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Atmospheric Chemistry and Physics Discussions

Interactive comment on "A multi-model evaluation of aerosols over South Asia: Common problems and possible causes" *by* X. Pan et al.

X. Pan et al.

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We would like to thank the referee #1 for his/her thoughtful and constructive comments that have helped us to improve the quality of this manuscript. Below are <our responses> to the [comments from referee #1]: ————————

[General comments]: Pan et al., 2014 discuss the multi-model evaluation of aerosol distributions over the South Asian region. The focus is on understanding the common problems in model-simulated aerosol properties and possible causes of underestimation of model-simulated aerosol properties. Even though model underestimation of aerosol proper-ties over South Asia are previously reported in regional-scale analysis (e.g. Reddy etal., 2004; Ganguly et al., 2009), the multi-model evaluation of aerosol

distributions over South Asia could be useful for the scientific community.

The paper is generally well written and the possible causes of underestimation of AOD such as relative humidity and emission amount are quite interesting. The multi-model simulated aerosol properties are evaluated using different observation data sets (e.g. ISRO-GBP, ICARB and satellites).

Dust aerosol underestimation is previously reported as one of the possible causes in AOD underestimation especially in pre-monsoon season over South Asia. However, the inter-model differences and pre-monsoon underestimations are not well described in the manuscript. These points need to be addressed in the manuscript in context with the existing literature. The following comments should be addressed before the manuscript would be satisfactory for publication in ACP.

<Response>: Yes, dust is the dominant aerosol during the pre-monsoon season over South Asia. We add more information about dust, please refer to the reply to the Specific comments 2) below.

[Specific comments]: 1) In Section 4.1 and 4.2, large diversity among model-simulated AOD is visible. The possible causes of inter-model differences over IGP region are not clear from the manuscript. Varying wet /dry deposition rates and emission fluxes do cause significant variations in a single model, but these uncertainties do not explain most of the inter-model differences. Textor et al. [2007] also found that inter-model differences were only partially explained by differences in emission inventories. Bond et al., [2013] pointed out large differences in modelled horizontal and vertical transport are largely responsible for the inter-model diversity for BC distributions. It could be useful if authors highlight the most significant parameter in the model need to be focused for improving the aerosol distributions over South Asia instead of one general sentence that mentioned the manuscript (Page 19119, lines 15-19). <Response>: Thanks for the suggestion. We have added a new section in the manuscript to address the inter-model diversity issue with a new table 3. We found (1) for aerosols with dominant

anthropogenic origin (i.e. BC, OA and SO4), the largest diversity among models occurs in the treatment of dry deposition, with diversities of dry deposition amount ranging 35-45% across three species. The diversity of wet deposition is relatively smaller with a range of 12-26%. (2) The chemical production of sulfate in gaseous phase among models (4 models) also has large diversity (about 77%); (3) BC has the largest diversity of mass extinction efficiency (i.e. MEE) among models compared to other species, with a diversity of 52% compared to 27-28% for other species.

<Response>: Thanks for the suggestion. We have added a new section in the manuscript to address the inter-model diversity issue with a new table 3.We found (1) for aerosols with dominant anthropogenic origin (i.e. BC, OA and SO4), the largest diversity among models occurs in the treatment of dry deposition, with diversities of dry deposition amount ranging 35-45% across three species. The diversity of wet deposition is relatively smaller with a range of 12-26%. (2) The chemical production of sulfate in gaseous phase among models (4 models) also has large diversity (about 77%); (3) BC has the largest diversity of mass extinction efficiency (i.e. MEE) among models compared to other species, with a diversity of 52% compared to 27-28% for other species.

[Specific comments] 2) In Section 5, different possible cause for AOD and AAOD underestimation is described. The underestimation of natural aerosols (e.g. dust) emission flux may also lead to error in total aerosol distributions. Previous studies reported that dust emission flux underestimation can lead to underestimation of model-simulated AOD over South Asia/IGP during pre-monsoon (MAM) season (e.g. Cherian et al., 2012). Few information are reported in the manuscript Section 2.2 (Page 19103, lines 1-5). In Fig.5, the pre-monsoon season (MAM) AOD is not well captured by most of models over Kanpur. The spatial distribution of AOD is also partially captured by all models during this season (Section 4.3). This could be due to missing dust transport to Kanpur from dust source regions. It could be useful if authors provide more information about the inter-model.

<Response>: Yes, the underestimation of dust emission flux may also lead to error in total aerosol distribution in models during pre-monsoon season, in particular the model ECH. We have added information of dust size distribution (highlighted in gray) in the existing Table 1 (see below). In addition, we examine the dust budgets of the monthly emission, dry and wet depositions, load, lifetime, MEE and AOD (new Table 3). The dust emission itself has very large diversity among the models (about 130%), and the diversity of dry (and settling) deposition is as large as 115%. The difference in treatment of dust size bin in models significantly contributes to these diversities among models (see Table 1).

[Specific comments] 3) The information about aerosol refractive index for each species used in the different models is missing from the paper. For example, Black Carbon and Dust AAODs are strongly depending on refractive indices used in the model. The refractive index information could be useful for understanding the inter-model differences in AAODs. It could also useful for providing the future model improvements of AAOD distributions over South Asia.

<Response>: We have added information of aerosol refractive index at 550nm for each species in the existing Table 1 (highlighted in yellow). The real part of refractive indices of each aerosol at 550nm is similar among these seven models, and they are based on Optical Properties of Aerosols and Clouds (OPAC) (Hess et al., 1998) with slight modifications in some models. However, the imaginary parts are varying among models even by a factor of 10 for species SO4 and SS. In particular for BC, the most absorbing aerosol, the imaginary part of refractive index (representing light absorption) is 0.44 in four models and 0.71 in three models. This large diversity of BC refractive indices among models is reflected in BC mass extinction efficiency (i.e. MEE) as shown in the new table 3 with a diversity of 52% compared to 27-28% for other species. Bond and Bergstrom (2006) recommended a higher value of 0.79 for the imaginary part of BC refractive index at 550nm, based on agreement between measured real and imaginary parts of the refractive index of light absorbing carbon. Therefore, we suggest

implementing the BC refractive indices from Bond and Bergstrom (2006). For dust, the light absorption is less than that of BC. The imaginary of dust refractive index ranges from 0.0011 (ECH) to 0.008 (GE5).

[Technical comments]: 4) Page 19099, line 8: aboved?

<Response>: Corrected. Modifying “aboved” to “above”.

[Technical comments]: 5) Page 19110, line15: It is interesting to see nitrate rather than dust dominate AOD over northern India in the Had Gem model. Whether this is the reason for satellite observed AOD well simulated during winter by this model over South Asia?

<Response>: Yes, in the HadGEM2 model, the nitrate aerosol AOD contributes significantly to the feature of high AOD along IGP during winter (DJF), see the Fig. S1. Wintertime surface observations also showed that the surface nitrate concentrations are comparable to the sulfate (Fig.10), which was not represented by most of the models. Therefore, we think that it is important to have nitrate in a model to reproduce the satellite retrievals over South Asia. However, HadGEM2 likely overestimates nitrate in April and October, and underestimates dust in pre-monsoon and monsoon season (March-July).

[Technical comments]: 6) Page 19112, Section 4.5: Moorthy et al., [2013] pointed out that improvement in the atmospheric boundary layer (ABL) parametrization in GOCART model over tropical region might improve the model-simulated BC distributions. How the authors comment about this?

<Response>: The PBL is an important factor to determine the surface concentration of aerosols including BC, besides the factor of strength of emission sources. In winter, the averaged ABL is 400-500 meters in the model GOCART (similar meteorological data used by GEOS5), about the double of the observed ABL, thus a better-constrained ABL in GOCART and GEOS5 could be helpful. Unfortunately we don’t have ABL information

from other models, so it is hard to address this point in general in the previous ACPD manuscript. In addition, we would like to add that the column AAOD during wintertime is underestimated as well, although in a less degree than surface concentration (by a factor of 3 verse 10). Considering the fact that the aerosol is confined to near surface due to the low ABL in winter, the underestimation of both surface concentration and AAOD together indicates a fundamental problem – winter time BC emissions might be underestimated in these models. The biofuel emission, the major emission source of BC, is supposed to be higher in the winter due to a higher demand of heating. A constant anthropogenic emission amount throughout of a year, however, is used by the model in this study, which makes the winter underestimation worse.

[Technical comments]: 7) Page 19113, line 24: It is not clear what “low bias” means? Rewrite the sentence.

<Response>: Corrected. We have changed “despite the low bias of BC concentration” to “despite the underestimation of BC surface concentration”.

[Technical comments]: 8) Page 19114, line 7: Only BC surface concentrations are severely underestimated over IGP? All the models underestimate sulphate by 5-50% (Page 19115, line 15).

<Response>: “BC surface concentrations are severely underestimated over IGP”. This sentence is a short summary based on the preceding analysis in section 4. The referee is right that the models also underestimate sulfate by 5-50%. But this point is discussed later in the following sections, and thus it is inappropriate to address this in the BC section.

[Technical comments]: 9) Page 19114, line 17: Correct the sentence.

<Response>: Rewrite the sentence of “Figure 10 shows the comparisons between seven models and in-situ measurements from the ISRO-GBP land campaign at four stations in the IGP for December 2004.” to “ Figure 10 shows the comparisons among

seven models and between models and in-situ measurements (ISRO-GBP land campaign) for December 2004 at four stations which are located in the IGP region."

[Technical comments]: 10) Page 19115, line 15: What is the reason for sulphate underestimation? Is it related to the sulphate chemistry scheme used in each models?

<Response>: Thanks you for bringing up this question. Yes, the underestimation of sulfate surface concentration might be caused by not accounting for aqueous phase oxidation in the models. Observations show that foggy weather is very common in IGP during winter, which favors the formation of sulfate in aqueous phase. However, the much lower relative humidity than observation (Fig. 10) thus the drier condition in models (except for the HAD) would inhibit this reaction. Sulfate concentration, however, is found low in HAD as well although with high relative humidity. There could be additional reasons, such as low concentration of oxidants (H2O2 and OH). Unfortunately, it is difficult to quantify here because the information of chemical productions of sulfate of this model was not available in the AeroCom database.

[Technical comments]: 11) In the Conclusion section, point 2 (Page 19120): BC concentrations are better captured by models over Kharagpur. This should be mentioned in this section.

<Response>: Thanks for pointing out this, we have added the sentence of "BC concentrations are better captured by models over Kharagpur, where the BC emissions are mostly from the burning of coals in power plants."

[Technical comments]: 12) In the Conclusion section, point 4 (Page 19121): Better represent nitrate in the models is not clear. Whether Nitrate emissions or chemistry scheme used in the models?

<Response>: Clarify as this "However, NO3- is either not considered in 4 out of 7 models or significantly lower than observations in other 2 models, suggesting a need to add the NO3- aerosol component or improve the chemistry scheme in these models."

[Technical comments]: 13) Figures 4, 5 and 6: Quality is poor. Lines and colours are not clearly visible.

<Response>: All three figures are modified according to referee's request. All modified figures are listed in the end of this file.

[Technical comments]: 14) Figure 7a-d: Its very difficult to compare spatial distribution of AOD in different seasons. Better provide mutli-model mean and deviation against observations and move these figures into supplementary information.

<Response>: Considering these figures are only figures in this manuscript to demonstrate the unique spatial distribution of AOD (various locations of maxima AOD in different seasons), we prefer to keep these figures in the main text. In order to make the comparison of different seasons easier, we have rearranged the figure 7 with grouping all three satellites into Figure 7a and all seven models into Figure 7b. In this way, four seasons from one model/satellite are shown in one figure.

——————— Reference:

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Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., KÂĺarcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, J. Geophys. Res., 118, 5380–5552, doi:10.1002/jgrd.50171, 2013.

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Arabian Sea region during ICARB using satellite data and a general circulation model, Atmos. Chem. Phys., 12, 1287-1305, doi:10.5194/acp-12-1287-2012, 2012.

Hess, M., KÂĺopke, P., and Schult, I.: Optical properties of aerosols and clouds: The software package OPAC, B. Am. Meteorol. Assoc., 79, 831–844, doi: http://dx.doi.org/10.1175/1520-0477(1998)079<0831:OPOAAC>2.0.CO;2, 1998.

Textor, C., Schulz, M., Guibert, S., Kinne, S., Balkanski, Y., Bauer, S., Berntsen, T., Berglen, T., Boucher, O., Chin, M., Dentener, F., Diehl, T., Feichter, J., Fillmore, D., Ginoux, P., Gong, S., Grini, A., Hendricks, J., Horowitz, L., Huang, P., Isaksen, I. S. A., Iversen, T., Kloster, S., Koch, D., Kirkevåg, A., Kristjansson, J. E., Krol, M., Lauer, A., Lamarque, J. F., Liu, X., Montanaro, V., Myhre, G., Penner, J. E., Pitari, G., Reddy, M. S., Seland, Ø., Stier, P., Takemura, T., and Tie, X.: The effect of harmonized emissions on aerosol properties in global models – an AeroCom experiment, Atmos. Chem. Phys., 7, 4489-4501, doi:10.5194/acp-7-4489-2007, 2007.

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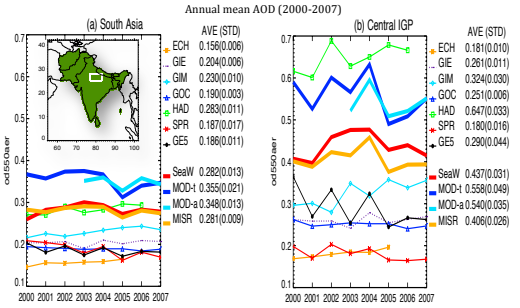

Figure 4. The annual averaged mean AOD for 2000-2007 over (a) South Asia (the green area in the map); (b) Central IGP (77°-83°E; 25°-28°N, the white box in that map). The thin curves with symbols represent seven models, and the thick curves represent four NASA remote sensors, with corresponding multi-year averaged annual mean AOD and the standard deviation followed.

Fig. 1.

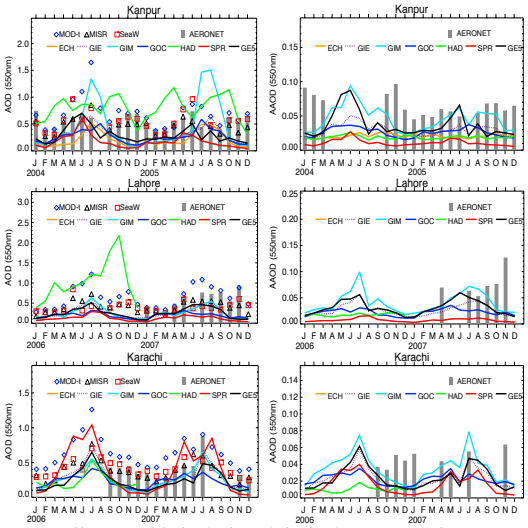

Figure 5. Monthly mean AOD (left column) and AAOD (right column) in a two-year period over 3 AERONET stations in South Asia. The gray bar represents measurement from AERONET. The thin curves represent seven models, and symbols represent three NASA remote sensors.

Fig. 2.

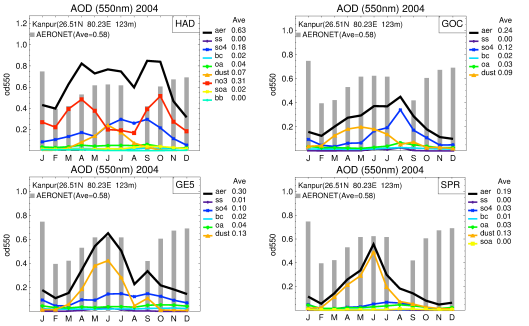

Figure 6. AOD of total aerosol (aer) and components (ss, so4, bc, oa, dust, no3, soa and bb) at Kanpur for 2004 in 4 models, HAD (upper left), GOC(upper right), GES (lower left) and SPR (lower right). The gray bar represents measurement from AERONET. The annual mean AOD value is followed after the name of each symbol. NOTE: bc and oa represent emission from fossil fuel only and bb represents emission from biomass burning only).

Fig. 3.

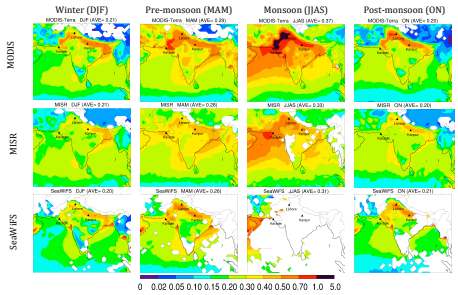

Figure 7a. Spatial distribution of AOD over South Asia in 4 seasons averaged for 2000–2007 in three satellite observations. The corresponding area averaged annual mean AOD value is listed in each panel (domain:0–36°N; 55°E–100°E). Three AERONET stations used in this study are labeled in the maps. Regions in white indicate insufficient sampling sizes of aerosol retrievals due to the presence of bright surface or frequent cloud cover in satellite data.

Fig. 4.

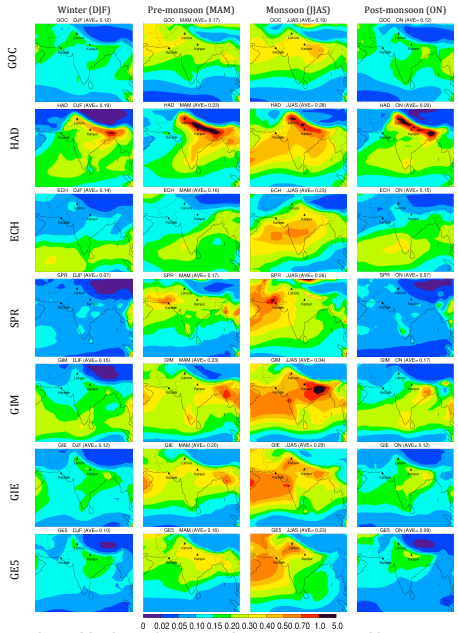

Figure 7b. Spatial distribution of AOD over South Asia in 4 seasons averaged for 2000–2007 in seven models (the first three models with the anthropogenic emissions from A2-MAP and the rest with A2-ACCMIP). The corresponding area averaged annual mean AOD value is listed in each panel (domain:0–36°N; 55°E–100°E). Three AERONET stations used in this study are labeled in the maps.

Fig. 5.

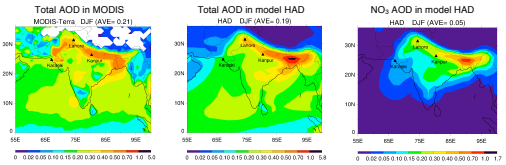

Fig. S1. The total AOD and NO_3 AOD during the winter of 2000-2007.

Fig. 6.

Table 1. General information of multi-models.

Model	HadGEM2	GOCART-v4	ECHAM5-HAMMOZ	GISS-modelE	GISS-MATRIX	SPRINTARS	GEOSS-GOCART
ID	HAD	GOC	ECH	GIE	GIM	SPR	GE5
Time range	2000-2006	2000-2007	2000-2005	2000-2008	2000-2007	2000-2008	2000-2008
Res. [a]	1.8×1.2×38	2.5×2×30	2.8×2.8×31	2.5×2×40	2.5×2×40	1.1×1.1×56	2.5×2×72
Anthrop. Emi. [b]	A2-MAP	A2-MAP	A2-MAP	A2-ACCMIP	A2-ACCMIP	A2-ACCMIP	A2-ACCMIP
BB Emi. [c]	GFED2	GFED2	GFED2	GFED2	GFED2	GFED2	GFED2
Met. Field	ERA- Interim	GEOS-DAS	ECMWF analysis	NCEP wind	NCEP-wind	NCEP/NCAR	MERRA
Refractive index 550nm SO4	1.53 – 1e-7i	1.43-1e-8 i	1.43-1e-8i [e]	1.528-1e-7i	1.528-1e-7i	1.43-1e-8i	1.43-1e-8i
Refractive index 550nm BC	1.75 – 0.44i (FF) [d]	1.75-0.44i	1.85-0.71i	1.85-0.71i	1.85-0.71i	1.75-0.44i	1.75-0.44i
Refractive index 550nm OA	1.54 – 0.006i (FF)	1.53-0.006i	1.53-0.0055i	1.527-0.014i	1.527-0.014i	1.53-0.006i	1.53-0.006i
Refractive index 550nm Dust	1.52 – 0.0015i	1.53-0.005Si	1.517-0.0011i	1.564-0.002i	1.564-0.002i	1.53-0.002i	1.53-0.008i
Refractive index 550nm SS	1.55 – 1e-7i Aged BB: 1.54 – 0.018i	1.50-1e-8 i	1.49-1e-8i	1.45-0i	1.45-0 i	1.38-4.26e-9i	1.50- 1e-8i
Additional Species [f]	NO_3	-	-	NO_3	NO_3	-	-
Dust Size distribution (μm) [g]	6 bins 0.0316-0.1-0.316-1.0-3.16-10-31.6	8 bins 0.1-0.18-0.3-0.6-1.0-1.8-3.0-6.0-10.0	Accum. mode: 0.05<r_m<0.5 coarse mode: r_m>0.5	5 bins 0.1-1-2-4-8-16	4 bins 0-1-2-4-8	6 bins 0.1-0.22-0.46-1.0-2.15-4.64-10.0	8 bins 0.1-0.18-0.3-0.6-1.0-1.8-3.0-6.0-10.0

[a] Spatial resolutions (°latitude × °longitude × number of vertical levels).
[b] Anthropogenic emission data are from either A2-ACCMIP or A2-MAP (refer to Diehl et al. 2012).
[c] Biomass burning emission data (refer to Diehl et al. 2012).
[d] FF is fossil fuel and BB is biomass burning.
[e] As for EHCAM5-HAMMOZ model with a mixed aerosol scheme, the refractive index for each of the 7 modes is calculated as the volume weighted average of the refractive indices of the components of the mode, including the diagnosed aerosol water.
[f] Additional aerosols besides commonly included aerosol species, i.e. SO_4^{2-} (sulfate), Dust, SS (sea salt), BC (black carbon), and OA(organic aerosol). Here NO_3^- is nitrate.
[g] Listed are the edges of bin size range in all models except for ECH in which r_m is modal radii.

Fig. 7.

Table 3. The statistics of the aerosol parameters over South Asia (61.5°-90.0°E, 5.0°-36.0°N)

Parameter	Unit	#	Mean	Median	Min	Max	Stdev	Diversity [a]
				SO_4				
Emi [b]	$Tg(SO_2)/a$	7	8.42	8.49	6.93	9.79	0.84	10%
Cheaq[c]	$Tg(SO_4)/a$	4	0.36	0.39	0.19	0.48	0.13	36%
Cheg[d]	$Tg(SO_4)/a$	4	0.33	0.23	0.16	0.71	0.26	**77%** [h]
Wet	$Tg(SO_4)/a$	7	6.47	5.97	5.38	8.58	1.21	19%
Dry	$Tg(SO_4)/a$	7	1.02	0.92	0.32	1.48	0.43	**42%**
Dry/Dry+Wet	%	7	17	17	6	22	6	35%
Life time	days	7	5.17	4.64	3.71	9.27	1.90	37%
Load	$Tg(SO_4)$	7	0.09	0.08	0.05	0.15	0.03	34%
MEE[e]	$m^2/g(SO_4)$	4	8.81	9.16	5.53	11.39	2.43	28%
AOD	Unitless	4	0.07	0.07	0.04	0.08	0.02	27%
				BC				
Emi	Tg/a	7	0.68	0.68	0.62	0.71	0.04	5%
Wet	Tg/a	7	0.36	0.36	0.29	0.42	0.04	12%
Dry	Tg/a	7	0.17	0.20	0.06	0.22	0.06	35%
Dry/Dry+Wet	%	7	33	37	15	41	10	29%
Life time	days	7	7.98	6.89	4.48	14.35	3.31	**42%**
Load	Tg	7	0.01	0.01	0.007	0.020	0.004	38%
MEE	m^2/g	4	7.16	7.62	2.77	10.60	3.72	**52%**
AOD	Unitless	4	0.008	0.009	0.003	0.01	0.003	44%
				OA				
Emi[f]	Tg/a	7	3.19	3.12	2.05	4.07	0.64	20%
Load	Tg	7	0.05	0.04	0.03	0.07	0.01	27%
Wet	Tg/a	7	2.17	1.98	1.50	3.26	0.56	26%
Dry	Tg/a	7	0.80	0.86	0.30	1.37	0.36	**45%**
Dry/Dry+Wet	%	7	29	32	15	38	9	**31%**
Life time	days	7	6.20	5.95	4.56	9.20	1.60	26%
MEE	m^2/g	4	5.33	5.28	3.61	7.14	1.47	28%
AOD	Unitless	4	0.020	0.019	0.016	0.024	0.004	18%
				DUST				
Emi	Tg/a	7	96.34	39.21	6.42	356.46	125.33	**130%**
Load	Tg	7	1.28	1.25	0.25	2.51	0.68	53%
Wet	Tg/a	7	72.78	67.62	20.58	171.48	47.29	65%
Dry + Sed[g]	Tg/a	7	100.84	45.97	1.72	330.85	115.95	**115%**
Dry/Dry+Wet	%	7	53	60	11	78	25	46%
Life time	days	7	4.34	4.25	1.48	8.34	2.25	52%
MEE	m^2/g	4	0.67	0.60	0.54	0.92	0.18	27%
AOD	Unitless	4	0.09	0.09	0.06	0.14	0.04	41%

[a]. The diversity is defined as the ratio of mean and standard deviation (i.e. mean/stdev). The largest and second largest diversities in each species are highlighted in bold.
[b]. The emission of so_2, including anthropogenic and biomass burning emission.
[c]. The chemical production of SO_4 in aqueous phase reaction (i.e. SO_2 reacts with H_2O_2).
[d]. The chemical production of SO_4 in gaseous phase reaction (i.e. SO_2 reacts with OH).
[e]. Mass extinction efficiency, defined as the ratio of AOD and load (i.e. AOD/load).
[f]. Sum of anthropogenic emission, biomass burning emissions and secondary organic aerosol.
[g]. Dry deposition plus sedimentation.
[h]. The top two largest diversities in each species are highlighted in bold.

Fig. 8.