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Supplement of

Less atmospheric radiative heating by dust due to the synergy of coarser size and aspherical shape

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This document contains Supplementary Tables, which are summarized below:

- **Table S1.** Comparison of model estimates with semi-observationally based (SOB) data of regionally averages of dust aerosol optical depth at 550 nm ($DAOD_{550}$) in summer (June, July, and August). The size-resolved dust concentration and particle shape in IMPACT-Sphere-Mineral-V83 (E1) was adjusted to DustCOMM in DustCOMM-Asphere-DB19-V83 (E2). At the same time, we maintained the consideration of asphericity on the gravitational velocity and kept the dust concentrations unaltered between E1 and IMPACT-Asphere-DB19-DB17 simulations (E3).
- **Table S2.** Comparison of model estimates with SOB data of regionally averages of dust aerosol optical depth at 550 nm ($DAOD_{550}$) in winter (December, January, and February), spring (March, April, and May), and autumn (September, October, and November). The size-resolved dust concentration and particle shape in IMPACT-Sphere-Mineral-V83 (E1) was adjusted to DustCOMM in DustCOMM-Asphere-DB19-V83 (E2).
- **Table S3.** Comparison of model estimates with SOB data of dust clear-sky SW radiative effect efficiency at the surface ($W \cdot m^{-2}\ AOD^{-1}$).
- **Table S4.** Comparison of model estimates with SOB data of dust clear-sky SW radiative effect efficiency at TOA ($W \cdot m^{-2}\ AOD^{-1}$).
- **Table S5.** Comparison of model estimates with SOB data of dust clear-sky LW radiative effect efficiency at the surface ($W \cdot m^{-2}\ AOD^{-1}$).
- **Table S6.** Comparison of model estimates with SOB data of dust clear-sky LW radiative effect efficiency at TOA ($W \cdot m^{-2}\ AOD^{-1}$).

Table S1. Comparison of model estimates with semi-observationally based (SOB) data of regionally averages of dust aerosol optical depth at 550 nm ($DAOD_{550}$) in summer (June, July, and August). The size-resolved dust concentration and particle shape in IMPACT-Sphere-Mineral-V83 (E1) was adjusted to DustCOMM in DustCOMM-Asphere-DB19-V83 (E2). At the same time, we maintained the consideration of asphericity on the gravitational velocity and kept the dust concentrations unaltered between E1 and IMPACT-Asphere-DB19-DB17 simulations (E3).

Number	Region name	Region coordinates	SOB data	E1	E2	E3
A1	Mid-Atlantic	4–40°N, 50–20°W	0.143 ± 0.005	0.094	0.083	**0.148**
A2	African West Coast	10–34°N, 20–5°W	0.365 ± 0.016	**0.357**	0.294	0.563
A3	Northern Africa	26–40°N, 5°W–30°E	0.207 ± 0.016	**0.197**	**0.194**	0.310
A4	Mali/Niger	10–26°N, 5°W–10°E	0.462 ± 0.044	**0.379**	**0.397**	0.597
A5	Bodele/Sudan	10–26°N, 10–40°E	0.310 ± 0.018	**0.297**	0.349	0.469
A6	Northern Middle East	26–40°N, 30–50°E	0.164 ± 0.015	0.209	**0.168**	0.327
A7	Southern Middle East	0–26°N, 40–67.5°E	0.330 ± 0.044	0.438	0.384	0.691
A8	Kyzyl Kum	26–50°N, 50–67.5°E	0.154 ± 0.034	0.307	**0.201**	0.481
A9	Thar	20–50°N, 67.5–75°E	0.319 ± 0.029	0.167	0.156	**0.265**
A10	Taklamakan	30–50°N, 75–92.5°E	0.171 ± 0.026	0.040	0.094	0.064
A11	Gobi	36–50°N, 92.5–115°E	0.102 ± 0.035	**0.032**	**0.117**	**0.051**
A12	North America	20–45°N, 80–130°W	0.028 ± 0.010	**0.010**	**0.030**	**0.016**
A13	South America	0–55°S, 80–55°W	0.010 ± 0.006	**0.009**	**0.013**	**0.015**
A14	Southern Africa	10–35°S, 10–40°E	0.013 ± 0.005	**0.014**	**0.020**	**0.022**
A15	Australia	10–40°S, 110–160°E	0.010 ± 0.005	**0.005**	**0.013**	**0.008**
	Area weighted mean		0.127	0.122	0.120	0.192
	Correlation coefficients			0.86	0.91	0.86
	Root mean square errors			0.08	0.06	0.16

SOB data of the $DAOD_{550}$ were averaged over 2004–2008 (Ridley et al., 2016; Adebiyi et al., 2020). The bold represents the data which fell within ± 2 times standard deviation of the measurements. The area weighted mean, correlation coefficients, and root mean square errors were also shown.

Table S2. Comparison of model estimates with SOB data of regionally averages of dust aerosol optical depth at 550 nm ($DAOD_{550}$) in winter (December, January, and February), spring (March, April, and May), and autumn (September, October, and November). The size-resolved dust concentration and particle shape in IMPACT-Sphere-Mineral-V83 (E1) was adjusted to DustCOMM in DustCOMM-Asphere-DB19-V83 (E2).

Number	Region name	Winter			Spring			Autumn		
		SOB data	E1	E2	SOB data	E1	E2	SOB data	E1	E2
A1	Mid-Atlantic	0.064 ± 0.013	**0.045**	**0.072**	0.106 ± 0.008	0.026	0.034	0.084 ± 0.006	0.024	0.027
A2	African West Coast	0.180 ± 0.010	0.129	0.223	0.250 ± 0.019	0.127	0.145	0.233 ± 0.022	0.132	0.149
A3	Northern Africa	0.118 ± 0.011	0.029	**0.108**	0.219 ± 0.010	0.174	**0.200**	0.151 ± 0.016	0.092	**0.134**
A4	Mali/Niger	0.257 ± 0.019	0.215	0.377	0.441 ± 0.022	0.341	0.358	0.277 ± 0.023	0.247	**0.268**
A5	Bodele/Sudan	0.191 ± 0.006	0.149	0.360	0.339 ± 0.023	**0.340**	0.406	0.212 ± 0.021	0.223	0.276
A6	Northern Middle East	0.112 ± 0.011	0.038	0.165	0.223 ± 0.011	0.169	**0.226**	0.113 ± 0.019	0.115	**0.133**
A7	Southern Middle East	0.123 ± 0.018	0.056	**0.144**	0.204 ± 0.021	0.096	**0.176**	0.150 ± 0.020	0.157	**0.135**
A8	Kyzyl Kum	0.115 ± 0.017	0.028	**0.116**	0.176 ± 0.026	0.096	**0.204**	0.101 ± 0.018	0.129	0.138
A9	Thar	0.130 ± 0.029	0.024	**0.094**	0.238 ± 0.033	0.091	**0.173**	0.135 ± 0.037	0.072	**0.072**
A10	Taklamakan	0.119 ± 0.013	0.008	0.029	0.275 ± 0.027	**0.030**	0.110	0.104 ± 0.011	0.016	0.045
A11	Gobi	0.093 ± 0.022	0.006	0.028	0.192 ± 0.022	0.053	**0.183**	0.047 ± 0.021	0.018	0.091
A12	North America	0.010 ± 0.005	**0.003**	**0.027**	0.029 ± 0.011	**0.014**	**0.031**	0.012 ± 0.006	0.006	0.014
A13	South America	0.019 ± 0.011	**0.024**	**0.016**	0.013 ± 0.007	**0.013**	**0.011**	0.016 ± 0.009	0.022	**0.013**
A14	Southern Africa	0.016 ± 0.007	**0.02**	**0.011**	0.011 ± 0.005	**0.009**	**0.009**	0.016 ± 0.007	0.028	**0.012**
A15	Australia	0.025 ± 0.013	**0.016**	**0.028**	0.013 ± 0.006	**0.008**	**0.012**	0.023 ± 0.011	0.020	**0.020**
	Area weighted mean	0.072	0.040	0.085	0.117	0.068	0.097	0.078	0.063	0.069
	Correlation coefficients		0.83	0.89		0.84	0.89		0.88	0.88
	Root mean square errors		0.06	0.06		0.10	0.06		0.05	0.04

SOB data of the $DAOD_{550}$ were averaged over 2004–2008 (Ridley et al., 2016; Adebiyi et al., 2020). The bold represents the data which fell within ± 2 times standard deviation of the measurements. The area weighted mean, correlation coefficients, and root mean square errors were also shown.

Table S3. Comparison of model estimates with SOB data of dust clear-sky SW radiative effect efficiency at the surface ($W \cdot m^{-2}$ AOD^{-1}).

Number	Month	SOB data	E1	E2	E3	E5	E6	E7
R2	6,7,8	–65[a]	–70	–54	–48	–61	–71	–44
R3	6,7,8	–86[b]	–79	–60	–55	–78	–79	–49
R12	9	–69[c]	–72	–55	–50	–52	–71	–45
R14	4,5,6	–60[d]	–64	–50	–48	–57	–60	–39

Region number is defined in Table 4. The radiative effect efficiency is defined as the gradient of the linea least square fit applied to the AOD and dust radiative effect at each grid. The area weighted averages for land or ocean are listed. [a]Li et al. (2004). [b]Song et al. (2018). [c]Di Biagio et al. (2010). [d]Hansell et al. (2012).

Table S4. Comparison of model estimates with SOB data of dust clear-sky SW radiative effect efficiency at TOA ($W \cdot m^{-2}$ AOD^{-1}).

Number	Month	SOB data	E1	E2	E3	E5	E6	E7
R1	6,7,8	Near 0[a]	17	9	3	5	26	–6
R2	6,7,8	–35 ± 3[b]	–23	–24	–24	–29	–14	–29
R3	6,7,8	–27[c]	–29	–29	–30	–35	–18	–35
R4	6,7,8	–48 ± 4[d]	–28	–26	–27	–31	–18	–30
R12	9	–46[e]	–32	–28	–32	–32	–19	–33

Region number is defined in Table 4. The radiative effect efficiency is defined as the gradient of the linea least square fit applied to the AOD and dust radiative effect at each grid. The area weighted averages for land or ocean are listed. [a]Yang et al. (2009). [b]Li et al. (2004). [c]Song et al. (2018). [d]Christopher and Jones (2007). [e]Di Biagio et al. (2010).

Table S5. Comparison of model estimates with SOB data of dust clear-sky LW radiative effect efficiency at the surface ($W \cdot m^{-2}$ AOD^{-1}).

Number	Month	SOB data	E1	E2	E3	E4	E5	E7
R3	6,7,8	24[a]	22	25	11	15	17	20
R13	9	16[b]	29	27	15	16	19	22
R14	4,5,6	31–35[c]	51	43	23	25	29	31

Region number is defined in Table 4. The radiative effect efficiency is defined as the gradient of the linea least square fit applied to the AOD and dust radiative effect at each grid. The area weighted averages for land or ocean are listed. [a]Song et al. (2018). [b]Hansell et al. (2010). [c]Hansell et al. (2012).

Table S6. Comparison of model estimates with SOB data of dust clear-sky LW radiative effect efficiency at TOA ($W\cdot m^{-2}$ AOD^{-1}).

Number	Month	SOB data	E1	E2	E3	E4	E5	E7
R1	6,7,8	24 ± 1.3[a]	17.9	19.8	8.1	10.6	12.0	17.9
R3	6,7,8	9.5[b]	11.3	13.1	5.1	6.8	7.7	11.3
R4	6,7,8	9.0 ± 3.5[c]	8.8	10.9	4.1	5.6	6.4	8.8
R5	6,7,8	22[d]	14.9	16.0	6.7	8.6	9.6	14.9
R5	9	15[e]	12.5	11.7	5.7	6.2	6.9	12.5
R6	6,7,8	17[d]	16.6	20.1	7.4	10.7	12.0	16.6
R6	9	20[e]	17.0	16.4	7.7	8.6	9.6	17.0
R7	6,7,8	16[d]	19.8	21.3	9.0	11.5	13.1	19.8
R7	9	21[e]	13.1	13.3	6.1	7.3	8.2	13.1
R8	6,7,8	21[d]	14.1	14.7	6.4	8.0	8.9	14.1
R8	9	19[e]	10.9	8.4	5.0	4.6	5.0	10.9
R9	6,7,8	25[d]	10.5	9.7	4.7	4.9	5.4	10.5
R9	9	1[e]	8.0	6.0	3.6	3.0	3.2	8.0
R10	6,7,8	20[d]	15.1	13.7	6.7	7.0	7.7	15.1
R10	9	11[e]	10.9	9.2	5.0	4.8	5.3	10.9
R11	6,7,8	18[d]	17.6	17.7	7.9	9.1	10.1	17.6
R11	9	11[e]	10.9	9.2	5.0	4.8	5.3	10.9
R13	9	13[f]	10.5	12.4	4.8	6.4	7.3	10.5
R14	4,5,6	17–21[g]	14.6	13.2	6.0	6.6	7.5	14.6

Region number is defined in Table 4. The radiative effect efficiency is defined as the gradient of the linea least square fit applied to the AOD and dust radiative effect at each grid. The area weighted averages for land or ocean are listed. [a]Yang et al. (2009). [b]Song et al. (2018). [c]Christopher and Jones (2007). [d]Brindley and Russell (2009). [e]Zhang and Christopher (2003). [f]Hansell et al. (2010). [g]Hansell et al. (2012).