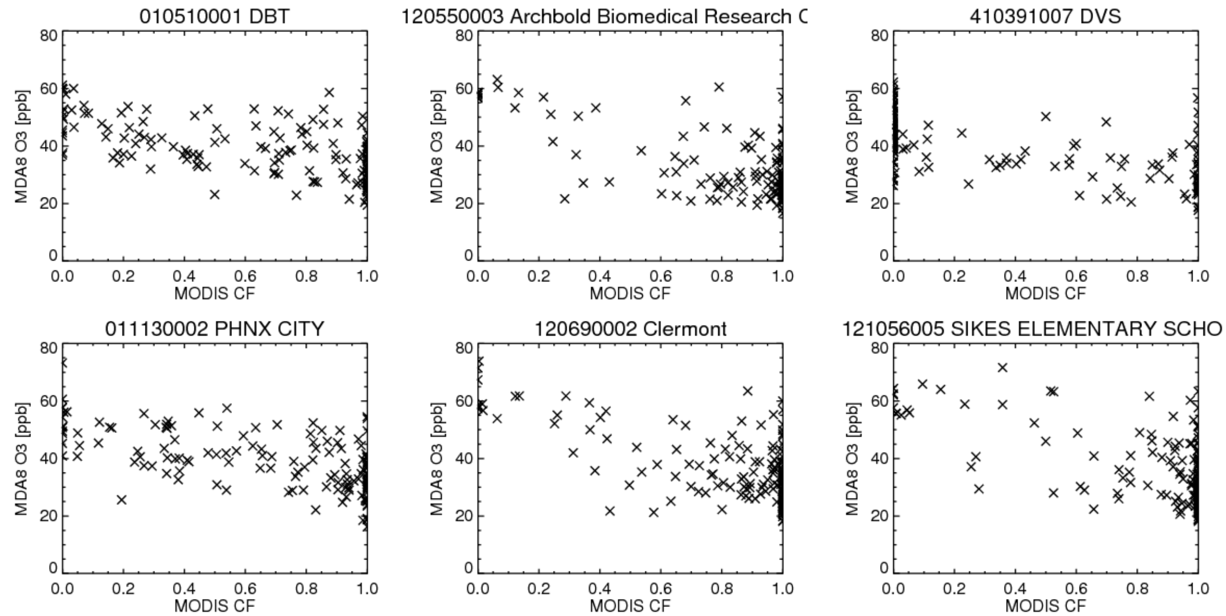

Figure R2. Scatter plots of MODIS CF & MDA8 ozone for 6 selected AQS sites.

General Comments: This paper addresses a very important issue: the source of ozone forecast bias in the NAQFC model. As this model is used extensively for operational air quality forecasting in the US, information of this type is certainly timely. The paper provides what is essentially a "back of the envelope" calculation of the impact of cloud cover on ozone forecasts. Since I have seen no prior work that addresses this issue systematically, it is a welcome addition. My main criticism is that the authors are claiming too much for their study. It can stand alone as a first rough guess calculation but probably isn't strong enough to support some of the conclusions in the paper. I think the paper is certainly worth publishing if the authors add some clarification concerning the limits of their conclusions.

Reply: Thanks for very productive comments. As mentioned in the general response, we have conducted additional analysis for each monitoring site's behavior. Also, we provide an estimation of maximum uncertainty because we intend to address that the impact of model cloudiness on O3 bias is worth further investigations.

We believe the mean of all data for each cloud fraction (CF) bin still has a meaning since local uncertainties (e.g. emission uncertainty) are independent of CF, so individual uncertainties are randomly distributed and can be averaged out. However, we strongly agree that current analysis with all site data can be limited due to the high uncertainty from local characteristics of individual sites. Hopefully, individual site analysis with better correlation will provide additional information.

Manuscript change: Additional analysis and descriptions are included – Figure 4 and line 175-186

Specific Comments:

p. 3221, line 6: re, trends in "frequency of photolysis", do you mean "rates" of photolysis?

Reply: We apologize for the confusion. It originally intended "amount of photochemical reactions". We removed this for better clarification.

p. 3222, line 15: Cloud fraction (fc) as diagnosed in the model is a function of RH, but it would be useful to know exactly what that function is as used in the experimental NAQFC.

Reply: In MCIP v3.6, cloud coverage is calculated in line 131-177 of bcldprc_ak.f90. We included it in the text.

The fractional cloud coverage used in the NAQFC is computed as following (Byun and Ching, 1999).

Cloud fraction (f_c^k) above the boundary layer:

$$f_c^k = \left[\frac{RH^k - RH_c}{1 - RH_c}\right]^2$$

Where RH^k is the relative humidity at vertical model layer k and RH_c is the critical relative humidity defined as $RH_c = 1 - 2\sigma_c(1 - \sigma_c)[1 + 1.732(\sigma_c - 0.5)]$ and $\sigma_c = p^k/p^{k_{PBL}}$

Cloud fraction with the convective boundary layer when $RH > RH_c$:

$$f_c^k = 0.34\,\frac{RH^k - RH_c}{1 - RH_c}$$

Byun, D.W. and J.K.S. Ching, 1999: Science Algorithms of the EPA Models-3 Community Multiscale Air Qualty (CMAQ) Modeling System., EPA/600/R-99/030, U.S. EPA. Page 12-49 – 51.

Manuscript change: Added descriptions and equations (line 69-78)

p. 3224, line 2: It would be interesting to know if the changes to the experimental NAQFC noted at this line reduced the bias of the model by a magnitude that is more or less than that by cloud fractions as estimated in this paper.

Reply: We do not have sensitivity test results for August 2014. For July 2011 case, ozone overestimation is reduced from 11.44 ppb to 7.63ppb by improved model processes and emission update (33% improvement). On the other hand, current manuscript estimates 35% adjustment from 5ppb ozone overestimation by CF difference in August 2014.

Kim, H., P. Lee, L. Pan, L. Judd, D. Tong, Y. Tang, T. Chai, B. Lefer, and I. Stajner, 2014: Comprehensive comparisons of NAQFC surface and column NO2 with satellites, surface, and field campaign measurements during 2009-2014, 2014 CMAS conference, Chapel Hill, NC

p. 3224, line 6: The cloud fraction difference is estimated at 1:30 LT but the metric of interest for ozone is the 8-hour running average. This raises a few questions that probably should be addressed in the text. For example, is an instantaneous measure of cloud fraction an accurate metric with which to compare the cumulative effects of clouds and sun over an 8-hour averaging period?

Reply: As described in the manuscript, afternoon time is chosen because it is when ground-level ozone shows its highest production efficiency, which builds up its daily maximum ozone level (e.g. MDA8 ozone). We agree more CF information will help a better comparison, but it is limited since the MODIS is polar orbital. It can be further investigated with geostationary CF information (e.g. GOES data)

Is it a good measure for high, stratiform clouds more than for low level buoyancy driven clouds?

Reply: We notice cloud type (high- & low-) can be important due to the wave-length dependency of photolytic reactions. Unfortunately, current MODIS standard product does not provide separate information on the level of cloud. Our future plan for this issue is to apply an advanced MODIS cloud algorithm to investigate impacts from high- and low- clouds on the ground level chemistry. We are currently utilizing Chang and Li (2005)'s cloud retrieval algorithm to separate standard MODIS total cloud information to low-, middle- and high- clouds, but do not think results are available for current manuscript.

Fu-Lung Chang and Zhanqing Li, 2005: A Near-Global Climatology of Single-Layer and Overlapped Clouds and Their Optical Properties Retrieved from Terra/MODIS Data Using a New Algorithm. *J. Climate*, **18**, 4752–4771. doi: http://dx.doi.org/10.1175/JCLI3553.1

Is it possible that the NAQFC model "catches up" with cloud fraction as the day increases. The NAQFC, based on the NAM, uses a boundary layer parameterization scheme that may, or may not, produce low level cloudiness at the proper time in the diurnal cycle.

Reply: Since MODIS is polar orbital instrument, we are not able to fully evaluate the diurnal evolution of current model's cloud field. However, there is no evidence that current NAQFC model generates more cloud in other hour. Figure R3 shows diurnal variation of NAQFC CF and MODIS CF from current CONUS domain (land only, August 2014), showing consistent underestimation of CF from NAQFC.

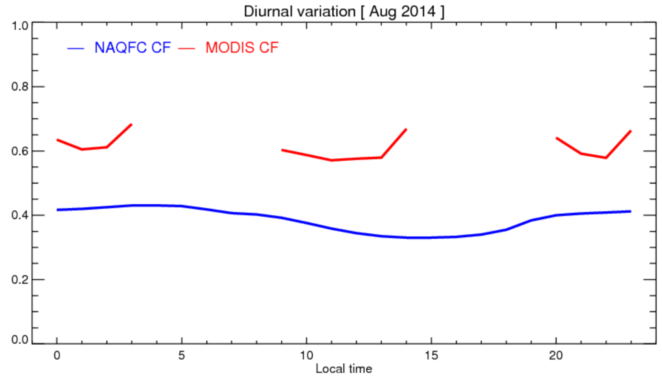

Figure R3. Diurnal variation of NAQFC CF and MODIS CF.

p. 3225, lines 20-23 and Figure 3: I didn't find this figure to be very enlightening. The text notes that Figure 3a shows "a clear separation of ground level ozone for each cloud fraction". _fig. 1 below. To be honest, I don't see much clarity in the scatterplot. Perhaps if a linear best fit line was superimposed? I find it useful for all "busy" scatterplots to include some fittted line in the figure along with the best fit equation and r and r2 values in a legend. That makes it more convenient for the reader who otherwise has to jump back a forth in the text – a table would be second best.

Reply: We agree that figure 3 is too noisy since it includes data from all sites. For better clarification we included individual site's analysis in Figure 4, showing its geographical distribution with better correlation. We corrected "clear separation" to moderate term. We also regenerated Figure 3 with fit line and equation.

Manuscript change: Figure 3 is replaced. Figure 4 and descriptions are included.

In any event, while the NAQFC shows less cloud cover, particularly in the near-overcast range, it is worth the effort to see whether there is a statistically significant difference between the two samples. Because we are looking at one month of data, a bit more statistical rigor would be very helpful. It's clear that cloud fraction effects are important but a little more information on the uncertainty of the estimates (that used mean values) would be very useful.

It would also be good to mention if there was anything unusual with respect to the climatology of the CONUS during August of 2014. I'm not certain that it affects the results shown here, but for the bulk of the CONUS, the summer of 2014 was a historically low ozone year – similar to 2013. As a result, the critical cases for air quality forecasts – those in the high end of the distribution (e.g., Code Orange), were scarce in 2014. _figure 2 below

Reply: Interannual variations of climatology indeed affect the base ozone level, but its sensitivity to CF in daily-timescale does not change significantly. As shown in Figure 4, the daily ozone variation due to CF change is much bigger than interannual variation, especially in southern states. To clarify this issue, we have extended analysis to 10 years (2005-2014). Seasonal variations of Ozone-to-CF sensitivity during 2005-2014 are shown in Figure R4, and they show clear seasonal variation without regard to interannual variability.

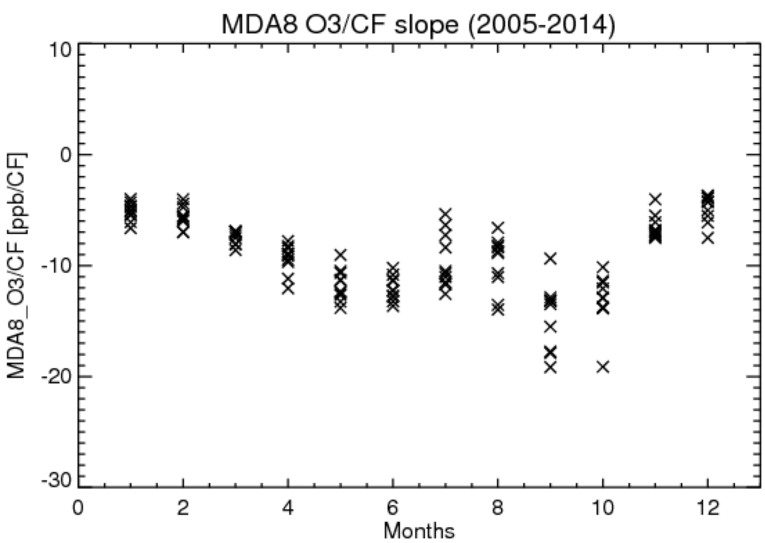

Figure R4. Seasonal variation of Ozone-to-CF sensitivity during 2005-2014.

The very clean conditions in 2014 may be a function of changing emissions but may also be associated with large scale weather patterns. See images below suggesting a cooler than normal August with large OLR anomalies (Figures via, http://www.esrl.noaa.gov/psd/data/composites/day/). _figures 3 and 4 below With reference to the statistical analysis, Figure 3d shows an extremely broad standard deviation band for all ranges of cloud fraction difference. As the conclusions that follow in text lean heavily on mean *values to express model sensitivity, this is a little troubling. It is what it is, of course, but the authors should point out that the data is very noisy so that later calculations that make use of them should be taken with a grain of salt. In this case, the "very rough" results at p. 3226, line 20, should be further qualified. For example, what is the range of possible sensitivity across the distribution of O3 differences? _figure 5 below In this regard, it might be worthwhile to choose a subset of data, perhaps set of monitors in a region, and see how this cloud fraction bias works on a local or regional level.*

Reply: We agree with the review's comment. We added in the text that the all data is very noisy, and analysis on the individual sites in Figure 4 can provide further information with better correlation. Correlation coefficients are also provided to show the uncertainty range. We expect that individual site's correlation can be improved if we can remove the impacts from emission (e.g. weekly pattern). Hopefully, we can pursue it in the following study.

p. 3226, line 5: -10.5ppb100%-1 looks like a typo.

Reply: Corrected

p. 3226, line 10: The use of the term "brighter" is a bit confusing here. "Brightness" is kind of a term of art in many other applications and may not be meant the same here. Is what the authors mean to say is that the model has fewer clouds?

Reply: Replaced to "have fewer clouds"

Conclusions: This is a good paper on a very interesting and timely subject. It should be published with revisions. In particular, the authors should qualify a few of their conclusions and better describe the underlying uncertainty of the data and the metrics used to estimate sensitivity, in particular the use of mean values in a noisy field of data.

Reply: Thanks again for very productive comment.