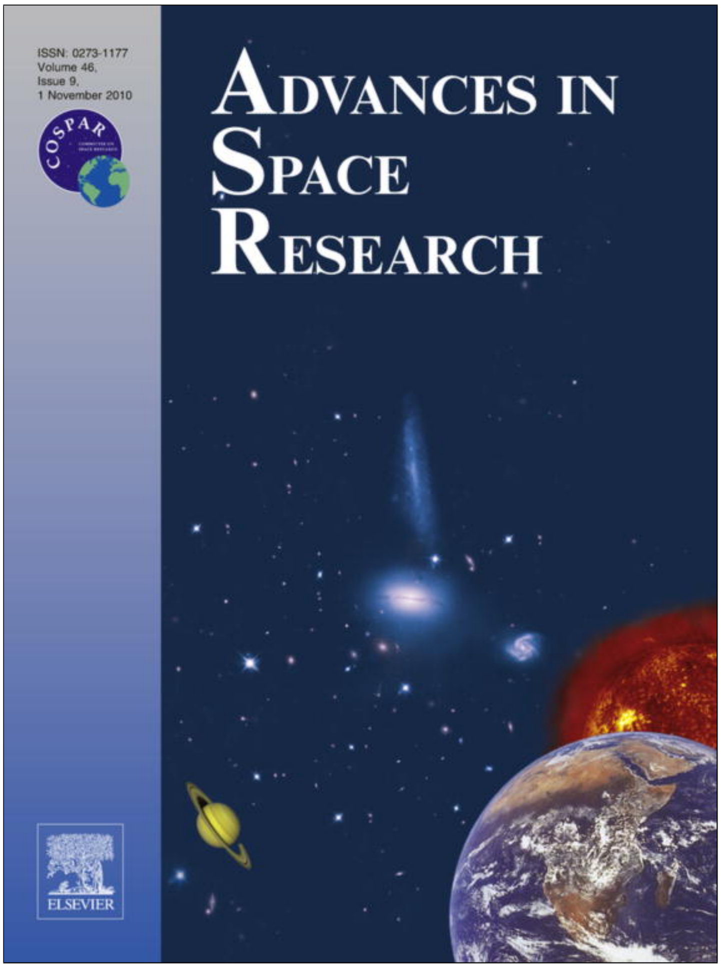
ISSN: 0273-1177
Volume 46,
Issue 9,
1 November 2010
COSPAR
ADVANCES IN
SPACE
RESEARCH
ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 46 (2010) 1162–1176
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Monitoring spatio-temporal variations in aerosols and aerosol–cloud interactions over Pakistan using MODIS data

Khan Alam [a,b,*], Muhammad Jawed Iqbal [c], Thomas Blaschke [b], Salman Qureshi [b,d], Gulzar Khan [a]

[a] Institute of Space and Planetary Astrophysics, University of Karachi, Karachi, Pakistan
[b] Department of Geography and Geology, University of Salzburg, Hellbrunnerstrasse 34, Salzburg 5020, Austria
[c] Department of Mathematics, University of Karachi, Karachi, Pakistan
[d] Department of Geography, University of Karachi, Karachi 75270, Pakistan

Received 16 September 2008; received in revised form 3 June 2010; accepted 14 June 2010

Abstract

Clouds are important elements in climatic processes and interactions between aerosols and clouds are therefore a hot topic for scientific research. Aerosols show both spatial and temporal variations, which can lead to variations in the microphysics of clouds. In this research, we have examined the spatial and temporal variations in aerosol particles over Pakistan and the impact of these variations on various optical properties of clouds, using Moderate Resolution Imaging Spectroradiometer (MODIS) data from the Terra satellite. We used the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model for trajectory analysis to reveal the origins of air masses, with the aim of understanding these spatial and temporal variabilities in aerosol concentrations. We also documented seasonal variations in patterns of aerosol optical depth (AOD) over Pakistan, for which the highest values occur during the monsoon season (June–August). We then analyzed the relationships between AOD and four other cloud parameters, namely water vapour (WV), cloud fraction (CF), cloud top temperature (CTT) and cloud top pressure (CTP). Regional correlation maps and time series plots for aerosol (AOD) and cloud parameters were produced to provide a better understanding of aerosol–cloud interaction. The analyses showed strong positive correlations between AOD and WV for all of the eight cities investigated. The correlation between AOD and CF was positive for those cities where the air masses were predominantly humid, but negative for those cities where the air masses were relatively dry and carried a low aerosol abundance. These correlations were clearly dependent on the meteorological conditions for all of the eight cities investigated. Because of the observed AOD–CF relationship, the co-variation of AOD with CTP and CTT may be attributable to large-scale meteorological variations: AOD showed a positive correlation with CTP and CTT in northern regions of Pakistan and a negative correlation in southern regions.

Keywords: Modis; Hysplit; AOD; CF; CTP; CTT

1. Introduction

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). Aerosols show both temporal and spatial variations, which can lead to variations in the optical properties of clouds. Atmospheric aerosol particles generally have variable diameters. They may be either directly emitted into the atmosphere, or formed by the oxidation of precursor gases, such as certain oxides or volatile organic compounds, where the resulting oxidation products either nucleate to form new particles or condense on pre-existing ones. Particles formed through these two routes are

* Corresponding author at: Department of Geography and Geology, University of Salzburg, Hellbrunnerstrasse 34, Salzburg 5020, Austria. Tel.: +43 664 4823199.
E-mail addresses: khan.alam@sbg.ac.at, khanalamso@gmail.com (K. Alam), salmanqureshi@uok.edu.pk (S. Qureshi).

0273-1177/$36.00 Crown copyright © 2010 Published by Elsevier Ltd. on behalf of COSPAR. All rights reserved.
doi:10.1016/j.asr.2010.06.025

referred to as primary and secondary particles, respectively (Finlayson-Pitts and Pitts, 1997; Seinfeld and Pandis, 1998). Particles in the atmosphere derive from natural sources as well as from anthropogenic activities (Seinfeld and Pandis, 1998).

Atmospheric aerosols influence the earth's weather and climatic system in many ways, both directly and indirectly, although the magnitude of this influence remains uncertain even today (IPCC, 2007). They have a direct effect through their ability to scatter and absorb solar radiation, and an indirect effect through their fundamental role in cloud microphysics. Through their indirect effect, aerosols change the size and density of cloud droplets thus modifying the cloud albedo, the cloud lifetime, and the precipitation (Twomey et al., 1984; Coakley et al., 1987; Kaufman and Nakajima, 1993; Kaufman and Fraser, 1997a,b; Ramanathan et al., 2001). Furthermore, since smaller cloud droplets are less efficient at producing precipitation than larger ones, an enhanced aerosol population will lead to a longer cloud life (Albrecht, 1989; Rosenfeld, 1999,2000). This phenomenon results in a lower rate of surface evaporation, a more stable and drier atmosphere, and consequently a reduction in cloud formation (Hansen et al., 1997).

The formation of clouds requires super-saturation, which, in the absence of aerosols, can only be realized under laboratory conditions and would not occur naturally within the atmosphere. Super-saturation is facilitated by the presence of aerosols, resulting in the condensation of water vapour onto particles. As the concentration of cloud condensation nuclei (CCN) increases, the cloud droplet number concentration (CDNC) also increases and the average cloud droplet becomes smaller and firmer, provided the amount of water vapour in the cloud remains constant.

Some absorbing aerosols may affect clouds in a quite different way, and reduce the amount of shortwave radiation arriving at the Earth's surface (Li, 1998; Li and Kou, 1998). Furthermore, heating due to absorption of solar radiation by aerosols reaches its maximum close to its uppermost level where the heating is stabilized which in turn suppresses convective activity and prevents cloud formation (Ackerman et al., 2000; Koren et al., 2004). 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, meteorological condition, with low altitude clouds influencing the AOD being one of the possibilities. Myhre et al. (2007) and Storelvmo et al. (2006) studied the indirect effects of aerosols on cloud parameters and compared modelled results with MODIS data. They found a negative correlation between AOD and Cloud Effective Radius (CER), but at the same time a positive correlation between AOD and Cloud Optical Thickness (COT).

Due to the large spatial and temporal extent of aerosols (desert dust, pollution, etc.) in the atmosphere (Rosenfeld, 2001), the interactions between aerosols and clouds can have substantial climatic impacts. This research focused on two main objectives. The first was to investigate the seasonal, temporal and spatial variations of MODIS AOD over various cities in Pakistan, including research into the origins of those air masses bringing aerosol particles to the vicinity of Pakistan. The second objective was to analyze the relationships between AOD and various cloud parameters using special correlation maps and time series plots, in order to understand the impacts of aerosols (AOD) on cloud microphysics. Brief discussions of the MODIS instrument and the HYSPLIT model are given in Section 2, followed by a delineation of the seasonal, spatial, and temporal variations in AOD and an investigation into the impacts of aerosols on cloud parameters in Section 3. Section 4 comprises a summary and the conclusions from this research.

2. Materials and methods

We retrieved AOD and cloud parameter data for the period between 2001 and 2006 from the MODIS Terra satellite. In our research, we focused on the AOD at a wavelength of 550 nm over land, as this is close to the peak of the solar spectrum and is therefore associated with major radiative effects (Papadimas et al., 2009). In addition, MODIS Aqua satellite images were acquired for June 1, 2006 and November 22, 2006. We used the HYSPLIT model (Draxler and Rolph, 2003) to determine the origins of air masses and to assess the influence that long-distance transport from various regions has on the aerosol load over Pakistani cities. Brief discussions of the MODIS instrument and the HYSPLIT model are given in the sub-sections below.

2.1. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument

The MODIS instruments onboard NASA's Terra and Aqua satellites (launched December 1999 and May 2002, respectively) have 36 spectral channels providing information on atmospheric, terrestrial, and oceanic conditions. They are useful for collecting large statistics on the impacts that aerosols have on clouds. They are also very useful in detailed studies of their local, regional, and global distributions, and their temporal dynamics, as well as for radiative forcing calculations. Aerosol retrieval is different over land (Kaufman et al., 1997) from over the oceans (Tanré et al., 1997), with MODIS aerosol retrievals over land not expected to be as accurate as over the oceans. The percentage error is thus consistently smaller over the oceans than it is over land (Remer et al., 2005). High albedo areas such as the Sahara Desert and snow or ice covered regions cause problems for the MODIS instrument, as do complex terrains, leading to a large bias in models and ground-based observations (De Meij et al., 2006).

The MODIS provides observations at moderate spatial (250–1 km) and temporal (1–2 days) resolutions over different portions of the electromagnetic spectrum. Several aerosol parameters are also retrieved at a 10 km spatial resolution from MODIS daytime data. Retrievals for cloud parameter studies have been described by Platnick et al. (2003). More detailed information on algorithms for the retrieval of aerosol and cloud parameters is available at http://modis-atmos.gsfc.nasa.gov. MODIS uses infrared bands to determine the physical properties of cloud in relation to cloud top pressure and temperature, and visible and near-infrared bands to determine optical and microphysical cloud properties (Jin and Shepherd, 2008). We selected four parameters (namely water vapour, cloud fraction, cloud top temperature and cloud top pressure) to investigate the impacts of aerosols on clouds. The monthly MODIS/Terra Level 3 product (version 005) with 1×1 degree spatial resolution (Dataset ID: MOD08_D3.005) was obtained from the NASA DAAC website http://disc.sci.gsfc.nasa.gov/giovanni.

2.2. The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model

In this study, the HYSPLIT model was used in combination with archived data to predict the path of an air parcel prior to its arrival at a given location, in what is known as a back-tracing or 'backward trajectory' approach. The meteorological input for the trajectory model was from the FNL dataset (reprocessed from the National Oceanic and Atmospheric Administration (NOAA) National Centre for Environmental Prediction's Final Analysis data by Air Resources Laboratory). In addition, several different pre-processor programs exist to convert NOAA, NCAR (National Centre for Atmospheric Research) re-analysis, ECMWF (European Centre for Medium-range Weather Forecasts), MM5 (The fifth generation NCAR/Penn state Mesoscale Model), and WRF (weather research and forecasting) model output fields into a format compatible for direct input into the model.

The HYSPLIT model has the ability to calculate up to 40 forward or backward trajectories at different altitudes, depending upon the user-requirements, with a horizontal grid of $1.5° \times 1.5°$ and a resolution of 500×500 m. In this study, the backward trajectories were calculated at 500, 1000, and 1500 m heights above-ground level to investigate the origin of air masses bringing particulate matter (such as desert dust, sea salt) into the various cities of Pakistan. The model can be run interactively from the website (http://ready.arl.noaa.gov/HYSPLIT.php). The web version has been configured with some limitations to avoid computational saturation of the web server. The registered PC version is complete, with no computational restrictions, but the user must obtain the necessary meteorological data files in advance. The unregistered version is identical to the registered version except that it will not work with forecasted meteorology data files.

3. Results and discussions

The spatial distribution of annual mean AOD at a wavelength of 550 nm has been plotted for the period from 2001 to 2006 (see Fig. 1a). This figure shows that aerosols had a marked impact on eight cities in Pakistan, namely Peshawar, Rawalpindi, Zhob, Lahore, Multan, D.G. Khan, Rohri and Karachi. Only these cities were included in this research, chosen because they cover large areas and are densely populated, producing high levels of emissions that result in high AOD values (Fig. 1b). These regions of Pakistan are of particular interest in this field of research because of the extreme variations in their geo-strategic locations, which result in the different weather patterns that, in turn, affect the aerosol load in each area.

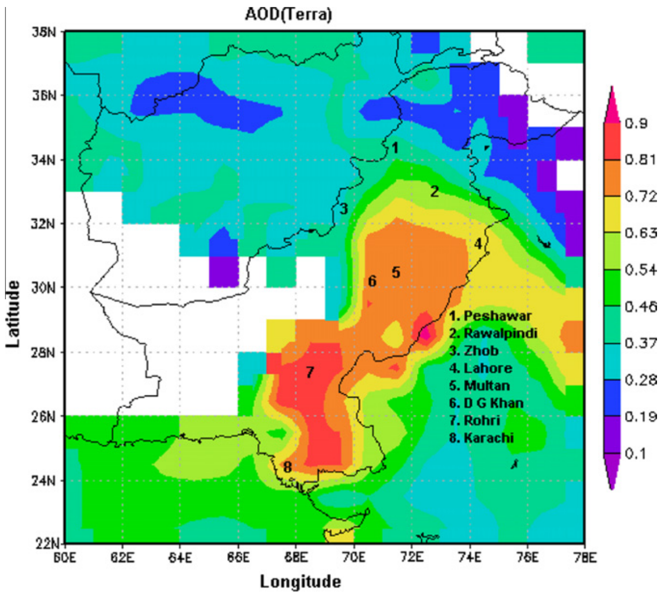

Fig. 1a. Spatial distributions of annual mean AOD at 550 nm for the period from 2001 to 2006.

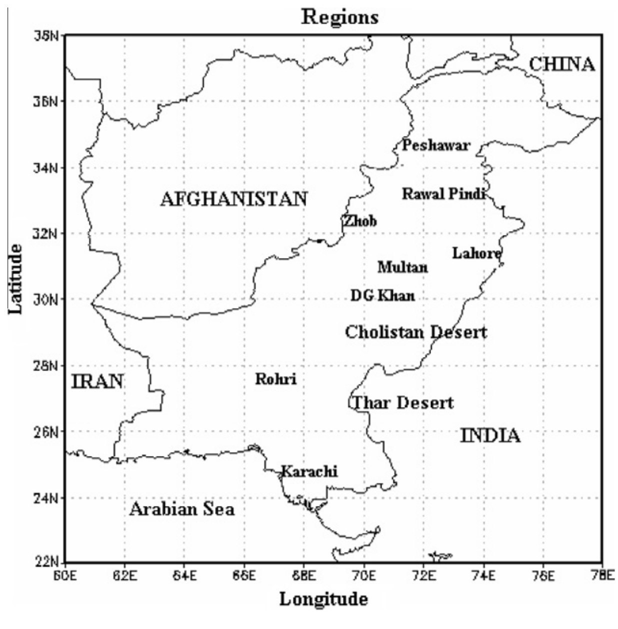

Fig. 1b. Geographical regions used in this study.

Table 1
MODIS (Terra) mean and standard deviation of AOD measured in some cities of Pakistan for different seasons during the period 2001–2006.

Regions	Mean AOD at 550 nm and SD			
	Winter	Autumn	Spring	Summer
Peshawar	0.26 ± 0.03	0.36 ± 0.08	0.34 ± 0.05	0.57 ± 0.11
Rawalpindi	0.22 ± 0.03	0.32 ± 0.09	0.35 ± 0.08	0.58 ± 0.14
Zhob	0.15 ± 0.03	0.27 ± 0.08	0.35 ± 0.07	0.52 ± 0.07
Lahore	0.42 ± 0.10	0.63 ± 0.10	0.57 ± 0.18	0.78 ± 0.25
Multan	0.52 ± 0.08	0.73 ± 0.14	0.69 ± 0.26	0.86 ± 0.26
D.G. Khan	0.46 ± 0.07	0.66 ± 0.12	0.65 ± 0.24	0.81 ± 0.27
Rohri	0.56 ± 0.06	0.61 ± 0.13	0.80 ± 0.25	0.92 ± 0.35
Karachi	0.26 ± 0.05	0.37 ± 0.15	0.41 ± 0.14	0.80 ± 0.34

3.1. Seasonal variations in aerosol optical depth (AOD)

Seasonal variations in AOD were analyzed for the eight cities selected. The mean AOD and standard deviation at 550 nm were calculated for the period 2001–2006 (Table 1). Very high mean AOD values were observed in almost all regions during the summer season, particularly in the southern parts of Pakistan which had an AOD greater than 0.9. Similar increases in AOD during the summer season have previously been reported for that portion of Pakistan situated between 22–25°N and 60–75°E (Munir and Zareen, 2006). Peshawar, in the north-west of Pakistan, has a mean AOD value of 0.258 and a standard deviation (SD) of ±0.037 in winter and 0.573 (SD ± 0.111) in summer. The city of Zhob has relatively clean air as the mean AOD is 0.154 (SD ± 0.038) in winter and 0.527 (±0.071) in summer. The AOD values generally increase from north to south, although the densely populated city of Lahore has a mean AOD of 0.424 (SD ± 0.107) in winter and 0.782 (SD ± 0.255) in summer. In comparison to Lahore Multan and D.G. Khan reveal very high average AOD values with mean AOD values in winter of 0.523 (SD ± 0.082) and 0.459 (SD ± 0.076), respectively, and in summer of 0.867 (SD ± 0.260) and 0.811 (SD ± 0.273). Rohri, which is the hotspot of dust aerosols, has the highest mean AOD value (0.920) in summer and also a high standard deviation (±0.352). In the south of Pakistan, Karachi reveals a mean AOD value of 0.256 in winter (SD ± 0.054) and a very high value of 0.801 in summer (SD ± 0.342), which can be attributed to the fact that it is a large urban, industrial area but at the same time a coastal city.

Seven-day backward trajectories starting from Karachi, Rohri, Multan, D.G. Khan and Lahore at 2300 h UTC and at altitudes of 500, 1000 and 1500 m above-ground level (AGL) were analyzed; examples of typical air mass backward trajectories are shown in Fig. 2. The AOD observed for these seven day backward trajectories was extremely high. The air masses that arrived at Karachi carried sea salt particles from the Arabian Sea and desert dust from the Dasht Desert in Iran, combined with industrial and vehicular pollution, which resulted in the elevated AOD values observed. The MODIS Aqua satellite captured an image of a dust storm that blew out over the Arabian Sea from the coast of Pakistan on June 1, 2006 (NASA Earth Observatory, 2006). The dust appears thickest to the south-west of Pakistan and some cloud cover also appears in the east

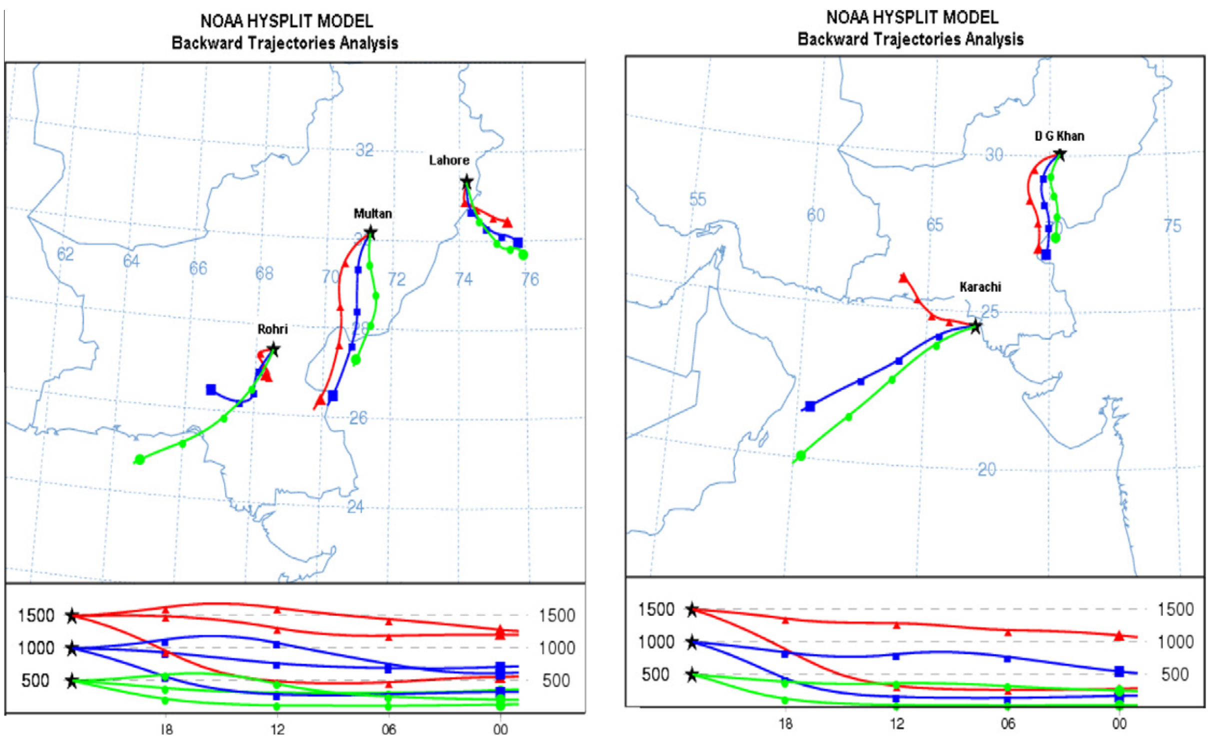

Fig. 2. Examples of typical air mass back trajectories of different heights in meters ending at 2300 UTC for Karachi, Multan, Lahore, Rohri, and D.G. Khan.

(Fig. 3a). The air masses arriving at Lahore from the Thar Desert in India carried dust particles which amalgamated with industrial and vehicular emissions to produce the high observed AOD values. A similar study was conducted by Biswas et al. (2008), who observed that pollutants emitted from factory stacks in Lahore, as well as neighbouring regions in Pakistan and western India, are the major sources of atmospheric aerosols over Lahore. In Multan and D.G. Khan, the highest AOD values were observed during the summer, with air masses arriving from both the Thar Desert in India and the Cholistan Desert in Pakistan. Similarly, high AOD values were found at the Rohri arid suburban site, with air masses arriving from the Arabian Sea as well as the Thar Desert, and combining with locally derived particulate matter. It can be concluded that aerosols from a variety of sources, such as desert dust, industrial emissions, vehicular emissions, and locally derived dust, amalgamate to increase the total AOD values in the cities of Pakistan.

The seasonal variation in AOD over Pakistani cities for the year 2006 is plotted in Fig. 4 (white grid shows that data are missing). The AOD can be seen to have increased from the month of April, reaching a maximum in the month of July followed by a decrease starting in September to a minimum in December. The windy winter weather in southern parts of Pakistan during November can, however,

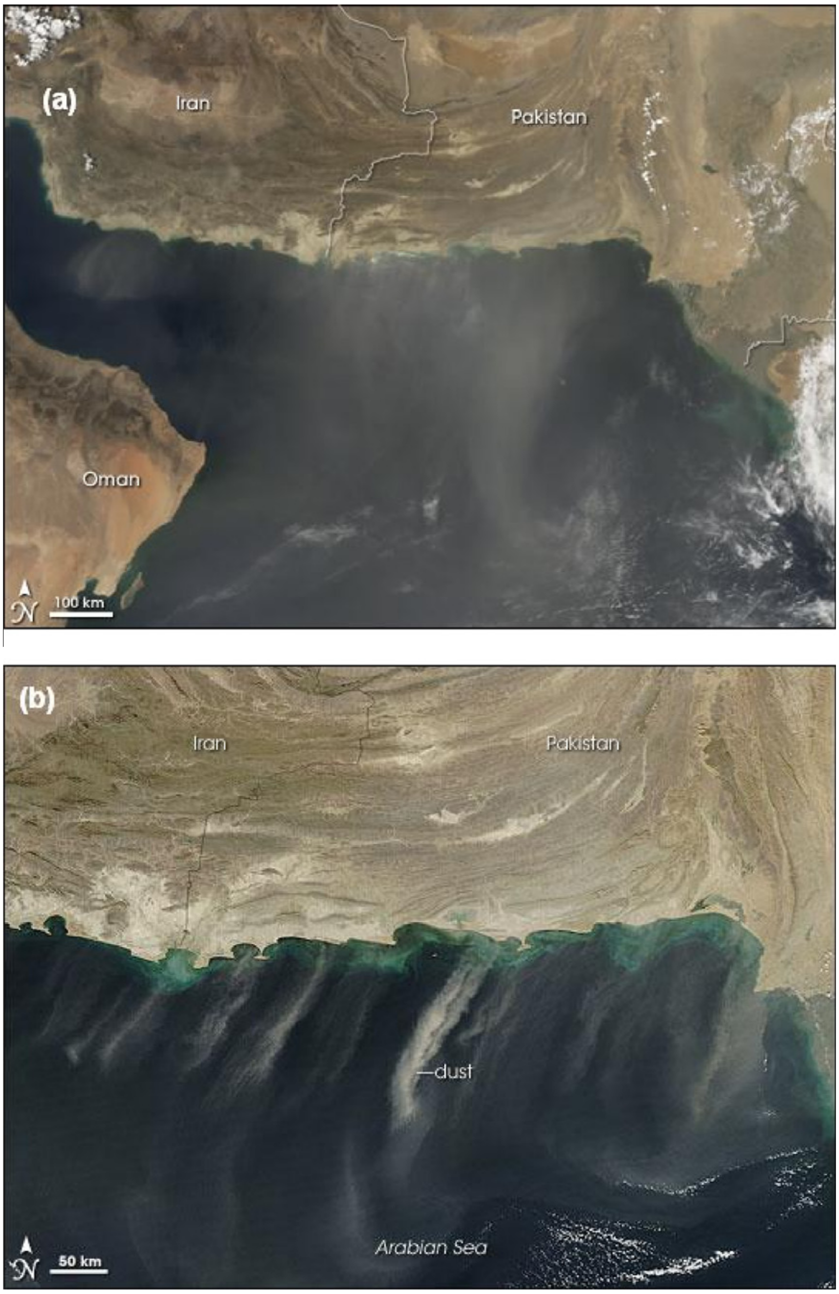

Fig. 3. (a) MODIS Aqua dust storm on June 1, 2006 and (b) On November 22, 2006 Over Arabian Sea.

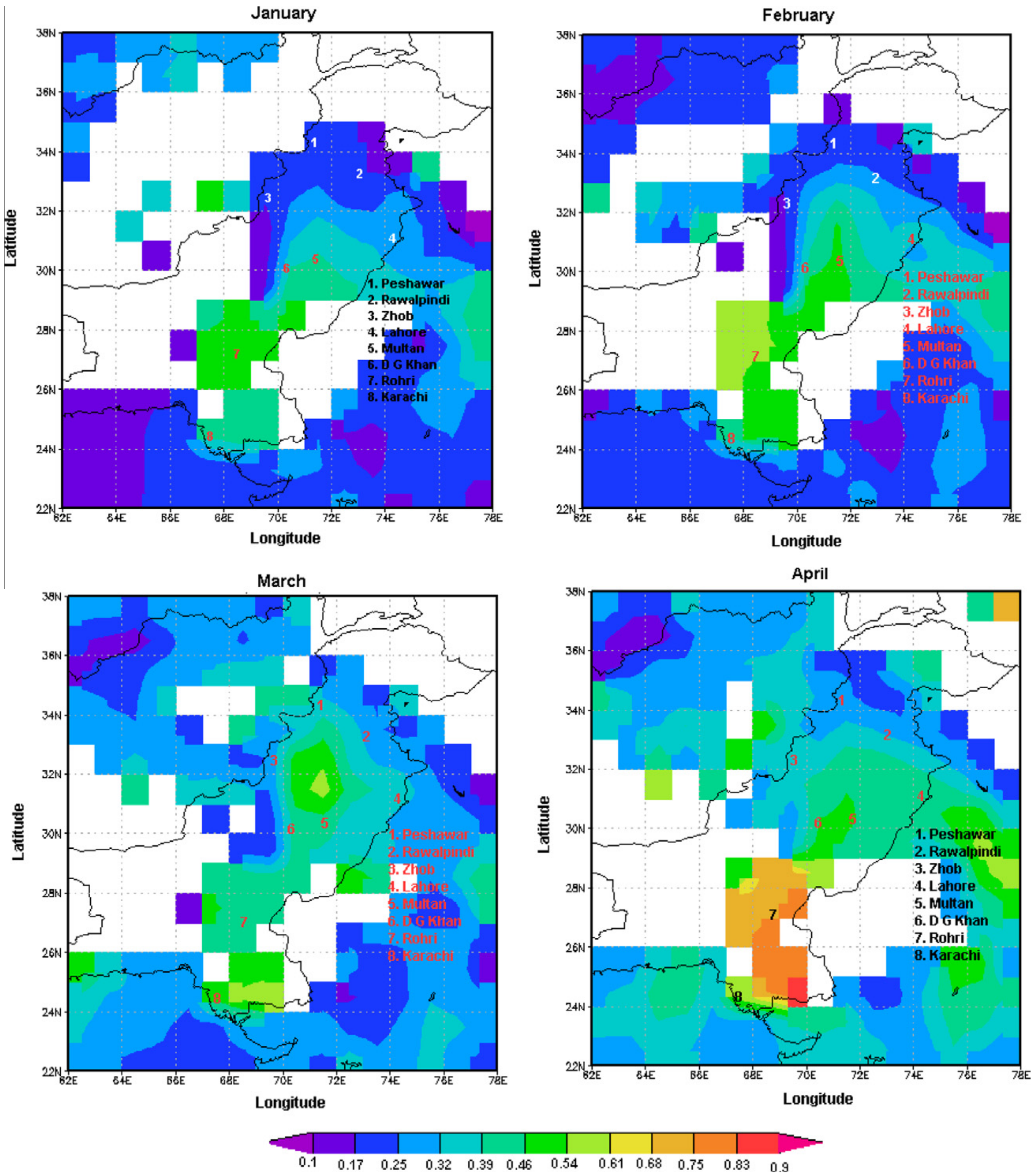

Fig. 4. Monthly mean AOD retrieved from MODIS for the year 2006 over Pakistan cities.

cause a small increase in AOD, such as that due to plumes of dust that blew off the coast from Pakistan and Iran on November 22, 2006 (Fig. 3b). The MODIS Aqua satellite captured an image of these dust plumes blowing over the Arabian Sea on that date (NASA Earth Observatory, 2006), in which the dust appears as elongated, pale beige clouds heading towards the south-west, with the thickest plume blowing from Pakistan, some 500 km east of the border with Iran. Other reasons investigated for the increases in aerosol concentrations during November involved some short-term weather disturbances. These short-term local disturbances are due to conventional currents and contrasts in weather conditions, such as extremely high temperatures, diurnal temperature ranges, and differences in humidity, which cause thunderstorms (with occasional heavy rain), dust storms (in particular) and extreme weather conditions. They occur during transition stages between two seasons, i.e. between March and

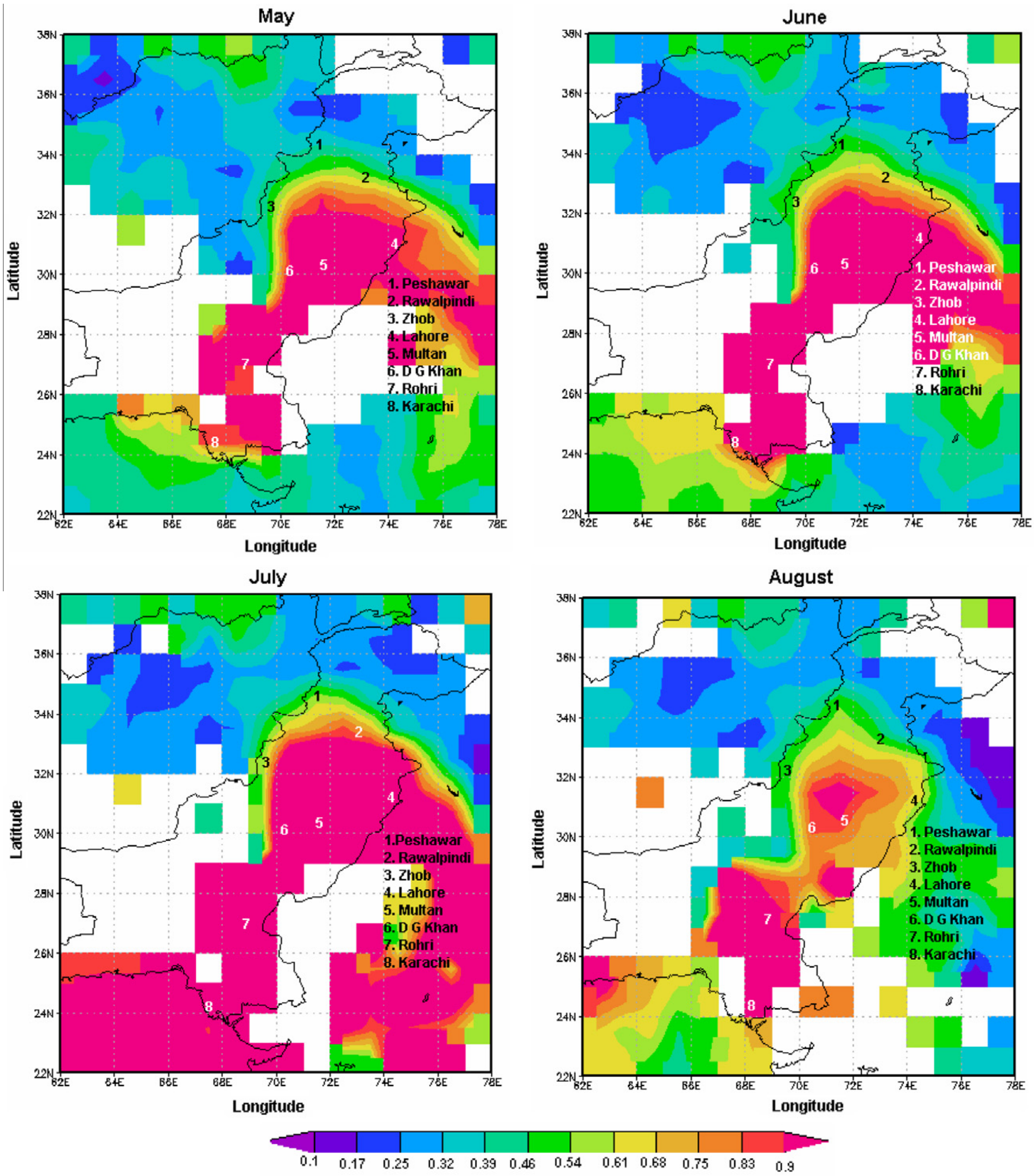

Fig. 4 (*continued*)

May, or September and November (Arsalan, 2002; Pithawalla, 1946; Qureshi, in press).

The maximum seasonal variation in AOD was observed in the southern parts of Pakistan, specifically over Rohri and Karachi, while variations in AOD were found to be lower in the north. During spring and autumn the AOD had a similar seasonal distribution in most regions, whereas during the winter and summer seasons the distribution shifted from low AOD values in winter to high values in summer (see Table 1). A similar seasonal variation was found on the Indian subcontinent by Prasad et al. (2004). Aerosol levels in the southern parts of Pakistan were much higher than in remote rural areas further north because of increases in urbanization and industrialization, dust storms, and salt particles blowing from the sea. Similar studies have been conducted by Kuniyal et al. (2009) and Aloysius et al. (2009), who concluded that the temporal and spatial variations in AOD were highly dependent

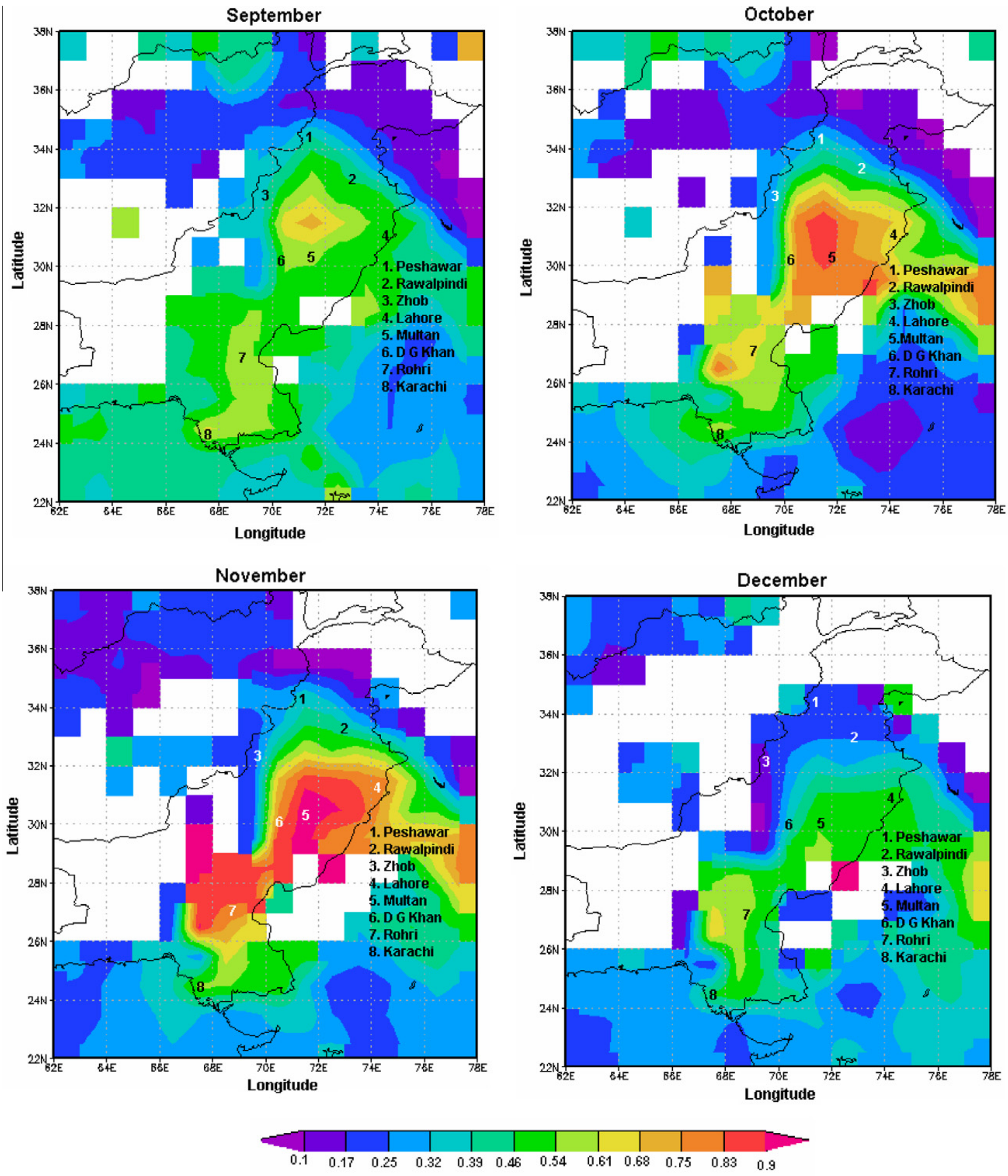

Fig. 4 (*continued*)

on both the travel pathways and the sources (e.g., desert dust, sea salt, smoke from burning biomass, and industrial pollution) of the air masses.

3.2. Relationships between aerosol optical depth and cloud parameters

This section deals with the relationships between AOD and cloud parameters for the eight selected Pakistani cities, through the use of spatial correlation. We used AOD as a surrogate for aerosol concentration and calculated the correlation coefficient for each set of parameters on a monthly basis, averaged annually, for the period from 2001 to 2006. Regional comparisons were conducted using correlation maps for the entire area. We also examined the relationships between AOD and cloud parameters using time series plots. Discussions of each of these relationships are presented individually in the following sub-sections.

3.2.1. Relationship between aerosol optical depth and water vapour

The MODIS retrievals provide separate column water vapour data for clear skies and for above clouds. We used the Terra above clouds data for water vapour for the period between 2001 and 2006. The spatial correlation between AOD and WV shown in Fig. 5a reveals that AOD and WV have a stronger positive correlation at higher latitudes than at lower latitudes. The highest positive correlations (correlation coefficient greater than 0.8) were found for both Peshawar and Rawalpindi, whereas lower levels of correlations greater than 0.7 were found for the other cities. The correlation coefficients between AOD and WV are listed in Table 2, and are positive for all eight of the cities investigated. The time series plot for AOD and WV (see Fig. 6) also shows these two parameters increasing and decreasing simultaneously. In Fig. 6 the AOD values higher than 1.0 are most probably contaminated with clouds. Uncertainty in AOD can occur due to contamination by both high altitude cirrus clouds and low altitude clouds (Kaufman et al., 2005a,b): cirrus clouds can increase the measured AOD by up to 0.015 ± 0.003 at 550 nm.

As discussed in Section 3.1, backward trajectory analysis suggests that the increase in summertime aerosol sources should result in higher AOD values in summer than during

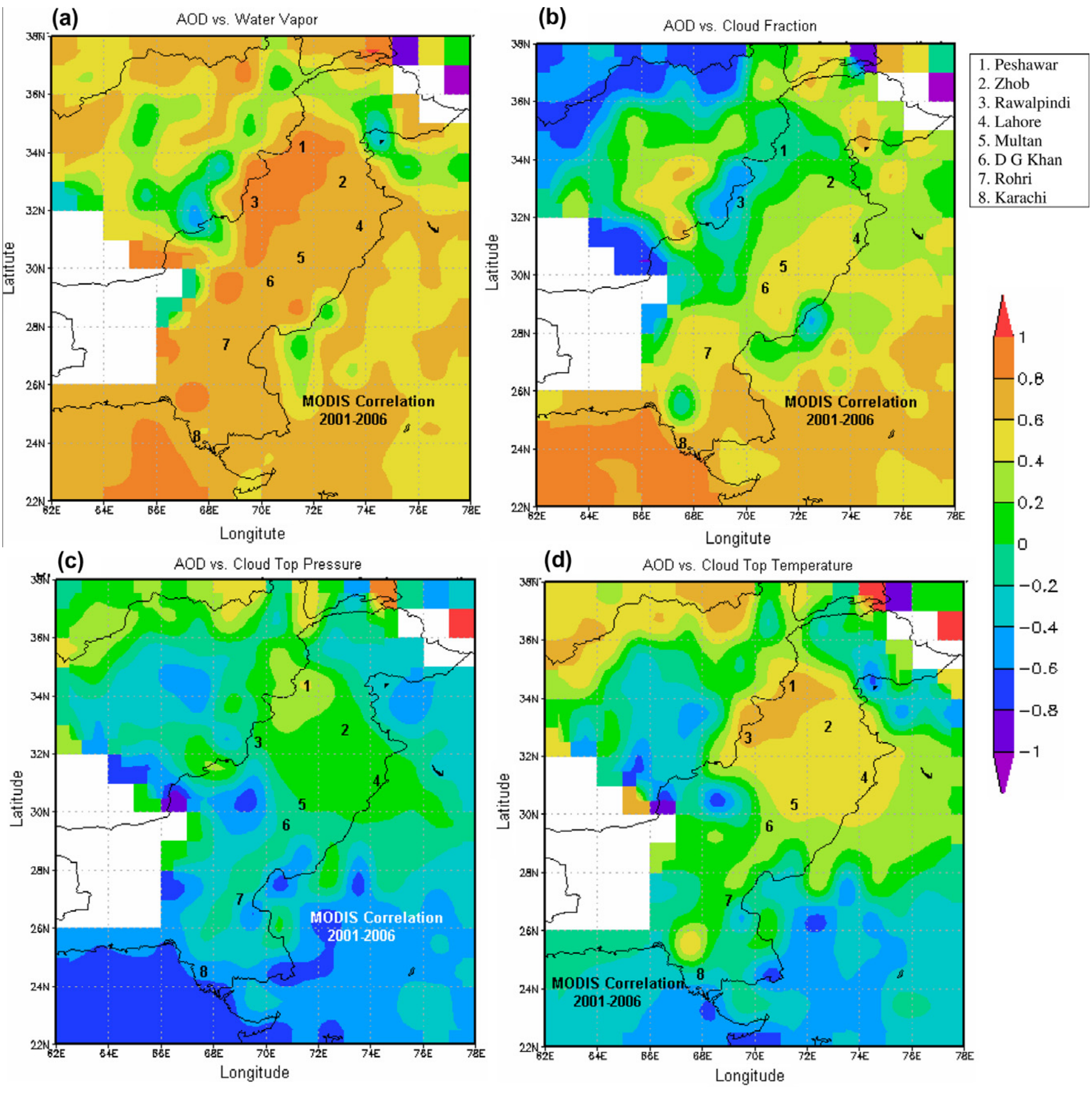

Fig. 5. Spatial correlation for AOD vs. (a) WV, (b) CF, (c) CTP, (d) CTT for the period 2001–2006.

Table 2
Correlation for aerosol optical depth (AOD) vs. cloud parameter.

Regions	Aerosol optical depth (AOD) vs.			
	WV	CF	CTP	CTT
Peshawar	0.88	0.20	0.44	0.73
Rawalpindi	0.84	0.39	0.07	0.53
Zhob	0.71	−0.37	−0.01	0.60
Lahore	0.74	0.57	0.04	0.40
Multan	0.78	0.56	0.03	0.48
D.G. Khan	0.81	0.29	−0.14	0.34
Rohri	0.71	0.51	−0.21	0.14
Karachi	0.72	0.85	−0.69	−0.37

the remainder of the year. We observed that WV is also higher during the summer, matching the increase in AOD and indicating the possibility of hygroscopic growth of aerosols. This is consistent with results obtained by Ranjan et al. (2007) in the neighbouring country of India. On the other hand, dust aerosols are less common or even absent in the atmosphere during the winter and, as a result, we also see less WV. It has been observed that the water-absorbing ability of aerosols varies for different types of aerosol. Shi et al. (2008) found that dust particles, which are dominant in the coarse fractions of aerosols, are mostly insoluble but can be hygroscopic if they become coated with sulphate or other soluble inorganic aerosols during transport. Mineral dust particles with a nitrate coating are also reported to be hydrophilic, while those without coating are commonly hydrophobic (Li and Shao, 2009). The hygroscopic nature of aerosols therefore depends upon the particular mixing of different types of particles as well as on meteorological parameters such as humidity, wind speed, wind direction, and temperature (Aloysius et al., 2009).

The water uptake of atmospheric aerosols is important as it can have a number of consequences: it can alter both the size and the chemical composition of particles, and consequently their optical properties. As an example of these consequences, Ogren and Charlson (1992) and Randles et al. (2004) have shown the effect of moisture on the scattering behaviour of aerosols. Cloud formation also depends on the amount of water vapour available for con-

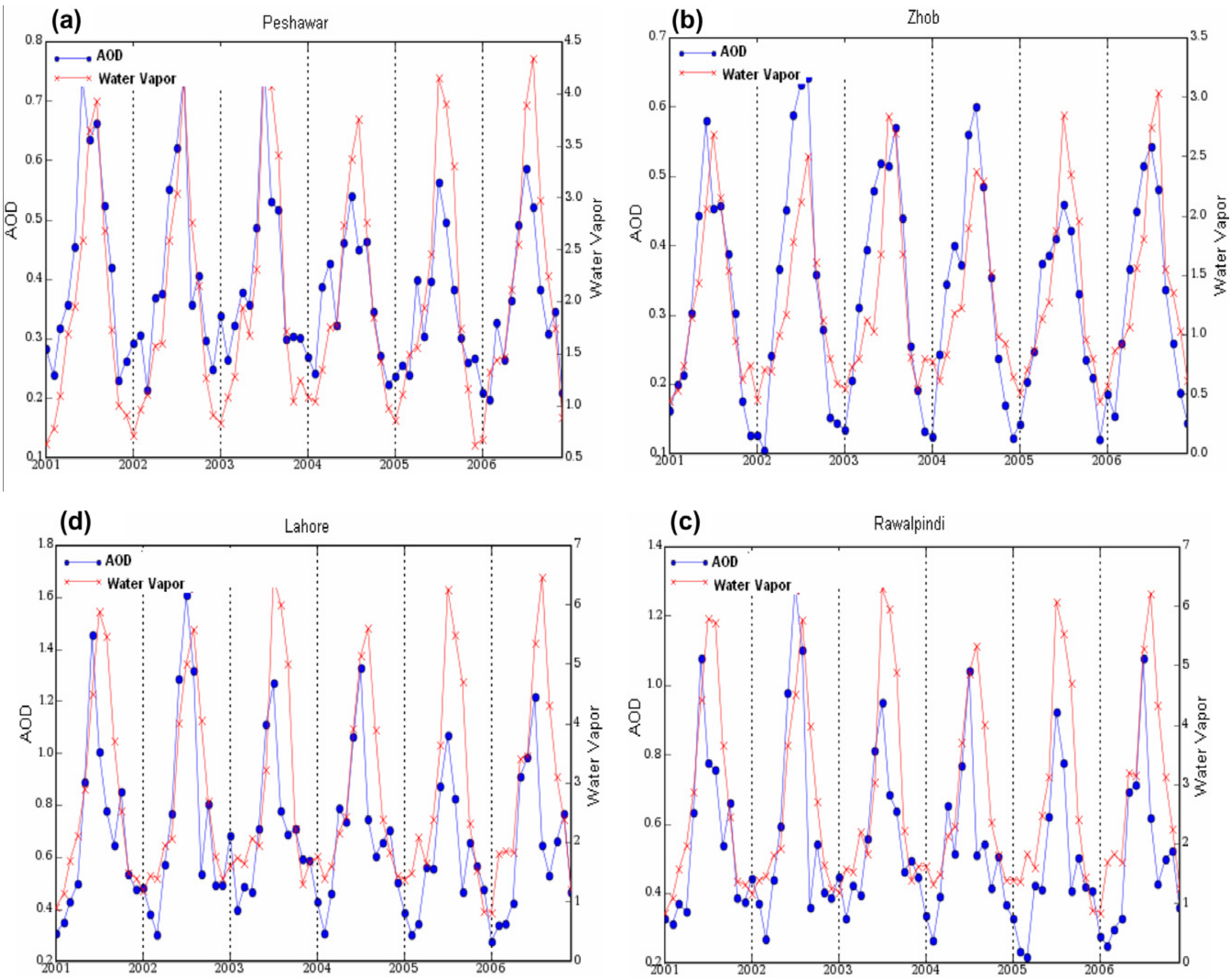

Fig. 6. Time series of area averaged of AOD and water vapour (cm) for eight cities of Pakistan for the period 2001–2006.

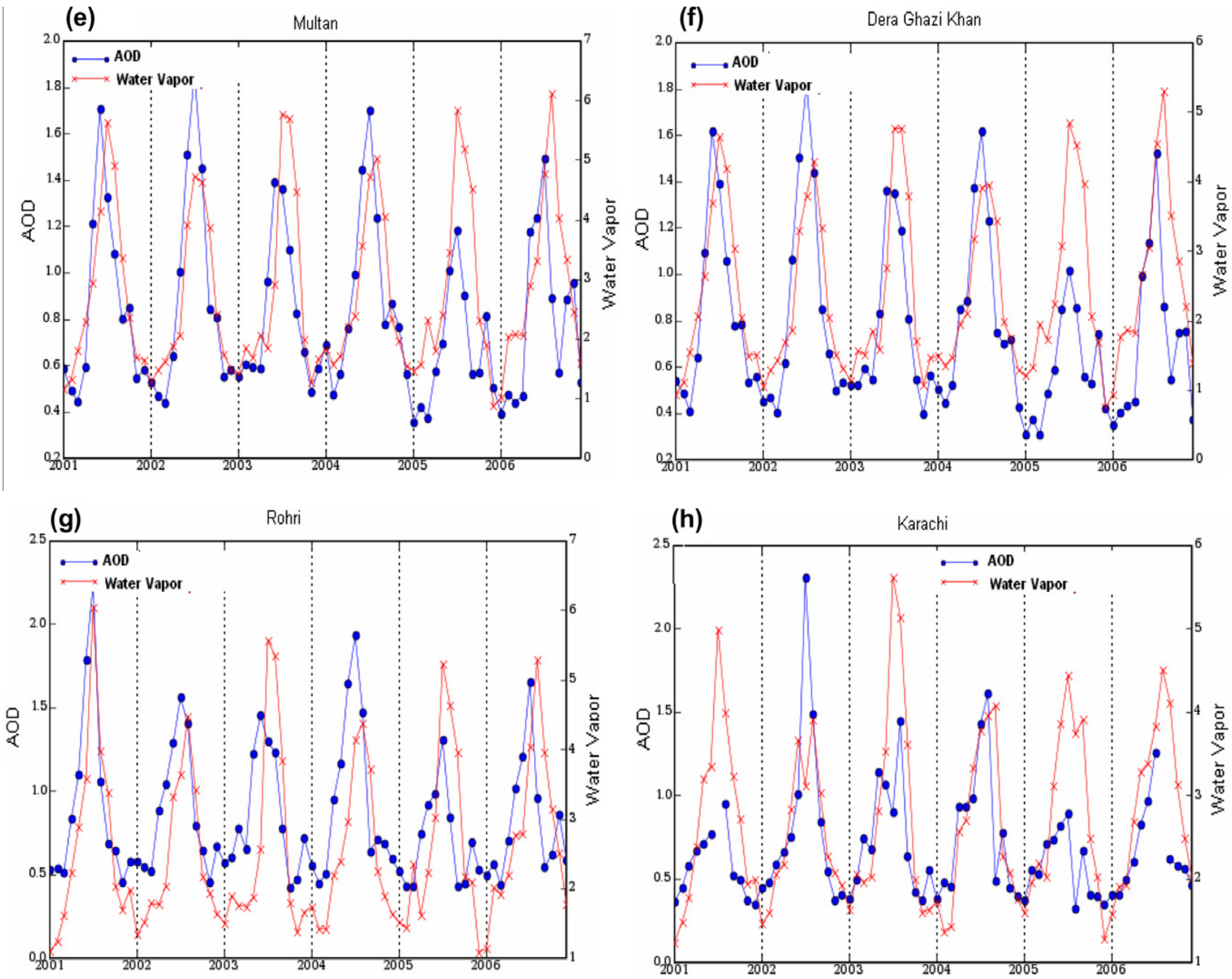

Fig. 6 (*continued*)

densation onto hydrophilic aerosols. Changes in aerosol water uptake behaviour can therefore, at least potentially, lead to changes in both direct and indirect radiative forcing on climate (IPCC, 2001). This water uptake on aerosols is therefore an important topic for aerosol modelling and for remote sensing, but one that carries many uncertainties.

3.2.2. Relationship between aerosol optical depth and cloud fraction

MODIS provides CF (or cloud cover) data for daytime and night-time, either separately or together: we used the combined data for our analysis. Our spatial correlation results for CF as a function of AOD, for the years from 2001 to 2006, are shown in Fig. 5b. Correlation coefficients for AOD and CF (see Table 2) were also calculated for this 6 year period: the correlation between cloud cover and AOD was found to be higher at lower latitudes and lower at higher latitudes. For example, the correlation between AOD and CF was greater than 0.96 in Karachi, whereas in Peshawar and Rawalpindi it was less than 0.3 and in some cases less than zero. It is also important to mention the marked increase in the correlation between CF with AOD in those regions dominated by biomass and dust aerosols, indicating that meteorological factors are influencing the relationship. Kaufman et al. (2005a,b) investigated the effects on cloud cover of meteorological parameters and found that it was influenced mainly by the air temperature at 1000 hPa of atmospheric pressure, temperature differences at 1000–750 hPa of atmospheric pressure, the AOD, the sea surface temperature, and the winds. Rosenfeld et al. (2001) found that those clouds formed in smoke typically showed slower growth of cloud particles and precipitation with altitude than dusty clouds. Desert dust formed clouds dominated by small droplets (effective radii <14 μm), led to little coalescence and suppressed precipitation.

Time series plots for spatial averages of AOD and CF (see Fig. 7) show that CF increased with AOD at all locations except for Karachi, where throughout the whole 6 year period (2001–2006) CF increased with AOD in July but in January the relationship became negative as CF increased but AOD decreased. This negative correlation

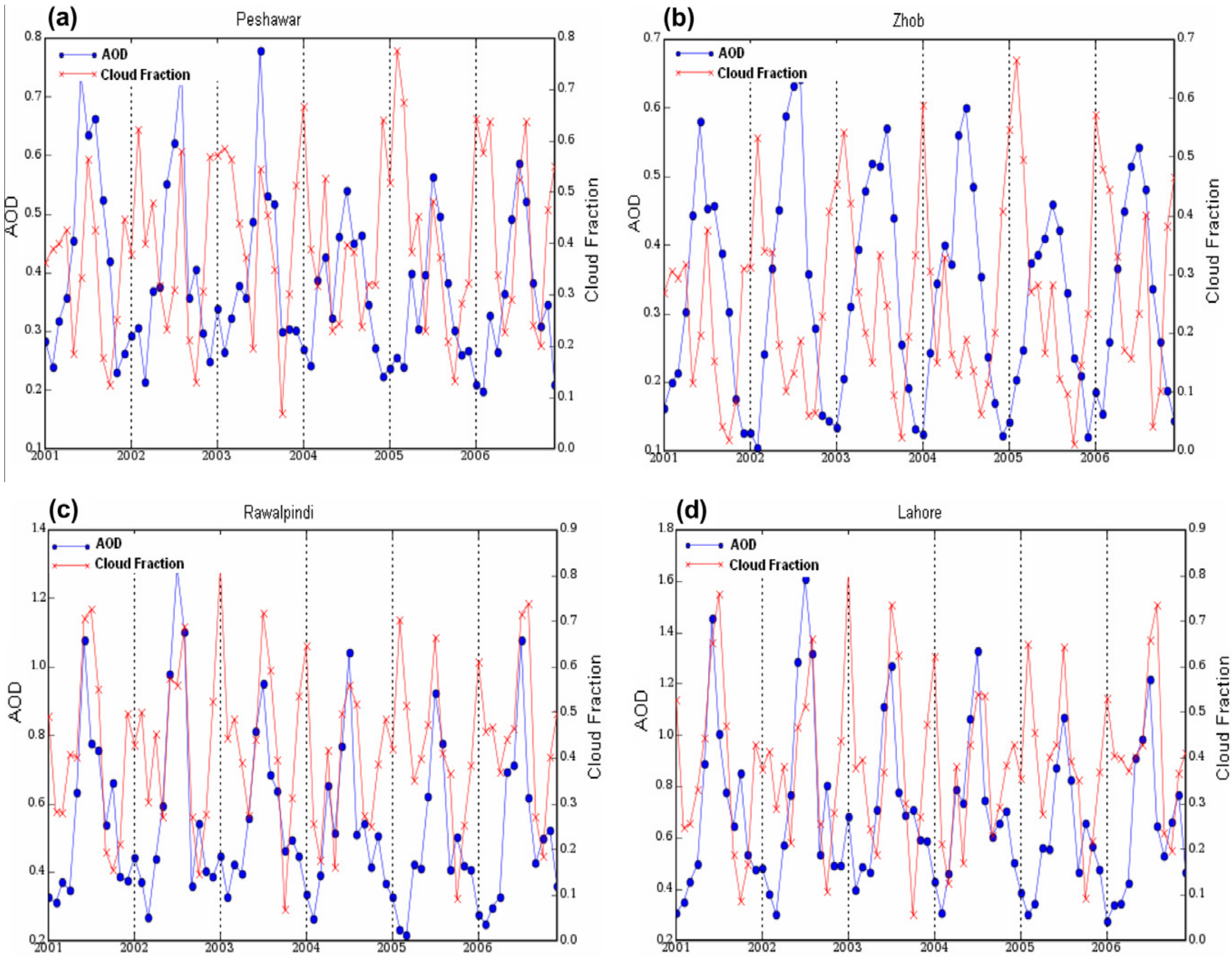

Fig. 7. Time series of area averaged of AOD and CF for eight cities of Pakistan for the period 2001–2006.

only occurred when the AOD fell below 0.3. As in our results regarding the relationship between AOD and WV, Myhre et al. (2007) found that an increase in relative humidity (RH) increased the AOD due to greater water uptake by the particles. Since RH is usually higher close to clouds than in areas of clear sky, an increase in CF with AOD may be a reflection of this effect. Kaufman et al. (2005a,b) investigated cloud cover increases in association with increases in aerosol concentrations and found that cloud properties change as a result of variations in large-scale atmospheric circulation that may also affect aerosol concentrations. For example, regions of low atmospheric pressure are convergence zones that tend to accumulate aerosols and water vapour, thus generating conditions favourable for cloud formation (Kaufman et al., 2005a,b; Chou et al., 2002).

In summary, the correlation between AOD and CF was high (correlation coefficient = 0.85) over the ocean and slightly lower but always positive towards to border with Afghanistan. This could be related to the complexity of the domain, the type of land surface (i.e. its 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 aerosol optical depth and cloud top pressure

CTP showed a negative correlation with AOD in the southern region of Pakistan (see Table 2). The spatial correlation between AOD and CTP has been plotted for the various cities of Pakistan over the period 2001–2006 (see Fig. 5c). It was observed that at lower latitudes there was a significant decrease in CTP relative to AOD (i.e. a negative correlation), while at mid-latitude this decrease was only moderate. At higher latitudes, AOD and CTP showed a positive correlation. Several studies (Myhre et al., 2007; Kaufman et al., 2005a) have reported that, except for some regions of low AOD, CTP decreased in most of the cities (higher cloud altitude) as AOD increased. This may 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 (Myhre

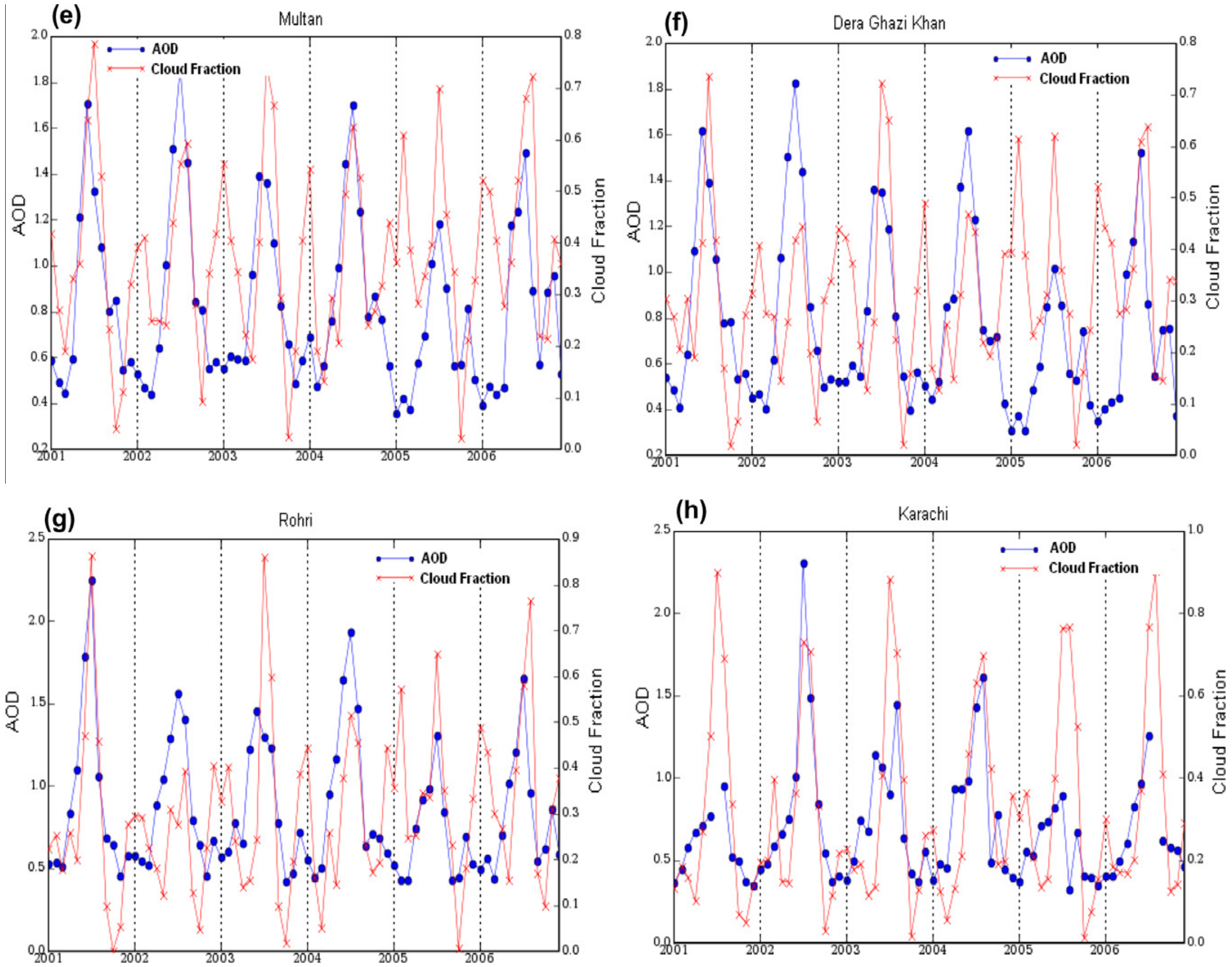

Fig. 7 (*continued*)

et al., 2007). In southern regions, CTP decreased as AOD increased.

3.2.4. Relationship between aerosol optical depth and cloud top temperature

The spatial correlation shown in Fig. 5d indicates that CTT increased as AOD increased in almost all regions investigated except for Karachi. As discussed in Section 3.2.2, AOD and CF showed a strong positive correlation over Karachi (correlation coefficient greater than 0.8); AOD and CTT, however, showed a negative correlation over the same area. Because of the CF–AOD relationship, co-variation of AOD with CTT due to large-scale meteorology might be ruled out as primary reason for the correlation found in MODIS data (Quass et al., 2009). There was a positive correlation between AOD and CTT at Peshawar, Zhob and Rawalpindi (see Table 2) indicating a consistent positive correlation at higher latitudes, whereas at Karachi (lower latitude) AOD and CTT showed a negative correlation. Overall, however, there was positive correlation between AOD and CTT, with meteorological situations being interpreted as the causative factors for the observed variations.

4. Conclusion

Using MODIS satellite data, the spatial and temporal (seasonal) variability of aerosols has been investigated in order to develop an understanding of the impact of aerosols on cloud parameters. The maximum AOD values were found in the summer, with lower values observed in winter for all of the selected cities. The highest AOD levels were found in the southern part of Pakistan because of vehicular and industrial emissions combining with sea salt particles blown from the Arabian Sea and dust particles blown from the Thar Desert during the windy summer months. Hygroscopic aerosols increased the AOD over the southern coastal areas of Pakistan during the humid summer season. It was found that the water vapour increased as AOD increased over almost all of the investigated cities of Pakistan. CF was found to increase together with AOD in those regions dominated by biomass and dust aerosols, whereas in regions dominated by marine and pollution aerosols there was good correlation between CF and AOD when AOD was below ~0.2 but a weaker correlation for higher AOD. CTP and AOD showed a negative correlation except in a few cities at higher latitudes. The suppression of the precipitation therefore impacts on cloud reflectivity by changing the CTP through a mechanism described by Myhre et al. (2007). CTT showed a positive correlation with AOD for the northern cities of Pakistan, but a negative correlation for the southern cities.

This study has some limitations as ground-based data is not available for the whole region. Ground-based data from the Aerosol Robotic Network (AERONET) is only available for two cities (Karachi and Lahore), and only for limited time-spans. It is therefore recommended that further research should integrate the ground-based data in order to develop a micro-scale understanding of the interactions investigated. Furthermore, in order to tackle radiative forcing due to the effects of WV in the troposphere, additional remote sensing data should also be integrated. Differentiation between low-level and high-level clouds, for example, by using infrared satellite data to detect the presence of cirrus clouds or determine overall cloud thickness (Chakrapani et al., 2002) would be beneficial in the quantification of AOD.

Acknowledgement

We would like to thank Pierre Madl (Institute of Physics and Biophysics University of Salzburg, Austria), Ms. Rizla Zareen and Siraj Munir (SUPARCO, Pakistan) for their erudite suggestions. We gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT model used in this study. The images used in this paper were acquired using GES-DISC's interactive online visualization and analysis infrastructure ('Giovanni') as a part of NASA's Goddard Earth Sciences (GES) Data and Information Services Centre (DISC).

References

Ackerman, A.S., Toon, O.B., Stevens, D.E., Heymsfield, A.J., Ramanathan, V., Welton, E.J. Reduction of tropical cloudiness by soot. Science 288, 1042–1047, 2000.

Albrecht, B. Aerosol, cloud microphysics, and fractional cloudiness. Science 245, 1227–1230, 1989.

Aloysius, M., Mohan, M., Babu, S.S., Parameswaran, K., Moorthy, K.K. Validation of MODIS derived aerosol optical depth and an investigation on aerosol transport over the South East Arabian Sea during ARMEX-II. Ann. Geophys. 27, 2285–2296, 2009.

Arsalan, M.H. Monitoring spatial patterns of air pollution in Karachi metropolis: A GIS perspective. Ph.D. dissertation, University of Karachi, Pakistan, 2002

Biswas, K.F., Ghauri, B.M., Hussain, L. Gaseous and aerosol pollutants during fog and clear episodes in South Asian urban atmosphere. Atmos. Environ. 42, 7775–7785, 2008.

Chakrapani, V., Doelling, D.R., Rapp, A.D., Minnis, P. Cloud thickness estimation from GOES-8 satellite data over the ARM-SGP site, in: Twelfth ARM Science Team Meeting Proceedings. St. Petersburg, Florida, 2002.

Chou, M.-D., Chan, P.-K., Wang, M. Aerosol radiative forcing derived from SeaWiFS-retrieved aerosol optical properties. J. Atmos. Sci. 59, 748–757, 2002.

Coakley, J.A., Bernstein, R.L., Durkee, P.A. Effects of ship stack effluence on cloud reflectance. Science 237, 953–1084, 1987.

De Meij, A., Krol, M., Denterner, F., Vignati, E., Cuvelier, C., Thunis, P. The sensitivity of aerosol in Europe to two different emission inventories and temporal distribution of emission. Atmos. Chem. Phys. 6, 4287–4309, 2006.

Draxler, R.R., Rolph, G.D. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website (http://www.arl.noaa.gov/ready/hysplit4.html). NOAA Air Resources Laboratory, Silver Spring, MD, 2003.

Finlayson-Pitts, B.J., Pitts, J.N. Tropospheric air pollution: Ozone, airborne toxics, polycyclic aromatic hydrocarbons, and particles. Science 276, 1045–1052, 1997.

Hansen, J., Sato, M., Ruedy, R. Radiative forcing and climate response. J. Geophys. Res. 102, 6831–6864, 1997.

IPCC. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, United Kingdom, New York, NY, USA, p. 881, 2001.

IPCC. Climate Change: The Physical Science Basis. Cambridge University Press, New York, pp. 131–216, 2007.

Jin, M., Shepherd, J.M. Aerosol relationships to warm season clouds and rainfall at monthly scales over east China: Urban land versus ocean. J. Geophys. Res. 113, D24S90, doi:10.1029/2008JD010276, 2008.

Kaufman, Y.J., Fraser, R.S. Confirmation of the smoke particles effect on clouds and climate. Science 277, 1636–1639, 1997a.

Kaufman, Y.J., Fraser, R.S. The effect of smoke particles on clouds and climate forcing. Science 277 (5332), 1636–1639, 1997b.

Kaufman, Y.J., Nakajima, T. Effect of Amazon smoke on cloud microphysics and albedo – analysis from satellite imager. J. Appl. Meteorol. 32, 729–744, 1993.

Kaufman, Y.J., Tanré, D., Remer, L.A., Vermote, E.F., Chu, A., Holben, B.N. Operational remote sensing of tropospheric aerosol over land from EOS Moderate-resolution Imaging Spectroradiometer. J. Geophys. Res. 102, 17051–17067, 1997.

Kaufman, Y.J., Remer, L.A., Tanré, D., Li, R.-R., Kleidman, R., Matto, S., Levy, R., Eck, T., Holben, B.N., Ichoku, C., Martins, V., Koren, I. A critical examination of the residual cloud contamination and diurnal sampling effects on MODIS estimates of aerosol over ocean. IEEE Trans. Geosci. Remote Sens. 43, 2886–2897, 2005a.

Kaufman, Y.J., Koren, I., Remer, L.A., Rosenfeld, D., Rudich, Y. The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic ocean. Proc. Natl. Acad. Sci. USA 102 (32), 11207–11212, 2005b.

Koren, I., Kaufman, Y.J., Remer, L.A., Martins, J.V. Measurement of the effect of Amazon smoke on inhibition of cloud formation. Science 303, 1342–1345, 2004.

Kuniyal, C.J., Thakur, A., Thakur, K.H., Sharma, S., Pant, P., Rawat, S.P., Moorthy, K.K. Aerosol optical depths at Mohal–Kullu in the northwestern Indian Himalayan high altitude station during ICARB. J. Earth Syst. Sci. 118, 41–48, 2009.

Li, Z. Influence of absorbing aerosols on the inference of solar surface radiation budget and cloud absorption. J. Climate 11, 5–17, 1998.

Li, Z., Kou, L. Atmospheric direct radiative forcing by smoke aerosols determined from satellite and surface measurements. Tellus (B) 50, 543–554, 1998.

Li, W.J., Shao, L.Y. Observation of nitrate coating on atmospheric mineral dust particles. Atmos. Chem. Phys. 9, 1863–1871, 2009.

Mahowald, N., Kiehl, K. Mineral Aerosol and Cloud Interaction. Abstract from the meeting held in Nice, Frances .Abstract no. 07872, 2003.

Munir, S., Zareen, R. Study of MODIS-derived cloud top temperature/pressure and aerosol optical thickness, in: 36th COSPAR Scientific Assembly Held in Beijing. China, 2006.

Myhre, G., Stordal, F., Johnsrud, M., Kaufman, Y.J., Rosenfeld, D., Storelvmo, T., Kristjansson, J.E., Berntsen, T.K., Myhre, A., Isaksen, I.S.A. Aerosol–cloud interaction inferred from MODIS satellite data and global aerosol models. Atmos. Chem. Phys. 6, 9351–9388, 2007.

NASA Earth Observatory Natural Hazards, Dust Storm over Pakistan. http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=16677, 2006.

Ogren, J.A., Charlson, R.J. Implications for models and measurements of chemical in homogeneities among cloud droplets. Tellus 44B, 208–225, 1992.

Papadimas, C.D., Hatzianastassiou, N., Mihalopoulos, N., Kanakidou, M., Katsoulis, B.D., Vardvas, I. Assessment of the MODIS Collections C005 and C004 aerosol optical depth products over the Mediterranean basin. Atmos. Chem. Phys. 9, 2987–2999, 2009.

Pithawalla, M.B., Kaye, P.M., Wadia, D.N. Geology and Geography of Karachi and its Neighbourhood. Daily Gazette Press, Karachi, pp. 18–30, 1946.

Platnick, S., King, M.D., Ackerman, S.A., Menzel, W.P., Baum, B.A. The MODIS cloud products: Algorithms and examples from Terra. IEEE Trans. Geosci. Remote Sens. 41 (2), 459–473, 2003.

Prasad, K.A., Singh, R.P., Ashbindu, S. Variability of aerosol optical depth over Indian subcontinent using MODIS data. J. Indian Soc. Remote Sens. 32 (4), 2004.

Quass, J., Ming, Y., Menon, S., Takemura, T., Wang, M., Penner, J.E., Gettelman, A., Lohmann, U., Bellouin, N., Boucher, O., Sayer, A.M., Thomas, G.E., McComiskey, A., Freingold, G., Hoose, C., Kristjánsson, J.E., Liu, X., Balkanski, Y., Donner, L.J., Ginoux, P.A., Stier, P., Feichter, J., Sednev, I., Bauer, S.E., Koch, D., Grainger, R.G., Kirkevåg, A., Iversen, T., Seland, Ø., Easter, R., Ghan, S.J., Rasch, P.J., Morrison, H., Lamarque, J.-F., Iacono, M.J., Kinne, S., Schulz, M. Aerosol indirect effects- general circulation model intercomparison and evaluation with satellite data. Atmos. Chem. Phys. Discuss. 9, 12731–12779, 2009.

Qureshi, S. The fast growing megacity Karachi as a frontier of environmental challenges: urbanization and contemporary urbanism issues. J. Geog. Reg. Plan., in press.

Ramanathan, V., Crutzen, P.J., Kiehl, J.T., Rosenfeld, D. Aerosol, climate, and the hydrological cycle. Science 294, 2119–2124, 2001.

Randles, C.A., Russell, L.M., Ramaswamy, V. Hygroscopic and optical properties of organic sea salt aerosol and consequences for climate forcing. Geophys. Res. Lett. 31, L16108, doi:10.1029/2004GL020628, 2004.

Ranjan, R.R., Joshi, H.P., Iyer, K.N. Spectral variation of total column aerosol optical depth over Rajkot: A tropical semi-arid Indian station. Aerosol Air Quality Res. 7 (1), 33–45, 2007.

Remer, L.A., Kaufman, Y.J., Tanré, D., Matto, S., Chu, D.A., Martins, J.V., Li, R.-R., Ichoku, C., levy, R.C., Kleidman, R.G., Eck, T.F., Vermote, E., Holben, B.N. The MODIS aerosol algorithm, products, and validation. J. Atmos. Sci 62, 947–973, 2005.

Rosenfeld, D. TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. Geophys. Res. Lett. 26, 3105–3108, 1999.

Rosenfeld, D. Suppression of rain and snow by urban and industrial air pollution. Science 287, 1793–1796, 2000.

Rosenfeld, D., Rudich, Y., Lahav, R. Desert dust suppressing precipitation: A possible desertification feedback loop. PNAS 98, 5975–5980, 2001.

Seinfeld, J.H., Pandis, S.N. Atmospheric Chemistry and Physics. John Wiley & Sons, New York, Chichester, Weinheim, 1998.

Shi, Z., Zhang, D., Hayashi, M., Ogata, H., Ji, H., Fujiie, W. Influences of sulfate and nitrate on the hygroscopic behaviour of coarse dust particles. Atmos. Environ. 42, 822–827, 2008.

Storelvmo, T., Kristjansson, J.E., Myhre, G., Johnsrud, M., Stordal, F. Combined observational and modeling based study of the aerosol indirect effect. Atmos. Chem. Phys. 6, 3583–3601, 2006.

Tanré, D., Kaufman, Y.J., Herman, M., Mattoo, S. Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiance. J. Geophys. Res. Atmos. 102 (D14), 16971–16986, 1997.

Twomey, S.A., Piepgrass, M., Wolfe, T.L. An assessment of the impact of pollution on the global albedo. Tellus 36B, 356–366, 1984.