Supplementary for

Aerosol Forcing of Extreme Summer Drought

Over North China

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**How does aerosol forcing weaken the summer mean MWI?**

The radiative effects of anthropogenic aerosol forcing on summer mean circulation are examined and shown in Fig. S1. In order to isolate the aerosol effects, the multimodel ensemble mean responses from the separate GHG and Nat simulations are subtracted from the historical_ALL. Aerosols have an overall cooling effect but the land born the most with a -0.5°C temperature anomaly and a positive SLP anomaly the northern Asian continent (see Fig. S1a). The weakened land-sea thermal contrast led to the weakening of the EASM and a reduction in summer precipitation over North China (Fig. S1b).

The impact of anthropogenic aerosol forcing on surface energy budget is examined to illustrate the mechanisms for cooling over northern Asian continent (Fig. S2a-d). In Fig. S2, downward is positive. A positive anomaly indicates less heat from surface to atmosphere. The cooling was caused by reduced surface shortwave radiation (Fig. S2a), and it further weakened evaporation and heat conduction leading to less latent and sensible heat flux from surface to atmosphere (Fig. S2c, d). In comparison, the change of longwave radiation is relatively small. To verify how aerosol forcing influences the surface shortwave radiation, the energy budget at TOA is further shown in Fig. S2e-f. The distributions of upward shortwave anomaly at TOA in total sky and clear sky are both similar to that of surface net shortwave radiation. It indicates a dominant role of the direct effect of aerosol forcing. Thus, the cooling over northern Asian continent is mainly caused by scattering of shortwave flux by anthropogenic aerosol.
Table S1 External forcing agents used in historical simulations (Song et al. 2014)

| No. | Model         | Natural forcing agents | Anthropogenic forcing agents |
|-----|---------------|------------------------|------------------------------|
|     |               | Solar | Volcanic | GHG | Aerosol |
| 1   | BCC-CSM1.1    | SOLARIS | A       | IIASA | C |
| 2   | BNU-ESM      | SOLARIS | A       | IIASA | E1 |
| 3   | CanESM2      | SOLARIS | S       | IIASA | E1 |
| 4   | CCSM4        | SOLARIS | A       | IIASA | C |
| 5   | CNRM-CM5     | SOLARIS | A       | IIASA | E1 |
| 6   | FGOALS-g2    | SOLARIS | -       | IIASA | C |
| 7   | HadGEM2-ES   | SOLARIS | S       | IIASA | E1 |
| 8   | MIROC-ESM    | SOLARIS | S       | IIASA | E1 |
| 9   | NorESM1-M    | SOLARIS | A       | IIASA | E1 |

SOLARIS: http://sparcsolaris.gfz-potsdam.de/cmip5.php;

S: Sato et al. (1993);

A: Ammann et al. (2003);

IIASA: http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page/welcome;

C: Three-dimensional aerosol distributions specified as monthly 10-year mean aerosol concentrations, derived using the CAM-Chem model, which is driven by the Lamarque et al. (2010); anthropogenic aerosols include organic carbon (OC), black carbon (BC) and sulfur dioxide (SO2).

E1: anthropogenic aerosol emissions taken from the Lamarque et al. (2010).
Table S2 Model names and the experiments used in this study. Hist, GHG and Nat stand for historical all, greenhouse gases and natural forcing simulations, respectively. Models in italics are excluded from attribution analysis in section 3.2.

| Model                | piControl Length (year) | Hist. Number of realizations | GHG. Number of realizations | Nat. Number of realizations |
|----------------------|-------------------------|------------------------------|------------------------------|-----------------------------|
| BCC-CSM1.1           | 500                     | 1                            | 1                            | 1                           |
| BNU-ESM              | 599                     | 1                            | 1                            | 1                           |
| CanESM2              | 996                     | 5                            | 5                            | 5                           |
| CCSM4                | 501                     | 3                            | 3                            | 3                           |
| CNRM                 | 600                     | 1                            | 1                            | 1                           |
| FGOALS-g2            | 900                     | 1                            | 1                            | 1                           |
| GFDL-CM3             | 500                     | 1                            | 0                            | 0                           |
|HadGEM2-CC           | 240                     | 1                            | 1                            | 1                           |
| HadGEM2-ES           | 337                     | 1                            | 1                            | 1                           |
| IPSL-CM5A-LR         | 1000                    | 3                            | 3                            | 3                           |
| MIROC-ESM           | 537                     | 1                            | 1                            | 1                           |
| MPI-ESM-LR          | 1000                    | 1                            | 0                            | 0                           |
| MRI-CGCM3           | 500                     | 1                            | 0                            | 0                           |
| NorESM1-M           | 501                     | 1                            | 1                            | 1                           |
| Total years         | 5471                    | 2175                          | 2175                         | 2175                        |
Figure S1 The multimodel ensemble average of mean circulation responses to historical aerosol forcing for 1860-2004: (a) surface temperature (shading, K) and SLP (hPa), (b) precipitation (shading, mm day$^{-1}$) and 850hPa winds (m s$^{-1}$).
Figure S2 Same as Figure S1, but for the radiation responses (W m$^{-2}$) to historical aerosol forcing. (a) surface net shortwave radiation, (b) surface net longwave radiation, (c) surface latent heat flux, (d) surface sensible heat flux, (e) upward shortwave radiation at TOA at total sky, and (f) upward shortwave radiation at TOA at clear sky. Downward is positive.
Figure S3 Change in the mean MWI (unit: m s\(^{-1}\)) in the historical simulations relative to piControl for (a) CanESM2 and (b) CCSM4. ALL, GHG, Nat, AA and LU indicate all forcing, greenhouse gases, natural, anthropogenic aerosol and land use forcing, respectively. The AA forcing is derived as subtracting the responses to natural and greenhouse gases from that to all forcing.
References for Auxiliary Material

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