The role of carbonaceous aerosols on short-term variations of precipitation over North Africa

Jin-Ho Yoon, Philip J. Rasch, Hailong Wang, V. Vinoj and Dilip Ganguly

1 School of Earth Sciences and Environmental Engineering, Gwangju Institute of Science and Technology, Gwangju, South Korea
2 Pacific Northwest National Laboratory, Richland, WA, USA
3 School of Earth, Ocean and Climate Sciences, Indian Institute of Technology Bhubaneswar, Odisha, India
4 Center for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India

Abstract

Subtropical North Africa has been subject to extensive droughts in the late 20th century, linked to changes in the sea surface temperature (SST). However, climate models forced by observed SSTs cannot reproduce the magnitude of the observed rainfall reduction. Here, we propose aerosol indirect effects (AIE) as an important positive feedback mechanism. Model results are presented using two sets of sensitivity experiments designed to distinguish the role of aerosol direct/semi-direct and indirect effects on regional precipitation. Changes in cloud properties due to the presence of carbonaceous aerosols are proposed as a key mechanism to explain the reduced rainfall over subtropical North Africa.

Keywords: Sahel rainfall; aerosol indirect effect; cloud lifetime effect

1. Introduction

Between 1950 and 1980, the Sahel, located between the tropical African rainforest and the Sahara, experienced a large reduction in rainfall (e.g. Nicholson, 2001; Dai et al., 2004). Various mechanisms have been proposed to explain this drought (e.g. Zeng et al., 1999; Nicholson, 2001; Giannini et al., 2003; Lu and Delworth, 2005; Hoerling et al., 2006). The long-term change in sea surface temperature (SST) over the Atlantic and Indian Oceans is a commonly accepted hypothesis (Giannini et al., 2003; Lu and Delworth, 2005; Hoerling et al., 2006) for the rainfall change in Sahel. However, most atmospheric general circulation models forced by the observed SST changes cannot simulate the magnitude of this drought (Scaife et al., 2009). Thus, alternative climate feedback processes such as atmosphere-land-vegetation feedbacks through soil moisture and vegetation albedo have been proposed as an amplifying mechanism (Charney et al., 1975; Zeng et al., 1999; Kucharski et al., 2013).

A growing number of studies have also examined the potential impact of aerosols on Sahel rainfall (e.g. Held et al., 2005; Ackerley et al., 2011; Booth et al., 2012; Wang et al., 2012a; Chang, 2013; Hwang et al., 2013; Dong et al., 2014). These studies have particularly focused on how sulphate aerosols or dust in the Northern Hemisphere affected rainfall in North Africa by creating inter-hemispheric SST gradients. It has also been suggested that volcanic eruptions may be an important player in determining rainfall amount in North Africa (Haywood et al., 2013). There are other ways that aerosols can be linked to droughts. For example, prolonged droughts in the Amazon have been associated with an increase in biomass burning (e.g. Scholze et al., 2006; Zeng et al., 2008) that may increase emissions of carbonaceous aerosols, but there are very few studies that have examined the climatic feedback of carbonaceous aerosols on droughts in North Africa. In this study, we explore the potential impact of additional carbonaceous aerosols loading on regional precipitation over North Africa.

There are two broad categories of aerosol effects. Direct effects refer to the influence that particles have on atmospheric radiative transfer via scattering and absorption. Indirect and semi-direct effects refer to the influence particles have on cloud properties with subsequent effects on radiative heating. Climate modelling studies have historically focused on direct effects because of the difficulty in treating more complex indirect effects (e.g. Chung and Zhang, 2004; Chung and Seinfeld, 2005). However, the microphysical interaction of cloud, aerosols, and precipitation (the ‘indirect effects’) can be an important factor in the hydrological cycle and climate (e.g. Albrecht, 1989; Ramanathan et al., 2005; Levy et al., 2013). Our study uses a global climate model with a predictive aerosol lifecycle to investigate the hydrological impact of carbonaceous aerosols over North Africa.

Carbonaceous aerosols including black carbon (BC) and organic carbon (OC) can affect the regional hydrological cycle of tropical monsoon regions through direct, semi-direct, and indirect effects (Ramanathan et al., 2005; Lau et al., 2006; Schulz et al., 2006; Jeong and Wang, 2010; Jiang et al., 2013). This has been observationally confirmed by both field campaigns.
and satellite observations (Warner and Twomey, 1967; Rosenfeld, 1999; Koren et al., 2004; Ramanathan et al., 2005; Huang et al., 2009a, 2009b, 2009c, 2009d; Martins et al., 2009). Aerosols have the potential to either increase or reduce clouds and precipitation (Rosenfeld, 1999; Koren et al., 2008), suggesting a complex relationship between aerosols, clouds, and precipitation (Jiang et al., 2006; Stevens and Feingold, 2009).

Our work focuses on carbonaceous aerosols emitted from North Africa mainly by biomass burning process (Figure S1) and their impact on regional precipitation with an emphasis on the ‘second indirect effect’, or, cloud lifetime effect. We are interested in the fast response of the climate systems to perturbations in aerosol forcing rather than the slower response involving changes in SSTs (e.g. Hansen et al., 2005; Ganguly et al., 2012b). Thus, we will examine how this effect changes the liquid water content, the height, and the lifetime of clouds and how these changes in turn affect the regional precipitation over North Africa. Section 2 describes the model simulations and methods. Section 3 presents results and Section 4 provides a summary and concluding remarks.

2. Experimental design and methods

This study uses the Community Atmosphere Model version 5.1 (CAM5.1; Neale et al., 2010) at 1.9° latitude × 2.5° longitude horizontal resolution with 30 vertical layers, the atmospheric component of the Community Earth System Model (CESM1.0.3). The model uses a modal aerosol treatment (Ghan et al., 2012; Liu et al., 2012) that allows interaction of aerosols and stratiform clouds (Park et al., 2014). However, it is cautiously noted that aerosols interact with warm stratiform clouds, but not with convective or ice clouds. The 3-mode version of the modal aerosol module (MAM3) is used here; aerosols are divided into three size-dependent modes: Aitken, accumulation, and coarse mode. Aerosols interact with modelled meteorological conditions through both radiative and microphysical processes. The rapid radiative transfer method for general circulation models (Iacono et al., 2008) provides the radiative transfer calculation, which interacts with internally mixed aerosols in each mode (Ghan and Zaveri, 2007). A two-moment formulation of microphysics scheme is used for stratiform clouds (Morrison and Gettelman, 2008), and aerosol activation is based on vertical velocity and aerosol properties (Abdul-Razzaq and Ghan, 2000). CAM5.1 has been found to simulate the seasonal cycle of rainfall over the African continent better than earlier versions of this model (Neale et al., 2010).

Our control scenario was run using the present-day (2000) aerosol emissions created for the Coupled Model Intercomparison Phase 5 (CMIP5) activity (Lamarque et al., 2010), using the technique proposed in a study of Southern African aerosol forcing by Sakaeda et al. (2011). Carbonaceous aerosol emissions over North Africa come primarily from biomass burning, and mainly from grass fires that have a distinct seasonal cycle (Figure S1). These fires reach a maximum/minimum during the dry/wet season, i.e. boreal winter/summer season. Therefore, our analysis focused primarily on biomass burning season, i.e. the boreal winter season (Figure S1). Present-day SSTs averaged over the period of 1982–2001 (Hurrell et al., 2008) and greenhouse gases are used consistently in all of our experiments. Each experiment is run for 21 years with the last 20 years used in our analyses.

Aerosol direct and indirect effects have been estimated by a couple of ways: (1) comparing multiple climate models that have either both direct and indirect effects or direct effect only (e.g. Guo et al., 2015) or (2) comparing two simulation configurations using different emissions scenarios (e.g. with and without carbonaceous emissions), with differences in these scenarios providing an estimate of the radiative forcing and climate response (e.g. Bollasina et al., 2011). As the climate itself has changed with the aerosols and clouds, it is difficult to clearly isolate the role of direct and indirect effects from other climate feedback processes. In this study, we have used a different approach by preventing aerosol to interact with radiation and allowing aerosols to affect only the cloud microphysics in one set of experiments.

Two sets of experiments with CAM5.1 were performed (Table 1). In the first experiment set (the ‘standard runs’), carbonaceous aerosols were allowed to interact with both the microphysical and radiative processes of clouds; aerosol direct, semi-direct, and indirect effects operate simultaneously. In the second set of experiments, the number and mass of aerosols were set as zero for the radiative transfer calculation, but the predicted aerosols were allowed to interact only with the cloud microphysics (the ‘no aerosol direct effects runs’). A similar experiment with CAM4, an earlier version of CAM5, was done by Sakaeda et al. (2011).

In addition to control simulations for the standard and the removed direct effects experiments, we also explored three emission scenarios in which carbonaceous aerosol emissions over North Africa (defined by the red rectangles shown in the panels of Figure 1) were set to zero for all seasons: (1) a scenario with no carbonaceous aerosol emissions (both BC and OC

| Table 1. A summary of sensitivity experiments. |
|-----------------------------------------------|
| Standard runs | No aerosol direct effects runs |
| Fully interactive: aerosol↔cloud↔radiation | No aerosols seen by radiation: aerosol↔cloud |
| Control Case 1 | Case 5 |
| No carbonaceous aerosol emissions Case 2, no carb | Case 6, no carb-F |
| No OC emissions Case 3, no OC | Case 7, no OC-F |
| No BC emissions Case 4, no BC | Case 8, no BC-F |
excluded, listed as ‘no carb’), (2) a scenario without OC emissions (listed as ‘no OC’), and (3) a scenario without BC emissions (listed as ‘no BC’). These scenarios were run for both the ‘standard’ set and ‘no direct aerosol effect’ set of simulations. In this way, we could identify the relative importance of BC and OC on aerosol direct, semi-direct, and indirect effects.

3. Results

Figure 1 shows the change in simulated rainfall relative to the standard simulation (case 1 in Table 1) due to the exclusion of carbonaceous aerosols (cases 2–4) during the boreal winter season. Rainfall decreases about 1 mm day$^{-1}$ over tropical Africa with the introduction of OC and BC (Figure 1(a)), implying that carbonaceous aerosols have the potential to reduce regional rainfall by about 25% of its climatology (Figure 2). Although an increase in rainfall is seen in some regions outside of the analysis domain (e.g. Madagascar), these increases are not statistically significant (Figure S4). Details of statistical significance are provided in the Supporting Information. Comparison between the simulations with only OC (case 3 in Table 1) and BC (case 4 in Table 1) suggests that OC plays a more important role in reducing rainfall in this area than BC (Figure 1(b)) while BC alone does not produce any systematic pattern of rainfall increase or decrease (Figure 1(c)).

The seasonal cycle of area-average rainfall change (%) over our analysis domain (20$^\circ$W–30$^\circ$E, 10$^\circ$S–15$^\circ$N), outlined by a solid red box in Figure 1, exhibits a large reduction (up to 25%) during boreal winter [December-January-February (DJF)] by carbonaceous aerosols (Figure 2). Note that only rainfall over land is considered in this analysis and that grey shading represents 25th and 75th percentile of precipitation anomaly from the 20-year mean in the control experiment (case 1). It is clear that adding both BC and OC over tropical and northern Africa can suppress rainfall by more than 20% during boreal winter season. Rainfall reduction due to OC is up to 15%, while that by BC is within natural variability except during February.

The effects of OC emissions dominate (Figure 2). This can be explained by the fact the total mass and number of OC are about four times greater than those of BC over this region (Figure S1) and also by the efficiency of OC in affecting regional water cycle. There are a number of effects associated with BC: heating in the lower troposphere increases stability near the surface and decreases it aloft, changing the environment and convection; the warmer air also tends to evaporate cloud drops more readily, suppressing convection (Ackerman et al., 2000; Koren et al., 2008). According to our simulations, these effects combined produce insignificant changes to rainfall in CAM5.1.

Preventing aerosols to interact with radiation in the model (cases 5–8 in Table 1) indicates that carbonaceous aerosols have a greater impact on precipitation through the aerosol indirect effects (AIE) (Figure 3). Rainfall reduction associated with case 6 is >2 mm day$^{-1}$ larger (Figure 3(a)) than the control (case 5 in Table 1). This is consistent with the hypothesis that AIE can ‘slow down’ the regional hydrological cycle for reason discussed in the next paragraph. These results also show that BC decreased rainfall (Figure 3(c)), illustrating the competition between
Figure 3. Same as Figure 1 except for no aerosol loading for radiation, i.e. cases 5 and 6 in (a), cases 5–7 in (b), and cases 5–8 in (c).

Figure 4. Spatial plots of change in cloud droplet number concentration (cm$^{-3}$) in (a), liquid water path (gm$^{-2}$) in (b), and total cloud fraction (%) in (c), and latitude-pressure (hPa) cross-section averaged over the longitudinal sections from 20°W to 30°E of CCN at 0.1 supersaturation (cm$^{-3}$) in (d), cloud liquid (gkg$^{-1}$) in (e), cloud fraction (%) in (f), and effective radius of liquid ($\mu$m) in (g) during northern winter season due to carbonaceous aerosols (cases 1 and 2). Cloud droplets, CCN, liquid water path, and cloud liquid increase while total cloud fraction and effective radius over land decrease.

Several mechanisms can be considered to explain the reduction in regional rainfall by carbonaceous aerosols. Among such mechanisms is the cloud ‘lifetime effect’, i.e. more aerosols in the atmosphere lead to more but smaller cloud droplets and eventually reduce the efficiency of rain production (Albrecht, 1989; Ramaswamy et al., 2001; Lohmann and Feichter, 2005; Stevens and Feingold, 2009), allowing clouds to persist for a longer time. Experiments with CAM5.1 demonstrate that this mechanism can be very important with carbonaceous aerosols, especially OC. Figure 4 illustrates how AIE of carbonaceous aerosols suppress regional hydrological cycle. Figure 4(a) and (d) shows an increase in the number concentrations of Cloud Condensation Nuclei (CCN) and cloud droplets. Figure 4(b) and (e) displays more liquid water inside clouds (liquid water path) while Figure 4(g) indicates smaller effective radius despite a reduced cloud fraction, especially over land (Figures 4(d) and (f) and S9). These results are largely consistent with the cloud lifetime effect depicted in Figure 1 of Stevens and Feingold (2009). However, cloud fraction simulated by CAM5.1 decreases in
Carbonaceous aerosols on rainfall change over North Africa

Figure 5. Same as Figure 4 except for specific humidity (g kg$^{-1}$) in (a), total diabatic heating (K day$^{-1}$) in (b), heating due to moist process (K day$^{-1}$) in (c), and local Hadley circulation depicted by ($v_D$, $\omega$) with colour shading in $-\omega$ (mb day$^{-1}$). $v_D$ is divergent component of meridional wind (m s$^{-1}$) and $\omega$ is pressure velocity.

response to carbonaceous aerosols (Figure 4(c)), which is likely caused by changes in the circulation patterns (Figure 5(d)). Particularly, a clear reduction in upward motion, maintained by both a weaker convergence zone near the surface and with divergence aloft, appears to be a main dynamical response to carbonaceous aerosols over North Africa. This in turn produces a reduction in atmospheric humidity (Figure 5(a)), which can be by two reasons: one is reduction of Surface Air Temperature (SAT) due to aerosol loading and clouds, and the other is divergent at lower troposphere, and associated cloud cover.

The pathway described earlier suggests that cloud lifetime effect can have a significant impact on climate and that the atmospheric hydrological cycle can be changed by regional carbonaceous aerosols emissions via changes to the atmospheric circulation at both local and continental/global scales (Figures 5(d) and S3). The clear reduction in total diabatic heating (Figure 5(b)) is primarily driven by moist process (Figure 5(c)) despite a significant warming in shortwave radiation due to carbonaceous aerosols (Figure S2(a)). This appears to be closely linked to an anomalous downward motion, which is opposite to the local Hadley circulation (Figure 5(d)) associated with a Matsuno-Gill-type circulation anomaly at continental and global scales (Figure S3) (Matsuno, 1966; Gill, 1980).

A remaining question is why the other seasons also exhibit decreasing rainfall, similar to that in the boreal winter (Figure S3), despite a weaker aerosol forcing over North Africa. First, changes in cloud microphysical properties are in the same direction as those in winter but with a weaker intensity (not shown). Second, rainfall may be reduced due to soil moisture memory. Reduction of rainfall during the preceding boreal winter drives change in land-surface properties, especially the soil moisture, which can carry information to next seasons (Figures 6 and S11). In other words, the strong AIE-induced rainfall change occurs during boreal winter. During the rest of the season, both AIE and reduced soil moisture can contribute rainfall decrease. A similar mechanism was proposed to explain how El Niño and Southern Oscillation (ENSO) induced winter rainfall has impact on regional water cycle during boreal summer over the United States despite the demise of a particular ENSO (Seager et al., 2005). Further study and more experiments are needed to fully understand the feedback of soil moisture changes to rainfall.

4. Conclusion

Carbonaceous aerosols emitted from biomass burning over North Africa slow down the regional hydrological cycle in CAM5.1 simulations. This is largely a consequence of the cloud lifetime effect of aerosols. More carbonaceous aerosols, and in particular, more OC, produce more cloud droplets with smaller sizes, thus increasing the condensed water path and the opacity of the clouds, which in turn reduces the energy reaching the surface (see Figure 4 and a summary schematic diagram in Figure S13). The response of the global
hydrological cycle is constrained by the change in water vapour mixing ratio in the lower troposphere in most of coupled climate models, for example, those discussed by Held and Soden (2006). However, our result indicates that aerosols and associated cloud response can also play an important role in controlling regional and global hydrological cycle.

The effect of BC is more complicated than that of OC. BC acts almost identically to OC when only AIEs are active in the ‘no aerosol direct effect’ experiments (cases 5–8 in Table 1). However, direct and semi-direct effects of BC likely counterbalance these results over North Africa resulting in no significant change in regional rainfall.

State-of-the-art climate models participating in CMIP5 activity are now capable of simulating both direct/semi-direct and indirect effects of aerosols. Our analysis suggests that aerosol indirect effect (cloud lifetime effect) can be important in the regional atmospheric hydrological cycle, on top of the Earth’s energy budget (Liu et al., 2012). However, this scenario becomes more complicated when changes in the rainfall and local meteorology also affect land-surface properties and regional/global atmospheric circulation as a consequence (Figure 2). A more systematic or hierarchical approach is needed to analyse fully coupled climate simulations by including various feedback loops.

There are three important caveats to this work. First, accurately capturing regional aerosol optical and microphysical properties with the standard CAM5.1 (and other global models) is still a challenge (e.g. Wang et al., 2012b, 2013). For example, the aerosol optical depth simulated by CAM5.1 is too low compared to observation over the Indian monsoon region (e.g. Ganguly et al., 2012a). Also, aerosols directly interact only with the stratiform clouds in CAM5.1, but not with the convective clouds, as in many other global climate models. This can be an important issue because aerosols in convective clouds have been proposed to invigorate convection further (e.g. Rosenfeld et al., 2008, 2014). A couple of attempts to simulate interaction between aerosols and convective clouds have been made using a regional (Lim et al., 2014) and a global climate model (Song and Zhang, 2011; Song et al., 2012). However, precipitation change due to aerosol forcing in the models that include interaction with both stratiform and convective clouds appears to be very complicated and more work is needed to tease out those effects. Second, the experiments in this study were done with fixed SSTs. Therefore, the longer timescale pathways through which aerosol can influence SSTs (e.g. Evan et al., 2009) and associated precipitation changes remains to be investigated with a coupled climate model. Third, the intensity of the aerosol indirect effect simulated by global climate model still has large uncertainty (e.g. Wang et al., 2012b).

Acknowledgements

We would like to acknowledge support from the US Department of Energy, Office of Science, Biological and Environmental Research (BER) through the Earth System Modelling programme. Comments from anonymous reviewers are helpful in improving the manuscript. We also thank Drs Carl Berkowitz and Zhao Chun at Pacific Northwest National Laboratory (PNNL) for providing helpful comments on an earlier version of the manuscript. PNNL is operated for the US Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RL01830. JHYoon was also partly supported by the funding from the Korean Polar Research Institute through the grant of PE16100.

Supporting information

The following supporting information is available:

Figure S1. Present-day emission of black carbon (a) and organic carbon (b) from all different sources over Northern Africa (20°W–50°E, EQ–20°N). The total mass of OC is about four to five times more that of BC during its major burning season, i.e. northern winter. This is consistent with total number of particles emitted (not shown).

Figure S2. Same as Figure 5 except for heating due to shortwave radiation process in (a), and heating due to long-wave radiation process (K day$^{-1}$) in (b).

Figure S3. Change in lower tropospheric wind at 700 mb and rainfall due to carbonaceous aerosols over Northern Africa in (a) and long-wave stream function with divergent wind at 700 mb in (b) during northern winter season. Same label is used to shade rainfall in (a) as Figure 1. Contour interval of stream function is $1.0 \times 10^{-5} \, \text{m} \, \text{s}^{-1}$ with positive value shaded. Strong divergence at the lower troposphere centred at the tropical Africa and weak trade winds along the equatorial Atlantic Ocean are simulated. Carbonaceous aerosols induce change in atmospheric moist processes and total diabatic heating through aerosol indirect effect (AIE), which results in atmospheric circulation response not only in regional but also global scales well explained by Gill-type solution (Matsumo, 1966; Gill, 1980).

Figure S4. Seasonal evolution of anomalous rainfall (mm day$^{-1}$) forced by carbonaceous aerosols (cases 1 and 2) including December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), September-October-November (SON), and annual mean.

Figure S5. Seasonal evolution of precipitation simulated by the control experiment of CAM5.1.

Figure S6. Seasonal evolution of precipitation from CRU (Harris et al., 2014).

Figure S7. Seasonal evolution of AOD simulated by the control experiment of CAM5.1.

Figure S8. Seasonal evolution of AOD from MISR (Wu et al., 2011).

Figure S9. Change in effective radius at 850 hPa due to carbonaceous aerosols (cases 1 and 2).

Figure S10. Seasonal evolution of AOD–AOD_dust simulated by the control experiment of CAM5.1.

Figure S11. Seasonal evolution of soil moisture change (mm) at top 1m due to carbonaceous aerosols (cases 1 and 2).
Figure S12. Seasonal evolution of anomalous net surface radiation (W m⁻²) forced by carbonaceous aerosols (cases 1 and 2) including DJF, MAM, JJA, SON, and annual mean.

Figure S13. A schematic diagram of carbonaceous aerosol’s impact on regional atmospheric hydrological cycle over tropical Africa simulated by CAM5.1. More carbonaceous aerosols, especially organic carbon, produce more cloud droplets, more liquid in clouds and liquid water path, smaller drops, and slow down rainfall process. This is consistent with traditional AIE liquid in clouds and liquid water path, smaller drops, and slow especially organic carbon, produce more cloud droplets, more precipitation.

References

Abdul-Razzak H, Ghan SJ. 2000. A parameterization of aerosol activation 2. Multiple aerosol types. Journal of Geophysical Research – Atmospheres 105: 6837–6844.

Ackerley D, Booth BBB, Knight SHE, Highwood EJ, Frame DJ, Allen MR, Rowell DP. 2011. Sensitivity of twentieth-century Sahel rainfall to sulfate aerosol and CO(2) forcing. Journal of Climate 24: 4999–5014.

Ackerman AS, Toon OB, Stevens DE, Heymsfield AJ, Ramanathan V, Ackerman AS, Toon OB, Stevens DE, Heymsfield AJ, Ramanathan V, Albrecht BA. 1989. Aerosols, cloud microphysics, and fractional cloudiness. Science 245: 1227–1230.

Bollasina MA, Ying M, Ramaswamy V. 2011. Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science 334: 502–505.

Booth BBB, Dunstone NJ, Halloran PR, Andrews T, Bellouin N. 2012. Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability (vol. 484, p. 228). Nature 484: 534.

Chang EK. 2013. CMIP5 projection of significant reduction in extratropical cyclone activity over North America. Journal of Climate 26: 9903–9922.

Charney J, Stone PH, Quirk WJ. 1975. Drought in Sahara – biogeophysical feedback mechanism. Science 187: 434–435.

Chang SH, Seinfeld JH. 2005. Climate response of direct radiative forcing of anthropogenic black carbon. Journal of Geophysical Research – Atmospheres 110: D11102.

Chang CE, Zhang GJ. 2004. Impact of absorbing aerosol on precipitation: dynamic aspects in association with convective available potential energy and convective parameterization closure and dependence on aerosol heating profile. Journal of Geophysical Research – Atmospheres 109: D22103.

Dai AG, Lamb PJ, Trenberth KE, Hulme M, Jones PD, Xie PP. 2004. The recent Sahel drought is real. International Journal of Climatology 24: 1323–1331.

Dong B, Sutton RT, Highwood E, Wilcox L. 2014. The impacts of European and Asian anthropogenic sulfur dioxide emissions on Sahel rainfall. Journal of Climate 27: 7000–7017.

Evan AT, Vimont DJ, Heidinger AK, Kossin JP, Bennartz R. 2009. The role of aerosols in the evolution of tropical North Atlantic Ocean temperature anomalies. Science 324: 778–781.

Ganguly D, Rasch PJ, Wang H, Yoon J-I. 2012a. Climate response of the South Asian monsoon system to anthropogenic aerosols. Journal of Geophysical Research – Atmospheres 117: D13209.

Ganguly D, Rasch PJ, Wang H, Yoon J-I. 2012b. Fast and slow responses of the South Asian monsoon system to anthropogenic aerosols. Geophysical Research Letters 39: L18804.

Ghan SJ, Zaveri RA. 2007. Parameterization of optical properties for hydrated internally mixed aerosol. Journal of Geophysical Research – Atmospheres 112: D10201.

Ghan SJ, Liu X, Easter RC, Zaveri R, Rasch PJ, Yoon J-H, Eaton B. 2012. Toward a minimal representation of aerosols in climate models: comparative decomposition of aerosol direct, semidirect, and indirect radiative forcing. Journal of Climate 25: 6461–6476.

Giannini A, Saravanan R, Chang P. 2003. Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. Science 302: 1027–1030.

Gill AE. 1980. Some simple solutions for heat-induced tropical circulation. Quarterly Journal of the Royal Meteorological Society 106: 447–462.

Guo L, Turner AG, Highwood EJ. 2015. Impacts of 20th century aerosol emissions on the South Asian monsoon in the CMIP5 models. Atmospheric Chemistry and Physics 15: 6367–6378.

Hansen J, Sato M, Ruedy R, Nazareno L, Lacis A, Schmidt GA, Russell G, Aleinov I, Bauer M, Bauer S, Bell N, Cairns B, Canuto V, Chandler M, Cheng Y, Del Genio A, Faluvegi G, Fleming E, Friend A, Hall T, Jackman C, Kelley M, Kiang N, Koch D, Lean J, Lerner J, Lo K, Menon S, Miller R, Minnis P, Novakov T, Oinas V, Perlwitz J, Rind D, Romanou A, Shindell D, Stone P, Sun S, Tausnev N, Thresher D, Wielicki B, Wong T, Yao M, Zhang S. 2005. Efficacy of climate forcings. Journal of Geophysical Research – Atmospheres 110: D18104.

Haywood JM, Jones A, Bellouin N, Stephenson D. 2013. Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. Nature Climate Change 3: 660–665.

Held IM, Soden BJ. 2006. Robust responses of the hydrological cycle to global warming. Journal of Climate 19: 5696–5699.

Held IM, Delworth TL, Lu J, Findell KL, Knutson TR. 2005. Simulation of Sahel drought in the 20th and 21st centuries. Proceedings of the National Academy of Sciences of the United States of America 102: 17891–17896.

Hoerling M, Hurrell J, Eischeid J, Phillips A. 2006. Detection and attribution of twentieth-century northern and southern African rainfall change. Journal of Climate 19: 3989–4008.

Huang J, Adams A, Wang C, Zhang C. 2009a. Black carbon and West African monsoon precipitation: observations and simulations. Annales Geophysics 27: 4171–4181.

Huang J, Zhang CD, Prospero JM. 2009b. Large-scale effect of aerosols on precipitation in the West African monsoon region. Quarterly Journal of the Royal Meteorological Society 135: 581–594.

Huang JF, Zhang CD, Prospero JM. 2009c. Aerosol-induced large-scale variability in precipitation over the tropical Atlantic. Journal of Climate 22: 4970–4982.

Huang JF, Zhang CD, Prospero JM. 2009d. African aerosol and large-scale precipitation variability over West Africa. Environmental Research Letters 4: 15006, doi: 10.1088/1748-9326/4/1/015006.

Hurrell JW, Hack JJ, Shea D, Caron JM, Rosinski J. 2008. A new sea surface temperature and sea ice boundary dataset for the Community Atmosphere Model. Journal of Climate 21: 5145–5153.

Huang Y-T, Frierson DMW, Kang SM. 2013. Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century. Geophysical Research Letters 40: 2845–2850.

Iacono MJ, Delamere JS, Mlawer EJ, Shephard MW, Clough SA, Collins WD. 2008. Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models. Journal of Geophysical Research – Atmospheres 113: D13103.

Jeong GR, Wang C. 2010. Climate effects of seasonally varying biomass burning emitted carbonaceous aerosols (BBCA). Atmospheric Chemistry and Physics 10: 8373–8389.

Jiang HL, Xue HW, Teller A, Feingold G, Levin Z. 2006. Aerosol effects on the lifetime of shallow cumulus. Geophysical Research Letters 33: L14806.

Jiang Y, Liu X, Yang X-Q, Wang M. 2013. A numerical study of the effect of different aerosol types on East Asian summer clouds and precipitation. Atmospheric Environment 70: 51–63.

Koren I, Kaufman YJ, Remer LA, Martins JV. 2004. Measurement of the effect of Amazon smoke on inhibition of cloud formation. Science 303: 1342–1345.

Koren I, Martins JV, Remer LA, Afargan H. 2008. Smoke invigoration versus inhibition of clouds over the Amazon. Science 321: 946–949.

Kucharski F, Zeng N, Kalnay E. 2013. A further assessment of vegetation feedback on decadal Sahel rainfall variability. Climate Dynamics 40: 1453–1466.

Lamarque FJ, Bond TC, Eyring V, Granier C, Heil A, Klimont Z, Lee D, Liouasse C, Mieville A, Owen B, Schultz MG, Shindell D, Smith SJ, Stjepst F, Van Aardenne J, Cooper OR, Kainuma

© 2016 The Authors. Atmospheric Science Letters published by John Wiley & Sons Ltd on behalf of the Royal Meteorological Society.
M. Mahowald N, Mcconnell JR, Naik V, Riahi K, van Vuuren DP. 2010. Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmospheric Chemistry and Physics* **10**: 7017–7039.

Lau KM, Kim MK, Kim KM. 2006. Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau. *Climate Dynamics* **26**: 855–864.

Levy H II, Horowitz LW, Schwarzkopf MD, Ming Y, Golaz J-C, Naik V, Ramaswamy V. 2013. The roles of aerosol direct and indirect effects in past and future climate change. *Journal of Geophysical Research – Atmospheres* **118**: 4521–4532.

Lim K-SS, Fan J, Leung R, Ma P-L, Singh B, Zhao C, Zhang Y, Zhang G, Song X. 2014. Investigation of aerosol indirect effects using a cumulus microphysics parameterization in a regional climate model. *Journal of Geophysical Research – Atmospheres* **119**: 906–926.

Liu X, Easter RC, Ghan SJ, Zaveri R, Rasch P, Shi X, Lamarque JF, Gettelman A, Morrison H, Vitt F, Conley A, Park S, Neale R, Hannay C, Ekman AML, Hess P, Mahowald N, Collins W, Iacono MJ, Bretherton CS, Flanner MG, Mitchell D. 2012. Toward a minimal representation of aerosol direct and indirect effects: model description and evaluation. *Geoscientific Model Development* **5**: 31.

Lohmann U, Feichter J. 2005. Global indirect aerosol effects: a review. *Atmospheric Chemistry and Physics* **5**: 715–737.

Lu J, Delworth TL. 2005. Oceanic forcing of the late 20th century Sahel drought. *Geophysical Research Letters* **32**: L22706.

Martins JA, Silva Dias MAF, Gонкальес FLT. 2009. Impact of biomass burning aerosols on precipitation in the Amazon: a modeling case study. *Journal of Geophysical Research – Atmospheres* **114**: D02207.

Matsuno T. 1966. Quasi-geostrophic motions in the equatorial area. *Journal of the Meteorological Society of Japan* **44**: 19.

Morrison H, Gettelman A. 2008. A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part I: description and numerical tests. *Journal of Climate* **21**: 3642–3659.

Neale RB, Chen C-C, Gettelman A, Lauritzen PH, Park S, Williamson DL, Conley AJ, Garcia R, Kinnison D, Lamarque JF, Marsh D, Mills M, Smith AK, Tilmes S, Vitt F, Morrison H, Cameron-Smith P, Collins WD, Iacono MJ, Easter RC, Ghan S, Liu X, Rasch PJ, Taylor MA. 2010. Description of the NCAR Community Atmosphere Model (CAM 5.0). *NCAR Technical Note. National Center for Atmospheric Research, Boulder, CO.*

Nicholson SE. 2001. Climatic and environmental change in Africa during the last two centuries. *Climatic Research* **17**: 123–144.

Park S, Bretherton CS, Rasch PJ. 2014. Integrating cloud processes in the community atmosphere model, version 5. *Journal of Climate* **27**: 6821–6856.

Ramanathan V, Chung C, Kim D, Betteg T, Buja L, Kiehl JT, Washington WM, Fu Q, Sikka DR, Wild M. 2005. Atmospheric brown clouds: impacts on South Asian climate and hydrological cycle. *Proceedings of the National Academy of Sciences of the United States of America* **102**: 5326–5333.

Ramaswamy V, Boucher O, Haigh J, Hauglustaine D, Haywood J, Myhre G, Nakajima T, Shi GY, Solomon S. 2001. Radiative forcing of climate change. In Climate Change 2001: The Scientific Basis, Houghton JT, Ding Y, Griggs DJ, Noguer M, Van Der Linden PJ, Dai X, Maskell K, Johnson CA (eds). Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge and New York, NY.

Rosenfeld D. 1999. TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophysical Research Letters* **26**: 3105–3108.

Rosenfeld D, Lohmann U, Raga GB, O’Dowd CD, Kulmala M,uzzi S, Reissell A, Andreae MO. 2008. Flood or drought: how do aerosols affect precipitation? *Science* **321**: 1309–1313.

Rosenfeld D, Sherwood S, Wood R, Donner L. 2014. Climate effects of aerosol–cloud interactions. *Science* **343**: 379–380.

Sakaeda N, Wood R, Rasch PJ. 2011. Direct and semidirect aerosol effects of southern African biomass burning aerosol. *Journal of Geophysical Research – Atmospheres* **116**: D12205.

Scaife AA, Kucharski F, Folland CK, Kinter J, Brönnimann S, Freerday D, Fischer AM, Grainger S, Jin EK, Kang IS, Knight JR, Kusunoki S, Lau NC, Nath MJ, Nakaegawa T, Pegion P, Schubert S, Sporyshev P, Syktus J, Yoon JH, Zeng N, Zhou T. 2009. The CLIVAR C20C project: selected twentieth century climate events. *Climate Dynamics* **33**: 603–614.

Scholze M, Knorr W, Arnell NW, Prentice IC. 2006. A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* **103**: 13116–13120.

Schulz M, Texier C, Kinne S, Balkansky I, Bauer S, Berntsen T, Berglen T, Boucher O, Dentener F, Guibert S, Isaksen ISA, Iversen T, Koch D, Kirkevag A, Liu X, Montanaro V, Myhre G, Penner JE, Pitiari G, Reddy S, Seland O, Siter P, Takemura T. 2006. Radiative forcing by aerosols as derived from the AeroCom present-day and pre-industrial simulations. *Atmospheric Chemistry and Physics* **6**: 5225–5246.

Seager R, Kushner Y, Herweijer C, Naik N, Velez J. 2005. Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000. *Journal of Climate* **18**: 4065–4088.

Song X, Zhang GJ. 2011. Microphysics parameterization for convective clouds in a global climate model: description and single-column model tests. *Journal of Geophysical Research – Atmospheres* **116**: D02201.

Song X, Zhang GJ, Li JLF. 2012. Evaluation of microphysics parameterization for convective clouds in the NCAR community atmosphere model CAM5. *Journal of Climate* **25**: 8568–8590.

Stevens B, Feingold G. 2009. Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature* **461**: 607–613.

Wang C, Dong S, Evan AT, Foltz GR, Lee S-K. 2012a. Multidecadal covariability of North Atlantic sea surface temperature, African dust, Sahel rainfall, and Atlantic hurricanes. *Journal of Climate* **25**: 5404–5415.

Wang M, Ghan S, Liu X, L’Ecuyer TS, Zhang K, Morrison H, Ovchinnikov M, Easter R, Marchand R, Chand D, Qian Y, Penner JE. 2012b. Constraining cloud lifetime effects of aerosols using A-Train satellite observations. *Geophysical Research Letters* **39**: L15709.

Wang H, Easter RC, Rasch PJ, Wang M, Liu X, Ghan SJ, Qian Y, Yoon JH, Ma PL, Vinoy V. 2013. Sensitivity of remote aerosol distributions to representation of cloud–aerosol interactions in a global climate model. *Geoscientific Model Development* **6**: 765–782.

Warner J, Twomey S. 1967. Production of cloud nuclei by cane fires and effect on cloud droplet concentration. *Journal of the Atmospheric Sciences* **24**: 704.

Zeng N, Neelin JD, Lau KM, Tucker CJ. 1999. Enhancement of inter-decadal climate variability in the Sahel by vegetation interaction. *Science* **286**: 1537–1540.

Zeng N, Yoon JH, Marengo JA, Subramaniam A, Nobre CA, Mariotti A, Neelin JD. 2008. Causes and impacts of the 2005 Amazon drought. *Environmental Research Letters* **3**: 014002, doi: 10.1088/1748-9326/3/1/014002.