## Response to Referee #2

## Interactive comment on "Beijing Climate Center Earth System Model version 1 (BCC-ESM1): Model Description and Evaluation" by Tongwen Wu et al.

### General

The paper presents a description and an evaluation of the tropospheric aerosols included in the Beijing Climate Center Earth System Model. The paper consists of a quite general overview and my main concerns relate firstly to the description of the aerosol scheme which is rather vague in several parts. Furthermore, it is not so clear what is specific or not to this aerosol scheme, what has been developed and/or adjusted, compared to other schemes already in place in other climate models. Secondly, the evaluation is mostly qualitative, and when some quantitative information is provided, it often refers to quite old references.

Both issues needs to be addressed quite thoroughly for the paper to progress in the review process. This requires quite some work. My list of particular points appears below.

***We thank reviewer #2 for his/her carefully reading our manuscript. We have revised the manuscript accordingly. We showed more details and descriptions of the aerosol scheme, and added an evaluation for O3 simulation which is helpful to complement aerosols. We also presented more quantitative information, and comparisons with recent observation and references.***

### Questions/remarks

1. paragraph "Model description": this paragraph needs some rewriting as some features, eg ACGM3, AVIM2, are presented twice

***We have rewritten this paragraph in "2. Model description". The components of the atmosphere, the land, the ocean and the sea ice in BCC-ESM1 are described in separate paragraph.***

2. L146: what is the reference for the "weighted-combination"? Please provide more details.

***In the revision, we have reworded this sentence to make our point clearer and rewritten this paragraph in lines 127-137 as "Dry deposition velocities for the 15 trace gases including O3, CO, CH4, CH2O, CH3OOH, H2O2, NO2, HNO3, PAN, CH3COCH3, CH3COOOH, CH3CHO, CH3COCHO, NO, and HNO4 are not computed interactively and directly interpolated from MOZART2 climatological monthly mean deposition velocities (https://en.wikipedia.org/wiki/MOZART(model)) which are calculated offline (Bey et al., 2001; Shindell et al., 2008) using a resistance-in-series scheme originally described in Wesely (1989). The dry deposition velocities for the other 15 species including MPAN, ONIT, ONITR, C2H5OH, POOH, C2H5OOH, C3H7OOH, ROOH, GLYALD, HYAC, CH3OH, MACROOH, ISOPOOH, XOOH, HYDRALD, and H2 are calculated using prescribed deposition velocities of O3, CO, CH3CHO, or land surface type and surface temperature following the MOZART2 (Horowitz et al., 2003)."***

3. L156: is turbulent transport included? if not, then you are missing sub-grid scale transport and the overall distribution of chemical species would be quite different considering this sub-grid scale transport. Please explain what is your rationale for presenting an evaluation without these processes.

***Yes, Vertical transport of gas tracers and aerosols due to deep convection is not yet included in the present version of BCC-AGCM3-Chem, which process is considered as a part of the deep convection and occurs generally in a small spatial region on a GCM-box with low-resolution (2.8 °lat.×2.8 °lon.). Another consideration is that a large uncertainty exists to treat transport of those water-soluble tracers by deep convection. But this effect will be involved in the next version of BCC model. We have added those expressions in lines 146-151.***

4. L173: the Wesely approach has 3 terms. Why did you retain only two terms? Please indicate if you compute the terms interactively or not. This is at the moment not clearly stated.

***Yes, the Wesely (1989) approach has 3 terms. We have cleared clarified this in lines 184-187 in the revised manuscript as "The dry deposition velocity of SO2 follows the resistance-in-series approach of Wesely (1989) using the formula, $W_{SO2} = 1/(r_a + r_b + r_c)$, in which $r_a$, $r_b$, and $r_c$ are the aerodynamic resistance, the quasi-laminar boundary layer resistance, and the surface resistance, respectively and they are interactively computed in each model time step."***

5. L179: it seems to me that the reactions listed in Table 2, and their reaction rates, are the same as the ones that appear in Lamarque et al. 2012. This should be noted in the paper, as therefore both the chemistry and the aerosol modules of the BCC-ESM1 and CAM-Chem used for generating what the authors refer as the "CMIP5 recommended" aerosol concentrations are quite similar. This should be made quite clear in the paper. Possibly a paragraph in the paper could be dedicated to what is specific to this scheme, if this is relevant.

***Yes, the reactions listed in Table 2 are referred to CAM-Chem (Lamarque et al., 2012). We have rewritten the description in lines 178-180 in the revised manuscript as "The present version of aerosol scheme belongs to a bulk aerosol model and mainly refers to the scheme of CAM-Chem (Lamarque et al., 2012), but the nucleation and coagulation of aerosols are still ignored."***

6. L182: there is no reference to DMS in Benkowitz 1996. Please clarify what you mean.

***That is our confusion about the reference. In the revision of the manuscript, we have reworded this sentence in lines 193-196 as "The main source of DMS is from oceanic emissions via biogenic processes. It is prescribed with the climatological monthly data that are extracted from MOZART2 package (https://www2.acom.ucar.edu/gcm/mozart-4)."***

7. L191: is there a reference for this assumption?

***That is related to "NH3". In the first version of manuscript, we make a mistake about NH3. In fact, the previous version of BCC-ESM did not include NH3 simulation in the chemistry scheme. But in the frozen version of BCC-ESM1 that is used in this work, NH3 is already set as a prognostic variable following CAM4 (Lamarque et al., GMD, 2012). So we added a description about NH3 in "2.1 SO2, DMS, NH3, and Sulfate" and Table 1, Table 2, and Table 4 in the revised manuscript.***

8. L215: please clarify why in this paragraph about OC and BC your write about "soluble gases"?

***We have rewritten the description in line 226-228 as "OC2 and BC2 are soluble aerosols, and their sinks are primarily governed by wet deposition. Their in- and below-cloud scavenging follows the scheme of Neu and Prather (2011)".***

9. L224: what are the values of this scaling factor?

***We have clarified it in lines 236-237 as "S is a scaling factor and set to $4.05x10^{-15}$, $4.52x10^{-14}$, $1.15x10^{-13}$, $1.20x10^{-13}$ for four bins of sea salt aerosols (Table 4), respectively."***

10. L252: Wu et al 2019 is not in the list of references; and what do you mean by "it is parameterized", what is "it"? Do you refer to the aerosol first indirect effect or to the first and second effects? Please provide further details, in particular if you parameterize the second indirect effect of aerosols that not all climate models consider

***We have added Wu et al 2019 in the list of references, and added a paragraph in "2.5 Effects of aerosols on radiation, clouds, and precipitation" to describe the treatment of aerosol indirect effect in BCC-ESM1. In the first version of manuscript "it is parameterized" means "liquid cloud droplet number concentration is parameterized". Its details are added.***

11. L257: "historical" is not an AerChemMIP simulation but rather a CMIP6 simulation that will be a basis for a large number of CMIP6 analyses, including some AerChemMIP analyses, but also other MIPs analyses. Please correct this wording throughout the document. If the simulation you present is an historical CMIP6 simulation, please indicate the baseline name of the corresponding files on the ESGF. Do you present one ensemble member or several members?

***We have rewritten description about "historical" experiment in "3. Experiment design for the 20th century climate simulation". It followed the historical simulation protocol designed by CMIP6 (Eyring et al., 2016) which is named as "historical" in the Earth System Grid Federation (ESGF). The protocol details the historical experiment forced with emissions evolving from 1850 to 2014 refer to Collins et al. (2017). Three members of historical experiments are conducted and the first member is analyzed in this work.***

12. L264: "only $O_3$ is a prognostic variable": what about $CH_4$, it is part of the chemistry scheme and therefore it is also a prognostic variable isn't it? what about also $CO_2$?

***CH4 and N2O may be selected as prognostic variables. But both are suggested in AerChemMIP to take prescribed values for the historical experiment. CO2 is also prescribed using CMIP6 historical forcing data. We have clarified this point in lines 307-312 in the revised manuscript.***

13. L274: the CMIP6 anthropogenic emissions are meant to cover all that is required for a climate model. Can you explain why this was not the case for your model?

***Anthropogenic emissions for most tracers are available in the CMIP6 data. But we cannot find anthropogenic emission data for H2 and N2O that we need. The details about the emission data used are given in the revised manuscript.***

14. L276: to my knowledge there is no such CMIP6 recommendation for hydrophobic and hydrophilic forms. Please rephrase your sentence.

***Yes, there is no such CMIP6 recommendation for hydrophobic and hydrophilic forms. So, we use monthly lumped emissions of black carbon and organic carbon aerosols and then we divided them separately to 80% of BC and 50% of OC emitted in their hydrophobic forms (BC1 and OC1) and the rest being in their hydrophilic forms (BC2 and OC2) following the work of Chin et al. (2002). This is cleared in lines 333-337.***

15. L279 and following: please describe in more details the formation of Secondary Organic Aerosol from vegetation that you consider? what comes out of MEGAN2.1, are they related to OC2 only, and not OC2 and OC1? ...

***OC does not belong to biogenic volatile organic carbons (VOCs). The hydrophilic organic carbon (OC2) can be formed from natural biogenic volatile organic compound (VOC) emissions. It is calculated online in the land component model BCC-AVIM2 and assumed to equal to 10% of monoterpenes emission following the algorithm of Chin et al. (2002). Those expressions are added in lines 348-352.***

16. L291: factor 2-4 high: this is a strong affirmation! The Ge et al. 2016 study is older than the CMIP6 data. How do they relate? And furthermore, do you have a stratospheric aerosol scheme that uses these data? If yes, please describe the scheme, if not please clarify your sentence.

***The work of Ge et al. 2016 is not mentioned, and this statement is now removed in the revised manuscript. As for stratospheric aerosol, we only considered SO4. We have rewritten this paragraph in lines 354-360 as "As there is no stratospheric aerosol scheme in BCC-ESM1, concentrations of sulfate aerosol at heights from 5 to 39.5 km, which volcanic origin, are directly prescribed using the CMIP6-recommended data (Thomasson et al., 2018) from 1850 to 2014. The effects of surface SO2 emissions from volcanic eruption on the variation of SO2 in the atmosphere and then on the variation of tropospheric SO42- concentration are considered, and the SO2 emissions from 1850 to 2014 are downloaded from the IPCC ACCMIP emission inventory (http://accent.aero.jussieu.fr/ACCMIP.php)."***

17. L304: please clarify what the MOZART2 data package include, data? Chemistry code?...

***We have clarified those in lines 374-376 as "Climatological values of NO, NO2, HNO3, CO and N2O5 at the top two layers are extracted from MOZART2 data package available at the Website (https://www2.acom.ucar.edu/gcm/mozart-4), originated from the Study of Transport and Chemical Reactions in the Stratosphere (STARS, Brasseur et al., 1997)."***

***Yes, MOZART2 data package includes data and chemistry code.***

18. L307: to my knowledge the CMIP6 data package does not include neither $CH_4$, nor $N_2O$: what do you refer here to?

***We have checked them. The CMIP6 data package includes zonally and monthly values of CH4 and N2O.***

19. Table 1 and Table 4: there are incoherences between species listed in both Tables. For example, CH3COCHO is not emitted in Table 1 and has emissions in Table 4. Please carefully check consistency between these tables.

***We have corrected the incoherence between Tables 1 and 4.***

20. L318: “only a small warming”: please quantify this

***We have rewritten this paragraph in lines 381-395 of the revised manuscript and added the time series of global SST in Figure 1.***

21. L324: mean and uncertainty should not be of different orders. Please correct here and in other places in paper.

***We have corrected those expressions in “3.4 The preindustrial model states”***

22. L331: these are not concentrations but rather loads, and what is the reference for these “CMIP5 recommended concentrations”?

***Figures 2a-2c show the time series of global annual total masses in the troposphere (integrated from the surface to 100 hPa) in the last 450 years of the piControl. It is derived from CMIP5 recommended concentrations. The reference of CMIP5 data is Lamarque et al. (2010) and has added in the text.***

23. L338: why do you think there is such a distribution?

***We added some words about the distribution of SO42- in year 1850 in lines 411-415 of the revised manuscript as “We can compare them with CMIP5 recommended concentrations in year 1850, considered as the reference state in the pre-industrial stage. At that time, there are fewer anthropogenic/biomass SO2 emissions, the SO4 over land are evidently smaller than those over oceans especially over the tropical Pacific and Atlantic Oceans, where DMS can be oxidized to SO2 and then form SO4.”***

24. L350: in addition to pointing out similarities, please address differences between CMIP5 and BCC-ESM1 outputs, and why there are such differences/similarities

***We have added sentences in lines 428-432 as “Relative lower relations for sulfate, black carbon and organic carbon are possibly caused as different anthropogenic emission sources are used in BCC-ESM1 and to create CMIP5 data. Dust and sea salts belong to natural aerosols and depend on the land and sea surface conditions, so their spatial distributions are easy to be captured and have relatively higher correlations between CMIP5 data and BCC-ESM1 simulations.”***

25. L376: what is this particular "NCAR data package"

***We have corrected it in lines 485-487. It is MOZART2 data package.***

26. L378: sentence "This decrease trend possibly results from the prescribed emissions have not year-to-year variations and ..." is not clear

***It is modified in lines 487-491 as “As shown in Fig 7a, the global amount of DMS in the whole atmosphere was about 0.12 Tg during 1850-1900 and decreased to 0.055 Tg in 2010. This decrease trend maybe partly results from the speeded rate of DMS oxidation with global warming, and the loss of DMS gradually exceeds the source of ocean DMS emission to cause a net loss of DMS in the atmosphere since 1910s”***

27. L386: the sentence "The trends of global BC and OC burdens are similar to that of sulfate, but they showed continuous increases from 1950 to present." is not clear

***This sentence is modified in lines 496-499 of the revised manuscript as "As for global BC and OC burdens, BCC-ESM1 results show continuous increases since 1850s, especially from 1950 to present. From 1910's to 1940's, the CMIP5 data show a slight decrease of BC and OC burdens in the atmosphere."***

28. L390: "was slightly enhanced from 1950 to 2000" : I rather see a similar burden in 1950 and in 2000. Please be clearer, and do you have evidence of increasing soil dryness during that period?

***We have corrected its description in lines 501-504. Global dust burden in the period from 1980 to 2000, not from 1950 to 2000, shows evident increase. The details about the temperature and soil moisture in drought areas will be explored in other paper.***

29. L400: "largely due to stronger wind speed": differences could be due to differences in underlying DMS concentrations in the oceans. What supports your affirmation?

***DMS emission from the ocean is computed by wind near the sea surface. We have not compared the wind simulations in BCC-ESM with the data used in Liu et al. (2005). So, we cancelled the original description to account for their difference of DMS emission from oceans between BCC-ESM1 and the values in Liu et al. (2005).***

30. L406: air traffic is part of anthropogenic activities; please rephrase your sentence, and what about biomass burning emissions? biomass burning emissions, $SO_2$ from volcanic eruption?

***We have modified descriptions in lines 512-516. There are three parts of SO2 source listed in Table 5. One is produced from the DMS oxidation, the second is from airplane emissions to the atmosphere, and the rest included emissions from anthropogenic activities and volcanic eruption at surface.***

31. L407: you indicate that volcanic emissios are not included. I wonder in Figure 3 what corresponds to the area of large loads of sulfate around Central America?

***Corrected it. Volcanic emission of SO2 at surface is included.***

32. L423: it seems that the total of 45.2 Tg/yr for OC is incoherent with what appears in Figure 4b; please correct.

***In the Table 6, the units of OC sources and sinks are Tg (OM)/yr in order to compare with the data of Liu et al. (2012), and assumed OC equal to OM/1.4. We have transferred the units of OC sources and sinks to Tg (OC) yr−1 in Table 6 to keep coherence with the data in Figure 4b.***

33. L490: please provide some quantitative information with these plots, as for instance appears in the AeroCom web page with scatter plots (https://aerocom.met.no/cgi-bin/surfobs_annualrs.pl)

***We have added some statistical values such as Table 7 to list the regional mean and spatial standard deviation, minimum and maximum values at IMPROVE and EMEP network sites versus simulated concentrations of sulfate (SO42-), organic carbon (OC), black carbon (BC),***

***and the spatial correlation between observed and simulated multi-years averaged annual means.***

34. L500: please provide some quantitative elements on the extinction coefficients, also single scattering albedo and asymmetry parameter3

***As limited length of the text, the other optical feature of aerosols such as extinction coefficients, single scattering albedo and asymmetry parameters, and even their feedbacks on radiation and global temperature change will be explored in the other paper. It is mentioned in lines 706-709 in "5. Summary and discussions"***

35. L502 (and paragraph): do you show a 1997-2003 average or the 2008 year as indicated in the figure; please provide quantitative information (bias, rmse..., or normalized figures as you prefer). This comment is valid for all figures. They should all be accompanied with some quantitative information

***We have added Table 7 to list the regional mean and spatial standard deviation, minimum and maximum values at IMPROVE and EMEP network sites versus simulated concentrations of sulfate (SO42-), organic carbon (OC), black carbon (BC), and the spatial correlation between observed and simulated multi-years averaged annual means.***

36. L516: I don't feel the evaluation is "comprehensive" so far. Please review this affirmation as you make some progress in a future version of the paper3

***"comprehensive" is changed to "primary" in line 660.***

37. L530: you indicate that you used prescribed concentrations for CH4, and in Table 4 you indicate that you consider $CH_4$ emissions. Please clarify

***CH4 is a prognostic variable in the chemistry scheme of BCC-ESM1. So, emission of CH4 listed in Table 4 is used to simulate CH4 concentration, but some WMGHGs such as CH4, N2O, CO2, CFC11 and CFC12 according to the experimental protocol of AerChemMIP are prescribed using CMIP6 prescribed concentrations (to replace prognostic values of CH4 and N2O from the chemistry scheme). It is clarified in "3. Experiment design for the 20th century climate simulation" in the revised manuscript.***

38. L541: there is no such compararison of all of these aerosols with observations. Please be more precise.

***Modified the description in lines 684-685 in the revised manuscript as "Global budgets of aerosols were evaluated through comparisons of BCC-ESM1 results for 1990-2000 with reports in various literatures for sulfate, BC, OC, sea salt, and dust.".***

39. L560: I don't understand "How about the GHGs simulations in the AeroChemMIP historical run?" please be clearer and more precise4

***O3 is evaluated in this work. Other GHGs such as CH4 and N2O concentrations can be simulated when forced with emissions and their simulations also need to be evaluated in future. Those are added at the end of "5. Summary and discussions".***

40. Figure 4: please add biomass burning emissions, if not done yet, or indicate if they are already part of the figur4

***Modified the captions of Figure 4, and all the biomass burning emissions are included in natural emissions in (a)-(c).***

41. Figure 14: do you compare monthly observations averaged over 1998-2005 with monthly model outputs averaged over 1998-2005? please formulate more precise.

***The data plotted in Figure 14 (it is numbered to Figure 15 in the revised manuscript) are multi-years averaged annual means over the available years 1990–2005 for IMPROVE sites and 1995–2005 for EMEP sites and corresponding simulations. The caption of Figure 15 is rewritten as "Scatter plots showing observed versus simulated multi-years averaged annual mean sulfate (SO4), organic carbon (OC), black carbon (BC) mixing ratios at IMPROVE and EMEP network sites. Observations are averages over the available years 1990–2005 for IMPROVE sites, and 1995–2005 for EMEP sites."***

**Minor questions/remark1at the paper focuses on tropospheric aerosols**

1. L1: the title is misleading and should be changed at the paper focuses on tropospheric aerosols

***This is a very good suggestion. The title "Beijing Climate Center Earth System Model version 1 (BCC-ESM1): Model Description and Aerosols Simulation Evaluation" is changed to "Beijing Climate Center Earth System Model version 1 (BCC-ESM1): Model Description and Aerosols Simulation Evaluation"***

2. L49: "Besides gaseous"

***In the revision, we have rewritten this sentence to "Besides gaseous components, atmosphere also contains various aerosols, which are important for cloud formation and radiative transfer." in lines 52-53 of the revised manuscript.***

3. L51: aerosol are particles; so change "aerosol particles" to "aerosols"

***It is modified in line 54 of the revised manuscript.***

4. L59, and others: homogeneise writing of chemical compounds, for instance O3

***Expressions for chemical compounds similar to O3 in the whole text are modified to keep homogenies.***

5. L99: "BCC-ESM1 is a fully-coupled global climate-chemistry-aerosol model ": it seems to me that BCC-ESM1 is more than that; I would say it is an "Earth System Model with interactive chemistry and aerosol components" if you want to insist on these components

***We thank the reviewer for pointing this out. This sentence is rewritten to "BCC-ESM1 is an Earth System Model with interactive chemistry and aerosol components." in lines 101-102 of the revised manuscript.***

6. L120: change “used” to “uses”

***It is corrected.***

7. L122: please clarify “ranged to”

***The sentence is rewritten to “MOM4-L40 uses a tripolar grid of horizontal resolution with 1 º longitude by 1/3 º latitude between 30 ℑ and 30 ℕ ranged to 1 º longitude by 1 º latitude from 60 ℑ and 60 ℕ poleward and 40 z-levels in the vertical.” in lines 161-163.***

8. L145: it is not clear whether deposition velocities are computed interactively, as in Wesely, or consist of monthly means.

***We have clarified those expressions in lines 127-137 of the revised manuscript.***

9. L198: remove “Its”

***In the revision, we have removed the word “Its”.***

10. L238: please be more precise on the Web page

***The Web page is https://svn-ccsm-inputdata.cgd.ucar.edu/trunk/inputdata/atm/cam/dst/. It is denoted as in line 251 in the revised manuscript.***

11. L252: Wu et al 2019 is not in the list of references; and what do you mean by “it

is parameterized”, what is “it”?

***The reference of Wu et al.(2019) is added in the list of references. The sentence “it is parameterized” means “liquid cloud droplet number concentration is parameterized”. We have added the description about its parameterization in “2.5 Effects of aerosols on radiation, cloud, and precipitation” in the manuscript.***

12. L263: AGCM-Chem1: is this the correct name of the model?

***“BCC-AGCM3-Chem” is the name of the atmosphere component model of BCC-ESM1. It is corrected in line 261 of the revised manuscript.***

13. L264: please reformulate “at each model step and interacts with radiations”

***We have rewritten this expression in lines 307-310 of the revised manuscript.***

14. L276: add “see Table 4”

***It is modified.***

17. L283: MEGAN acronym already introduced

***It is modified.***

18. L310: change “1850 AD conditions” to “1850 conditions”.

***It is modified.***

19. L317: change “600” to “450”

***It is modified.***

20. L385: early 1980s

***It is modified.***

21. L513: please correct the North American coordinates; and correct also in Figure 14 the European coordinates; and furthermore the coordinates you indicate in the text do not correspond to those of Figure 14

***Figure 14 is numbered to Figure 19 in the revised manuscript. We have corrected the legends in Figure 19 and the expressions in the text.***

22. L543: in relevant literature

***“in relevant literatures” is corrected to “in relevant literature”.***

23. Table 1: please indicate that interactive surface emissions are considered for sea salt and dust

***We added the expression “In the column of surface emission, interactive surface emissions are considered for sea salt and dust.” in the caption of Table 1.***

24. Table 5: I could not find figures for the sinks of DMS in Liu 2005 Table 4. Where do your figures come from?

***It is our mistake as our references confusing and cancelled in the revised manuscript.***

25. Table 6: f for Ginoux 2001

***Ginoux et al. (2001) is added in the list of references.***

26. Figure 1: change SAT into tas official CMIP6 variable

***It is modified in Figure 1.***

27. Figure 5: what is the "20th historical simulations"? Same question in caption of Figure 11

***The expression of “20th historical simulations” is changed to “CMIP6 historical simulations” in Figures 7 and 14 in the revised manuscript.***

28. Figure 5: change "blue" to "black”

***It is modified. Figure 5 is renumbered to Figure 7 in the revised manuscript.***