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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Aerosol indirect effect on the grid-scale clouds in the two-way coupled WRF-CMAQ: model description, development, evaluation and regional analysis" *by* S. Yu et al.

S. Yu et al.

smyu111@hotmail.com

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Shaocai Yu et al. Shaocaiyu@zju.edu.cn

We thank the anonymous referee #3 for the constructive and helpful comments, the incorporation of which has led to a substantially improved manuscript.

Reviewer #3(Comments):

General Comments This paper describes a new, coupled meteorology and chemistry model system that is based on WRF and CMAQ and its initial application over the continental US at a 12-km grid resolution and eastern Texas at a 4-km resolution during

August and September of 2006. Different from some online-coupled models that integrate meteorology and chemistry into one model system such as WRF/Chem, WRF and CMAQ are coupled via a coupler with 2-way meteorological and chemical data exchange but one single executable program. The two-way coupled WRF-CMAQ accounts for both direct and indirect aerosol effects, in particular, the first, second and glaciation aerosol indirect effects. It treats both cloud droplet and ice number concentrations as prognostic variables that depend on aerosol predictions of CMAQ and meteorological predictions of WRF. Developed and supported by the U.S. EPA, CMAQ has been widely applied and extensively evaluated for both scientific and regulatory applications worldwide since its first release in late 1990s'. Inclusion of indirect aerosol effect treatments in CMAQ represents a significant advancement and milestone in air quality modeling in terms of scientific understanding of the complex relationship between air pollutants and climate change and the development of integrated win-win emission control strategies for air quality management and climate change mitigation. The paper represents the first documentation of the two-way coupled WRF-CMAQ with aerosol indirect effect and the first comprehensive evaluation of its capability in reproducing shortwave cloud forcing and other cloud properties. The model development and evaluation involve substantial efforts that should be recognized in both air quality and climate communities. The results demonstrated the scientific merits to treat aerosol indirect effects in air quality models. I therefore strongly support its publication on ACP. The paper is overall well written and organized. The literature review section is quite comprehensive. The method for model development and evaluation is technically sounds. It can be accepted with minor revisions.

Reply:

We thank the reviewer for the overall positive assessment of the manuscript and strong support for this work.

The paper would be strengthened by incorporating the following points: 1) The significance and policy implications of the two-way coupled WRF-CMAQ should be pointed

ACPD
13, C13124–C13138, 2014

out in the abstract and conclusion sections.

Reply:

Thanks a lot for helpful suggestion. To address the reviewer's comments, the following sentence "This work shows that inclusion of indirect aerosol effect treatments in WRF-CMAQ represents a significant advancement and milestone in air quality modeling and the development of integrated emission control strategies for air quality management and climate change mitigation" has been added in the abstract of the revised manuscript.

2) Scientific objectives should be stated clearly and explicitly in the Introduction section.

Reply:

Thanks a lot for helpful suggestion. To address the reviewer's comments, the following sentence ""The purpose of this paper is twofold. First, this study implements. . .... Second, this study examines the model performance. . ." has been used in the revised manuscript.

3) In the simulation design section (Section 2), the reasons and purposes for the four simulations, WRF/CAM, WRF/RRTMG, WRF-CMAQ/CAM, and WRF-CMAQ/RRTMG should be provided.

Reply:

Thanks a lot for helpful suggestion. To address the reviewer's comments, the following sentence "The comparison results of WRF-CMAQ/CAM and WRF-CMAQ/RRTMG simulations can indicate the effects of radiation schemes on the model performance on air quality and cloud properties. For reference, WRF/CAM and WRF/RRTMG simulations are also carried out to show how CMAQ air quality model helps improve the WRF performance on cloud properties." has been added in the revised manuscript.

4) In Section 3, the evaluation protocol for model performance (e.g., variables selected

ACPD

13, C13124–C13138, 2014

for model evaluation, criteria/threshold values to judge model performance, time period for simulated cloud data processing against satellite data) should be described.

Reply:

Thanks a lot for helpful suggestion. To address the reviewer's comments, the following sentences "To evaluate model performance, regression statistics along with three measures of bias (the mean bias (MB), normalized MB (NMB) and normalized MB factor (NMBF)), and three measures of error (the root mean square error (RMSE), normalized mean error (NME) and normalized mean error factor (NMEF)), and correlation coefficient (r) (Yu et al., 2006, Gustafson and Yu, 2012) were calculated. Following the protocol of the IMPROVE network, the daily (24-h) PM2.5 concentrations at the AQS sites were calculated from midnight to midnight local time of the next day on the basis of hourly PM2.5 observations. To evaluate the model performance on cloud properties, following Harrison et al. (1990), the shortwave (longwave) cloud forcing SWCF (LWCF) at the TOA was calculated as the difference between the clear-sky reflected shortwave (outgoing longwave) radiation and the all-sky reflected shortwave (outgoing longwave) radiation at the TOA for both models and CERES observations" has been added in Section 3 of the revised manuscript.

5) In Section 4, the coupled model underpredicts some aerosol species (e.g., NH4+, SO42-) but overpredicts the other species (e.g., OC and EC). Please discuss the impacts of such biases on the accuracy in the aerosol indirect effect predictions. In section 4.3, some discussions should be added regarding how will the inclusion of aerosol indirect effects improve precipitation.

Reply:

Thanks a lot for helpful suggestion. To address the reviewer's comments, the following sentence "On the other hand, underestimation of PM2.5 over the land areas of the EUS in August of 2006 as shown in Table 5a may also cause the underestimation of the CCN concentrations, leading the underestimation of cloud fields" has been added

ACPD
13, C13124–C13138, 2014

in the revised manuscript. In section 4.3, the new sentence “This is because of the fact that inclusion of aerosol indirect effects in the cases of WRF-CMAQ can improve the model simulations of cloud fields as shown before relative to the WRF default cases, leading to the improvement of precipitation simulations.” has been added in the revised manuscript.

6) The paper is a bit too long, and can be shortened. Some tables (e.g., Tables 2, 3, 4, 7, and 8, Figures 4, 8, 12, 16, 18, 21, 23) can be moved to supplementary material. The conclusion section can also be shortened a bit to avoid repetition of results that are already discussed in previous sections.

Reply:

Thanks a lot for helpful suggestion. Since this is first comprehensive evaluation of newly-developed WRF-CMAQ modeling system, we feel that the readers would like to see all results in the paper instead of in supplementary material portion. So we still keep all these information in the current form.

Specific Comments (1) Page 25651, line 8, change “CASTNet” to “CASTNET”, please make the same change throughout the paper text, tables and figures.

Reply:

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(2) Page 25651, lines 16-17, change “Both models” to “Both simulations”, as you are using one model system with two different configurations, so you refer to two simulations, not two models.

Reply:

Thanks a lot for helpful suggestion. To address the reviewer’s comments, the following sentence “both configurations” has been used in the revised manuscript because we feel that simulations can be referred to model results of every day.

ACPD

13, C13124–C13138, 2014

(3) Page 25654, lines 25-29, the resulting coupled met and AQ models using the first and second approaches should be the same, as they are integrated model systems, which is different from the coupled model using the 3rd approach. This should be indicated clearly.

Reply:

Thanks a lot for helpful suggestion. To address the reviewer's comments, the following sentence "The first approach is to integrate meteorology and atmospheric chemistry such as MM5/Chem (Grell et al., 2000) and WRF/Chem (Grell et al., 2005) and GATOR-GCMOM model (Jacobson, 2001a, b) which are created by adding atmospheric chemistry to the existing meteorology models. The second approach is to combine existing meteorology and air quality models into a single executable program with 2-way meteorological and chemical data exchange such as the two-way coupled WRF-CMAQ model (Wong et al., 2012)." has been used in the revised manuscript.

(4) Page 25656, lines 1-2, to avoid using two "used" in one sentence, please change "The RRTMG and CAM radiation schemes are used because these two schemes are used in many studies." to "The RRTMG and CAM radiation schemes are selected because these two schemes are used in many studies."

Reply:

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(5) Page 25656, line 8, change "observation" to "observational"

Reply:

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(6) Page 25656, please describe the scientific objectives of your work before section 2. Also, in section 2.1, please describe why Aug-Oct 2006 was selected.

Reply:

ACPD
13, C13124–C13138, 2014

Thanks a lot for helpful suggestion. This is done in the revised manuscript. The new sentence “This is because of fact that there are a lot of observational data for the summer of 2006” has been added in the revised manuscript.

(7) Page 26659, line 12, change “Note that “OTHR” specie” to “Note that “OTHR” species”

Reply:

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(8) Page 25660, line 4, change “using a aerosol activation scheme for multiple externally mixed lognormal modes” to “using an aerosol activation scheme for multiple externally-mixed lognormal modes”

Reply:

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(9) Page 25659, line 18, change “Yu et al., 2007a, b, 2004, 2005, 2008” to “Yu et al., 2004, 2005, 2007a, b, 2008”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(10) Page 25660, lines 6, 7, 13, 16, change “Abdul-Razzak and Ghan (2002, 2000)” to “Abdul-Razzak and Ghan (2000, 2002), as the citation order should be chronologically. Lines 16-17, change “(Abdul-Razzak and Ghan, 2002, 2000; Abdul-Razzak et al., 1998)” to “(Abdul-Razzak et al., 1998; Abdul-Razzak and Ghan, 2000, 2002)”

Reply:

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(11) Page 25661, line 2, change “Where” to “where”

Reply:

ACPD
13, C13124–C13138, 2014

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(12) Page 25661, line 8, change “Here” to “here”

Reply:

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(13) Page 25662, line 2, change “Hanel” to “Hänel”

Reply:

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(14) Page 25662, line 9, change “from the different investigators.” To “from different investigators.”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(15) Page 25663, lines 3, 14, 20, change “Abdul-Razzak and Ghan, 2002, 2000” to “Abdul-Razzak and Ghan, 2000, 2002”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(16) Page 25663, change “scheme for treatment of cloud droplet nucleation and vertical diffusion of cloud droplets simultaneously” to “scheme for simultaneous treatment of cloud droplet nucleation and vertical diffusion of cloud droplets”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(17) Page 25664, line 1, change “Morrison et al.,” to “Morrison et al.”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(18) Page 25664, line 15, change “study to avoid to double accounting” to “study to avoid double-accounting”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

ACPD
13, C13124–C13138, 2014

(19) Page 25664, line 16, change “the effective radius; Slingo (1990)” to “the effective radius. Slingo (1990)”. (note that this sentence should be split into two sentences).

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(20) Page 25666, line 16, change “Where” to “where”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(21) Page 25667, line 12, change “cloud microphysics scheme which is based on the approach of Meyers et al. (1992) is” to “cloud microphysics scheme, which is based on the approach of Meyers et al. (1992), is” to increase readability.

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(22) Page 25667, line 14, change “allow estimation” to “allow an estimation”.

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(23) Page 25667, line 23, change “Where” to “where”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(24) Page 25668, section 3, change the subtitle from “Observational data sets” to “Observational data sets and evaluation protocol” In addition to the description of obs data, please describe your evaluation protocol, e.g., what statistics matrix did you use to evaluate the results, and what criteria/threshold values did you use to determine good vs. poor model performance.

Thanks a lot for helpful suggestion. This is done in the revised manuscript as described before.

(25) Page 25669, line 9, change “clouds and the aerosols” to “clouds and aerosols”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(26) Page 25669, section 3.2, what is the time resolution/overpassing time of the

ACPD

13, C13124–C13138, 2014

CERES data? Is it once per day? If so, is a consistent time period (i.e., during the satellite overpassing time) used to compare model predictions with the CERES data?

Thanks a lot for helpful suggestion. As described in the manuscript, monthly means are calculated using the combination of observed and interpolated parameters from all days containing at least one CERES observation.

(27) Page 25670, section 4.1.1, since the focus of this paper is aerosol and its indirect effect, suggest to move Table 4 and most discussions on O3 to supplementary material.

Thanks a lot for helpful suggestion. Again, since this is first comprehensive evaluation of newly-developed WRF-CMAQ modeling system, we feel that the readers would like to see all results in the paper instead of in supplementary material portion. So we still keep all these information in the current form.

(28) Page 25670, move lines 4-11, "To evaluation: : :. PM2.5 observations." To section 3 after description of surface and satellite data.

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(29) Page 25670, lines 11-12, why August and September 2006 were chosen? Some justifications for this selection should be provided in section 2.

Thanks a lot for helpful suggestion. This is done in the revised manuscript as described before.

(30) Page 25670, lines 14 and 21, change "both models" to "both simulations"

Thanks a lot for helpful suggestion. This is done in the revised manuscript

(31) Page 25670, line 20, change "indicating the overestimation" to "indicating that the overestimation"

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(32) Page 25671, line 8, change "both models" to "both simulations"

ACPD

13, C13124–C13138, 2014

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(33) Page 25672, lines 6, 8, and 18, change “both models” to “both simulations”

Thanks a lot for helpful suggestion. This is done in the revised manuscript..

(34) Page 25672, line 9, change “with the NMB < _6 %” to “with NMBs within _6 %.”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(35) Page 25672, line 18, change “with the NMB < _7 %” to “with NMBs within _7 %.”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(36) Page 25673, lines 3, 12, 24, 25, change “both models” to “both simulations”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(37) Page 25673, line 5, change “As pointed by” to “As pointed out by”

Thanks a lot for helpful suggestion. This is done in the revised manuscript..

(38) Page 25673, line 25, change “with the NMB < 15%” to “with NMBs < 15%”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(39) Page 25674, line 1, change “with NMB< 6 %.” to “with NMBs < 6 %”.

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(40) Page 25674, lines 2-3, “gaseous SO2 concentrations were not oxidized enough to produce aerosol SO42- in the models over the WUS.” Is this due to uncertainties in gas-phase chemistry or the aqueous-phase chemistry? Please elaborate likely causes for the insufficient oxidation.

Thanks a lot for helpful suggestion. To address the reviewer’s comments, the following sentence “One of the reasons is due to the fact that the model generally underestimate the cloud fields over the WUS, causing the underestimation of aqueous SO42-

ACPD

13, C13124–C13138, 2014

production." has been added in the revised manuscript.

(41) Page 25674, lines 6-7, "This indicates too low NOx emissions in the emission inventory over the WUS." Is this statement supported by references or analyses in this work? Please provide relevant references or justifications.

Thanks a lot for helpful suggestion. This sentence has been deleted in the revised manuscript. .

(42) Page 25674, lines 13, 23, 25, 26-27, 29, change "both models" to "both simulations"

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(43) Page 25674, line 14, change "the NMB < 20%" to "NMBs < 20%"

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(44) Page 25674, line 15, change "NMB <ôĂĂĂ11%" to "absolute NMBs within 11%" Note that since NMB is negative, only an absolute value of NMB that is < 11% can be considered a good performance, for larger absolute values such as 30%, even through it satisfies "-30% < ôĂĂĂ11%, it actually means poorer performance, instead of better performance.

Thanks a lot for helpful suggestion. This is done in the revised manuscript. We agree.

(45) Page 25675, lines 1, change "both models" to "both simulations"

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(46) Page 25676, the two simulations with met only, WRF/CAM and WRF/RRTMG should be mentioned in the simulation design section. The reasons and purposes for those met only runs should be provided.

Thanks a lot for helpful suggestion. This is done in the revised manuscript as described before.

ACPD
13, C13124–C13138, 2014

(47) Page 25676, lines 9, 13, change “wattsmôĂĂĂ2” to “W môĂĂĂ2”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(48) Page 25676, lines 19-22, please explain why the WRF-CMAQ/CAM produced more cloud than the WRFCMAQ/RRTMG over the CONUS.

Thanks a lot for helpful suggestion. We don’t know the reason why the WRF-CMAQ/CAM produced more cloud than the WRFCMAQ/RRTMG over the CONUS. Maybe they used different way to calculate the radiative effect of cloud. This is beyond of this research.

(49) Page 25677, line 20, change “CMAQ/CAM, WRF-CMAQ/RRTMG” to “CMAQ/CAM and WRF-CMAQ/RRTMG”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(50) Page 25678, line 4, change “the slightly overestimations” to “the slight overestimations”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(51) Page 25678, line 8, change “WRF-CMAQ/CAM, WRF-CMAQ/RRTMG” to ‘WRFC-MAQ/ CAM and WRF-CMAQ/RRTMG”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(52) Pagte 25678, line 19, change “shows that” to “show that”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(53) Page 25678, lines 22, 26, change “both models” to “both simulations”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(54) Page 25679, line 24, change “generally underestimations” to “general underestimations”

ACPD

13, C13124–C13138, 2014

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(55) Page 25680, line 20, change “All models” to “All simulations”

Thanks a lot for helpful suggestion. This is done in the revised manuscript. .

(56) Page 25681, line 8, change “Figure 24 and Table 12 indicates” to “Figure 24 and Table 12 indicate” Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(57) Page 25681, line 23, change “these cells” to “these grid cells”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(58) Page 25682, line 12, change “a uniform internal mixtures” to “ uniform internal mixtures”

Thanks a lot for helpful suggestion. This is done in the revised manuscript. .

(59) Page 25682, line 13, change “Abdul-Razzak and Ghan (2002, 2000)” to “Abdul-Razzak and Ghan (2000, 2002)”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(60) Page 25682, lines 7-11, what are the likely reasons for those overestimations?

Thanks a lot for helpful suggestion. To address the reviewer’s comments, the following sentence “One of the reasons is because of too much SO2 emissions in the emission inventory.” has been added in the revised manuscript.

(61) Page 25683, line 29, Page 25684, lines 6, 11, change “both models” to “both simulations”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(62) Page 25684, line 15, change “have significant” to “show significant”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

ACPD
13, C13124–C13138, 2014

(63) Page 25688, line 28, change “Hanel” to “Hänel” , line 29, “ityat” should be “ity at”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

(64) Page 25700, please add a column (column 2) to explain the full name of each Species

Thanks a lot for helpful suggestion. Since the full name of each species has been explained in the text part and some name may be very long such as AALK represent SOA formed by the absorptive partition of condensable oxidation products of long alkanes, it will be redundant if we add them here in Table again.

(65) Page 25704, for a fair comparison, the statistics from 12-km and 4-km simulation should be calculated using observations in the 4-km domain. Was this done for Table 6? If so, please add this in the evaluation protocol section.

Thanks a lot for helpful suggestion. Yes, this is done in the revised manuscript.

(66) Page 25714, figure 2. Please use the same color for the parentheses for “Interaction and feedback”

Thanks a lot for helpful suggestion. This is done in the revised manuscript.

Interactive comment on Atmos. Chem. Phys. Discuss., 13, 25649, 2013.