



Dust-rainfall feedbacks in the West African Sahel

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[1] Dust aerosols can suppress rainfall by increasing the number of cloud condensation nuclei in warm clouds and affecting the surface radiation budget and boundary layer instability. The extent to which atmospheric dust may affect precipitation yields and the hydrologic cycle in semiarid regions remains poorly understood. We investigate the relationship between dust aerosols and rainfall in the West African Sahel where the dust-rainfall feedback has been speculated to contribute to sustained droughts. We find that the amount of dust loadings is negatively correlated with rainfall values, suggesting that dust entrained in the atmosphere can significantly inhibit rainfall in this region.

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1. Introduction

[2] Atmospheric aerosols affect processes such as the Earth's surface radiation budget [e.g., Kaufman *et al.*, 2002], global biogeochemical cycles [Duce *et al.*, 1991; Okin *et al.*, 2004], and the hydrological cycle [Ramanathan *et al.*, 2001]. Desert dust contributes to approximately half of the total atmospheric aerosols burden which is estimated at 1500 Tg per year [Andreae, 1995; Ramanathan *et al.*, 2001]. Most of the mineral dust residing in the atmosphere comes from West Africa, with the Sahel region representing the major source [Prospero and Nees, 1986; N'Tchayi Mbourou *et al.*, 1997]. Atmospheric aerosols modify the incoming and outgoing radiation [Tegen *et al.*, 1997] directly through scattering and absorption and indirectly by impacting cloud formation processes [Levin *et al.*, 1996]. These direct and indirect effects are linked to weakened hydrologic cycles with the overall effect of reduced water availability in the biosphere [Ramanathan *et al.*, 2001]. The feedback between dust aerosols and rainfall might lead to a self-sustained process of desertification [Rosenfeld *et al.*, 2001]. Dust particles have been observed to suppress rainfall by promoting the formation of small cloud droplets that do not ordinarily reach the size of rain droplets, and possibly increasing cloud evaporation owing to increased absorption of solar radiation [Lohmann and Feichter, 2005].

[3] Dust aerosols can contribute to surface cooling and enhance warming in the mid troposphere, thereby increasing atmospheric stability and reducing convection with the net effect of decreasing rainfall [Brooks, 2000]. The

reduced rainfall amounts lead to drier soil conditions and less vegetation. Increased exposure of soil to wind shear and reduced soil moisture, in turn, enhances dust mobilization which further increases dust concentration in the atmosphere [Rosenfeld *et al.*, 2001]. Despite the recognized importance of dust-rainfall feedbacks, their impact on the hydrologic cycle in areas located at the desert margins such as the West African Sahel has never been quantified. Previous studies [e.g., Rosenfeld, 2000; Adhikari *et al.*, 2005] have focused on the analysis of physical and microphysical mechanisms of rainfall suppression. Only few studies have employed correlation analysis to investigate the relationship between aerosols and clouds over several rainy seasons. Mahowald and Kiehl [2003] conducted a long-term correlation analysis on dust and cloud amount over North Africa and the North Atlantic. They reported that the positive correlation observed over the west coast of North Africa was due to rainfall suppression which leads to longer cloud lifetime and high cloud amount when aerosol levels are high. It is still unclear whether these mechanisms could significantly affect the total rainfall yield throughout the rainy season in the West African Sahel.

[4] The transition zone between the Saharan desert and the humid equatorial region of Africa is affected by high interannual rainfall variability [Nicholson, 2000]. Drought conditions have persisted in this region since the late 1960s, coinciding with a concurrently increasing trend in dust emissions [Brooks, 2000]. Convective rainfall contributes to approximately 75% of total rainfall in the Sahel [Nicholson, 2000]. Because short-lived convective clouds are most prone to aerosol-induced effects on rainfall [Rosenfeld *et al.*, 2001], dust aerosols are likely to have a major impact on rainfall in this region affected by frequent dust-laden atmospheric conditions. This study, therefore, uses rain gauge data and remotely sensed atmospheric dust loads to assess the existence of a significant causal relation between dust and rainfall in the West African Sahel. It is also assessed whether the impact of dust aerosols on precipitating systems is hydrologically

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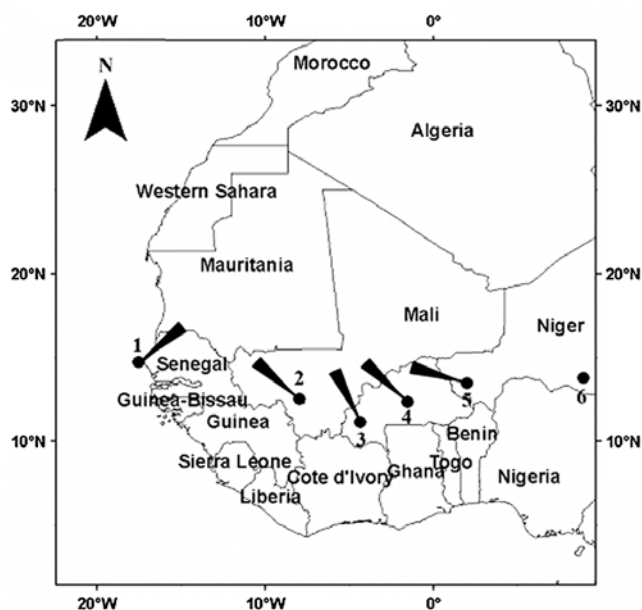


Figure 1. Stations (labeled with numbers as in Table 1) chosen for the study in Sahel region. Arrows point to the direction with the highest mean AI. The station Zinder did not exhibit a statistically significant mean AI for different directions.

significant, i.e., whether rainfall yields are significantly reduced by atmospheric dust.

2. Data and Methods

[5] The effect of atmospheric aerosols on precipitation processes over the Sahel region was investigated during the period 1996–2005 (1999 excluded owing to the large number of missing data) for six stations (Table 1) along a longitudinal transect extending from 17°W to 9°E (Figure 1). The Total Ozone Mapping Spectrometer (TOMS) Version 8 Aerosol Index (AI) was used as a proxy for estimating atmospheric dust loads. TOMS, on board the Earth Probe satellite platform, provides aerosol data from July 1996 to the end of 2005. TOMS AI is based on the ultraviolet

scattering properties of the aerosols. Absorbing aerosols such as desert dust and smoke give positive values while small nonabsorbing aerosols give negative values [Hsu *et al.*, 1999; Herman *et al.*, 1997]. We concentrate on the wet season (June through September) when biomass burning activities are minimal [Clerici *et al.*, 2004].

[6] The TOMS data sets are presented as daily values of AI for 1° latitude × 1.25° longitude grids. Recent studies have shown that TOMS AI is consistent with surface based observations of the aerosol concentrations over Sahara and Sahel [Washington *et al.*, 2003; Torres *et al.*, 2002; Moulin and Chiapello, 2004]. To account for the instrumental uncertainties, the AI values less than 0.6 were removed [e.g., Hsu *et al.*, 1999]. This threshold value also ensured that the days chosen in our analysis contained considerable dust loads.

[7] Daily rainfall values were obtained from the Global Summary of the Day, National Climatic Data Center (NCDC). The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model [Draxler, 1997; Draxler and Rolph, 2003; Walker *et al.*, 2000] was used to calculate the back trajectories of air parcels passing the study site on a particular day. Owing to the constraints in data availability the model was run with NCAR/NCEP (National Center for Atmospheric Research/National Center for Environmental Prediction) global reanalysis meteorological data [Kalnay *et al.*, 1996] for the year 1996, Final Run (FNL) archive from 1997 through 2004, and GDAS1 (Global Data Assimilation System) archive for 2005 on the NOAA (National Oceanic and Atmospheric Administration) READY system (G. D. Rolph, Real-time Environmental Applications and Display sYstem (READY) Website, 2003, (<http://www.arl.noaa.gov/ready/hysplit4.html>)). The trajectories were run at 1500 m above mean sea level as TOMS AI is not sensitive to aerosols present in the first kilometer above surface [e.g., Torres *et al.*, 2002].

[8] The impact of dust on rainfall was investigated by a regression analysis and included data from June to September, the typical wet season in the Sahel region. The rainfall value at a station on day (*T*) was paired with the dust loads of the region where the coordinates of the 1-day and 3-day back-trajectory end points fall in. The back-trajectory analysis was used to avoid the rainfall scavenging effect which

Table 1. Location, Mean Annual Aerosol Index ($\langle AI \rangle$), and Mean Annual Rainfall (MAR) Measured at the Six Stations Considered in This Study^a

| Station Number, Name | Country | Coordinates | $\langle AI \rangle^b$ | MAR, mm | Slope, ^c mm | R^2 ^c | Slope, ^d mm | R^2 ^d | Direction |
|-------------------------|--------------|-------------------|------------------------|---------|------------------------|--------------------|------------------------|--------------------|---------------------|
| 1, Dakar | Senegal | (14.73°N, 17.5°W) | 2.30 | 434 | −0.4 (3) | 0.78 (3) | −0.56 (3) | 0.81 (3) | ESE (3) |
| 2, Bamako | Mali | (12.53°N, 7.95°W) | 1.72 | 869 | insignificant | insignificant | insignificant | insignificant | ENE (1), WNW (3) |
| 3, Bobo-Dioulasso | Burkina-Faso | (11.16°N, 4.31°W) | 1.61 | 831 | −1.03 (3) | 0.71 (3) | −0.92 (3) | 0.58 (3) | ENE (3) |
| 4, Ouagadougou | Burkina-Faso | (12.35°N, 1.51°W) | 1.76 | 722 | −0.7 (1) | 0.83 (1) | −0.85 (1) | 0.65 (1) | ENE (1), WNW (1) |
| 5, Niamey | Niger | (13.48°N, 2.02°E) | 1.99 | 569 | −0.7 (1) | 0.87 (1) | −0.66 (1) | 0.78 (1) | ESE (1) |
| 6, Zinder | Niger | (13.78°N, 8.98°E) | 1.94 | 400 | −0.3 (3) | 0.62 (3) | −0.34 (3) | 0.7 (3) | insignificant |

^aMean annual aerosol index. $\langle AI \rangle$; mean annual rainfall, MAR. The dependence of precipitation on upwind aerosol index is expressed by the slope and the R^2 values of the linear regression (see text). The significant regression results according to different direction categories are under column ‘Direction.’ The numbers in brackets denote the use of 1-day or 3-day back-trajectory analyses for the AI. All the R^2 values are significant at $p < 0.05$.

^bWet season only.

^cDays with precipitation <50 mm.

^dAll days during wet season.

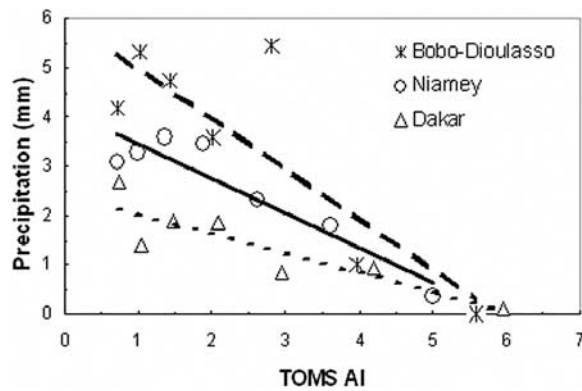


Figure 2. Negative relation between daily rainfall (days with precipitation <50 mm, only) and AI determined using data from three rain stations (R^2 values are reported in the third column in Table 1).

can confound our results when rainfall and dust amounts are taken on the same day and at the same location. Moreover, by using this approach we do not relate the AI to rainfall measured at the same location. This fact allowed us to investigate the effect of dust on precipitation without the confounding factors due to the effect of rainfall on dust emissions from the same location. Dust concentrations for upwind stations were represented by the average TOMS AI of the four neighboring 1° latitude \times 1.25° longitude grids to the coordinate on one or 3 days before day (T). This duration of 1–3 days corresponds to the average residence time of desert dust, as reported by previous studies [*Ramanathan et al.*, 2001]. The AI values were divided logarithmically into seven bins and regressed against the average of their corresponding rainfall values. The same analysis was repeated for days when rainfall values were less than 50 mm and grouped according to the air parcel flow direction categories (Table 1). The t-test was performed to assess whether each AI group had statistically different mean rainfall values at each station. Further, to investigate the dust source regions in the Sahel, origins of the air parcel from the back-trajectory analysis were categorized into eight directions with respect to the specific station. ANOVA test was used to assess if there were statistically significant differences between the dust loads originating from each direction group. Frequency of high dust events, defined as $AI > 1.9$ after *Middleton and Goudie* [2001], was computed to assess the consistency of the direction group with the highest dust loads.

[9] The existence of a statistical dependence between dust concentration (i.e., AI) and precipitation would not necessarily prove a causal relation between these two variables. In fact, this dependence could result from a relation between specific humidity (SH) and dust load. For example, if dust laden air masses are consistently drier, a negative relation between rainfall and AI index would not be necessarily indicative of an effect of rainfall suppression by dust. To investigate this point, we included some statistical tests involving AI, rainfall, and specific humidity. To this end, we calculated the vertically averaged specific humidity between the ground surface and 850 hPa using the NCAR/NCEP reanalysis data [*Kalnay et al.*, 1996]. We used a two sample Kolmogorov-Smirnov (KS) goodness of

fit hypothesis test to determine if there is any difference in either 1–3 days antecedent dust concentrations or specific humidity values between rainy days and days with no rain. The KS test is applied to empirical cumulative distribution functions for two samples to test if both samples can be drawn from the same underlying distribution. We apply the KS test to data for each station and prevailing wind direction independently. We conduct three sets of comparisons: (1) antecedent dust concentrations on days without rain versus days with rain, (2) antecedent specific humidity on days without rain versus days with rain, and (3) dust concentrations on days below the median station/direction specific humidity versus dust concentrations on days above the median station/direction specific humidity. Test 3 is designed to determine whether, for a given case, specific humidity and dust concentrations are independent. For those cases where Test 3 is insignificant (i.e., no relationship between dust and specific humidity), we can be confident that the two are acting (if at all) independently on precipitation. Test 1 and 2 are used to assess the statistical relation between antecedent dust levels or antecedent specific humidity, and rainfall occurrences. Additionally, we calculated and tested (Test 4) the correlation between rainfall depth (i.e., amount of rain falling during a rainy day) and the AI index.

3. Results and Discussion

[10] We focused on the results obtained for the wet season (June–September) and assessed the relationship between daily rainfall and the AI at upwind locations (Table 1). The wind direction groups with the highest average AI is depicted in Figure 1 for each station. The prevailing flows coincided with the directions giving the highest frequencies of dust events. These wind directions for the five eastern stations point to an area between southern Mauritania and western Mali, which is a known important dust source region [*Middleton and Goudie*, 2001, *Prospero et al.*, 2002]. A negative relationship was estimated between the rainfall amounts and AI values (Figure 2). This relationship provided evidence for a statistically significant reduction in rainfall yields with high dust loads. Overall, at the 1500-m altitude, the dominant flow direction (Figure 3, compass diagrams) was easterly over all stations (Figure 3). The exception was Zinder, Niger which experienced dominant southwesterly flows that transported marine air masses to the area. ANOVA tests showed significant differences ($p < 0.05$) between the AI levels at back-trajectory endpoints in each direction category except for Zinder.

[11] Restricting the analyses to $AI > 0.6$ ensured that the atmosphere had considerable dust amounts, and reduced uncertainties in the analyses due to instrumental uncertainties of detecting low dust loadings [*Hsu et al.*, 1999]. The mean AI for rain and nonrainy days tested with t-test showed significant difference ($p < 0.05$) for Dakar, Niamey, and Zinder. These three stations had fewer rainy days and higher average aerosol loadings than the other three locations (Table 1). These results indicated that the relationship between dust and precipitation may not be apparent if the atmosphere does not have sufficient dust loads. Dust-rainfall feedbacks were investigated by regressing the AI data from upwind source regions against the rainfall amounts at each station. The results showed a significant negative

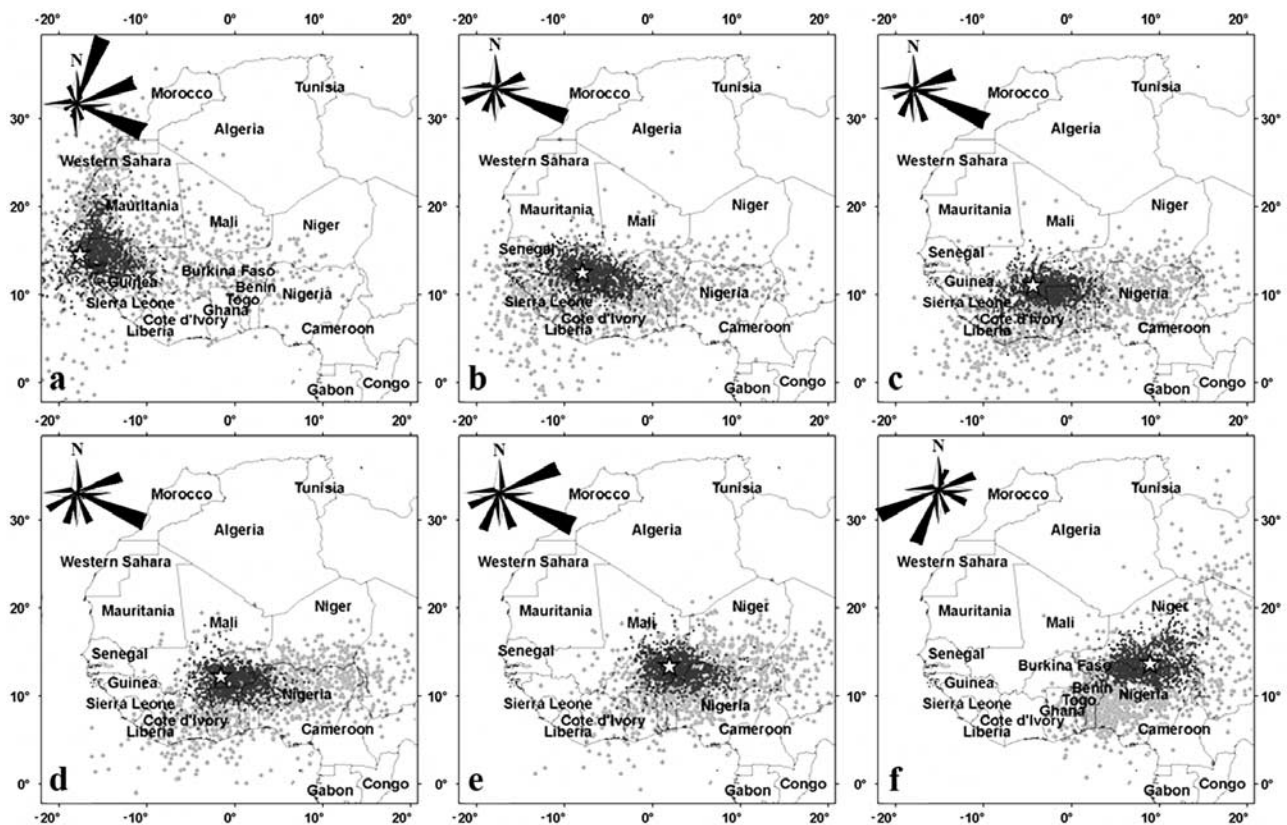


Figure 3. One-day (dark dots) and 3-day (light dots) back-trajectory endpoints for (a) Dakar, (b) Bamako, (c) Bobo-Dioulasso, (d) Ouagadougou, (e) Niamey, and (f) Zinder. Compass diagrams on the top left of the maps show the frequency distributions of the eight direction categories for the 3-day back-trajectories.

relationship between upwind dust loadings and rainfall at all stations except Bamako, suggesting that dust in the atmosphere suppresses precipitation at a daily timescale (Table 1). The same analysis was repeated for AI values binned separately for each direction of back-trajectory endpoints (Table 1). Only the results for the directions exhibiting significant negative relationships (i.e., ENE, ESE, and WNW) were reported in Table 1. The WNW in Bamako and Ouagadougou corresponded to the direction with the highest average AI whereas ENE and ESE were the more frequently occurring directions for most stations. In spite of the negative relation between rainfall and AI found in the case of Bamako for the WNW and ENE directions, no significant relationship was found when all directions were included. This resulted because of the low frequency of occurrences of ENE and WNW directions.

[12] The statistically significant relationship found between dust and daily rainfall (wet season only) in five Sahelian stations suggests that dust aerosols may significantly inhibit rainfall. However, this analysis does not conclusively prove the occurrence of rainfall suppression by atmospheric dust. As indicated in section 2, some confounding effects could arise from the possible existence of interdependence between dust load and atmospheric humidity. The three KS tests indicated in the methods were used to address this point. It was found the case of Dakar, Niamey and Zinder (which, as noted, are the stations with on average fewer rainy days and higher dust loadings) the negative relation between rainfall and AI does not arise as

an effect of a dependence between AI and specific humidity. The first test (Test 1) statistically evaluates differences in the AI distribution between rainy and nonrainy days. Data from Dakar and Niamey show (Table 2) that AI is higher in nonrainy than in rainy days. We exclude that this difference might result from the existence of significantly higher values of SH in days with low dust loadings (assessed with Test 3) because (1) the AI-SH relation was either insignificant (Test 3) or significant with p-values smaller than those of Test 1 (i.e., the direct dependence of AI on rainfall occurrence was stronger); or (2) there was no significant relation (except for Niamey, NWW) between SH and rainfall occurrence (Test 2). In the case of Zinder the negative dependence between AI and rainfall yields along one of the most frequent directions is mostly contributed by a significant decrease in rainfall depth with increasing dust loadings (Test 4).

[13] In conclusion, we found a significant negative relation between dust loadings and precipitation along a zonal transect across the West African Sahel, the major dust source in the World. This relation does not result from the fact that more rain leads to less dust emissions, in that dust loadings were taken at upwind locations using back-trajectory calculations. Rather, we argue that the dust loadings have an impact on the rainfall regime, in that they are able to inhibit precipitation. We have tested that in the three stations that receive more dust and less rain (i.e., Dakar, Niamey and Zinder; see Table 1) the significant statistical relations found between dust loadings and rainfall occur-

Table 2. Statistical Relations Among Aerosol Index (AI), Specific Humidity (SH), Rainfall Occurrence, and Rainfall Depth^a

| Station | Back-Trajectory | Direction | Test 1 (p-Value) (High AI–No Rain) | Test 2 (p-Value) (Low SH–No Rain) | Test 3 (p-Value) (Low SH–High AI) | Test 4 (p-Value) (High AI–Low Rain Depth) |
|---------|-----------------|------------|---------------------------------------|--------------------------------------|--------------------------------------|--|
| Dakar | 1 day | <i>NEE</i> | 0.0001 | 0.001 | 0.056 | 0.29 |
| | | <i>SSW</i> | 0.0030 | 0.207 | 0.332 | 0.39 |
| | | <i>SSE</i> | 0.0001 | 0.105 | 0.131 | 0.98 |
| | 3 day | <i>ESE</i> | 0.0001 | 0.009 | 0.001 | 0.59 |
| | | <i>NEE</i> | 0.0060 | 0.051 | 0.219 | 0.81 |
| | | <i>SSW</i> | 0.0360 | 0.939 | 0.959 | 0.0749 |
| Niamey | 1 day | <i>ESE</i> | 0.0040 | 0.176 | 0.131 | 0.97 |
| | | <i>NNE</i> | 0.0290 | 0.859 | 0.184 | 0.83 |
| | | <i>NWW</i> | 0.0950 | 0.006 | 0.002 | 0.40 |
| Zinder | 1 day | <i>SSE</i> | 0.0710 | 0.647 | 0.034 | 0.56 |
| | | <i>NEE</i> | 0.8820 | 0.111 | 0.020 | 0.095 |
| | | <i>ESE</i> | 0.0680 | 0.027 | 0.110 | 0.61 |

^aRainfall depth is depth of precipitation on rainy days. Test 1 statistically evaluates (KS test) the difference in the distribution of AI in rainy versus nonrainy days (with high AI in days with no rain); Test 2 evaluates (KS test) differences in the distribution of SH in rainy/nonrainy days; Test 3 evaluates (KS test) the difference in AI distribution in days with above-/below-median SH (with low SH corresponding to high AI); Test 4 statistically evaluates the dependence between AI and daily rainfall on rainy days. The table reports the p-values of the four tests only for those directions in which some significant dependence between AI and rainfall was observed. Italics indicate the more frequent directions, while boldface values highlight that the test is significant (a 10% confidence level was used). Abbreviations: ns, not significant; r, correlation coefficient.

rences does not result from the existence of lower values of specific humidity in air masses that are dust laden. Moreover, our results indicate that dust appears to be acting on rainfall through a threshold effect, as suggested by the fact that (1) the highest AI stations have the lowest rainfall yields, and (2) for these same stations, the KS results show dust acting independently of specific humidity. However, this analysis does not indicate which mechanism (direct versus indirect effects) is more important in dust suppressing rainfall. This is partly due to the complexity of the precipitation process which is controlled by both large-scale dynamics such as the air jet systems and local factors such as convection and availability of atmospheric moisture [Nicholson, 2000]. This study supports the conclusion that an inverse relationship exists between dust and precipitation. This negative dependence statistically supports our argument that dust aerosols suppress rainfall thereby leading to a significant reduction in rainfall yields when dust loads are relatively high.

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