

Article

Aerosol—Cloud Interaction with Summer Precipitation over Major Cities in Eritrea

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Abstract: This paper presents the spatiotemporal variability of aerosols, clouds, and precipitation within the major cities in Eritrea and it investigates the relationship between aerosols, clouds, and precipitation concerning the presence of aerosols over the study region. In Eritrea, inadequate water supplies will have both direct and indirect adverse impacts on sustainable development in areas such as health, agriculture, energy, communication, and transport. Besides, there exists a gap in the knowledge on suitable and potential areas for cloud seeding. Further, the inadequate understanding of aerosol-cloud-precipitation (ACP) interactions limits the success of weather modification aimed at improving freshwater sources, storage, and recycling. Spatiotemporal variability of aerosols, clouds, and precipitation involve spatial and time series analysis based on trend and anomaly analysis. To find the relationship between aerosols and clouds, a correlation coefficient is used. The spatiotemporal analysis showed larger variations of aerosols within the last two decades, especially in Assab, indicating that aerosol optical depth (AOD) has increased over the surrounding Red Sea region. Rainfall was significantly low but AOD was significantly high during the 2011 monsoon season. Precipitation was high during 2007 over most parts of Eritrea. The correlation coefficient between AOD and rainfall was negative over Asmara and Nakfa. Cloud effective radius (CER) and cloud optical thickness (COT) exhibited a negative correlation with AOD over Nakfa within the June–July–August (JJA) season. The hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model that is used to find the path and origin of the air mass of the study region showed that the majority of aerosols made their way to the study region via the westerly and the southwesterly winds.

Keywords: aerosol-cloud-precipitation; aerosol optical depth; cloud effective radius; cloud optical thickness; HYSPLIT



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1. Introduction

Precipitation (rainfall) is the primary mechanism for transporting water from the atmosphere back to the Earth's surface, a fundamental physical process that links aspects of climate, weather, and the global hydrological cycle [1]. However, it displays the largest variability in both spatiotemporal distribution and magnitude [2]. Responses to the rainfall shift are already being observed in the levels of many terrestrial water sources [3]. These could be considered as possible indicators of future water tension linked to climate variability [4]. Clouds are most important in atmospheric thermodynamics and dynamics. Thick clouds or deep convective clouds dominate the tropical atmosphere and account for 60% of the observed precipitation [5,6]. The response of clouds to changes in the ambient aerosol differs depending on the cloud type or aerosol regime [7]. The Earth's atmospheric radiation budget is directly influenced by aerosols with their ability to either scatter or absorb the incoming solar radiation or influence the processes of the formation of clouds

and precipitation indirectly [8]. Aerosols can affect the properties of clouds by acting as cloud condensation nuclei and/or ice nuclei. Aerosols range from nanometers (nucleation of liquid and solid particles) to several micrometers (growth of droplets) in size and some even more [9]. Studies such as [10–12] indicated the dominance of anthropogenic aerosols over the land as well as urban areas. Aerosols can change the intensity of solar radiation scattered back to space, absorbed in the atmosphere, and reaching the surface of the Earth, known as the aerosol direct radiative effect. On the other hand, aerosols can modify cloud characteristics indirectly and influence precipitation in several ways. The influences are (1) cloud lifetime increases due to the high competence of the aerosol particles for the available water in the atmosphere, resulting in a decrease in precipitation, known as an aerosol indirect effect (cloud lifetime effect); (2) that aerosols can reduce the amount of solar radiation reaching the earth due to decreasing the size of cloud droplets into smaller sizes (reducing the cloud effective radius) that can further increase the density of cloud droplets, known as an aerosol indirect effect (the cloud albedo effect) [13]; (3) that aerosols can heat the air mass that causes evaporation of the cloud droplets in the atmosphere by re-emitting the absorbed solar radiation as thermal radiation, known as a semi-direct effect [14]. Therefore, aerosols that can act as cloud condensation nuclei (CCN) can change the amount and type of precipitation or the dynamics and behavior of clouds. The present change in the top of the atmosphere net radiation since 1750 (preindustrial era) due to all aerosol effects (indirect plus direct) estimated by climate models is -1.2 Wm^{-2} with a range of -0.2 to -2.3 Wm^{-2} [14]. Based on model predictions, the aerosol's effect on precipitation seems to be more uncertain, varying from zero to a decrease of 0.13 mm/day [14]. Due to the lack of global measurements and optical properties of the aerosol mixture, the indirect radiative effects of aerosols are more complex and not certain when we compare them with the direct radiative effects [14]. In almost all clouds, the aerosol indirect effects, namely, cloud albedo effect, cloud lifetime effect, and semi-direct effect, occur [8], while the glaciation indirect effect (where an increase in ice nuclei increases the precipitation efficiency) and thermodynamic effect (where smaller cloud droplets delay freezing and produce super cooled clouds) occur in mixed-phase clouds [14]. The aerosol indirect effects that occur in mixed-phase clouds can either decrease or increase precipitation [14]. In mixed-phase clouds, the aerosol indirect effects are vital as their potential magnitude of influence on precipitation is medium and needs to be examined to reduce the uncertainty in aerosol indirect effects [14,15]. Therefore, using the above illustrations, the role and impact of aerosols on summer monsoon rainfall over Eritrea can be the main guide to the influence of aerosols on clouds and precipitation, with their type, source, and absorbing or scattering behavior.

Rainfall is the main source of fresh water in Eritrea. The high precipitation variability in both time and space has a role in exacerbating the existing water stress in the region. Even with the use of conventional mitigation measures to combat water shortages and support the efficiency of water management schemes, the water demand will still surpass the available water resources. The inadequacy of environmental water supplies will make the need for enhanced sources, storage, and recycling of freshwater inevitable. Therefore, enhancing precipitation through weather changes is one of the possible means to improve water supply and reduce the existing water stress.

An increase in precipitation maintains the annual average flow of rivers, ecological health, and related ecosystems. However, the success of weather modification depends on an adequate understanding of aerosol-cloud-precipitation (ACP) interactions. For example, aerosols in the atmosphere can act as CCN to modify cloud microphysical processes [10,16]. The potential modification may result in a change in the intensity, location, and type of precipitation [17,18]. Therefore, modeling the effects of aerosols on clouds and precipitation provides insights into key ACP processes.

This study aimed at understanding the effects of aerosols on clouds and precipitation in the major cities of Eritrea located in different regions of the country. That is, to determine the spatial-temporal variability of aerosols, clouds, and precipitation in Eritrea.

An additional aim was to find out the type of relationship between aerosols, clouds, and precipitation in Eritrea in consideration of the source and behavior of aerosols over the study region.

This paper is composed of the following sections: Section 2 outlines the study area and the prevailing meteorological conditions. Section 3 elucidates the results and discussion, while Section 4 presents the summary and conclusions drawn from the present findings.

2. Materials and Methods

2.1. Study Area and Meteorology

Eritrea borders on both the east and west sides different surrounding regional aerosol hot spots or giant sources of aerosols. Figure 1a shows a plot of the global distribution of aerosols around the world in 2001–2018. Eritrea experiences an effect of aerosols from both the east and west sides. Regions in the both east and west sides of Eritrea have predominantly desert dust aerosols, because of the great Sahara Desert in the west and the Arabian Desert in the East. Moreover, biomass burning also has a significant role in the movement of aerosols to Eritrea.

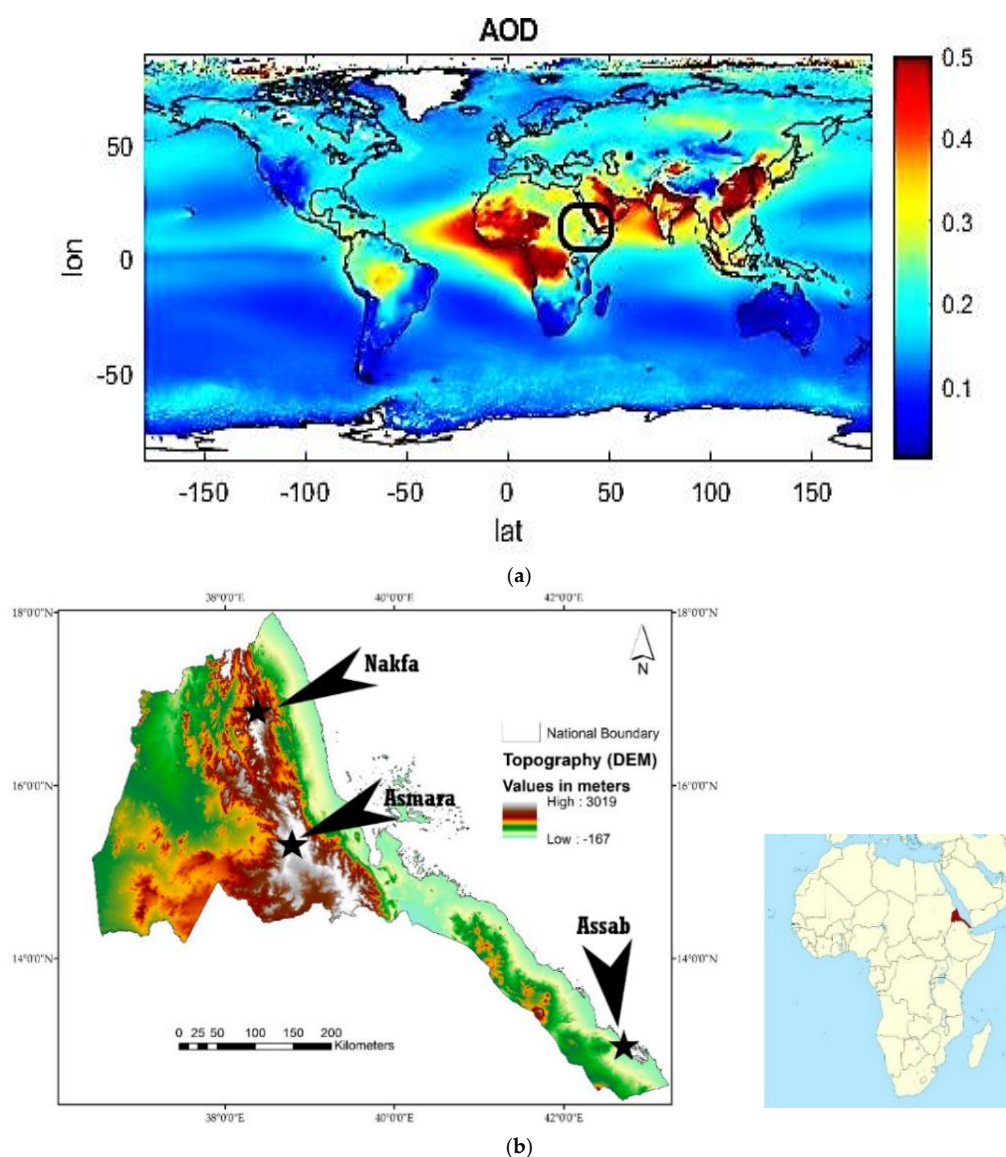


Figure 1. (a) Plot of the global distribution of aerosols around the world in the years (2001–2018). The color bar refers to the aerosol optical depth (AOD) and (b) topography [19] and geography of Eritrea [20].

The Eritrean landmass consists of semi deserts, arid lowlands, moist lowlands, moist highlands, arid highlands, and sub humid highlands [19] and is characterized by tropical and subtropical climatic conditions, resulting in a variety of temperatures, rainfall, and relative humidity, which can cause a variation of the aerosol characteristics. Figure 1b gives a summary of the cities utilized in the study. The cities are comprised of synoptic stations in Eritrea. Namely Asmara ($15^{\circ}19' \text{ N}$, $38^{\circ}55' \text{ E}$), Assab ($13^{\circ}1' \text{ N}$, $42^{\circ}43' \text{ E}$), and Nakfa ($16^{\circ}39' \text{ N}$, $38^{\circ}28' \text{ E}$).

The Eritrean summer monsoon is mainly from June to August namely, June—July—August (JJA) (big rain season). Although it is affected by other factors, the Intertropical Convergence Zone (ITCZ) is the main factor that plays a role in producing the summer monsoon rainfall of Eritrea. However, due to the focus of the study, the other factors are not stated here. On the surface streamline map, ITCZ lies over south Egypt or the north Sudan (Figure 2c).

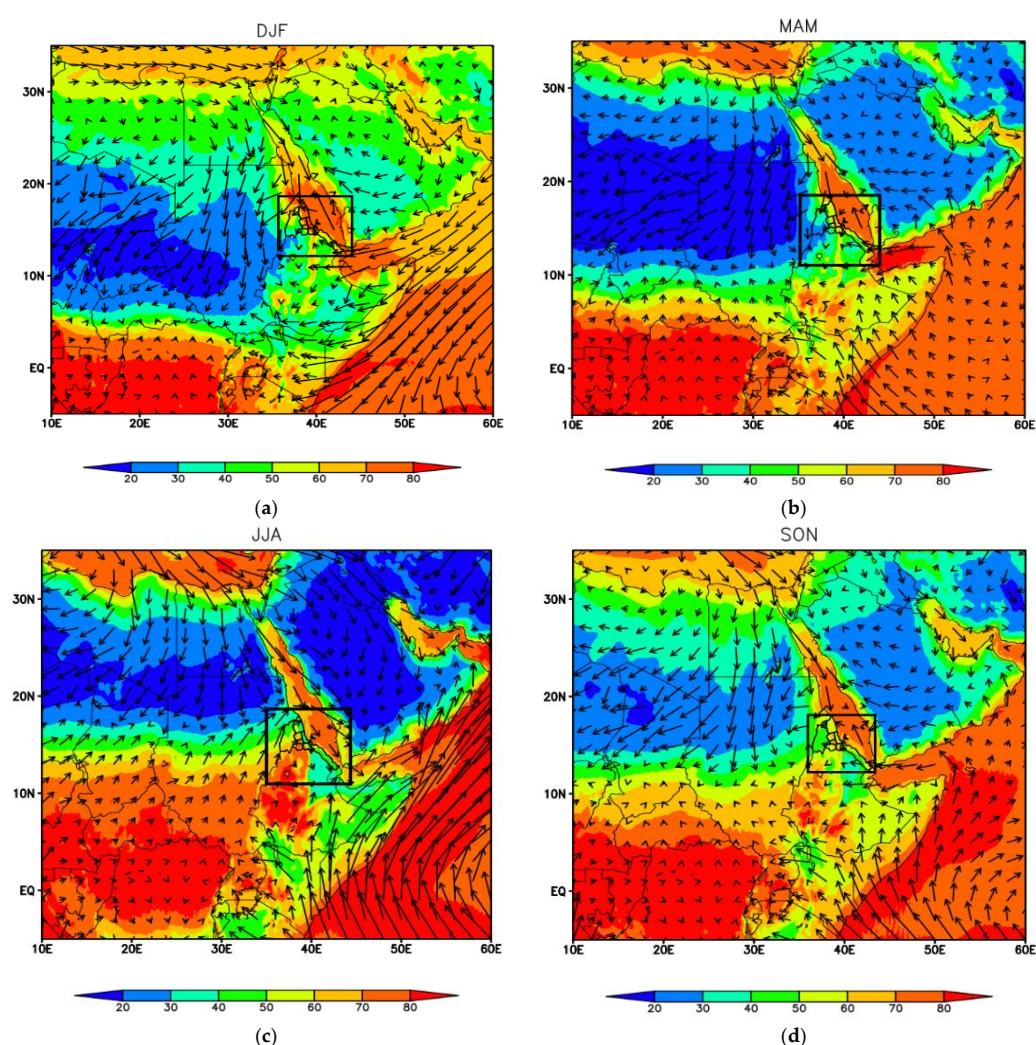


Figure 2. Relative humidity (RH) (%) at 1000hpa vs. synoptic winds (ms^{-1}) over the Red Sea, Eritrea, Middle East, East and Horn of Africa, and Northeastern Africa during (a) winter (December–January–February (DJF)), (b) summer (June–July–August (JJA)), (c) spring (March–April–May (MAM)) and (d) autumn (September–October–November (SON)). Shaded contours represent relative humidity, and the arrows represent the wind.

According to Figure 2c, during the monsoon season, the winds are moist, and a much stronger tropical jet stream reaching West Africa that induces winds from the South Atlantic Ocean comes to the Eritrean region via the Congo Basin with high relative humidity ($>70\%$),

especially to the central parts of Eritrea. The rainfall exhibits large variability over both spatial as well as temporal scales and consists of interactions between land and sea (the Red Sea). The Eritrean summer monsoon lasts from June to August and is the main rainy season in Eritrea that accounts for 80% or more of the total precipitation, except for the coastal areas, like Assab. July is the core rainy month of the monsoon season, as the rainfall in July reaches 30% or more of the total rainfall during the annual rainy season (June–July–August) (Tables 1–3). Both monthly (July) and seasonal (JJA) mean distributions of aerosol clouds and rainfall over the study region (Figure 1b) are plotted in (Figure 4) for the year 2007. The year 2007 is chosen to be the focus of the study because it was among the monsoon years with the highest amount of rainfall recorded during most of the last two decades (Tables 1–3).

2.2. Satellite-Derived Data

Aerosol and cloud data are retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) remote sensor onboard the two Earth-observing system (EOS) Terra and Aqua satellites. MODIS Collection Level 3 V 6.1 data, quality assured (QA) daily at 0.55 μm for aerosol optical depth (AOD), cloud effective radius (CER), and cloud optical thickness (COT) with a resolution of $1^\circ \times 1^\circ$ from 2001 to 2018, were used. MODIS Level 3 atmospheric data is a $1^\circ \times 1^\circ$ gridded atmospheric product that spans more than 24 h [15,21]. The data cover from 2001 to 2018 refers to Terra. The verification and comparison of AOD extracted from Terra and Aqua using a ground-based aerosol robotic network (AERONET) solar/sky radiometer [22] showed that AOD from Terra and Aqua has small differences and largely agrees both on land and in the sea [23]. The cloud data used include two parameters, namely, CER and COT. When the COT value is 50, the error in MODIS retrieval is less than 0.1 μm , while for an optically thinner cloud with a CER of 4 μm and an optical thickness of one, the error will increase to 0.3 μm [24]. The average error of CER and COT is estimated to be about 13% [25]. Although the absolute errors in a single MODIS retrieval may be large, the error in the observed relative change in CER is small [26,27].

The absorbing aerosol index (AAI) is extracted from both the Total Ozone Mapping Spectrometer (TOMS), an Earth probe that can measure the Level 3 1° latitudes $\times$ 1.25° longitudes and the Aura Ozone Monitoring Instrument (OMI), which is the latest version with a $1^\circ \times 1^\circ$ grid resolution. The study used the average daily AAI data from the TOMS during the years 2001 to 2004 and daily Level 3 global gridded data from the OMI for the years between 2005 and 2018. AAI is calculated as the difference between the observed and estimated model absorption and non-absorption spectral emissivity at 331 and 360 nm. The values of AAI greater than 0.2 indicate absorptive aerosols while a higher negative AAI value (less than -0.2) indicates smaller non-absorptive aerosols, that is, pure scattering, while an AAI value close to zero (± 0.2) indicates that there are clouds or larger absorbent particles [28].

Precipitation data are retrieved from a quality assured gridded Tropical Rainfall Measuring Mission (TRMM) 3B42 (daily) product with a $0.25^\circ \times 0.25^\circ$ spatial resolution [29]. The dataset covered the period between 2001 and 2018. The primary goal of the TRMM is to determine the four-dimensional distribution of precipitation in the tropics [30]. TRMM is a satellite of a joint mission program with a low-inclination (equatorial) orbit [31].

Table 1. Annual rainfall (mm) in July and total annual rainfall in JJA from 2001 to 2018 over Asmara (Asm) with the mean calculated. The percentage amount of rainfall in July, the percentage difference in July, and total rainfall from the mean (2001–2018) for each year are also given. – indicates % deficit and + denotes % excess of the mean rainfall in July and for the season.

Month/Season	Year																		Mean
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	
	Asm																		
July	185	81	138	58	126	99	187	74	184	115	53	80	65	65	65	83	39	50	97 ± 48
Total JJA	365	185	291	195	279	241	311	126	236	193	218	115	215	187	169	207	155	194	216 ± 64
July %	51	44	47	30	45	41	60	59	78	60	24	70	30	35	38	40	25	26	45 ± 16
% diff in July	+91	−16	+42	−41	+30	+2	+92	−24	+90	+18	−46	−17	−33	−33	−33	−14	−60	−49	
% diff in total	+69	−14	+35	−10	+29	+12	+44	−42	+9	−11	+1	−47	−1	−13	−22	−4	−28	−10	

Table 2. Annual rainfall (mm) in July and total annual rainfall in JJA from 2001 to 2018 over Assab (Asb) with the mean calculated. The percentage amount of rainfall in July, the percentage difference in July, and total rainfall from the mean (2001–2018) for each year are also given. – indicates % deficit and + denotes % excess of the mean rainfall in July and for the season.

Month/Season	Year																		Mean
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	
	Asb																		
July	19	17	5	10	20	19	12	15	11	20	6	11	11	10	6	45	5	14	14 ± 9
Total JJA	61	39	55	30	62	78	31	42	76	53	30	34	47	37	34	89	24	46	48 ± 19
July %	31	43	10	33	32	24	41	35	14	37	20	32	24	28	19	51	21	30	29 ± 10
% diff in July	+37	+22	−62	−30	+41	+35	−11	+7	−22	+40	−59	−20	−19	−26	−54	+220	−65	−1	
% diff in total	+27	−18	+15	−38	+29	+63	−36	−12	+58	+10	−38	−28	−2	−24	−30	+85	−51	−4	

Table 3. Annual rainfall (mm) in July and total annual rainfall in JJA from 2001 to 2018 over Nakfa (Nkf) with the mean calculated. The percentage amount of rainfall in July, the percentage difference in July, and total rainfall from the mean (2001–2018) for each year are also given. – indicates % deficit and + denotes % excess of the mean rainfall in July and for the season.

Month/Season	Year																		Mean
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	
	Nkf																		
July	64	21	42	15	47	45	81	39	52	46	27	13	21	51	27	68	24	82	43 ± 21
Total JJA	151	68	92	94	137	92	175	70	95	90	85	40	113	120	95	128	90	168	106 ± 35
July %	43	30	45	16	34	48	46	56	55	51	32	33	18	42	29	53	26	49	39 ± 12
% diff in July	+50	−52	−3	−66	+9	+4	+89	−8	+22	+6	−36	−70	−52	+18	−36	+59	−45	+91	
% diff in total	+42	−35	−13	−11	+29	−13	+65	−34	−10	−15	−19	−62	+7	+13	−11	+21	−15	+58	

2.3. Methods

2.3.1. Anomaly and Spatial Analysis

Monthly (July) and seasonal (JJA) anomalies are used in this study to detect the variabilities in AAI, AOD, CER, COT, and rainfall. The anomaly analysis used refers to the period from 2001–2018. The anomaly is a quite useful tool that can aid in a series of deviations from the average (mean) value. MATLAB is the tool used to both calculate and plot the anomaly. Mathematically, the anomaly is calculated as follows:

$$x_{dt} = x_t - \bar{x} \quad (1)$$

where $t = 1, 2, \dots, n$.

The spatial plots that refer to 2007 (monsoon year) are plotted according to the evaluation made from the accumulated rainfall measurements of Tables 1–3.

2.3.2. Correlation Coefficient

A correlation coefficient is used as a numerical measure of a statistical relationship between the variables. In calculating the correlation coefficient, variables of a given observational dataset are compared with a sample component of another random variable of known distribution. Excel software is the tool used to execute the correlation between the variables for both the tables as well as the scatter plots. As a tool of analysis, the correlation coefficients represent the relations between the five given variables AAI, AOD, CER, COT, and rainfall, and the correlation was calculated for all the variables from 2001–2018. The correlation coefficient evaluated the CORREL function in between the variables as a function of the Excel software. The scatter plots also followed the same rule except they refer to values of correlation greater than or equal to +0.5 or less than or equal to −0.5 from the given reference tables of correlation. The correlation values are in the range from −1 to +1, where ± 1 indicates the strongest possible correlation and 0 the least possible correlation. For a sample, r_{xy} commonly represents the correlation coefficient $\{ \displaystyle r_{\{xy\}} \}$ and is referred to as the sample correlation coefficient or sample Pearson correlation coefficient. We can obtain a formula for r_{xy} $\{ \displaystyle r_{\{xy\}} \}$ by substituting estimates of the covariance and variances based on a sample into the formula below. Given paired data $\{ \displaystyle \left\{ (x_{\{1\}}, y_{\{1\}}), \dots, (x_{\{n\}}, y_{\{n\}}) \right\} \{ (x_1, y_1) \dots (x_n, y_n) \}$ consisting of n $\{ \displaystyle n \}$ pairs, $\{ \displaystyle r_{\{xy\}} \}$

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (2)$$

where n is the sample size and X_i, Y_i are the individual sample points indexed with i .

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (3)$$

The sample mean is shown in Equation (3), and analogously for y .

2.3.3. Hybrid Single-Particle Lagrangian Integrated Trajectory Analysis

In this study, the model calculation method used is a hybrid between the Lagrangian approach and the Eulerian approach. The Lagrangian approach uses a moving frame of reference as the air parcel moves from its initial location. The Eulerian approach uses a fixed three-dimensional grid as a frame of reference. It is archived four times a day at 00:00, 06:00, 12:00, and 18:00 UTC. National Centers for Environmental Prediction (NCEP) post-processing of the Global Data Assimilation System (GDAS) converts data from the spectral coefficient form to 1° latitude-longitude (360×181) grids. It also converts data from sigma levels to mandatory pressure levels. The HYSPLIT model output is in gridded binary (GRIB) format. The model computed the puff or advection of a particle from the

average of the three-dimensional velocity vectors at the initial position, $P(t)$, and first-guess position, $P'(t + \Delta t)$. Linear interpolation of velocity vectors in both space and time was used. Equation (4) gives the first-guess position.

$$P'(t + \Delta t) = P(t) + V(P, t)\Delta t \quad (4)$$

The final position is then:

$$P(t + \Delta t) = P(t) + 0.5V(P, t) + V(P', t + \Delta t)\Delta t \quad (5)$$

During the simulation, the integration time step (Δt) can vary. Advection distance per time step should be less than the grid spacing in all computations. Trajectory analysis uses the integration method. Greater precision cannot be achieved using higher-order integration methods due to the linear interpolation of data from the grid to the integration point. If the trajectories exit the meteorological data grid, they are usually terminated. However, advection continues along the surface if trajectories intersect the ground. For back trajectory analysis, the day back trajectories starting with 1500 or 3000 m heights are to be calculated.

3. Results and Discussion

3.1. Time Series Analysis Based on Anomaly

AOD, AAI, and rainfall in Eritrea show great spatial variations. Note that the values of AAI represent the real values without calculating the anomaly because the real values of AAI correspond to the type of aerosols (Figure 3a). In the past two decades, aerosol characteristics have shown large regional, seasonal, and interannual variations (Figure 3).

In the study area, in the past 18 years, the AOD anomalies around Assab were significantly positive, which indicates that AOD in the surrounding Red Sea has increased in the past two decades. During 2011, AOD anomalies were significantly higher (Figure 3b). The rainfall in the 2011 monsoon season was significantly low (Tables 1–3). Consequently, longer drought conditions in July 2011 may have helped the accumulation and increase in desert dust and smog, which could have led to an increase in AOD (Figure 3b). On the other hand, rainfall was at its peak in 2007 when we compare it with the other years from 2001–2018. This is backed up by the observation that during the 2011 monsoon season, there were positive anomalies of AOD and negative anomalies of precipitation (Figure 3b,e). This reduction in rainfall may be related to an increase in cloud lifetime. In Assab, although the result yielded an increase in the aerosol amount, the amount of rainfall did not show a significant trend result.

During 2007, most areas in Eritrea exhibited low AAI values (Figure 3a). It should be recalled that positive values of AAI indicate absorbing aerosols (desert dust, biomass burning, and sea salt aerosols) [32]. AAI values may also become low owing to wet removal [15]. Therefore, this can show us that either the relative amount of aerosols was lower because of the wet removal or the aerosols were of a non-absorbing (scattering) type in the year 2007. Emissions were higher in the coastal parts of Eritrea, especially in Assab, where the aerosols tend to be more of an absorbing type due to the presence of sea salt particles, and emissions were relatively lower in the central and western parts (Figure 4b). Therefore, these results indicate that the inverse relationship between AAI and rainfall may change due to differences in aerosol sources and types (absorbing versus scattering) (Figure 3). AAI showed higher deviations from the mean during July and JJA 2003, but no such features were seen in AOD. These inter-annual variations may result in low correlation values. In the last two decades, other parameters such as AAI, CER, and COT have hardly shown a significant change.

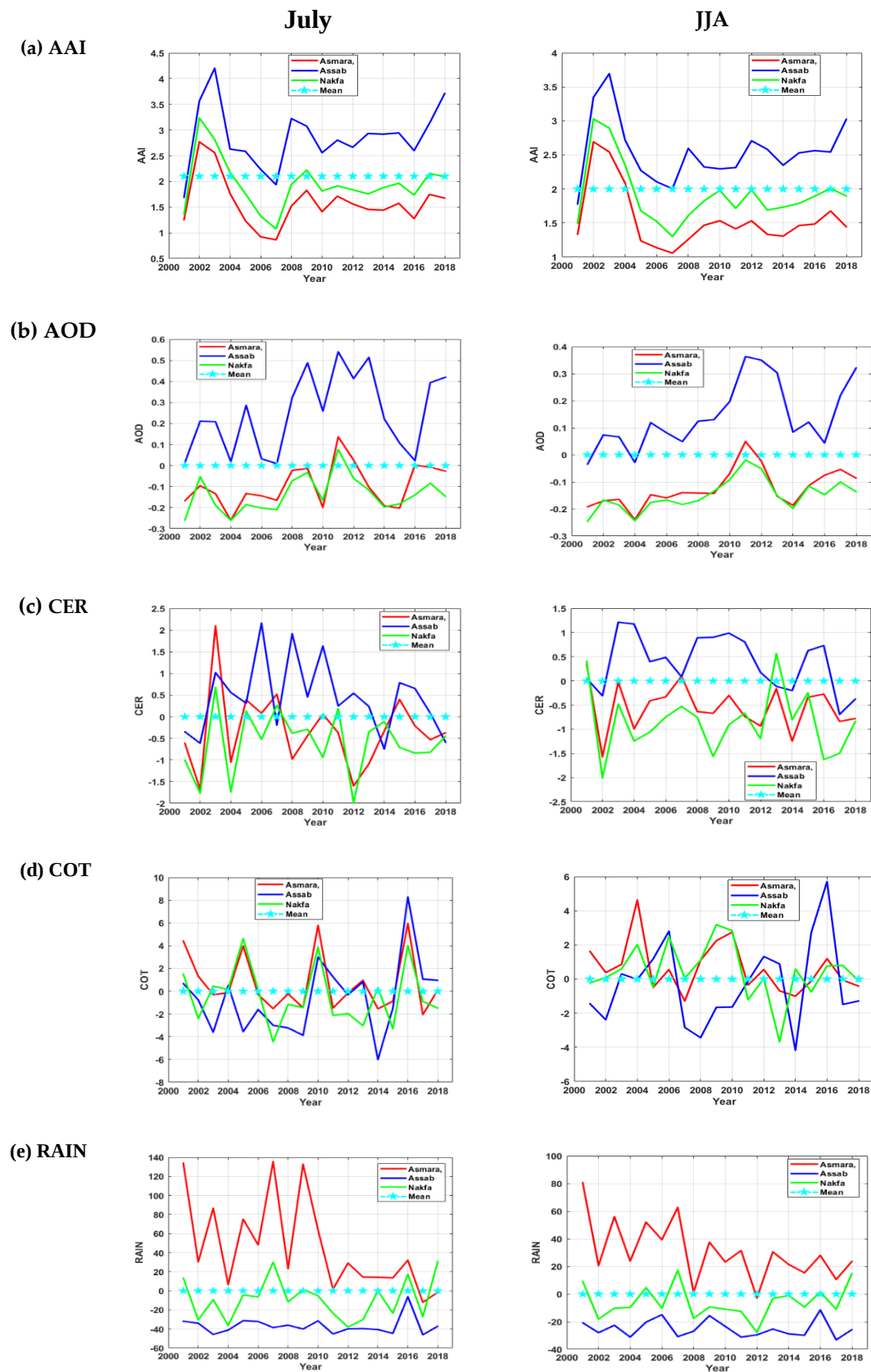


Figure 3. Time series with its mean (light blue dots) for (a) absorbing aerosol index (AAI) and anomaly in comparison to the mean anomaly (light blue dots) for (b) aerosol optical depth (AOD), (c) cloud effective radius (CER) (μm), (d) cloud optical thickness (COT), and (e) rainfall in mm/h in Asmara, Assab, and Nakfa from 2001–2018.

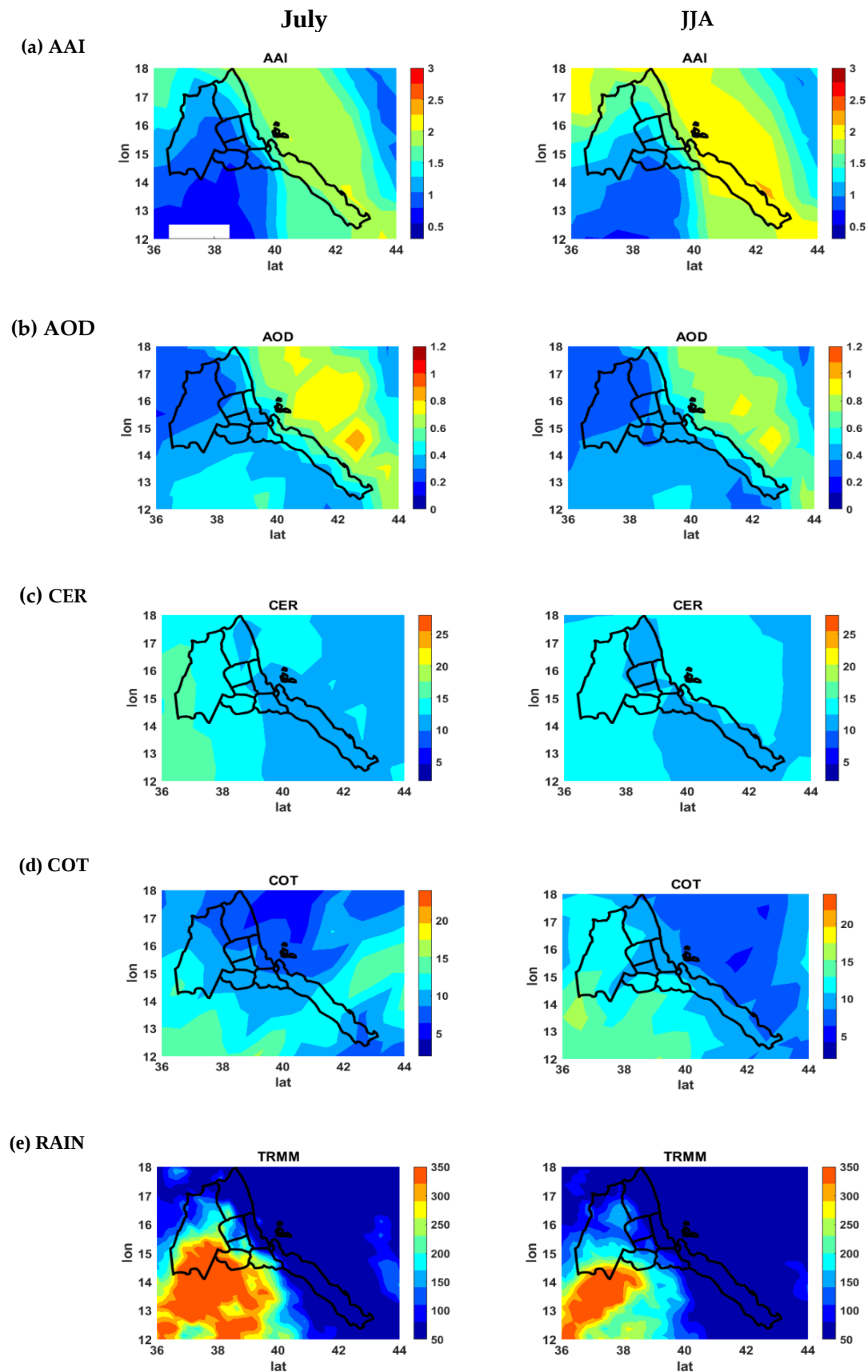


Figure 4. (a) AAI, (b) AOD, (c) CER (μm), (d) COT, and (e) rainfall (mm) in July and JJA of 2007. Since it is a normal monsoon year, the aerosols, cloud characteristics, and rainfall of 2007 are shown.

In 2007, CER values were $\leq 14 \mu\text{m}$ (Figure 4c), and COT was distributed from 5 to 10 in most of the study area (Figure 4d). CER and COT anomalies in different regions of Eritrea showed values close to the average of July and JJA in 2011 (Figure 3c,d). Meanwhile, AOD and rainfall had opposite trends to each other, indicating that there is a correlation between aerosols and precipitation. This provides proof for an indirect radiation effect with observational evidence for the impact of aerosols on rainfall (cloud lifetime impact). These results emphasize the fact that when aerosols (especially the non-absorbers) become abundant, they can increase the cloud lifespan and reduce precipitation [15].

3.2. Monthly (July) and Seasonal (JJA) Spatial Plot

The AOD in July is higher than in January (winter), April (pre-monsoon), and October (post-monsoon) (Figures 4 and 5), while the western and southern parts of the central region experienced lower values of AOD compared with other regions. In Figures 4 and 5, the monsoon seasonal average (JJA) and monthly average of July had higher AOD, AAI, and rainfall amounts in comparison with January, April, and October.

During the JJA season, the Southern Red Sea region and Assab areas are influenced by emissions from land/sea particles of the Red Sea northerly winds and partially from the Arab Desert, a region with higher aerosol loadings (see Figure 2c). Besides, this may result in higher AAI values (Figure 4a). In both July and JJA, AOD, AAI, CER, COT, and rainfall had higher values in Asmara, the Red Sea, and eastern Eritrea than the rest of the monthly references of Figure 5. The increase in AOD in July was mainly due to the increase in relative humidity, which led to an increase in the hygroscopicity of water-soluble aerosols [33]. It was found that an increase in AOD caused by an increase in hygroscopicity overwhelmed the removal of moist aerosols [33]. At the end of the summer monsoon season, wind speed and relative humidity showed a drop (Figure 2c,d). Similarly, the winds to the study area (represented by arrows) showed a shift of direction from southwesterly to southeasterly. Therefore, when averaged throughout the season, the aerosol characteristics showed a decrease.

These findings indicated that there were changes in AOD, AAI, and rainfall in different regions of Eritrea. During January, April, and October, most parts of Eritrea do not experience rainfall (Figure 5); COT appeared to have higher values in Assab and the coastal regions of the study area during January (Figure 5d), and the same was true for Nakfa up to the eastern escarpment. In October, the northwestern parts of Eritrea appeared to have higher values of COT. CER was almost the same throughout the year on each side of the reference locations (Figures 4 and 5). Since aerosols effectively act as cloud condensation nuclei, changes in aerosol properties are expected to adjust the optical properties of clouds, such as CER and COT [15]. The precipitation threshold CER was found to be $14 \mu\text{m}$ [34], which has been used as the threshold CER in many studies on land and for the ocean [26,35,36].

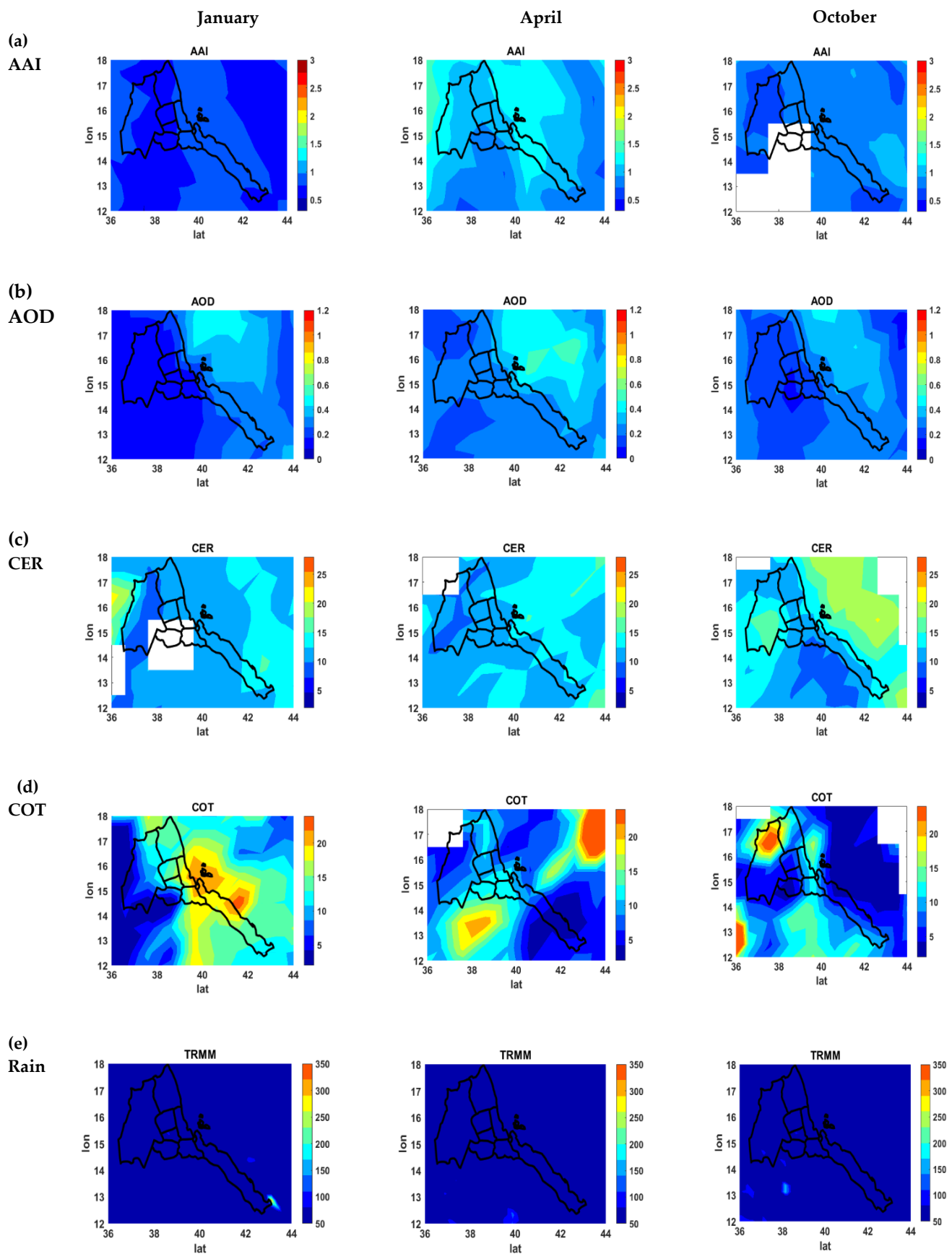


Figure 5. (a) AAI, (b) AOD, (c) CER (μm), (d) COT, and (e) rainfall (mm) in January, April, and October 2007 for comparison.

3.3. Correlation between Aerosols, Clouds, and Rainfall

Based on the 18-year data from 2001 to 2018 for July (Tables 4–9), correlation coefficient analyses were obtained for AOD, AAI, rainfall, CER, and COT, with their corresponding scatter plot diagrams shown in Figures 6–9. AOD and rainfall showed a negative correlation in Asmara and Nakfa; the correlation between the two is negative but lower than that of Assab. In Asmara and Nakfa, it is expected that AOD decrease during heavy rain due to wet removal. However, a less negative correlation between AOD and rainfall could occur due to (a) ineffective removal of aerosols by wet deposition, (b) aerosol replenishment due to natural sources (especially sea salt), and (c) an increase in the existing hygroscopicity during the summer monsoon period (high RH $\geq$ 80%) which produces water-soluble aerosols [15]. In July, the correlation between AOD and AAI was relatively higher in Assab. On average, during the monsoon season, there is a weak negative correlation between AOD and AAI in Asmara and Nakfa (Tables 4–9). There was a weak negative correlation between AAI and rainfall in some cases in July and JJA (Tables 4–9). This may be due to the type of aerosols moving toward the study area. The negative correlation between rainfall and AAI suggests that there was wet removal of aerosols; then, a positive correlation between rainfall and AAI indicates that either there was an inefficient removal of aerosols near the ground or the aerosols were of a non-absorbing (scattering) type.

Table 4. The correlation coefficient values between AOD, rainfall, AAI, CER, and COT over Asmara in July between 2001 and 2018.

Region	AOD	Rainfall	AAI	CER	COT
Asmara					
AOD	1.0				
Rainfall	−0.245	1.0			
AAI	0.142	−0.199	1.0		
CER	−0.264	0.374	−0.058	1.0	
COT	−0.175	0.222	−0.188	0.005	1.0

Table 5. The correlation coefficient values between AOD, rainfall, AAI, CER, and COT over Assab in July 2001 to 2018. The correlation coefficient (R) values of ≥ 0.468 (critical R-value) are highlighted in bold.

Region	AOD	Rainfall	AAI	CER	COT
Assab					
AOD	1.0				
Rainfall	−0.408	1.0			
AAI	0.456	−0.323	1.0		
CER	−0.118	0.132	−0.051	1.0	
COT	−0.092	0.602	−0.179	0.071	1.0

Table 6. The correlation coefficient values between AOD, rainfall, AAI, CER, and COT over Nakfa in July 2001 and 2018.

Region	AOD	Rainfall	AAI	CER	COT
Nakfa					
AOD	1.0				
Rainfall	−0.337	1.0			
AAI	0.334	−0.429	1.0		
CER	0.008	0.446	−0.186	1.0	
COT	−0.332	0.213	−0.090	0.000	1.0

Table 7. The correlation coefficient values between AOD, rainfall, AAI, CER, and COT over Asmara in JJA between 2001 and 2018. The correlation coefficient (R) value ≥ 0.468 (critical R-value) is highlighted in bold.

Region	AOD	Rainfall	AAI	CER	COT
Asmara					
AOD	1.0				
Rainfall	−0.364	1.0			
AAI	−0.206	−0.100	1.0		
CER	−0.071	0.681	−0.389	1.0	
COT	−0.286	−0.048	0.334	−0.029	1.0

Table 8. The correlation coefficient values between AOD, rainfall, AAI, CER, and COT over Assab in JJA between 2001 and 2018. The correlation coefficient (R) value ≥ 0.468 (critical R-value) is highlighted in bold.

Region	AOD	Rainfall	AAI	CER	COT
Assab					
AOD	1.0				
Rainfall	−0.303	1.0			
AAI	0.125	−0.156	1.0		
CER	−0.255	0.310	0.059	1.0	
COT	0.026	0.485	0.033	0.280	1.0

Table 9. The correlation coefficient values between AOD, rainfall, AAI, CER, and COT over Nakfa in JJA between 2001 and 2018. The correlation coefficient (R) values ≥ 0.468 (critical R-value) are highlighted in bold.

Region	AOD	Rainfall	AAI	CER	COT
Nakfa					
AOD	0.1				
Rainfall	−0.441	1.0			
AAI	−0.052	−0.444	1.0		
CER	−0.193	0.347	−0.455	1.0	
COT	−0.128	−0.206	0.120	−0.550	1.0

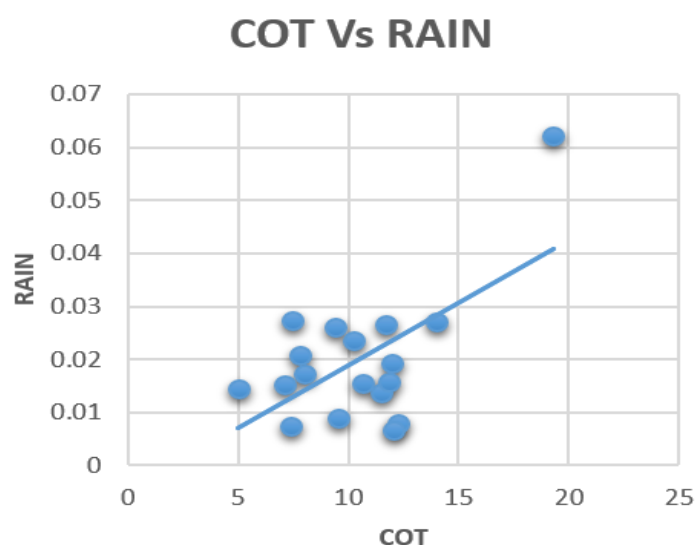


Figure 6. Scatter plot of COT vs. rainfall over Assab in July shows the correlation plot of highlighted bold values given in Table 5.

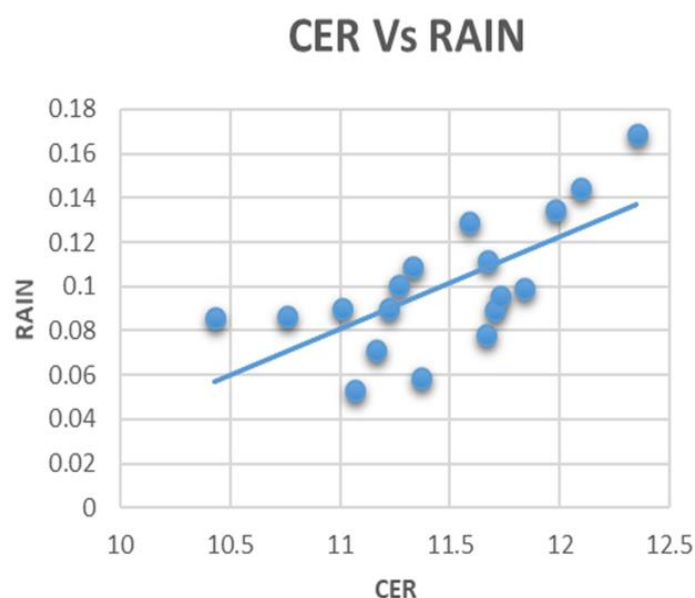


Figure 7. Scatter plot of CER vs. rainfall over Asmara in JJA that shows the correlation plot of highlighted bold values given in Table 7.

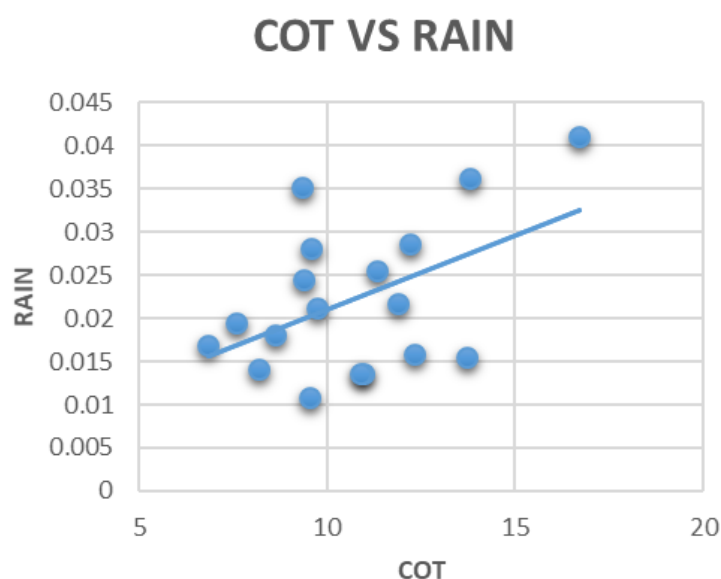


Figure 8. Scatter plot of COT vs. rainfall over Assab in JJA that shows the correlation plot of highlighted bold values given in Table 8.

The above correlation tables showed that during JJA, CER and COT exhibited a negative correlation with AOD in Nakfa (Table 9 and Figure 9). This feature was different from Asmara and Assab. In Asmara and Assab, CER and COT exhibited a positive correlation with rainfall during both July and JJA. During JJA, a negative correlation of COT with precipitation is seen in Nakfa (Table 9), while there was a positive correlation of CER with precipitation. The negative correlation between COT and rainfall may be due to a combination of meteorological events and due to an inverse of the indirect effect of aerosols caused by heterogeneous ice nucleation [26]. Information on the respective changes in CER in warm and icy clouds is needed to check this effect. The relevant results obtained through the analysis of aerosol–cloud behaviors and rainfall in Eritrea and adjacent ocean areas are very consistent with the indirect effects of aerosols (CER decreases with the increase in AOD and AAI).

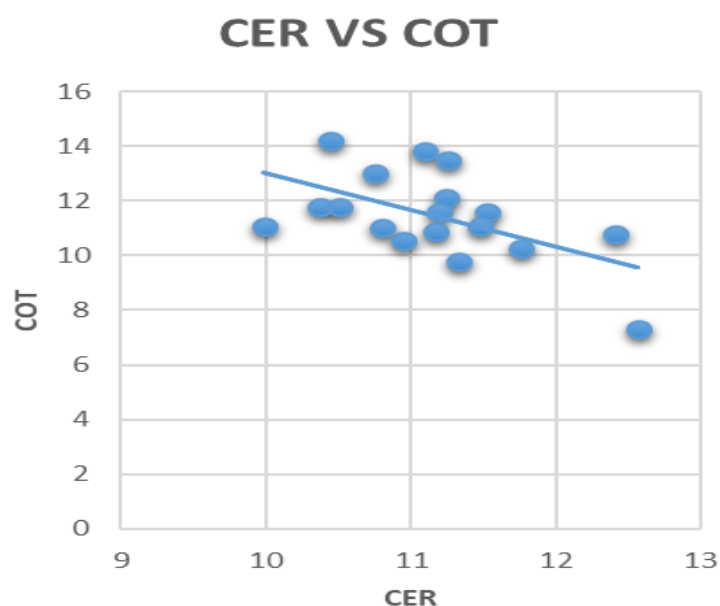


Figure 9. Scatter plot of CER vs. AAI and CER vs. COT over Assab in July shows the correlation plot of highlighted bold values given in Table 9.

Therefore, due to the decrease in precipitation, the lifetime of aerosols can increase. The fine mode aerosols are more affected by rain than the coarse mode particles, leading to a decrease in mid-visible AODs [37]. The drier conditions that exist due to deficient rainfall could facilitate an increase in more light-absorbing aerosols (dust and smoke) [35], resulting in higher AODs. Additionally, these aerosols can get transported to higher heights (2–4 km) because of prevailing strong convection and can give rise to a heating rate of >0.5 K/day, leading to a burn-off of clouds (semi-direct effect) which can further suppress the rainfall, thus producing a feedback effect [38]. Besides, the analysis of aerosol, cloud, and rainfall characteristics on land (Eritrea) and adjacent ocean areas (Asmara and Assab) shows that aerosol-cloud interactions and related aerosol indirect effects may differ on a spatial scale.

3.4. HYSPLIT Model

The model calculation method used is a hybrid between the Lagrangian approach and the Eulerian approach. The Lagrangian approach uses a moving frame of reference as the air parcel moves from its initial location. The Eulerian approach uses a fixed three-dimensional grid as a frame of reference. It is archived four times a day at 00:00, 06:00, 12:00, and 18:00 UTC. The HYSPLIT model output is in gridded binary (GRIB) format. The model computed the puff or advection of a particle from the average of the three-dimensional velocity vectors at the initial position, $P(t)$, and first-guess position, $P'(t + \Delta t)$ [39,40]. Five-day backward trajectory analysis was utilized to identify the sources of atmospheric aerosols at 500, 1000, and 1500 meters above ground level (MAGL). The trajectories were computed for the start, middle, and end of the JJA season (see Figure 10a–i). The main reason to run the HYSPLIT model during these periods is that according to the given precipitation index of Tables 1–3, 2007 was a year that had the highest precipitation recorded within the last two decades over the whole of the study domain. Besides, the spatial and temporal analysis is also done according to this year.

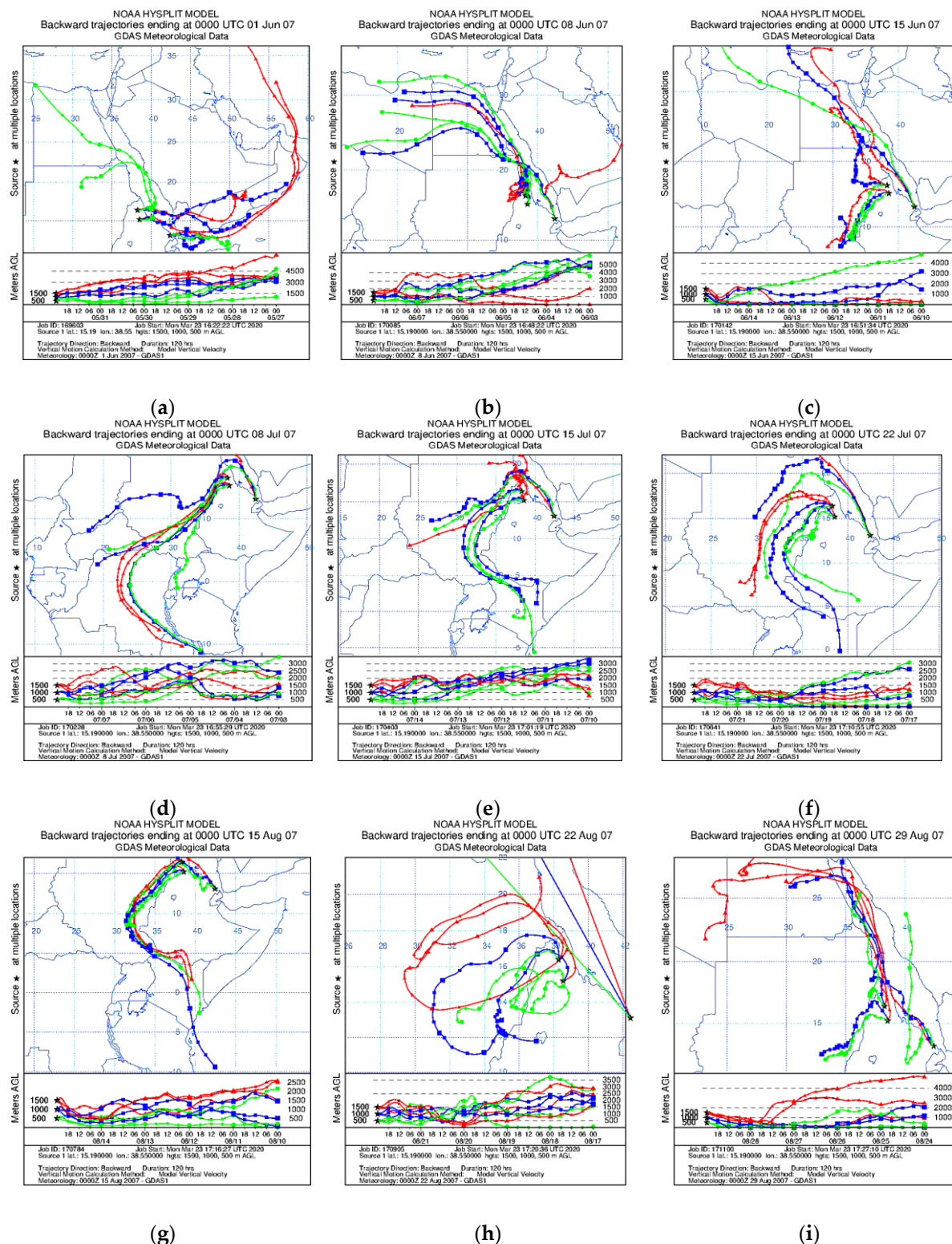


Figure 10. HYSPLIT back trajectory during the start (a, b, c), middle (d, e, f), and end (g, h, i) of JJA of the year 2007.

At the beginning of JJA, backward trajectories identified that the continental source regions were the Arabian deserts, the North African region (route of the Red Sea), and Sudan at all levels. The selected continental stations included Asmara, Assab, and Nakfa. Locations of maritime source regions were the Red Sea and the Arabian Peninsula. Except

Assab, Asmara and Nakfa got air sources from the northern parts of the Red Sea region and Northeast Africa.

In the middle of JJA season except for Nakfa at 1500 MAGL and Assab at 1000 MAGL; the source regions for all stations were from the central African region, which is highly dominated by biomass burning, originating from the areas such as Kenya and Congo.

At the end of JJA, southwesterly winds acted as a long way source of air mass to the study region at 500, 1000, and 1500 MAGL. These patterns continued towards the mid-end season (Figure 10h). Therefore, generally, regions of origin were located in North Africa, the northern Red Sea, west and southwestern areas of Sudan. In Eritrea, active regions of aerosol emission occurring seasonally include Sudanian zones, northern Africa, and the Sahel.

Other regions identified by previous studies include the Indian Ocean, Arabian Desert, Arabian Sea, Arabian Peninsula, and the Indonesia forest fires that occurred in 1997. At different levels, the sources of the transported particles are variable. Aerosol particles undergo vertical mixing inland of Eritrea. Further, several high mountains (>2000 m) are situated near the central highlands. They include Mount Embasoira, and the top peaks of the eastern and western escarpment. These mountains block the eastward transport of the Sahel smoke. Therefore, these mixed aerosols accounted for increased rainfall over locations with a large amount of rain based on TRMM rainfall.

4. Conclusions

The effects of aerosols on clouds and precipitation over Eritrea and the surrounding sea (Red Sea) have not been studied, and almost no observational studies linking aerosols with precipitation have been carried out. According to a study, the Eritrean summer monsoon rainfall was found to decrease from 1930–2010 [41]. When comparing with earlier studies, light-absorbing aerosols play a limited role in affecting the multi-decadal trend of the monsoon. However, here, it can be seen from observational studies that the study area is surrounded by relatively heavy absorptive (desert dust and sea salt) particles and mineral mixtures, such as carbon dust (Figure 1a), which may change the monsoon rainy season, and this impact of changes has led to an increase/decrease in rainfall in Eritrea. Most cities in Eritrea have low AOD in winter (January), spring (April), and autumn (October), and high AOD in summer (July). The summer monsoon rainfall in Eritrea is uneven because of large-scale interruption, called monsoon rupture, occurring throughout Eritrea. During the break period, aerosols build up over a region. AOD in 2011 (a drought year) was high over Eritrea (the three chosen cities). AAI was higher in 2002 and 2003 when compared to normal monsoon years. AOD and AAI showed a positive correlation over Assab (see Table 5 and Figure 6) and showed a weak negative correlation in exceptional cases over the other parts. In Eritrea, CER and COT correlated negatively with AOD, which is very consistent with the indirect radiative effect of aerosols. It is found that rainfall has a significant positive correlation with COT and CER over Assab and Asmara, respectively (see Tables 5 and 7, Figures 6 and 7). Over Assab, AAI has a negative correlation with CER in which the absorbing aerosols have a negative influence on CER. Based on the spatiotemporal analysis, the region of the coastal areas of the Red Sea had a higher loading of aerosols, which could be mostly of sea salt particles. Moreover, this results in lowering the amount of rainfall in areas with more influence of aerosols. According to the HYSPLIT model, in the central and western regions, the effect of aerosols on rainfall (rate of precipitation) seems to have an indirect effect based on the type of aerosols that flow to those areas.

The HYSPLIT backward trajectory model used in these studies showed that the majority of aerosols made their way to the Eritrean region through Sudan and the Sahelian region. Therefore, according to the HYSPLIT trajectory model analysis, the westerly and the southwesterly winds are the most dominant sources of aerosols during the summer monsoon. Moreover, this can prove that desert dust is the major type of aerosol in the Eritrean region during the summer monsoon.

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