Author's response to interactive comments by anonymous referee #1:

The authors would like to thank the referee for very constructive review comments. Each of the review comments are repeated below in bold font, followed by our replies.

Interactive comment on "A production-tagged aerosol module for earth system models, OsloAero5.3 – extensions and updates for CAM5.3-Oslo" by Alf Kirkevåg et al.

The article untitled "A production-tagged aerosol module for earth system models, OsloAero5.3 – extensions and updates for CAM5.3-Oslo" by A. Kirkevag et al. presents in a very detailed way updates in the modelisation of aerosols that is used in the atmospheric component of the Norwegian Earth System Model (NorESM). This updated version called OsloAero5.3 is here tested in the CAMS5.3 atmospheric model which is part of the Community Earth System Model 1.2 (CESM). With regards to the CMIP6 project, OsloAero5.3 is planned to be integrated/merged with CEMS2 to form the NorESM2 model, but the version presented in this article could be used for the early phase of CMIP6. Therefore, in addition to being of value to the aerosol modelling community, the discussions in the article are fully relevant to the CMIP6 exercise.

The article is very well written, and provides a thorough review of changes from a previous version documented in Kirkevag et al. 2013, together with an analysis of several aerosol diagnostics. Several changes have been mode, including ones to the aerosol sources, aerosol nucleation, soa production, and aerosol-cloud interactions. The analysis presents comparisons not only with results from the previous version of the aerosol model, but also with observations, with results from other aerosols models, in particular those of the AeroCom community, and with other aerosol studies. The analysis attempts to document in details the advances and setbacks of this new version. Although the article is very long, in particular in the aerosol model description part, I would recommend it for publication in GMD as it is, as details in any part can be of interest to some scientists in the aerosol community. I include below a few comments that will require only minor corrections in the document.

Thank you for these encouraging words. Having a good and well documented basis paper for the pre-CMIP6 model version and for present and planned AeroCom experiments are indeed among the main purposes of the manuscript, while at the same time hoping it can be of use for researchers within the field in general.

• it would be interesting to include information of the added computational cost required to use this aerosol model, possibly in comparison to the other aerosol models of CESM (MAM3 and MAM7). In particular, which/now many of the tracers listed in Table 1 are transported by the model? Also, please add some details on the chemical mechanism used in conjunction to this aerosol model (line 6 page 8)

All the aerosol tracers in Table 1 are transported by the model, as mentioned on p. 5, line 25. To clarify this also in Table 1, we change the text in the caption to

«Transported aerosol tracers in CAM5.3-Oslo».

For completeness, we suggest to add also the list of gas tracers transported in the model, in a sentence at the end of the Table 1 caption:

«The aerosol precursor and oxidant gas tracers transported by the model are: SO_2, H_2SO_4, DMS, isoprene, monoterpene, SOAG_LV, SOAG_SV, and H_2O_2.»

To answer the question about model cost, we suggest to add a new paragraph at the end of Sect 2.1 (p. 6):

«The total number of transported aerosol and gas tracers in OsloAero5.3 is 29 (21 aerosol and 8 gas tracers, see Table 1), compared to 20 (15 and 5) in MAM3 and 37 (31 and 6) in MAM7. Comparing CAM5.3-Oslo simulations using OsloAero5.3 with MAM3, we find a ca. 49% increase in model cost (50% for the atmosphere module alone). Much of the relatively large increase in model cost compared to MAM3 is due to the multi-dimensional table look-ups and interpolation calculations for aerosol optical properties and sizes in OsloAero5.3. For comparison, according to Liu et al. (2012), CAM5.1 set up with MAM7 runs about 30% slower than with MAM3.»

Although described to some degree in the first paragraph of Sect. 2, we agree that more detailed information about the chemical mechanisms should be provided, and suggest to add the following explanatory text after line 6 on page 8:

«The chemical mechanisms in OsloAero5.3, for sulfur and oxidant chemistry as well as the SOA chemistry in (R1) – (R6), have been described in more detail by Karset et al. (2018), Sect 2. For an overview of the chemical reactions and the respective reaction rate coefficients, see Table 2 in Karset et al. (2018).»

- **page 2 line 2: "while it...": please clarify this part of the sentence**

We here try to convey with just a few words that some regional biases are of opposite sign to the globally averaged bias, and we hope this is clarified by the following reformulation:

«Comparing clear-sky column integrated optical properties with data from ground based remote sensing, we find a negative bias in optical depth globally, however not as strong as in CAM4-Oslo, but with positive biasess in some areas typically dominated by mineral dust emissions.»

- **page 2 line 4: "overestimated" shouldn't it be changed to "underestimated"**

We here compare the biases in clear-sky absorption with those of optical depth (all in CAM5.3-Oslo), which are both overestimated in some of the most dust dominated areas, although they are underestimated globally. These regional overestimates are smaller (or even of opposite sign) for absorption than for optical depths, as described in more detail on p. 28, lines 11-16. So we do mean «less overestimated» for these particular regions. In case the meaning of this sensentence is unclear to the referee because of how it is formulated, we suggest to reformulate it slightly, to:

«Aerosol absorption has a larger negative bias than the optical depth globally. This is reflected in a lower positive bias in areas where mineral dust is the main contributor to absorption.»

- **page 13 line 19: is the proportional coefficient you use that of the references?**

As mentioned in l. 11, C is just a (non-adjustable) unit conversion coefficient, not given in any of the references. Since k_600 in the model is given with units cm/h, M_DMS as g/mol, and C_DMS as nmol/L, C = 2.778E-15 in the model code, which gives F_DMS with units kg/m2/s in Eq. 4. To clarify, we will change the text on l. 11 from «C is a unit conversion coefficient» to

«C is a unit conversion coefficient in the model code (not a tuning factor)».

- **page 15 line 8: please provide details on the vertical resolution (extension, distribution of levels)**

We may here add the following information

«In hybrid sigma pressure coordinates, the uppermost eta level mid (or top of the level) value is 3.64 (2.26), and for the lowermost level it is 992.56 (985.11). The number of layers below approximately 1 km and 2 km height a.s.l. are 5 and 8, respectively.»

• page 17 line 26: please comment on the fact that in Figure 5 the Nudge and Amip lines are quasi identical in the troposphere

We propose to add at the end of this paragraph:

«Note that NUDGE_PD and AMIP_PD yield almost identical results in the troposphere. This indicates that the nudging, as long as we are not nudging the temperature, only has modest effects on the convective transport and mixing of BC in the model (see also Fig. 4).»

• page 19 line 28: comment on the interest of self nudging

We are not sure what the referee would like to see added to the text here, but we tentatively add at the end of the paragraph, on line 3, p. 20:

«An important effect of nudging is that it constrains the model's natural variability (Kooperman et al., 2012), which is useful in calculations of the indirect effect of aerosols since it reduces the simulation length required to obtain sufficiently high signal to noise ratios. When nudging to a meteorology produced by the model itself (self-nudging) instead of using data from reanalysis (such as the ERA data), one additionally obtains model meteorology and climate which are more consistent with the model's own, innate behaviour, which in turn lends more confidence in, e.g., estimates of effective radiative forcing, but is less useful for the purpose of comparing modeled aerosol properties with observations.»

We furthermore suggest to add at p. 33, line7:

«Note, however, that nudging to the ERA data instead of the model's own meteorology only has small impacts on anthropogenic cloud forcing: Karset et al. (2018) applying self-nudging (and when using the same oxidant levels as in the present study) in CAM5.3-Oslo, estimated it to -1.32 W m^{-2}, very close to our estimate -1.34 W m^{-2} (SW + LW ERF ACI in Table 10).»

• page 21 line 3 change "better than" to "better"

The sentence spanning lines 2-4 is awkwardly phrased, but «better than» is correct to use here, see Table 7. In order to make it clearer, we suggest to rewrite this sentence to:

«For the climatological averaged data, the Pearson correlation coefficient R (hereafter often just referred to as the correlation) is slightly better for the nudged than for the un-nudged AMIP simulation, where instead the normalized mean bias NMB (hereafter often just referred to as the bias) is slightly better.»

• page 29 line 7: please clarify "as the source of the largest negative biases" where do you see that in Figure 7?

Thank you for pointing this out: this part of the text is not very well formulated. We suggest to change this and the preceeding sentence to:

«Regionally, ANG4487CS is most underestimated in Northern Africa (defined as above, i.e. extended to include sites along the European coast of the Mediterranean, -35%), followed by Europe (defined as above, -32%), Australia (-31%), India (-20%), East Asia (-10%), and smallest in North America (-7%).

This pattern (see also Fig. 7) seems to point towards dust as a source of large negative biases, which is consistent with an excessive mineral dust contribution to the total aerosol (as also indicated by the regional OD550CS biases), or alternatively, overestimated dust particles sizes (opposite of what we found as a potential cause of the positive bias in ABS550CS).»

• page 30 line 1: please add a few details about this dataset

We here propose to add

«This data set is a climatology of cloud droplet number concentration (monthly mean, in-cloud 1°x1° CDNC values plus associated uncertainties for warm clouds) based on 13 years of Aqua-MODIS observations over the global ice-free oceans.».

• page 34 line 13: is this excess of BC in the upper troposphere common/uncommon in other models?

Although CAM4-Oslo was among the more extreme o the AeroCom models in that respect, it was not unique: e.g., HadGEM2 is more extreme in many regions, as can be seen from model – HIPPO intercomparison in Samset et al. (2014, see Fig. 2) (doi:10.5194/acp-14-12465-2014). We may therefore add at the end of this paragraph (on line 18):

«Note that there is a general tendency for models participatig in the AeroCom project to overestimate the aircraft measurements aloft in remote regions (Samset et al., 2014).».

We also suggest to add a reference to the AeroCom intercomparison paper by Kipling et al. (2016) in the sentence on lines 14-16:

«This may be related to aerosol aging and to how aerosols are transported and scavenged in deep convective clouds (see e.g. Kipling et al., 2016): also the mass concentrations of the other aerosol components have been reduced (aloft) from CAM4-Oslo to CAM5.3-Oslo.»

• page 56: Table 6 legend: I suggest to change "monthly European and Global data" to "monthly data". Please explain "(or world oceans in the case of dust)". Please indicate for how many models you have clear-sky information.

The suggested text change from "monthly European and Global data" to "monthly data" looks fine, and will be done in the updated manuscript.

The term «world oceans in the case of dust» is clumsy, but makes sense when looking at the actual map of available stations at aerosom.met.no, where we see that most of the observation sites are located on islands and along the coasts of the continent, see http://aerocom.met.no/cgi-bin/aerocom/surfobs_annualrs.pl?PROJECT=NorESM&MODELLIST=NorESM-Ref2017&FULL=explicit&INFO=nohover&PERFORMANCE=ind&YEARFILTER=ALLYEARS&PSFILTER=ALLVARS&Type0=SITELOCATION&Ref0=AEROCE&Run0=CAM53-Oslo_7310_MG15CLM45_5feb2017IHK_53OSLO_PD_UNTUNED&Parameter0=SCONC_DUST&Station0=WORLD&Year0=an9999&Period0=mALLYEAR. We suggest to reformulate «and Global = nearly all continents (or world oceans for the case of dust) are represented.» to:

«and Global = nearly all continents or world oceans (island sites) are represented.»

We do not know the exact number of AeroCom models (among those we compare results with) which have clear-sky information on aerocom.met.no. This question was taken up by the AeroCom community during phase II of the project, which resulted in an attempt of documentation via a wiki page: https://wiki.met.no/aerocom/optical_properties. Among the 10 AeroCom model versions (in addition to our own) which are both appearing in the wiki and in Tables 6-8 in the present study (GISS-MATRIX, GISS-modelE, GOCART-v4Ed, HADGEM2-ES, INCA, MPIHAM_V2_KZ, OsloCTM-v2, SPRINTARS-v384, and TM5.V3), only one estimates clear-sky in a similar way as we do, i.e. by using weights based on total 2D cloud cover but all-sky RH for hygroscopic growth of the aerosol: SPRINTARS_v384 averages only AOD for time steps and grid points with CLDTOT<0.2, using all-sky RH in these almost cloudfree cases. GISS-MATRIX, GMI and GOCART_v4E average all-sky AOD (no cloud cover weighting), also based on growth factors from all-sky RH. GISS-MATRIX also provide clear-sky optics, but this has not been used at aerocom.met.no. Although not very clear from the wiki, the rest of the models seem to estimate AOD (tacitly meant to be a clear-sky parameter) for all cloud conditions, but based on hygroscopic particle growth using a clear-sky RH value, defined as the RH in the clear-sky fraction (the value which gives a grid-mean all-sky RH when the cloudy part of the grid is assumed to be saturated). Furthermore, all but one of the 10 models calculate AOD as averages over both night and daytime values, as in CAM4-Oslo and CAM5.3-Oslo.

As described, the CAM4-Oslo and CAM5.3-Oslo data on aerocom.met.no contain both clear-sky and all-sky aerosol optics (for some selected wavelengths) by using the 2D clear-sky fraction weighted AODs as clear-sky AOD. In these models the two measures do differ significantly. However, in an early version of CAM6-Oslo, where we have changed to using clear-sky RH hygroscopic growth for the optics calculations, and otherwise introduced only minor changes in aerosol treatment, the relative difference between all-sky and clear-sky weighted global optical depth has been reduced from ~20% (in CAM5.3-Oslo) to ~10% or less. Although the AeroCom wiki does not provide any quantative answers to how much the clear-sky and all-sky optical propertes differ for other AeroCom models, the models which assume hygroscopic growth based on RH in the clear-sky fraction of the model grid-cell, instead for the all-sky RH as in our model, may therefore also have relatively small differences between all-sky and clear-sky weighted optical properties.

This was a long answer to a short question, for which we unfortunately cannot give an exact reply. We suggest a very short summary of the above to be added in the manuscript, by changing a part of the caption of Table 6 (lines 8-11) from «Optics diagnostics listed for the AP2 and AP3 models are mostly clear-sky values, in the sense that the clear-sky humidity of the grid cell is used for calculating the hygroscopic swelling. CAM4-Oslo and CAM5.3-Oslo compute all-sky optical properties using the average humidity of the grid cell. Clear-sky (CS) properties are represented by a cloud fraction weighted average of the all-sky properties.» to

«Optics diagnostics listed for most of the AP2 and AP3 models (exact number is not available) are clear-sky values, in the sense that the clear-sky humidity of the grid cell is used for calculating hygroscopic swelling of the aerosol. Information about this for 11 of the AP2 models included here, plus some others, may be found at https://wiki.met.no/aerocom/optical_properties. CAM4-Oslo and CAM5.3-Oslo compute all-sky optical properties using the average humidity (RH) of the grid cell. Clear-sky (CS) properties are instead represented by a 2D cloud-free fraction weighted average of the all-sky properties. Only a few other AeroCom models follow a similar clear-sky optics definition, and the optics data submitted to AeroCom for a few of the models are all-sky values both in terms of cloud conditions and RH for hygroscopic growth.»

• page 58 in Table 7 legend, change "Table 9" into "Table 6"

Thank you, this will be corrected as suggested.

• page 59 : please add "and column integrated optical properties" in the legend

Thank you, this will be corrected along the lines suggested, from «near surface concentration values» to «near surface concentration and column integrated optical parameter values.

• page 62: indicate meaning of AWNC, FREQL, AREL. CDNUMC non needed in legend.

CDNUMC is the model variable name for what we in the manuscript denote CDNCcol, and we can removed from the table caption as requested. The first 3 variable names are perhaps not needed in the legend either, but they indicate how we calculate the in-cloud parameters from the variables in the model output. To describe this better without degrading the readability, we suggest to first simplify the caption text to:

«Table 11: All-sky and clear-sky aerosol optical depth (OD) and absorptive optical depth (ABS) at 550 nm, Liquid Water Path (LWP), in-cloud cloud droplet number concentrations (CDNC)* and effective cloud droplet radius (Reffl)** at 860 hPa (model layer 24), and Ice Water Path (IWP). Also shown are the column integrated CDNC (CDNCcol) and Ice Crystal Number Concentration values (ICNCcol, calculated as part of the post-processing).»

and instead add details about the calculation of in-cloud parameters as footnotes to the table:

*CDNC is calculated as the average cloud water concentration AWNC (a grid average multiplied with the fractional occurence of liquid at each time step), divided by the fractional occurence of liquid, FREQL

**Reffl is calculated as the average froplet effective radius AREL (a grid average multiplied with the fractional occurence of liquid at each time step), divided by the fractional occurence of liquid, FREQL

• page 66: meaning of etax1000? please add a couple of levels in the stratosphere

All model levels are already plotted, but I assume you mean a couple of extra tick marks and tick lables: this will be added to the figure. The meaning of etax1000 is the model (hybrid coordinate) eta level multiplied by 1000, which will be added to the figure caption at the end of the first sentence, as «(eta x 1000 is the model hybrid coordinate eta level multiplied by 1000)».

• page 71: I believe ERF ari are shown; it would be clearer to indicate this on top of the figures and in the legend

The terminology used in Fig. 9 is in line with that of Ghan et al. (2013). We realize that this may be a bit confusing, since we also use the terms ERFari and ERFaci in the main text and in Table 10. Due to the slightly different definition of ERFari and ERFaci from that of IPCC AR5, which is explained in the Introduction, mentioned specifically in Table 10 and slightly discussed in Sect. 5, we would prefer to keep the Ghan terminology in Fig. 9 (as in Fig. 10). This is to avoid unnecessary confusion when comparing with other studies using the IPCC AR5 terminology.

• finally, in general zooming in the figures degrades their quality; this needs to be corrected

The original figures are probably better than they look when encapsulated in the pdf document used for the review process, but this will be checked again and dealt with, as far as the maximum allowed figure file size of 5MB (and 30MB in total) permits.