Aerosol-rainfall relationship over the Middle East and North Africa (MENA) region from observations

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Abstract

Water is an essential element of life and rainfall. The amount of rainfall directly affects the spatial and temporal distribution of water resources on the Earth. Rainfall has direct impact on agricultural production, daily life activities, and human health. Atmospheric aerosols are essential for rainfall formation; therefore, understanding how dust compositions and distributions affect the regional rainfall pattern is of utmost importance, particularly in the region with high atmospheric dust loading, such as the Middle East and North Africa (MENA). Although aerosol-rainfall research has gained increased attention in the last few decades, many details of aerosol-cloud-rainfall interactions pathways remain unknown. In this work, dust-rainfall connection is examined using a large sample of Aerosol Optical Depth (AOD) and rainfall data from Moderate Resolution Imaging Spectroradiometer (MODIS) and Tropical Rainfall Measuring Mission (TRMM), respectively, obtained on daily basis for the years 2015 and 2016 over the MENA region. Observational analysis reveal that rainfall is oppositely related to AOD in low and high rainfall conditions. Exponentially decreasing (increasing) relationship with AOD under low (high) rainfall conditions, at a similar range of AOD in both cases, was observed. Further analysis using angstrom exponent data suggest that the positive (negative) relationship between AOD and rainfall could represent dust indirect effects during the mature (initial) stage of convection. This observational analysis provide a basis to predict rainfall under different dust loading conditions (AOD) using satellite data and provide a benchmark for improving the representation of dust effect on cloud and rainfall processes in the models, which currently have significant uncertainty. While dust and dust storms are considered nuances from air quality perspective, these results highlight their fundamental positive impact on Earth’s climate.

1. Introduction

Tiny aerosol particles floating in the atmosphere have several implications on the Earth's climate and its inhabitants. When they are concentrated near the surface, they pose threat to the human and animal health by degrading the air quality (Parajuli et al., 2019; Ukhov et al., 2020). Since they can scatter solar radiation back to space and absorb radiation within the aerosol layers, they can also affect the atmospheric circulations by causing heat imbalance on the surface of Earth and its atmosphere (e.g., Sokolik and Toon, 1996; Jacobson et al., 2006; Kalenderski and Stenchikov, 2016). They are also known to affect the rainfall patterns through various direct and indirect pathways (e.g., Lohmann and Feichter, 2001; Abbott and Cronin, 2021; Koren et al., 2005). Since the entire biosphere including human beings directly depend upon rainfall for their survival, changes in rainfall patterns can have broader, and long-term consequences. Unequal distribution of rainfall can affect the frequency and intensity of floods and droughts and affect the distribution of regional water resources. Changes in prevailing monsoon system and rainfall pattern can affect agricultural production, limit access to drinking water supply, and affect daily life activities. Therefore, understanding how the atmospheric aerosol in a region affects the regional rainfall pattern is of great concern.

Due to multiple feedbacks of aerosols on Earth's climate that occur through various direct and indirect pathways, it is not easy to understand their effect on rainfall. Dust can both increase and decrease rainfall by affecting local circulations through their direct effect (Jacobson et al., 2006; Rémy et al., 2015). For example, in West Africa, dust can reduce rainfall by inducing a cooling effect that decreases the meridional gradient of moist static energy (Konare et al., 2008). In contrast, dust can also enhance rainfall through dust-induced diabatic warming in the higher troposphere that enhances regional circulation (Jin et al., 2015) through the elevated heat pump effect (Lau et al., 2010).

Dust can also affect rainfall by directly altering the process of condensation. Only a fraction of all aerosol particles available in the atmosphere can nucleate or condense on the surface of atmospheric particles to form cloud droplets; these particles are called cloud condensation nuclei (CCN) (Stull, 2000; Dennis, 1980). Homogenous and heterogeneous nucleation are the nucleation that happens in the absence and presence of hydrophilic aerosol particles, respectively (Stull, 2000). The number density of CCN activated increases with the increase in supersaturation (Stull, 2000). Similarly, ice nuclei (IN) are specific atmospheric particles such as bacteria and dust, which promote the freezing of supercooled cloud droplets and produce ice crystals (Creamean et al., 2013). The mixed-phase cloud so produced initiates precipitation which is much more faster than supercooled, liquid-only cloud because of the faster growth rate of ice particles versus droplets (Pinsky et al., 1998). Ice crystals nucleate through different processes including homogeneous freezing, heterogeneous freezing, immersion freezing, contact freezing, and condensation freezing. These principles of indirect effects of aerosols on rainfall are mainly founded on the pioneering experimental works of Coulier (Coulier, 1875) and Aitken (Aitken, 1882), who showed the ability of tiny dust/aerosol particles to form clouds or fogs in a simple device (Verzár, 1959). Dust can act both as IN (Creamean et al., 2013), which mainly affect the cold cloud processes (Ansmann et al., 2005) and CCN, which mainly affects warm cloud processes (Li et al., 2010; Twohy, 2015).

A recent modeling study (e.g., Alizadeh-Choobari, 2018) has shown that aerosols increase rainfall during heavy rainfall events and suppress light rainfall events. Through observations, Li et al. (2011) found that aerosols increase (decrease) rainfall in clouds with high (low) liquid water content. Han et al. (2009) also showed show strong negative correlation between atmospheric dust loading and rainfall over the dust source regions of the Tibetan Plateau using observations. Although multiple new mechanisms have been proposed recently to explain the underlying causes of the increasing and decreasing effect of aerosols on rainfall (e.g., Fan et al. 2018; Grabowski and Morrison, 2020; Abott and Cronin, 2021), they are still debated and at times controversial (Alizadeh-Choobari, 2018) despite extensive research interest on the topic. Although the opposite effects of aerosols on light and heavy rainfall is well known, the exact relationship between aerosol loading and rainfall has not been found. In this context, there is a need to reexamine the dust-rainfall connections from a new perspective. Therefore, in this work, the effect of dust on rainfall over the MENA region is analyzed with an aim to answer the following particular research questions.

1. How is atmospheric aerosol loading related to rainfall?
2. Is there any physically based relationship between rainfall and AOD found in observations?

2. Data and Methods

2.1. Study domain and data

To understand dust-rainfall connections from observations, a diverse and comprehensive sample is created to include a range of dust and rainfall data observed in reality. For this observational study, the analysis is focused over the entire MENA region (-20 to 70E and 0 to 40N), outlined by the outermost box in Fig. 1 (d01). The area covers the Sahel region including some part of the African rain forest in the south and the northern regions that experience frequent dust storms, so a large range of possible rainfall and AOD values lie within the domain.

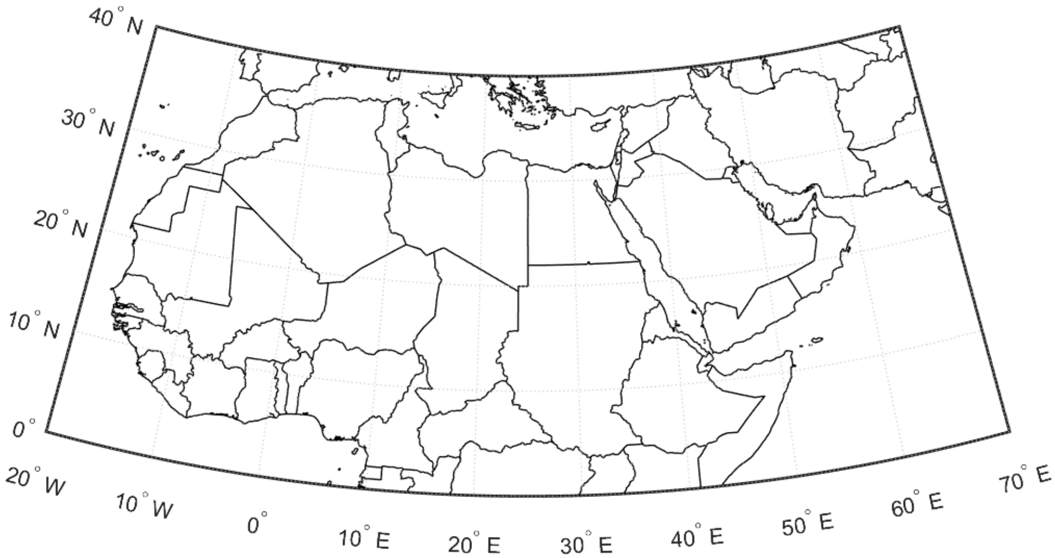

Figure 1. The study region showing the MENA region used for observational analysis.

Precipitation data from Tropical Rainfall Measurement Mission (TRMM) (Liu et al., 2012) is used in this study. The 3B42 daily-accumulated precipitation data (TRMM_3B42_Daily) available at 0.25°× 0.25° resolution, which are generated from the research-quality 3-hourly TRMM Multi-Satellite Precipitation Analysis TMPA (3B42). Further details of the rainfall retrieval algorithm can be found in Huffman et al. (2016).

For aerosols, Moderate Resolution Imaging Spectroradiometer (MODIS) level-2 Deep Blue AOD data (MYD04_L2 and MOD04_L2) at 550 nm (Hsu et al., 2004) are used, which are available daily, for the whole globe, at a resolution of ~ 0.1°× 0.1°. The MODIS AOD collection 6 dataset is used which has an enhanced Deep Blue aerosol retrieval algorithm (Hsu et al., 2013). Although a newer version (collection 6.1) is available (Sayer et al., 2019), we continue to use collection 6 because we did not notice remarkable difference in the spatial pattern of AOD between these two versions. We use the data with quality flag 1 (QF = 1). Although higher QF (2 or 3) is recommended for general use (Sayer et al., 2013), we use QF = 1 because using higher QFs reduces the number of samples considerably and there is no much added benefit of using higher-resolution, level-2 data compared to coarser-resolution, level-3 data when QF = 3 is used. The average of daily AOD from Terra and Aqua satellites is used for analysis, which represent measurements at ~10:30 a.m. and ~1:30 p.m. local time, respectively. We also use Angstrom Exponent (AE) at 470/660 nm from the same MODIS dataset. The AE is related to the size of dust particles because AE greater (smaller) than 0.75 typically represents fine-mode (coarse-mode) dust, respectively (Eck et al., 1999; Parajuli et al., 2017).

We also use the divergence ($\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$) data from European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis in this study. The horizontal divergence of the velocity field is related to the vertical motion with positive (negative) values indicating downward (upward) motion caused by diverging (converging) airflow.

2.3. Methods

The daily MODIS AOD and TRMM rainfall data over the MENA region (Fig. 1, d01) for the two entire years 2015 and 2016 are used. To extract the relationship between AOD and rainfall, an inverse approach is adopted as described below. In the first step, the TRMM rainfall data (0.25°× 0.25°) is remapped to the MODIS grid resolution (0.1°× 0.1°) using a first-order mass-conserving remapping technique, which is the preferred approach for rainfall data, as opposed to other commonly used interpolation techniques. Regridding results in 731 (time) x 400 (lat) x 900 (lon) grid cells, consisting of more than 263 million potential data points. Note that MODIS data contains many NaNs in the data because of cloud cover and other algorithm constraints so the actual data used for analysis are much less. As a quality control measure, only those grid cells that have at least 31 days of AOD data in the years 2015/16 are used. For consistency, since TRMM reports zero values when there is no precipitation, zero values are also replaced with NaNs in the TRMM dataset so that the statistical calculations are not biased. In the second step, the temporal correlations between AOD and rainfall are calculated in each grid cells. In subsequent analysis, the grid cells that shows p-value > 0.1 are masked out, to ensure that all the correlations calculated have more than 90% confidence level. In the third step, all daily-mean AOD values for 2015/16 over the MENA region were grouped into 33 different bins (0:0.1:3.25) and TRMM rainfall was extracted corresponding to those bins, separately for grid cells showing positive and negative correlations. The extracted rainfall data was then averaged spatially over all grid cells with the given sign of the correlation and plotted against the AOD data, resulting in two comparisons. The above process is summarized in the flow chart presented in Fig. 2.

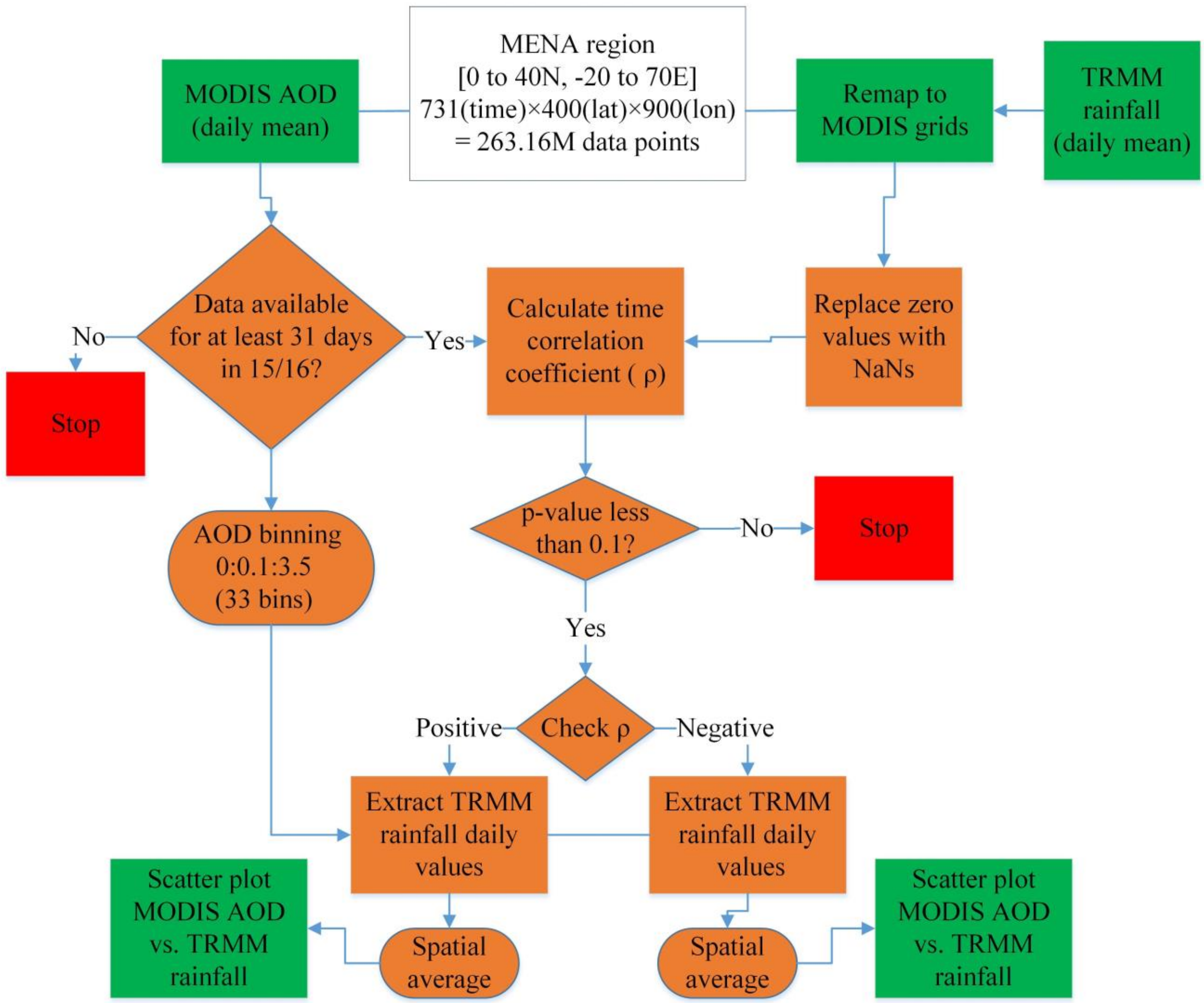

Figure 2. Flow chart showing the data processing steps and analysis procedure adopted to understand dust-rainfall connection from observations.

3. Results

In the observational sample, the daily rainfall values vary from zero to 311.8 mm and the AOD values range from zero to 3.5 forming a comprehensive sample. The 99th percentile of AOD and rainfall values are 1.02, and 55.63 (mm), respectively. The histogram of AOD and rainfall are shown in Fig. 3.

Figure 4 shows the spatial map of correlation coefficient (ρ) over the MENA region obtained as described in section 2.3. Rainfall is strongly correlated with AOD, some areas showing positive correlation and others showing negative correlation. Among the 360,000 (400×900) grid points in the map, 30% have positive ρ, 34.5% have negative ρ and the rest 35.5% have no data (NaN). There is no any identifiable spatial coherence in the grids with positive and negative correlation.

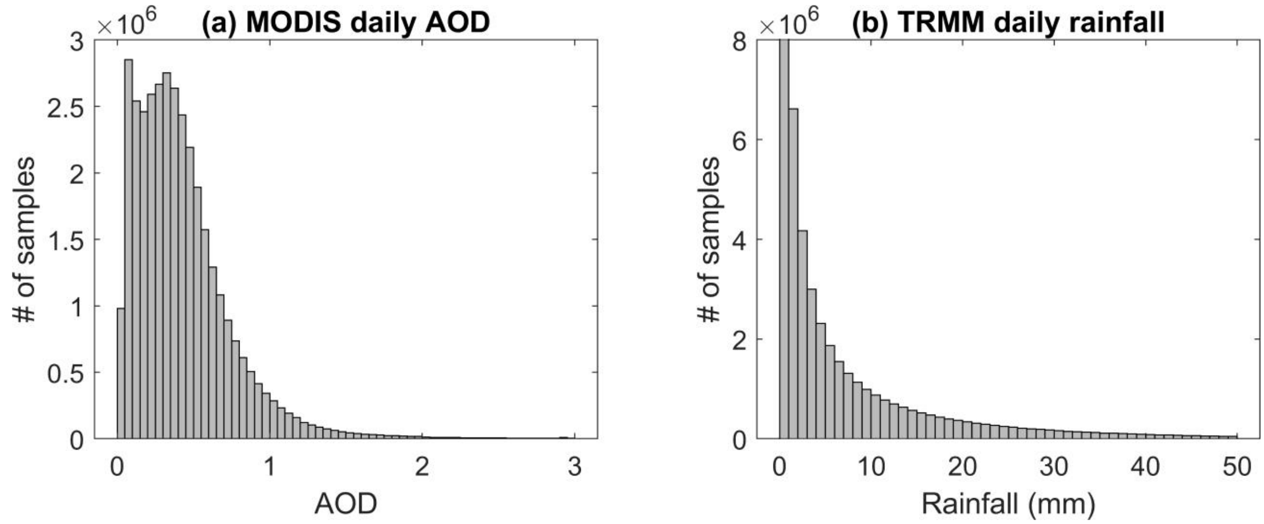

Figure 3. Histograms of daily MODIS AOD and TRMM rainfall data over the study domain (Middle East and North Africa) used for the analysis of dust-rainfall connections.

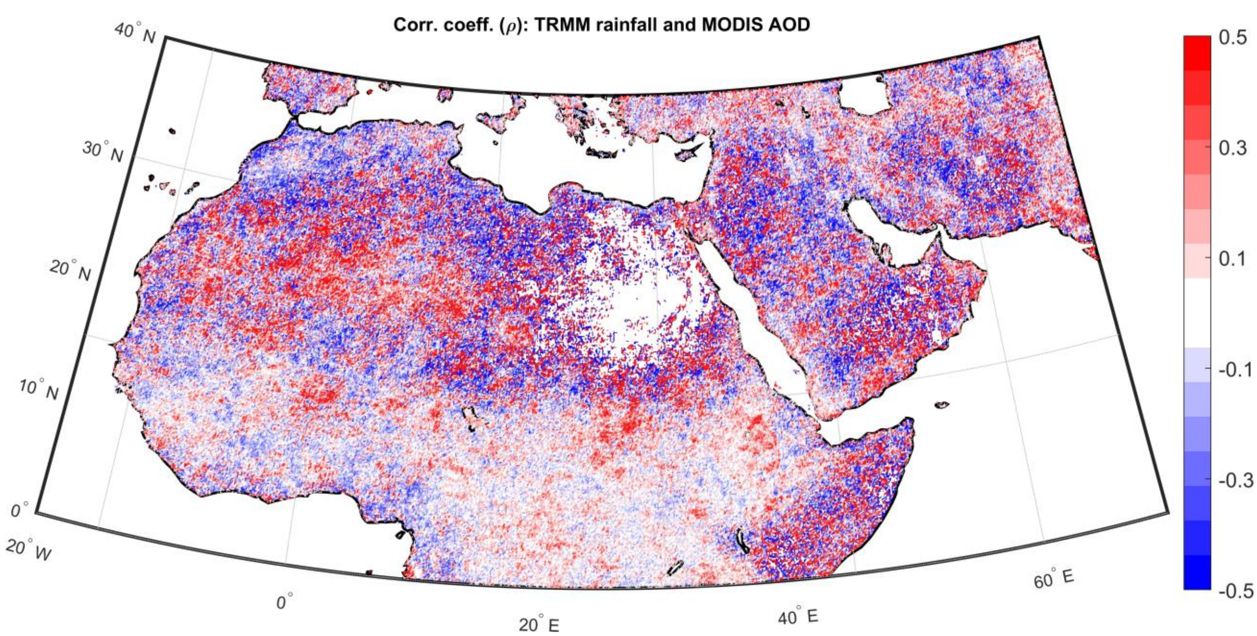

Figure 4. Spatial map of time correlation coefficient (ρ) between MODIS AOD and TRMM rainfall derived using daily-mean data for 2015/16.

Figure 5 shows the scatter plot between MODIS AOD and TRMM rainfall obtained after processing the data as described in section 2.3. Figure 5a and 5b correspond to grids with negative and positive correlations, respectively. Among the grids showing negative correlation, rainfall decreased exponentially with AOD, which is represented well with an exponential model as presented in eq. 1 below.

$$Rainfall = a \times e^{(b \times AOD)} \quad (1)$$

Where, a = 6.285 and b = -1.049.

Similarly, among the positively correlated grids, rainfall increased exponentially with AOD, which is fitted well by a two-term exponential model as shown in eq. 2 below.

$$Rainfall = a \times e^{(b \times AOD)} + c \times e^{(d \times AOD)} \quad (2)$$

Where, a = -0.001, b = 3.251, c = 3.195, and d = 0.774.

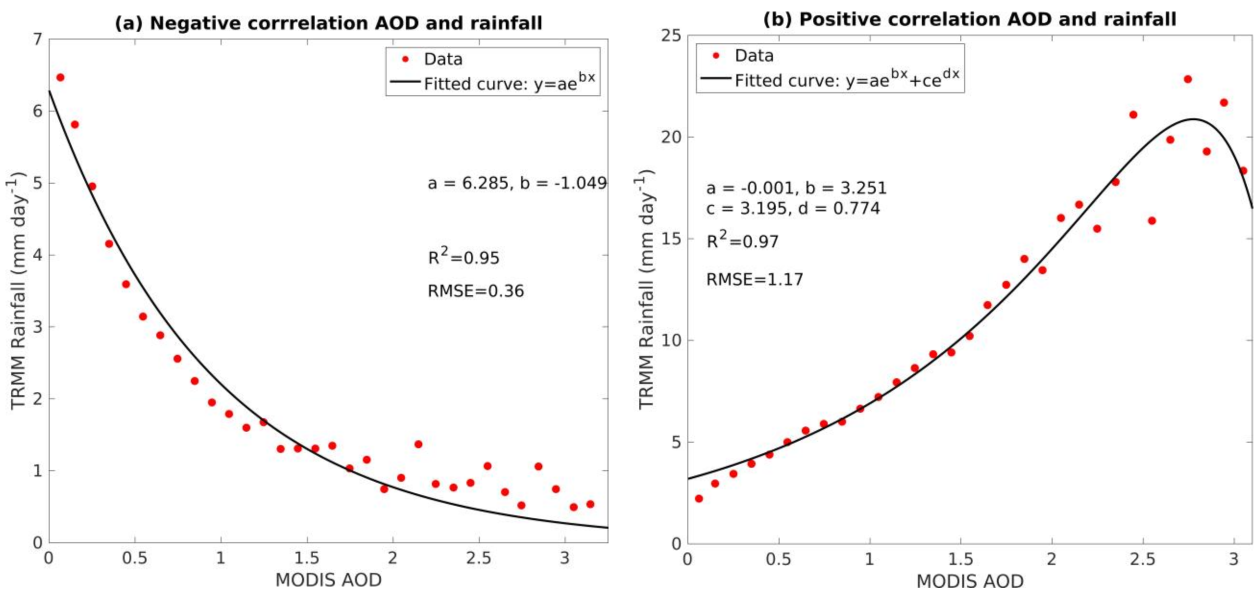

Figure 5. Scatter plot between MODIS AOD and TRMM rainfall obtained following the flow chart in Fig. 2 for grids with (a) negative correlations and (b) positive correlations.

As seen in Figure 5, AOD values range from 0 to ~ 3 in both cases meaning that the relationships represent a diverse environmental conditions possible in nature, from clear to very dusty, with the larger values corresponding to large-scale dust storms. One interesting feature of the plots worth noting is that the range of rainfall values are very different in the two cases, which suggests natural segregation of data in the grids with positive and negative correlations. Negative and positive relationship correspond to low ($0.5 - 6.5\ mm\ day^{-1}$) and high ($2 - 22.6\ mm\ day^{-1}$) rainfall conditions, respectively.

The negative correlations could be caused by three possible physical mechanisms. First and most likely, it could represent the suppression effect of aerosols on rainfall, which is a known process in the areas of deep convection in the early stage through aerosol invigoration (Koren et al., 2008; Chakraborty et al., 2018; Fan et al., 2018). Aerosol invigoration is a process in which aerosols delay the rainfall in the initial stage of convection but causes more rainfall in the mature stage because of the formation of deeper and bigger clouds (Andreae et al., 2004; Koren et al., 2005; Koren et al., 2008; Koren et al., 2010; Chakraborty et al., 2018; Fan et al., 2018). Presence of fine aerosol particles in the atmosphere facilitates formation of smaller cloud droplets and therefore suppress rainfall initially. This suppression allows the cloud droplets to reach the freezing point as they rise up to higher altitude. Upon freezing, these hydrometeors release more latent heat, which ultimately intensifies convective updrafts and associated cold rainfall (Koren et al., 2008; Lee et al., 2012).

Second, it could also mean the effect of wet deposition because the rainfall can wash out aerosols, which decreases the AOD. However, this is unlikely because the negative relationship is observed in the low-rainfall regime with average rainfall < 6 mm (Fig. 5a), where wet deposition would be very weak. Lastly, it could happen erroneously when aerosols lie above or below cloud layers, however, in such cases, a systematic correlation between AOD and rainfall as observed is unlikely. We note that the Deep blue algorithm has a rigorous cloud-screening method (Hsu et al., 2013), which effectively masks the cloudy pixels. Such cloud pixels appear as NaNs in the MODIS AOD data; therefore, our dataset does not represent cloudy conditions.

There are also multiple possible causes for the positive relationship. First, it could represent haboob-type dust events because dust storms and rainfall tend to occur together during these events (Anisimov et al., 2018). Second, it could also indicate the enhancement effect of aerosols on rainfall that occur through direct effect of dust on radiation (e.g., elevated heat pump hypothesis). However, most likely, the positive relationship could mean the indirect effect of aerosols, i.e., the increased aerosol concentration can contribute to more CCN and thus more rainfall, which is supported by regional observations as well (e.g., Pósfai et al., 2013). The observed positive relationship is consistent with a recent study by Choudhury et al., 2020, which demonstrated the association between high rainfall events with high AOD values using the same MODIS AOD and TRMM rainfall dataset for multiple years. However, the study did not show any quantitative connection as we showed (Fig. 5) and the underlying physical mechanism was not clear, which we explore further in this study.

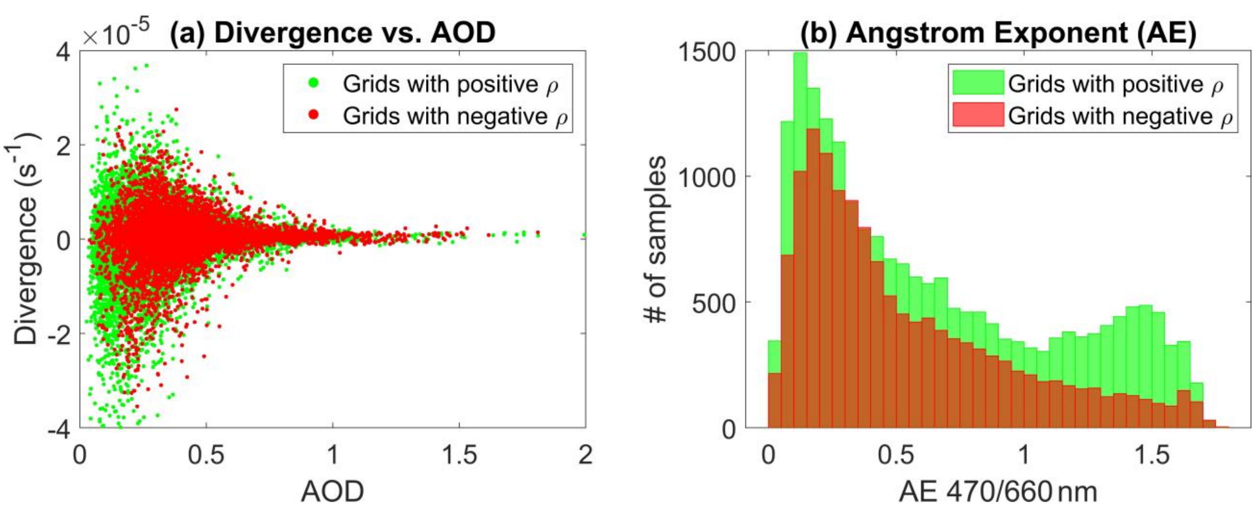

Figure 6. (a) Relationship between divergence and AOD (b) Angstrom Exponent (AE) in grids with positive and negative correlations between AOD and rainfall.

In order to understand the physical mechanism causing positive and negative correlations between AOD and rainfall, the divergence and AE data are examined.

Figure 6a shows the column-averaged divergence at a time closest to MODIS retrievals (12:00 UTC) averaged in time for the analysis period (2015-16), separately for grids with positive and negative correlations. In the grids with positive correlations, divergence and convergence both are much stronger than those with negative correlations. Stronger convergence and divergence both are associated with stronger surface winds, which cause stronger dust mobilization. Higher negative values represent stronger convergence, which simply means the occurrence of stronger convection. Since convection is associated with stronger upward motion, the aerosol particles reach the higher atmosphere. Higher positive values of divergence represents stronger downward motion, which is possibly related to haboob-type dust events because they are associated with stronger downdrafts in thunderstorms (Anisimov et al., 2019).

Figure 6b shows distribution of average AE calculated for the two cases. There is an interesting difference in the distribution of AE in positive and negative cases. While the distribution monotonously decreases towards larger values in the negative case, it starts to increase at ~ 1.10 in the positive case indicating the existence of a peculiar fine-mode component of aerosols. This indicates that fine-mode aerosol is contributing to the positive relationship between AOD and rainfall. The existence of fine-mode aerosols suggest that haboob-type dust events are not contributing to this positive relationship because haboob dust storms are near-surface dust events which are dominated by coarse-mode dust particles. Similarly, dominance of coarser particles in the negative case suggest that the negative relationship between AOD and rainfall is governed by coarse-mode aerosol particles. This analysis indicates that the aerosol indirect effects associated with convection likely cause the positive and negative relationship between AOD and rainfall. The negative relationship represent the initial stage of convection because coarser particles are more abundant in the lower atmosphere which suppress the rain initially as the increase in particle concentration facilitates formation of more cloud droplets. The positive relationship represent mature stage of convection, in which the dust particles reaching the higher atmosphere act as CCN/IN and contribute to cloud development and rainfall formation. In other words, these results support the idea of aerosol invigoration (e.g., Andreae et al., 2004; Koren et al., 2008; Chakraborty et al., 2018; Fan et al., 2018).

Discussion and Limitations

Although large sample of observational data is used in the analysis, there are some data limitations. The observed relationship between rainfall and AOD should be broadly considered as the association between atmospheric aerosols and rainfall, as the AOD represent contribution from all aerosol types not only dust. Some contamination from other aerosols in the study region is possible, for example, with biomass burning over the Sahel region (e.g., Bond et al., 2013) and with sulfate over the Arabian Peninsula (Pósfai et al., 2013; Ukhov et al., 2020; Parajuli et al., 2020). However, such effects are small since dust contributes more than 90% on AOD in the region (Parajuli et al., 2020).

The relationship between aerosol and rainfall is extremely complex particularly because the clouds are extremely chaotic with very high spatiotemporal variability. In this context, satellite data can only capture the localized correlations for a given AOD vs rain amount. This study thus does not fully capture the aerosol-rainfall relationship that is dependent upon the dynamics of clouds. In addition, the relationship between aerosol and rainfall could be dependent upon seasons, which should be explored further using longer-term data in future studies. Lastly, both the AOD and rainfall data are column-average properties, which do not show the distribution of aerosol concentration and rainfall in the vertical dimension (Parajuli et al., 2020). Therefore, it is important to look at their vertical distribution to understand the underlying microphysical processes governing dust-rainfall connections, which should be explored in future studies. Although the rainfall seems to be clearly associated with AOD in observations, the validity of the cause-and-effect relationship needs to be examined independently using model simulations.

This study has broader social and environmental implications because increased rainfall contributes to replenishing surface and ground water thus increasing the amount of fresh water resources in the region (Mostamandi et al., 2020). The results demonstrate a possible physically based association between dust and rainfall over the MENA region. While dust and dust storms are generally considered detrimental from an air quality perspective, this study highlights their positive contribution in making rain, an essential element of plant and animal life.

Conclusion

In this work, connection between dust and rainfall is examined using daily-scale satellite observations. A large data sample from the TRMM rainfall dataset and MODIS AOD dataset are analyzed for the years of 2015 and 2016 over the MENA region. Using these direct observations, a quantitative relationship between AOD and rainfall is extracted. Contrasting AOD-rainfall relationships are observed between high and low rainfall cases under a similar range of AOD variations. Rainfall decreased (increased) exponentially with AOD in low (high) rainfall cases, which are represented well with a one-term (two-term) exponential model. The physical basis of these relationships was explored using divergence and Angstrom Exponent data, which suggest that the positive (negative) relationship between AOD and rainfall could represent aerosol indirect effects during the mature (initial) stage of convection.

Data availability

MODIS AOD data were downloaded from http://ladsweb.nascom.nasa.gov/data/. TRMM data were obtained from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) available at https://disc.gsfc.nasa.gov/. ECMWF Operational Analysis data are restricted data, which were retrieved from http://apps.ecmwf.int/archive-catalogue/?type=4v&class=od&stream=oper&expver=1 with a membership. A copy of the data used in the analysis may be obtained by request to the author at psagar@utexas.edu.

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