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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.

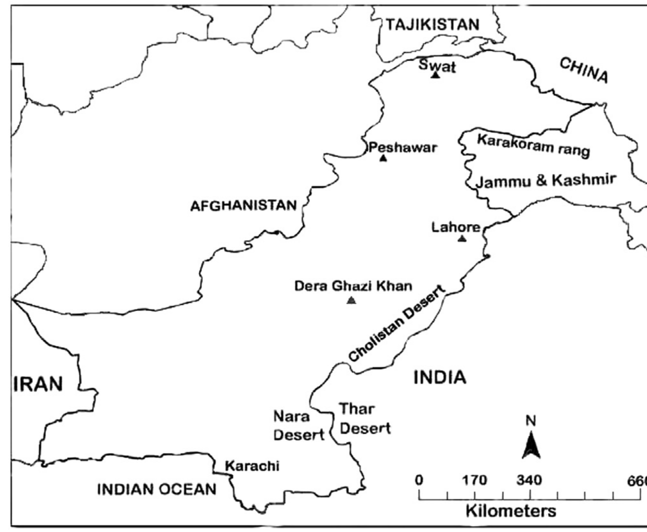

Fig. 1. Map of Pakistan showing the study sites.

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