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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·m$^{-2}$ AOD$^{-1}$).

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

- **Table S6.** Comparison of model estimates with SOB data of dust clear-sky LW radiative effect efficiency at TOA (W·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 | Correlation coefficients | Root mean square errors |
|----------------|--------------------|--------------------------|------------------------|
|                | 0.127              | 0.86                     | 0.08                   |

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 (DAOD550) 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     | Kyzyk 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 DAOD550 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.
| Number | Month | SOB data | E1 | E2 | E3 | E5 | E6 | E7 |
|--------|-------|----------|----|----|----|----|----|----|
| R2     | 6,7,8 | −65<sup>a</sup> | −70 | −54 | −48 | −61 | −71 | −44 |
| R3     | 6,7,8 | −86<sup>b</sup> | −79 | −60 | −55 | −78 | −79 | −49 |
| R12    | 9     | −69<sup>c</sup> | −72 | −55 | −50 | −52 | −71 | −45 |
| R14    | 4,5,6 | −60<sup>d</sup> | −64 | −50 | −48 | −57 | −60 | −39 |

Region number is defined in Table 4. The radiative effect efficiency is defined as the gradient of the line least square fit applied to the AOD and dust radiative effect at each grid. The area weighted averages for land or ocean are listed. <sup>a</sup>Li et al. (2004). <sup>b</sup>Song et al. (2018). <sup>c</sup>Di Biagio et al. (2010). <sup>d</sup>Hansell et al. (2012).
Table S4. Comparison of model estimates with SOB data of dust clear-sky SW radiative effect efficiency at TOA (W·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 linear 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).
| Number | Month | SOB data | E1 | E2 | E3 | E4 | E5 | E7 |
|--------|-------|----------|----|----|----|----|----|----|
| R3     | 6,7,8 | 24<sup>a</sup> | 22 | 25 | 11 | 15 | 17 | 20 |
| R13    | 9     | 16<sup>b</sup> | 29 | 27 | 15 | 16 | 19 | 22 |
| R14    | 4,5,6 | 31–35<sup>c</sup> | 51 | 43 | 23 | 25 | 29 | 31 |

Region number is defined in Table 4. The radiative effect efficiency is defined as the gradient of the linear least square fit applied to the AOD and dust radiative effect at each grid. The area weighted averages for land or ocean are listed. <sup>a</sup>Song et al. (2018). <sup>b</sup>Hansell et al. (2010). <sup>c</sup>Hansell et al. (2012).
Table S6. Comparison of model estimates with SOB data of dust clear-sky LW radiative effect efficiency at TOA (W·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\(^f\)    | 16.6| 20.1| 7.4 | 10.7| 12.0| 16.6|
| R6     | 9     | 20\(^g\)    | 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 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).