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# Variability of aerosol optical depth and their impact on cloud properties in Pakistan

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ABSTRACT

This study analyzes seasonal and temporal variations in aerosol optical depth (AOD), and the impact of these variations on the properties of clouds over five cities in Pakistan, using Moderate Resolution Imaging Spectroradiometer (MODIS) data, obtained from the Terra satellite during the period (2001–2011). The obtained results indicated seasonal variation in AOD, with a high value of 2.3, in summer and low values of 0.2, in winter for the costal part of the region. The relationship between AOD and other cloud parameters, namely water vapor (WV), cloud fraction (CF), cloud optical thickness (COT), cloud liquid water path (CLWP), cloud top temperature (CTT), and cloud top pressure (CTP) were analyzed. On a temporal scale, latitudinal variations of both WV and AOD produce high correlations ( > 0.6) in some regions, and moderate correlations (0.4–0.6) in the other regions. An increasing trend in CF with AOD was found over urban regions in the period of observations. The CF values were higher for Lahore than the other selected regions during the whole period. During autumn and winter seasons the correlation was found to be positive between AOD and CLWP, while negative correlation was observed during the other seasons for all the selected regions. COT showed negative correlation with AOD at all locations except Karachi during spring and summer seasons.

AOD showed a positive correlation with CTP and CTT for the spring season and a negative correlation was observed for summer for all investigated regions. Furthermore, in warm clouds AOD and CTP were negatively correlated for all regions except Peshawar, whereas, AOD and CTT were positively correlated for all regions except Karachi. In cold clouds the relationships between AOD and CTP, and AOD and CTT were negative, except Karachi. Thus meteorological parameters, geographical conditions, as well as warm and cold clouds are the causative factors for AOD and CTP, and AOD and CTT variations.



## 1. Introduction

Interactions between aerosols and clouds are a subject of substantial scientific research, due to the importance of clouds in controlling climate. Aerosols and clouds play a vital role in determining the climatic conditions of the Earth's atmosphere system. Cloud interactions with aerosols are hypothesized to be critical to understanding climate change, since clouds play such a pivotal role in controlling incoming and outgoing radiation (Houghton et al., 2001). Aerosols are known to impact the formation and life cycle of clouds. A wide range of studies have shown that anthropogenic aerosols can change clouds and their optical properties. (e.g. Alam et al., 2010; Ackerman et al., 2000; Andreae et al., 2004; Kaufman et al., 2005; Kim et al., 2003; Koren et al., 2004, 2005; Penner et al., 2004; Ramanathan et al., 2001; Rosenfeld, 2000; Rosenfeld et al., 2002; Schwartz et al., 2002).

Aerosols in nature play a significant role in the climatic conditions by interacting the cloud development. They affect cloud development by absorption and scattering of solar radiation. Several processes contribute to aerosol induced forcing, both directly, through effects on cloud albedo, and indirectly, through effects on the lifetime of rain or water vapors. Increasing concentrations of anthropogenic aerosol particles have an effect on the amount, as well as on the spatial and temporal distribution of clouds and precipitation, affecting the hydrological cycle (Forest et al., 2002). However, in spite of the progress, aerosols are the dominant uncertainty in radiative forcing. The indirect effect of aerosols on water clouds, whereby aerosol particles change the cloud's optical properties, is caused by aerosol-induced changes of the size and number of cloud droplets (Lohmann., 2002). This affects the lifetime of the water clouds and their shortwave radiative properties as well. Interactions between aerosols and clouds have become the subject of scientific research because of the importance of clouds in controlling climate (Mahowald and Kiehl, 2003). The aerosol–cloud interactions play a significant role in global climate, however, there are large uncertainties in the

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magnitude of the forcing (Charlson et al., 1992). Therefore, aerosols, clouds, and their interaction with climate is still the most indistinct area of climate change.

Myhre et al. (2007) found that several possibilities exist for aerosols and clouds to be interlinked through processes, rather than through physical aerosol–cloud interactions. One such possibility is the meteorological condition where low altitude clouds influence the AOD. Due to the large spatial and temporal extent of aerosols (desert dust, pollution, etc.) in the atmosphere, the interactions between aerosols and clouds can have substantial climatic impacts (Alam et al., 2010). To assess the regional and global climate change caused by aerosols in South Asia, detailed information is required on the atmospheric concentrations of aerosol in the region (Dutkiewicz et al., 2009).

A number of studies have been conducted to address the spatial and temporal variability of aerosols and clouds (Kumar, 2013; Balakrishnaiah et al., 2012; Alam et al., 2010). Balakrishnaiah et al. (2012) have investigated the spatial, temporal, and seasonal variation in aerosol properties and their relationship to various cloud parameters over major cities of southern India and noticed a high mean AOD in almost all regions in the summer season, whereas at Pune, Visakhapatnam and Hyderabad, the same observation was noticed during the monsoon season. Alam et al. (2010) recently analyzed the effect of aerosols on clouds. They showed that both smoke and pollution enhance the cloud formation over the regions Karachi and Lahore. High AOD values were found during the summer (June–August) season, due to dust activities in the southern parts of Pakistan. Kumar (2013) analyzed that AOD and cloud fraction correlation increases for those regions which have more particulate particles due to dust, biomass, industrial and domestic activities. Yi et al. (2012) have recently reported the relationship between aerosol and cloud precipitation. They found an increasing trend in cloud fraction with the increase of aerosol optical depth (AOD) over ocean regions under observation, while the reverse result was noticed in the model simulation. Kaufman et al. (2005a) and Koren et al.(2005) have analyzed the regional effect of aerosol on clouds. They reported that over the Atlantic Ocean from June to August, dust, smoke, or pollution each enhances the cloud formation and the cloud top height. In the present study, the investigation is carried out for warm and cold clouds' properties, as there is a lack of knowledge about the aerosol impacts on the properties of warm and cold clouds in this region. Both cold and warm clouds play important roles in the chemical quality of precipitation and eventually in the composition of the atmosphere. The major effect these clouds have on climate change is that they both cool and heat the planet (Allan, 2011), even as their own properties are determined by the cooling and heating of the atmosphere. Cold clouds have a net cooling effect, because they have a high albedo, and emit nearly as much infrared radiation to space as the surface would under clear skies (Nowicki and Merchant, 2004). Warm clouds almost form in the lower atmosphere by condensation onto aerosol particles composed of diverse compounds.

The present study investigates the spatio-temopral variations of aerosol and cloud properties and the relationship between AOD and cloud parameters. In this study we have used MODIS data to analyze the aerosol/cloud optical properties in terms of aerosol optical depth (AOD), water vapor (WV), cloud fraction (CF), cloud optical thickness (COT), cloud liquid water path (CLWP), cloud top temperature (CTT), and cloud top pressure (CTP).

## 2. Site description

The present study has been carried out in 5 different geographical locations of Pakistan, namely Swat, Peshawar, Lahore, Dera Ghazi Khan, and Karachi. The topographic variation makes Pakistan geographically unique for any study of spatio-temporal patterns (Alam et al. 2011c). A short description of each city is delineated in the following lines.

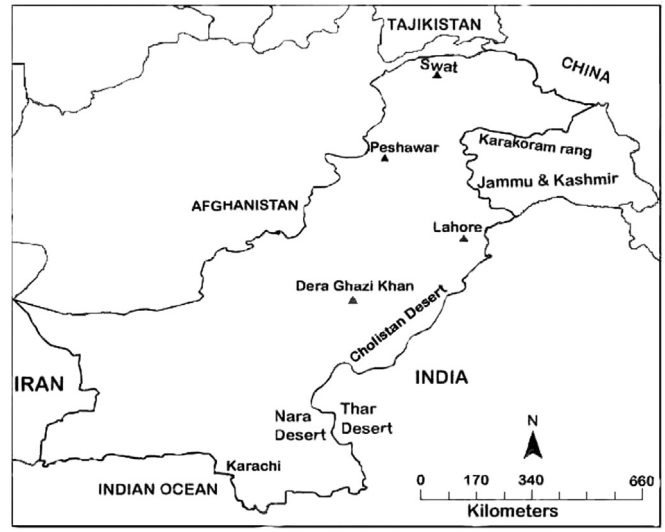


**Fig. 1.** Map of Pakistan showing the study sites.

Swat (34°61′N; 72°35′E) is a valley located in the North of Pakistan (see Fig. 1). The larger part of Swat is covered with high mountains and hills. Its population is approximately 1.32 million and sprawled over 10,360 km². Up till now the industrial site is not so developed in Swat, therefore the major sources of aerosols are smoke from wood stoves, burning oil, coal and tobacco products, motor vehicles, biomass burning, natural transport, physical and chemical processes, road dust, atmospheric gases, fossil fuel burning, etc,

Peshawar (34°02′N; 71°37′E) is located near the Pakistan-Afghanistan boarder (see Fig. 1) with a population of more than 24.44 million and covers an area of 1257 km². Factors such as local industries, agricultural activities, domestic fossil fuel burning, anthropogenic activities, like fuel combustion, smoke, traffic emission and open burning sources etc., contribute to the aerosol concentrations at this site.

Lahore (31°32′N; 74°22′E) is the second largest city of the country, bordering India, with a population of approximately 11 million and covering a total land area of 404 km². In addition to vehicular emissions from motor ways, emissions from coal and fuel combustion in the industrial sector, and biomass burning are the main local sources of aerosol in this industrial city.

Dera Ghazi Khan (DG Khan) (30°03′N; 70°38′E) is located at the junction of the four provinces of Pakistan. The aerosol concentrations monitored at this site are derived from the industrial sector, road dust, desert dust, smoke, and emission from heavy machinery etc.

Karachi (24°51′N; 67°02′E) is a coastal city located in the southwestern part of Pakistan on the Arabian Sea as shown in Fig. 1. It spans 3527 km², having a population of approximately 20 million. Aerosols, at this site, are mainly due to automobile exhaust gases, chemical pollutants by land vehicles, airborne dust, auto exhaust fumes/smoke and road side dust, and industrial emission etc.

### 2.1. Instrumentation

MODIS, onboard the Terra and Aqua satellites, provides relatively high spatial resolution (250–500-m) while achieving near global coverage on a daily basis (Salomonson et al.,1989). The

daytime Aqua overpass (13:30 LT) is chosen over the Terra overpass (10:30 LT) since clouds are more likely to be developed in the afternoon than the morning. The MODIS instrument provides high radiometric sensitivity (12 bit) in 36 spectral bands, ranging in wavelength from 0.41 μm to 14.4 μm. Out of 36 bands, two are imaged at a nominal resolution of 250 m at nadir, with five bands at 500 m, and the remaining 29 bands at 1 km. A $\pm 55^\circ$ scanning pattern at the EOS (Earth Observation Sensor) orbit of 705 km achieves a 2, 330-km swath and provides global coverage every 1 to 2 days. The spatial resolution of the MODIS instrument varies with spectral band, and ranges from 250 m to 1 km at nadir. These MODIS instruments offer an unprecedented look at terrestrial, atmospheric, and ocean phenomenology for a wide and diverse community of users throughout the world. Furthermore, they allow scientists the opportunity to study many of the Earth's terrestrial and oceanic characteristics such as ocean pollution, changes in landscape, amount of bound carbon, and others with a single instrument. MODIS data are useful for collecting various statistics on aerosol concentrations and the impacts that aerosols have on clouds formation (Alam et al., 2011c). For water vapor, the retrieval for the near-infrared region is adopted. MODIS uses an infrared band to determine the physical properties of clouds in relation to cloud top pressure and temperature. Visible and near-infrared bands are used to determine optical and microphysical cloud properties (Jin and Shepherd., 2008; Alam et al., 2010). In this study we have used a MODIS Terra Level-2 monthly AOD and cloud parameter data (MOD04_L2. in HDF format) at a spatial resolution of $10 \times 10$ Km and $5 \times 5$ Km, respectively. More detailed information on algorithms for the retrieval of aerosol and different cloud parameters is available at http://modis-atmos.gsfc.nasa.gov. The present study analyzes the seasonal variability of AOD, and the aerosol impact on different properties of clouds using MODIS Terra AOD and cloud parameter data from 2001 to 2011.

## 3. Results and discussion

### 3.1. Seasonal variations in AOD

Seasonal variations in AOD using MODIS data over a period of eleven years are shown in Fig. 2. The annual mean AOD at 550 nm was calculated for the period 2001–2011. The results from Fig. 2 show that aerosols have a marked impact on five cities in Pakistan, Swat, Peshawar, Lahore, DG Khan, and Karachi. These regions comprise major urban centers of Pakistan, with generally dense populations and variable distribution patterns of residential, industrial and commercial land use areas. These cities were included in this research because of their industrial sector, anthropogenic activities, and due to the extreme variations in their geo-strategic locations, which results in different weather patterns that, in turn, affect the aerosol load in each area (Alam et al., 2011c). High annual mean AOD values were observed in almost all regions during the summer season, whereas in Lahore and Karachi, high AOD values were also noticed during the winter season. Fig. 2 presents the AOD mean values, revealing a seasonal pattern with a higher AOD level during the spring and summer months, and comparatively lower AOD levels during the autumn and winter months. Data from Karachi, Lahore and DG Khan reveals very high mean AOD values over the whole period (2001–2011) as compared to the other cities investigated, of which the maximum values were found in summer (2.3, 1.8 and 1.5, respectively), whereas the minimum values (0.55, 0.66 and 0.61, respectively) were recorded during the winter season. This abrupt variation can be attributed to the fact that these are urban, industrial, and coastal areas. DG khan is an urban region which carries large AOD values during the summer and winter seasons (see Fig. 2) due to its close proximity to the Cholistan Desert, which leads to an increased persistence of dust aerosols, along with local vehicular emission. Alam et al. (2011a) found that AOD increases and higher AOD levels persist for longer periods of time over industrial and densely populated cities in Pakistan, as a result of anthropogenic activities (like urbanization, land use change etc.),. Ranjan et al. (2007) and Alam et al. (2010) concluded that water vapor (precipitate) and AOD are directly related to each other, and hence a higher concentration of water vapor in summer leads to a higher AOD. In addition, higher air temperatures tend to hold more vapors that feed aerosol to grow (Masmoudi et al., 2003), which might be the other reason causing the higher AOD levels in the summer time.

Another reason for a higher level of AOD values during summer is the dust storms occurring during that season. Similar increases in AOD during summer have previously been reported for the region of Pakistan situated between 22–25°N and 60–75°E (Alam et al., 2010). In the present study, even the lowest AODs were very high ($\geq 0.3$) at all the investigated locations, even during the years showing insignificant deviation. High AOD values (1.5 and 0.6, respectively) were observed over Peshawar and Swat during summer, while low AOD values (0.35 and 0.34, respectively) were noticed during the winter (Fig. 2). There was a large variation in AOD values between low values in winter and high values in summer, whereas, the pattern of AOD values in spring and autumn were quite similar to each other. The results indicate that an aerosol concentration increases with increased anthropogenic activities. The AOD values for Karachi, Lahore and DG Khan were higher than those of Peshawar and Swat, due to the enhancement in urbanization and industrialization, dust storms, and salt particles blowing from the sea (Alam et al., 2012).

### 3.2. Relationship between AOD and cloud parameters

The MODIS data consists of an enormous amount of data which is valuable for understanding how aerosols influence clouds (Myhre et al., 2007; Alam et al., 2010). This section deals with the temporal and spatial correlation between AOD and cloud parameters for the five selected cities across Pakistan for the period 2001–2011. We used AOD as a substitute for aerosol concentration and calculated the correlation coefficient for each set of parameters on a seasonal, as well as on an annual basis, throughout the observation period (2001–2011). The relationship between AOD and WV, and AOD and CF were examined using time series plots. Furthermore, COT, CLWP, CTP and CTT relationships with AOD were also investigated. The discussion of each of these relationships is presented individually in the following sub-sections.

#### 3.2.1. Relationship between AOD and water vapor

The MODIS retrieval data provides separate columns of WV data for clear skies, as well as data above the clouds. In the present study MODIS data was used for WV in the clear sky for the period 2001–2011. The correlations between AOD and WV (Table 1) reveal that AOD and WV have a strong positive correlation ($>0.6$) in some regions and moderate correlation (0.4–0.6) at other investigated regions during the spring, summer and autumn seasons. There was no significant relationship between AOD and WV during the winter season, since the dust aerosols were less common or even absent during winter, consequently, less WV was observed (Alam et al., 2010, 2011a). Low AOD values in winter, a global feature, is attributed to the removal of aerosols due to monsoon rains and decreased aerosol input due to a colder ground surface. Additionally, less hygroscopic growth of aerosols due to low WV content may lead to relatively lower AOD values

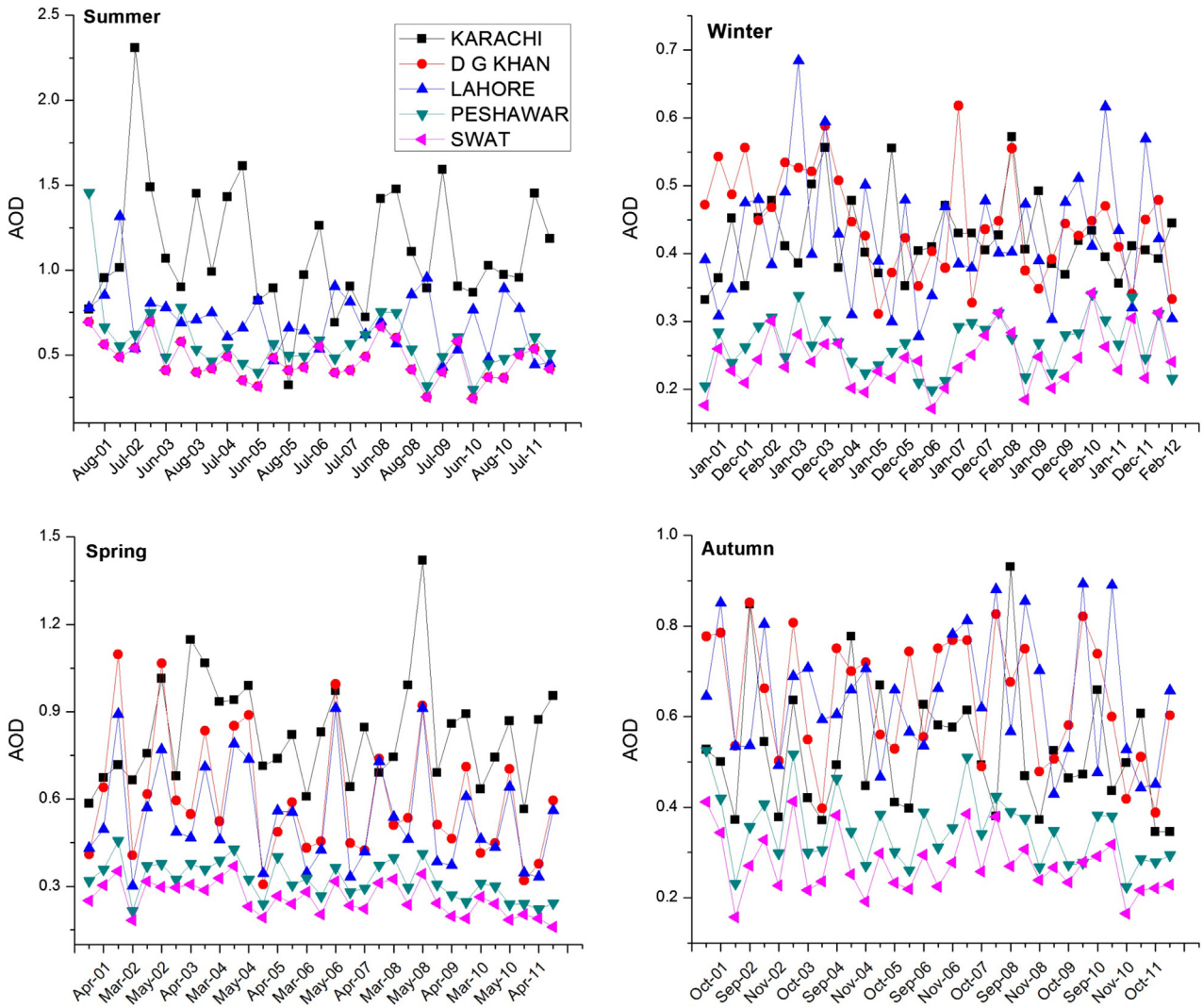


**Fig. 2.** Seasonal variations in AOD during (2000–2011) over different cities of Pakistan.

(Ranjan et al., 2007). Monthly variations of mean AOD and WV data for the period 2001–2011 are shown in Fig. 3(a–e). The present analysis showed that the coastal region widely experienced an elevated WV level (ranging from 1.0 to 5.89 cm) as shown in Fig. 3e, probably due to the fact that all the areas were either urban, industrial, or coastal. Alam et al. (2011c) have found that, as a result of anthropogenic activities (like urbanization, land use change etc.), AOD is increased and relatively higher AOD levels persisted for longer periods of time over industrial and densely populated cities in Pakistan. High mean AOD values i.e. 2.3 and 1.6 were observed over Karachi and Lahore, with corresponding WV values of 5.89 and 6.5, respectively (see Fig. 3(c and e)). Ranjan et al. (2007) have attributed the high AOD values observed during summer to an increase in the aerosol input, due to increased surface heating and resultant vertical mixing, dry surface conditions, and windblown dust. Fig. 3(a–e) shows a simultaneous increase and decrease in AOD and WV, a result in accordance with the findings of (Ranjan et al., 2007; EL-Askary and Kafatos, 2008; Alam et al., 2010; Balakrishnaiah et al., 2012). The relation between Aerosol and WV has an implication for the radiative forcing directly and indirectly (Tegen et al., 1996; Houghton et al., 2001; Hsu et al., 2003). EL-Askary and Kafatos, 2008 have found that aerosols cause a reduction in cloud droplet size and hence lead to suppression in precipitation. The direct effect results in radiation scattering due to an increase in aerosol particle size, accompanied by the uptake of WV. The black cloud episode is comprised mainly of anthropogenic pollutants acting as cloud condensation nuclei, leading to the formation of WV cover. The high AOD values over Lahore may be due to the irregular continuous emission, coupled with the stable meteorological conditions by weak wind currents (EL-Askary and Kafatos, 2008) as well as almost neutral stratification, which may result in high values of WV. Xin et al. (2007) found that due to high AOD values associated with slowly moving air masses are generally accompanied by higher perceptible WV. The present analysis demonstrates that high WV will be regionally observed over locations where high AOD will be also observed. The AOD value varied for DG Khan from (1.0–5.5) (see Fig. 3d) with a mean AOD of 1.8, due to the fact that during the transient seasons, mainly spring, the transported desert dust is a major contributor to AOD.

### 3.2.2. *Relationship between AOD and cloud fraction*

The relationship between AOD and CF has been plotted for various selected cities of Pakistan over the time period 2001–2011 (see Fig. 4(a–e)). Correlation of AOD with CF has also been calculated for the selected time period of eleven years, both seasonally (see Table 1), and annually (not shown here). The correlation between AOD and CF was found to be comparatively lower for urban regions and higher at coastal and desert stations.

**Table 1**
Seasonal correlation between AOD vs. Cloud parameters.

| Region | AOD vs. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CF | | | | CTP | | | | | | CTT | | | | | | WV | | | | | | COT | | | | | | CLWP | | | | | |
| | W | SP | SU | AU | W | SP | SU | AU | W | SP | SU | AU | W | SP | SU | AU | W | SP | SU | AU | W | SP | SU | AU | W | SP | SU | AU |
| Swat | 0.2 | −0.02 | 0.3 | −0.1 | −0.1 | 0.03 | 0.12 | 0.01 | −0.2 | 0.04 | 0.24 | 0.36 | −0.06 | 0.25 | 0.34 | 0.52 | −0.12 | −0.35 | −0.11 | −0.01 | −0.2 | −0.3 | 0.01 | 0.03 |
| Peshawar | 0.08 | −0.2 | 0.61 | −0.1 | 0.01 | 0.17 | −0.09 | 0.23 | −0.09 | 0.25 | −0.1 | 0.59 | 0.03 | 0.35 | 0.6 | 0.66 | 0.12 | −0.46 | −0.02 | −0.01 | 0.07 | −0.5 | 0.06 | 0.05 |
| Lahore | 0.23 | 0.19 | 0.39 | 0.03 | 0.4 | 0.67 | −0.15 | 0.29 | 0.46 | 0.75 | −0.15 | 0.14 | 0.07 | 0.69 | 0.3 | −0.23 | 0.27 | −0.48 | −0.09 | −0.21 | 0.11 | −0.5 | −0.22 | −0.25 |
| DG Khan | −0.39 | −0.37 | 0.31 | 0.31 | 0.48 | 0.23 | 0.12 | −0.3 | 0.44 | 0.52 | 0.24 | −0.08 | −0.09 | 0.55 | 0.34 | 0.32 | −0.19 | −0.29 | −0.16 | 0.19 | −0.2 | −0.4 | −0.17 | 0.15 |
| Karachi | 0.15 | 0.55 | 0.21 | 0.57 | −0.2 | 0.03 | −0.06 | −0.5 | −0.2 | 0.15 | 0.01 | −0.32 | −0.06 | 0.53 | −0.2 | 0.58 | 0.11 | 0.22 | 0.08 | 0.06 | 0.13 | −0.2 | −0.03 | 0.02 |

W = Winter, SP = Spring, SU = Summer, AU = Autumn.

Time series plots of AOD and CF (Fig. 4(a–e)) show that CF increased with AOD from April to mid-September at all locations throughout the whole period (2001–2011), but in November the mean AOD values go on decreasing to reach the lowest value in February to mid-March, and thereafter an increasing trend was observed. Conversely, the CF values started increasing from November and attained the highest value in March. From April to September, there was an increasing trend in AOD as well as in CF, thus AOD and CF were positively correlated during this period. In contrast, from November to mid-March, there was a decreasing trend in AOD as well as in CF. Therefore, during this period, AOD and CF were negatively correlated. The negative trend between AOD and CF was occurred only when the AOD value had fallen below 0.4, an outcome in good agreement with the findings of Alam et al. (2010) and Hoeve et al. (2011). In winter (December, January and February), relatively lower AOD values were observed due to less precipitation because of the dry climate of the region, resulting in lower AOD values. Walcek, (1994) have reported a good correlation between cloud cover, relative humidity (RH), and vertical velocity. The cloud cover decreases exponentially as humidity falls below 100%. The cloud cover also exhibits a weak negative correlation with the potential temperature lapse rate, and vertical shear of the horizontal wind in the middle atmosphere (Walcek, 1994).

The annual correlation between AOD and CF was greater than 0.6, 0.42 and 0.37 in Karachi Lahore and DG Khan, respectively. No obvious correlations were found between AOD and CF for Peshawar and Swat regions. These values were significantly different from the values recorded seasonally. For example, the correlation coefficient between AOD and CF was less than 0.4 for Lahore, and DG Khan, whereas for Karachi it was greater than 0.5 during summer (see Table 1). Among the five locations analyzed in this study, Swat recorded the lowest mean AOD values in the range of 0.1–0.6, because this place is far from any industrial or urban centers, leading to minimal local production of aerosols (see Fig. 4a). Albrecht et al. (1989) and Kaufman and Fraser (1997) found that in environments highly laden with water vapor, exhibiting low cloud condensation nuclei, additional aerosols may increase cloud fraction to a greater extent than in environments laden with less water vapor, due to the impact of a stronger updraft on the lifetime effect. It can be concluded that both large-scale meteorological factors, traced by seasonally varying WV and aerosol loading, may contribute to changes in warm CF in the investigated regions. It is also important to mention the marked increase in the correlation between AOD and CF. Alam et al. (2010) found that the correlation between AOD and CF was high over the ocean and slightly lower over the north, but always positive towards the border with Afghanistan. This increase may be due to the complexity of the domain, the type of land surface (albedo), the choice (classification) of aerosol mixtures applied in the MODIS retrieval for that particular area, the impact of meteorology on aerosol transport, and the aerosol chemistry.

### 3.2.3. *Relationship between AOD and cloud optical thickness*

COT showed a negative co-relation with AOD at all locations except Karachi during the spring and summer seasons (Table 1), as well as during the whole period of observation (2001–2011). The highest negative correlation ($>-0.4$) was found for Lahore, whereas the highest positive correlation ($>0.2$) was found for Karachi during summer. This may be attributed to the fact that Karachi is located in the vicinity of the Arabian Sea and is subjected to a component of sea and land breezes, as well as wet deposition, which contribute to a speedy clean-up of the atmosphere. Furthermore, Karachi being a coastal region experiences a high value of moisture as well, which ultimately results in an increased COT, as it depends highly on the moisture density and

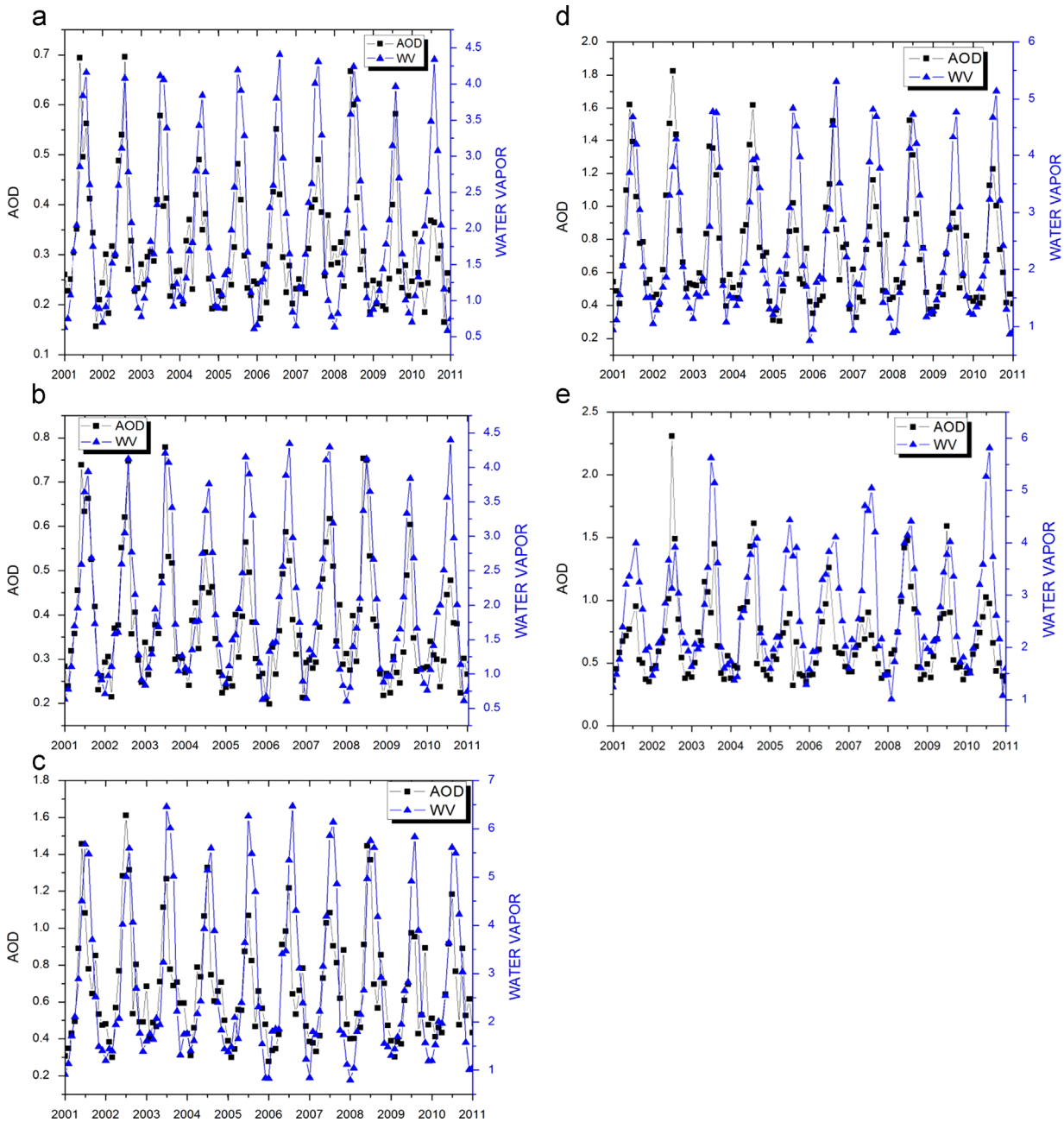


**Fig. 3.** (a–e) Spatial and temporal variation of AOD and Water Vapor during (2001–2011) in various cities of Pakistan. (a) SWAT. (b) PESHAWAR, (c) LAHORE, (d) D G KHAN and (e) KARACHI.

vertical depth of the cloud; subsequently, a positive correlation between the two parameters has been found. One of the reasons for the observed decrease in COT was the presence of absorbing aerosol, which causes cloud droplets to evaporate making clouds too thin (decreased COT), which is a legitimate physical process. On the other hand, the dark aerosol in and above the cloud may also decrease the cloud reflectance observed by the satellite, which the satellite retrieval interprets as a decrease in COT. It is concluded that the large decreasing trend in COT with AOD may be due to the radiative effect and retrieval artifacts as well. The present analysis showed a strong negative correlation between AOD and COT for Peshawar and Lahore in spring (see Table 1). Furthermore, COT is strongly dependent on cloud moisture since as the density of moisture increases, the value of COT increases or vice versa. One of the reasons for high COT is the presence of hygroscopic aerosol in the region. Alam et al. (2010, 2011b) found that hygroscopic aerosols increased the AOD over the southern coastal areas of Pakistan during the humid summer season, hence resulting in a high COT value in this region not only in summer but in spring and autumn as well, discussed in section 3.1.1. Several studies, for example, Hoeve et al. ( 2011) and Platnick et al. ( 2003) have reported that, apart from some regions of low AOD, COT was decreased in most of the cities with an increasing value of AOD. This might have resulted from the inhabitation of clouds development by absorbing aerosols (radiative effect/semi-direct effect). Hoeve et al. (2011) found that this variation may be due to a possible retrieval artifact, in which the measured reflectance in the visible is less than expected from a cloud top, either from the darkening of clouds through the addition of carbonaceous biomass burning aerosols within or above the clouds, or sub pixel dark surface contamination in the measured cloud reflectance.

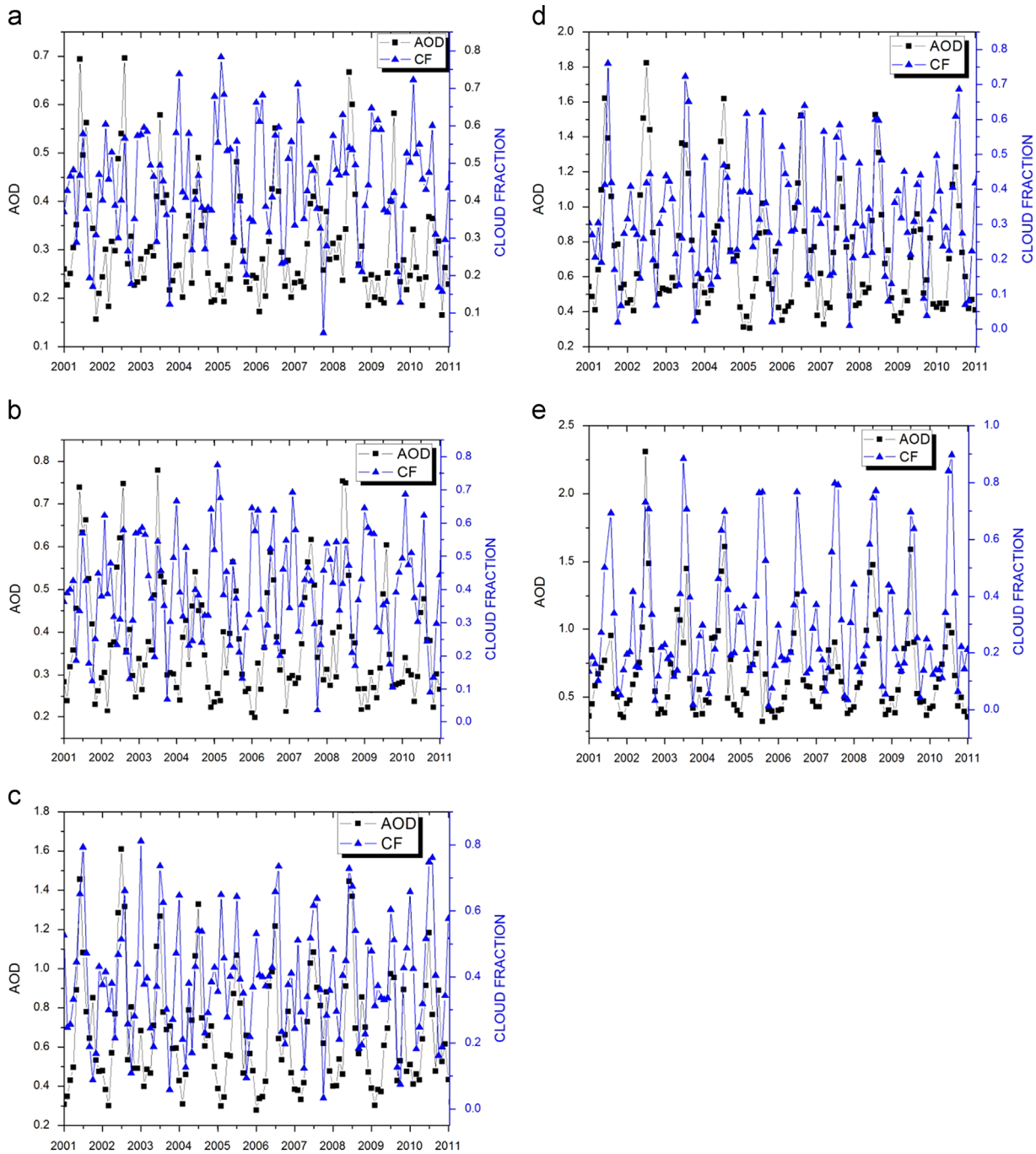


**Fig. 4.** (a–e) Spatial and temporal variation of AOD and Cloud Fraction during (2001–2011) in various cities of Pakistan. (a) SWAT. (b) PESHAWAR, (c) LAHORE, (d) D G KHAN and (e) KARACHI.

### *3.2.4. Relationship between AOD and cloud top pressure*

The correlation coefficients between AOD and CTP for various cities in Pakistan over the period 2001–2011 are shown in Table 1. There was a positive correlation between AOD and CTP for the Peshawar region during the period 2001–2011, whereas the data for Karachi showed a negative correlation for the same parameters. Furthermore, positive correlation was observed between AOD and CTP for the entire region in the spring season. Lahore appeared with a strong positive correlation (correlation coefficient = 0.67) in spring. Several studies, for example, Myhre et al. (2007), Kaufman et al. (2005) and Alam et al. (2010) have reported that except for some regions of low AOD, CTP decreased in most of the cities (higher cloud altitude) as AOD increased. This might have resulted from the suppression of the precipitation by increasing cloud lifetime and thus also affecting the cloud albedo and changing the cloud top pressure. Alam et al. (2010) investigated that at lower latitudes, there was a significant decrease in CTP in relation to AOD (i.e. a negative correlation), while at mid-latitudes this decrease was only moderate. Our analysis indicated a positive correlation for AOD with CTP and CTT in the northern regions of Pakistan and a negative correlation in the southern regions, which is in close agreement with the values reported by Alam et al. (2010) for the Pakistani regions. This co-variation of AOD with CTP and CTT may be attributed to large-scale meteorological variations.

The vertical wind velocity is the most important meteorological parameter influencing the cloud properties (Koren et al., 2005; Tripathi et al., 2007). Koren et al. (2005) reported that the correlation between vertical winds at 500 mb to the CTP and CF

is larger than 0.90 for all the investigated regions. On the other hand, the correlation between the vertical winds and AOD is 0.6 for some regions and negative −0.7 for other regions, suggesting different associations between meteorology and aerosol in these regions. Tripathi et al. (2007) analyzed the relationship between vertical winds and CTP in winter, pre-monsoon, monsoon, and post-monsoon seasons and the corresponding correlations coefficients are 0.26, 0.41, 0.63, and 0.6, respectively. The analysis suggests that during winter the relationship is less influenced by meteorology due to reduced updraft, whereas, during the monsoon season the aerosol effect is facilitated by favorable meteorological condition, due to strong updraft.

### 3.2.5. Relationship between AOD and cloud top temperature

The correlation between AOD and CTT for the selected sites during the studied period (2001–2011) is shown in Table 1. The present study shows a positive correlation between AOD and CTT for all regions, which is in agreement with the current understanding of aerosol–cloud interactions. However, the highest correlation coefficients between AOD and CTT were found to be 0.71 for Peshawar and 0.55 for Swat region, a result in accordance with the values reported by Alam et al. (2010). Furthermore, an overall negative correlation between AOD and CTT was observed in the winter season, except for Lahore and DG Khan. AOD and CTT is positively correlated both in winter and spring seasons over Lahore and DG Khan, with a strong positive correlation over Lahore ( > 0.6) and moderate correlation over DG Khan (correlation coefficient ~ 0.5). On the other hand, a negative correlation was noticed between AOD and CTT for Karachi, indicating a consistent negative correlation at lower latitudes. One of the reasons for this observation may be the fine mode aerosols, which constitute the majority of the haze during autumn and are found to be significantly coupled within the water column, subsequently resulting in a substantial decrease in CTT. In the higher latitude regions, e.g. northern areas, a positive correlation between AOD and CTT was observed. The observed relationship between AOD and CF, the co-variation of AOD with CTP, CTT and WV may be attributed to the large-scale meteorological variation.

Interesting variations were observed in AOD, CTP and CTT when the clouds were separated into two types of clouds on the basis of CTT, i.e. cold clouds (when CTT < 273 K) and warm clouds (when CTT > 273 K). In the warm clouds, AOD and CTP were negatively correlated in all regions except Peshawar, whereas AOD and CTT were positively correlated in all regions except Karachi (Table 2). On the other hand, AOD and CTP, and AOD and CTT were negatively correlated for the cold clouds except for Karachi. Thus meteorological parameters, geographical conditions, as well as warm and cold clouds are the causative factors for AOD and CTP, and AOD and CTT variations.

**Table 2**
Correlation between AOD vs. warm and cold clouds parameters.

| Region | Warm clouds | | Cold clouds | |
|---|---|---|---|---|
| | AOD vs. | | AOD vs. | |
| | CTP | CTT | CTP | CTT |
| Swat | −0.19 | 0.55 | −0.25 | −0.16 |
| Peshawar | 0.08 | 0.55 | −0.19 | −0.08 |
| Lahore | −0.36 | 0.13 | −0.42 | −0.03 |
| DG Khan | −0.41 | 0.22 | −0.43 | −0.17 |
| Karachi | −0.55 | −0.2 | 0.09 | 0.32 |

### 3.2.6. Relationship between AOD and cloud liquid water path

The present observations show a negative correlation between AOD and CLWP in all the selected regions during the period 2001–2011. Table 1 shows a negative correlation between AOD and CLWP for the entire region during the spring season. The correlation coefficients were −0.47 and −0.5 for Peshawar and Lahore respectively. During winter, there was a low positive correlation between AOD and CLWP for Lahore and Karachi. Over all, there was a moderate negative relationship between AOD and CLWP for the regions of Swat, Peshawar and DG Khan, and a low positive relationship for the Lahore and Karachi regions during the observation period (2001–2011), however, this can not be interpreted as an effect of aerosol–cloud interaction alone, as meteorological conditions also play an important role. Chmura (2004) reported a strong negative correlation between AOD and CLWP for polluted clouds, which contradicted the indirect aerosol effect. Storelvmo et al. (2006) noticed that water soluble aerosols grow due to humidity swelling, and this growth is an increasing function of relative humidity. As aerosols grow due to water uptake, they become optically thicker. Relative humidity is assumed to be particularly high in the vicinity of clouds. Humid areas typically correspond to areas with high cloud water content. This mechanism would lead to a positive correlation between AOD and CLWP and between AOD and COT as well, and thus depends strongly on the height and thickness of the cloud.

## 4. Conclusion

The present study analyzes the variation of aerosols and clouds using MODIS data, in order to develop an understanding of the impact of aerosols on cloud properties over various cities of Pakistan. Cloud parameters were selected here to represent MODIS information partly because of their critical role to atmosphere energy and water budgets, and partly because such information has rarely been studied in an integral fashion for atmosphere conditions over this region. It was observed that the WV and AOD were strongly correlated at almost all of the investigated locations. CF was found to increase with AOD in those regions dominated by biomass and dust aerosols. The correlation between AOD and CF was found to be comparatively lower at urban regions and higher at the coastal and desert stations. We analyzed that negative correlation between AOD and CF was found only when the AOD fell below 0.4. COT and AOD showed negative correlation at all locations except Karachi. Negative correlation was observed between AOD and CLWP in Swat, Peshawar and DG Khan, whereas positive correlation was observed for Lahore and Karachi. CTP and AOD showed a negative correlation at higher latitudes, except in a few cities. CTT showed a positive correlation with AOD for desert and northern regions of Pakistan, but a negative correlation for the southern region of the country. AOD and CTT are positively correlated for warm clouds in almost all the regions except Karachi, whereas AOD and CTT are negatively correlated for cold clouds in almost all the regions except Karachi.

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