Seasonal variability of aerosol optical properties and assessment of associated health risks in Pakistan using remote sensing.

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Uzma Basharat

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Abstract

Aerosols cause a severe impact on the earth's climate, human health, and ecosystem. By understanding the variability of optical properties of aerosol, the impact of aerosols on the climate, human health, and ecosystem can be known accurately. In this study, we have used datasets of aerosol optical depth (AOD) at 550nm, Angstrom exponent (440/870) (AE) along with soil moisture, natural difference vegetation index (NDVI), and evapotranspiration over Pakistan. To have more in-depth knowledge regarding aerosol variability. We have also analyzed the relationship of aerosol optical properties with temperature, relative humidity, wind speed, soil moisture, evapotranspiration, and precipitation. Aerosol burden (AOD > 0.5) is found to be high throughout the summer season and all over Pakistan whereas, in winter northern region of Pakistan is found to have a burden of fine mode particles (AE > 1) that adversely impact the health of human beings. Similarly, correlation results reveal that NDVI, soil moisture, and precipitation have an indirect relationship with AOD. Whereas, relative humidity, evapotranspiration, wind speed, and temperature have a direct relationship with AOD which means an increase in AOD increases the other parameters and vice versa. This study also includes the health risk assessment highlighting the hotspots of Pakistan where the level of pollution is vulnerable and human health is at greater risk. Based on the results ground truthing is also recommended in the future studies.

Chapter: 1 Introduction

Aerosols in the atmosphere can absorb and scatter light, changing atmospheric stability, which in turn affects cloud microphysics, longevity, and other characteristics. Aerosols can therefore indirectly affect the hydrological cycle, the temperature of the earth's surface, and ecosystems (Niu et al., 2012). One of the negative consequences of aerosols that contribute to the large-scale alteration of the earth's climate is the warming and cooling effects that are caused by scattering and absorption and absorption of sunlight, respectively.

The atmospheric column is heated as a result of the absorption and diffusion of dust particles. Aerosols are also known to have negative effects on air quality, visibility, and human health. The pattern of aerosol optical depth is therefore crucial for the appropriate evaluation of aerosol influences on a regional climate, taking into account the aforementioned factors (An et al., 2007; Boiyo et al., 2017; Kumar et al., 2015; Niu & Li, 2012; Pan et al., 2010; Ramanathan et al., 2001; Tai et al., 2010).

The aerosol optical depth (AOD), an optical characteristic that is defined as the incorporation of the absorbance values over a vertical plane of a unit cross-section, is the fundamental aerosol feature connected with the atmospheric column. As a result, AOD might be considered a suitable metric for the quantification and investigation of long-term trends in aerosols (Fan et al., 2018).

Aerosols are produced in two different ways; natural (i.e dust originating from deserts, fire in forests, and volcanic eruption) and anthropogenic activities (burning of crop residue and burning of fossils) (Jr et al., 1983.; Knippertz & Todd, 2012; Vimal et al., 2018). The weather conditions and the emission of aerosol from local sources make up the concertation of aerosol in a particular region. Due to population growth, fast urbanization, changes in land use, rising motorized traffic and expanding industrialization both inside and outside of cities, there are negative effects associated with an increase in aerosol levels. Seasonality, varied topography, and a complex-built environment were identified to be the primary causes of AOD variance throughout the region (Bibi et al., 2016; Kumar et al., 2015; Sen et al., 2017; Singh et al., 2018; Singh, Mhawish, et al., 2017a, 2017b; Singh, Murari, et al., 2017).

The diverse change in global climate patterns due to cooling and warming of the atmosphere is because of aerosols present in the atmosphere. However, having an understanding of aerosols and their interaction has become tough due to variations in the distribution of aerosols in the atmosphere (Zhao et al., 2019.). Therefore, Understanding the properties of aerosols at the local and global scales is necessary for a more accurate estimation of their climatic impact (Fan et al., 2018).

Angstrom exponent (AE) is a parameter that is used to identify the particles size of the aerosol in the atmosphere and it utilizes wavelength to estimate the size (Eck et al., 2001, 2003; Kalapureddy & Devara, 2010; O'Neill et al., 2001). AE equal to 1 indicates the presence of fine-sized aerosols in the air, originating from the burning of biomass and industrial pollution while AE values less than 1 indicate the presence of coarse size particles originating from dust or industries (Eck et al., 1999). During the monsoon season in 2006, AE was used as an indicator to examine the presence of types of particles over the Arabian sea and the Bay of Bengal (Kedia et al., 2009).

To give precise measurements of AOD together with other aerosol properties, a range of remote sensing technologies, ranging from ground-based to satellite-based techniques have been developed (Amiridis et al., 2005; Che et al., 2009; Holben et al., 1998; Kim et al., 2004). One of the widely used networks that provide dependable and ongoing data on aerosol properties is the ground-based aerosol robotic system (AERONET) (Giles et al., 2019; Holben et al., 1998).

However, because this technique can only be used for point observations, it cannot be applied to the wide range of spatial characteristics of aerosols.

As opposed to AERONET, satellite-based spatial data provides a great opportunity to track the characteristics of aerosols over a wider geographic area. Therefore, to have an understanding of aerosol trends different retrieval algorithms have been used including, “Advanced Very High-Resolution Radiometer (AVHRR)”, “Ozone Monitoring Instrument (OMI)”, “Multiangle Imaging Spectro-Radiometer (MISR)” and “ Sea-viewing Wide Field of view Sensor (SeaWiFS)” (Omar et al., 2005; Peralta et al., 2007).

Furthermore, different methods are used by the MODIS sensors onboard the Terra and Aqua satellites to provide long-term spatiotemporal properties of aerosols at local and global scales. The measurement of aerosol properties across a vast region with a large number of multiple measurements has become easier because of developments in satellite-based remote sensing of aerosols. The utilization of satellite data to examine the indirect impact of aerosol both temporal and spatial patterns at local and global scales have also been described in a growing body of research (Hsu et al., 2004; Kumar et al., 2018; Remer et al., 2008; Shahzad et al., 2018). A valuable tool for tracking and evaluating the overall aerosol balance and the radiative impact of aerosols on climate is satellite remote sensing (Farr et al., 2007; Kosmopoulos et al., 2008; Seinfeld et al., 2016; Tripathi et al., 2007).

Additionally, remote sensing using satellites has the advantage of allowing for the quick assessment of the distribution pattern and characteristics of aerosols across a wide area. Undoubtedly, this method offers a singular opportunity to determine regional and worldwide patterns for the distribution and characteristics of aerosols (Kosmopoulos et al., 2008).

Furthermore, fine ambient aerosols (PM2.5) possess a negative impact on the quality of air and human health. As the level of particulate matter is increasing day by day and posing an alarming situation for those living in developing countries (Gadi et al., 2019). The limit set by WHO for PM2.5 concentration was 50 μgm-3. Some studies showed the persistent presence of particulate matter (PM 2.5) in the atmosphere that causes major health risk issues to human health and is more toxic than PM10. Long-term exposure to PM2.5 causes a high rate of respiratory disorders and cardiovascular disease (Harrison et al., 2017).

Pakistan being an urbanized region in Asia has been predicted to increase particulate matter concentration by up to 60% by 2050. The concentration of particulate matter in a mega city of Pakistan i.e. Karachi was reported to be 668 μgm-3 (Rasheed et al., 2015). Hence, it showed that the concentration of PM2.5 was above national environmental quality standards for ambient air (Mehmood et al., 2019). Due to the presence of insufficient information, poor management and lack of public awareness very less analysis has been conducted.

Previously conducted studies have investigated the spatiotemporal distribution of aerosols and the impact of aerosols emitted from anthropogenic emissions over Pakistan (Ahmad et al., 2020; Ali et al., 2014; Mehmood et al., 2019; Tariq et al., 2015, 2016, 2017, 2021a, 2021b, 2021c; Tariq & Ul-Haq, 2018a, 2018b; Tariq & ul-Haq, 2020a, 2020b; ul-Haq et al., 2016).

According to our knowledge, no study has been conducted to analyze the correlation of aerosols with natural vegetation difference index (NDVI) and meteorological parameters on a seasonal basis over Pakistan. This study aims to investigate seasonal variations of AOD and AE and their relationship with NDVI, soil moisture, evapotranspiration, and meteorological parameters (i.e Wind speed, surface temperature, precipitation, and relative humidity) from 2002 to 2022 over

Pakistan. This study also aims to quantify the impact of $PM_{2.5}$ concentration to evaluate health risks by computing data on $PM_{2.5}$ with population density.

Chapter: 2 Literature review

There is a severe effect of aerosols on the health of humans, the climate, and the ecosystem. These effects can be understood in a better way by having in-depth knowledge and research regarding variability in aerosol optical properties.

Tariq et al., (2021) carried out a study in which AOD and AE were investigated along with the enhanced vegetation index to evaluate the impact of aerosols and their variability over Pakistan. They also evaluated the meteorological parameters to analyze the relationship between them and aerosol optical depth to acquire in-depth knowledge regarding them. Meteorological parameters included temperature, relative humidity, and wind speed. The results from the study indicated the presence of dust aerosols over Lahore and Karachi. These results were also validated with the results of data from MISR, SeaWiFS, and Terra as in the present study data was collected from MODIS. A negative correlation was observed between AOD and enhanced vegetation index. The higher value of AOD was found in northern areas of Pakistan during all seasons. However, AE was seen to be lower during the summer and spring seasons in southwestern areas of Pakistan.

Ali et al. (2020) investigated trends of AOD over different regions in Pakistan having data set downloaded from MODIS. For the assessment of climatic changes in global and regional areas, this study was conducted. Various test for statistical analysis was applied to assess the seasonal and annual trend of AOD. Some regions had an increasing trend for AOD during the winter season while the remaining had an increasing trend during the summer season. These changes in the trend of AOD are attributed to the meteorological parameters of the atmosphere. Few selected areas of Pakistan showed an increase in AOD due to high temperatures and low precipitation rates. Central plans of Pakistan during summers have the highest peak values for AOD due to the dense population and high rate of industrialization along with vehicular emissions. Some regions are found to have high AOD during winters and summers.

Similarly, a study was carried out by Khokhar et al. (2016) on the variability and characterization of aerosol in Pakistan. The study included not only AOD and meteorological parameters but also the particulate matter concentration during the 2014- 2015 winters. A significant correlation was found between "MODIS (AOD)" and "AERONET station" AOD data, especially for Lahore. Particulate matter concertation found through ground monitoring exceeded the NEQS level (National Environmental Quality Standards). It was also revealed that smoke and aerosols are major constituents of the fog formed in Pakistan. The spatial distribution, type, and origin of aerosols during the winter season were identified through this study.

Moreover, Xin et al. (2007) conducted a quantitative assessment of aerosols on regional climatic and environmental changes through sun photometers in China from 2004 to 2005. In this study, authors analyzed AOD and AE using 450, 500, and 650nm from august 2004 to September 2005. Northern sites of China were considered to be the cleanest regions because AOD ranged from 00.19 to 0.21 indicating the presence of fine-mode aerosol particles over there. surprising results were found in northern China at a few sites of the desert because AOD was relatively low ranging from 102 to 103 with AE ranging from 0.4 to 0.9 due to some dust episodes during this period. AOD observed at agricultural sites ranged from 1.03 to 0.9 and AE from 1.05 to 1.11. These results showed that inland urban and suburban sites did not have much difference in the values.

Tariq & ul-Haq (2020) evaluated AOD and AE over Pakistan along with meteorological parameters. AERONET data were collected from 2006-2014 for AOD at 500nm and Angstrom exponent at 440nm. The authors analyzed aerosol properties along with meteorological parameters including temperature, rainfall, dust storm, sea level, and relative humidity. AERONET (AOD) validated the MODIS (AOD) over Lahore. The results found for the AOD and AE during the July season validated that soil or dust aerosols dominated the atmosphere of Lahore. February was the month during which AOD was found to be lowest along with AE having values above 1.22 for AE, it indicates the presence of industrial aerosols. The maximum value for AE was found to be maximum in January and lowest in June similarly, AOD showed a positive correlation with meteorological parameters including temperature, relative humidity, visibility, rain, dust Storm, dew point, and rain. The negative relation of AOD with pressure and wind speed was detected. In the case of AE, a positive correlation was before relative humidity, and mean sea level pressure. Considering the negative correlation, it was seen with temperature, rain, dust storm, rain, and dew points

Similarly, Hammer et al. (2020) administered a long-term trend of fine particulate matter concentration, in which annual PM2.5 concentrations and their trend from 1998 to 2018 were estimated using data from satellite observations, chemical transport modeling, as well as ground-based monitoring. In this study author, combined AOD with aerosol optical properties. The estimates of PM2.5 were consistent with ground monitored. Simulations and long-term satellite AOD enabled the assessment of over 21 years, identifying the significant trend for India, Europe, and North America. A positive trend was seen for India and a negative for China was predicted from 2011 to 2018 that impacted the health of billions of people.

Klingmüller et al. (2016) conducted a trend analysis of the middle east using “MODIS” from 2000 to 2015. This study relates to the previously identified trend of AOD from 2001 to 2012. AOD in this study was analyzed with soil moisture, surface wind, and precipitation to find out such regions that have similar attributes of AOD over Saudia Arabia, Iraq, and Iran. Multiple linear regression was used to evaluate the trend of AOD with other factors like “soil moisture, precipitation, and surface wind” in controlling the dust cycle. Results of the study showed that the increased temperature decreases relative humidity thus increasing the drying of soil eventually leading to dust emission and an increase in AOD due to climate change.

Midyan et al. (2020) carried out a comparative study over turkey for validation of MODIS C6.1 AOD product with AERONET and MERRA-2. Data from four seasons and annual data was collected during the period from 2013 to 2017. Regression analysis was carried out to predict the efficient sensor. The regression results of seasonal and annual variations showed that MODIS show better results than MERRA2 and AERONET data. MODIS showed more efficient results than MERRA and AERONET in extreme events.

To understand more in-depth the chemistry of aerosol, a study was conducted on the evaluation of trend analysis of aerosol in the Indo-Gangetic Basin (Khanpur, Gandhi College, Lahore, and Jaipur). Lahore and Khanpur are industrial and agricultural sites similarly, Gandhi college is an agricultural area whereas, Jaipur is a deserted area. These four sites were considered to see aerosol climatology. The aerosol trend was analyzed through the MISR sensor along with MODIS-derived NDVI and ESA CCI (European Space Agency Climate Change Initiative) derived soil moisture in 2020. Sea salt and dust aerosols are found to be dominant in premonsoon and monsoon seasons. Coarse aerosols are found to be in high concertation as compared to fine-mode particles (Misra et al., 2020).

Weeberb et al. (2018) conducted a study regarding health risk assessment due to emissions from traffic. He conducted this study in Toronto and Hamilton area along with Canada using micro level approach using algorithm in order to estimate the emissions during congestion period. He estimated $PM_{2.5}$ related mortality along with cost of health linked with it. He found out that traffic had great impact on the health of workers especially during morning shift and economy of these above-mentioned areas. Majority there were more cardiovascular mortality rate then other diseases (Requia et al., 2018)

Another study was conducted by Tariq et al. (2022) regarding variation of $PM_{2.5}$ in Saudi Arabia and its link with health risk using remote sensing. He used updated $PM_{2.5}$ version satellite-based data to analyzed the trend analysis and standard deviational ellipse. He found out that each year $PM_{2.5}$ was increased with growth rate of 2.3%. more burden of $PM_{2.5}$ was in areas of southeast due to presence of sand dunes, and industrial areas over there. According to the unsupervised classification areas that came under the fast growth class were Ar-Riyad, Najran and Sharqiyah area (Tariq et al., 2022).

Similarly, Jian et al. conducted a study over China in 2015, to analyze the spatiotemporal pattern of $PM_{2.5}$ from 1999 to 2011. According to him $PM_{2.5}$ increases the mortality rate and reduces the life span of human being. He utilized ellipse analysis and conducted health risk assessment with $PM_{2.5}$. he found out significant increase in $PM_{2.5}$ concentration over central and eastern parts. There was increase in $PM_{2.5}$ concentration over year and year. Most polluted areas were north of Henan and south of Hebei. He emphases in his study to take controls immediately in order to reduce the risk to the human health (Peng et al., 2016).

Moreover, a study was conducted by Mehdi in 2019 in China. He conducted this study on $PM_{2.5}$ as they are known to be prone to lung cancer, cardiovascular disease along with respiratory diseases. This study would help the government to warn people and to make them mitigate with the complications being faced. Random forest model along with deep machine learning was used in this study. He used meteorological data, ground based data, and satellite-based data in this study (Joharestani et al., 2019).

Sagnik et al. conducted study over India on outdoor fine particulate concentration ($PM_{2.5}$) using remote sensing method. He has utilized “Multiangle Imaging SpectroRadiometer (MISR)” in order to estimate surface $PM_{2.5}$. this study showed that 51% of population face threshold of 35μg m− 3. Rural areas are more affected than urban areas and five hotspots are identified that are badly affected due to air pollution (Dey et al., 2012)

Another study carried out in China by Liang et al. in (2018) to evaluate the impact of urban planning on $PM_{2.5}$ pollution along with complications that are faced due to exposure to it. He utilized satellite based remote sensing data in his study to find out relationship between urban planning and $PM_{2.5}$ concentration. He also used local service data in order to measure the $PM_{2.5}$ pollution in Wuhan areas. The results of the study showed that road density, green spaces have significant impact on the $PM_{2.5}$ pollution exposure (Guo et al., 2019).

Chapter 3: Research methodology

2.1. Study area

Pakistan is a densely populated country having 225 million people located in it. It is located within latitudes and longitude of 24°-37° North and 61°-76° East. There lies the Himalaya and Karakoram range in northern areas of Pakistan (as shown in Fig.1). However, plains exist along with river Indus in the center which is very popular for agricultural purposes (Ashraf et al., 2013). In our study, we have selected all provinces of Pakistan i.e., Punjab, Sindh, Balochistan, and Khyber- Pakhtunkhwa. These provinces are selected based on different climatic conditions. Details of each province with the source of aerosols are discussed in Table 1. Punjab lies in the eastern region of Pakistan, a densely populated and industrialized area. Khyber- Pakhtunkhwa lies in the northern region of Pakistan which is rich in mineral deposits and is less urbanized due to hilly topography. Similarly, the southern-western region of Pakistan in which Balochistan and Sindh lie, is densely populated due to industrialization.

Table 1 Spatial bounding of provinces in Pakistan along with the anthropogenic sources of aerosols. Koppen – Geiger climate classification based on precipitation, vegetation, and seasonality in provinces of Pakistan (Kottek et al., 2006)

Provinces	**Spatial bounding**	**Climate classification and population density**	**Notable sources of aerosols**
Punjab	70° 18' 45" -27° 56' 57.12" E, 75° 35' 9.24"-33° 45' 0"N	Hot semi-arid area (BSh) having a high-density population.	Rice and wheat residue burning during pre- and post-monsoon, megacities (Lahore, Faisalabad), and power plants.
Sindh	65° 44' 31.92"-23° 54' 22.68" E,	Hot desert climate (BWh) along with the	Gawadar and Chahbar ports activities, burning of

	72° 46' 24.24"-29° 10' 46.92"N	highly dense population.	fossil fuels, dust/sand from the desert of Thar and Cholistan.
Balochistan	59° 56' 29.04"-25° 18' 45" E, 69° 57' 39.24"-32° 20' 37.68"N	Warm desert (BWh), less densely populated area.	Mining activities and sand dust.
Khyber Pakhtunkhwa	68° 22' 44.04"-32° 20' 37.68" E, - 73° 18' 2.88" 37° 37' 1.92" N	Humid subtropical climate (Cfa), moderately populated.	The coal is used for home heating during the winter season, dung burning, and forest fires.

Satellite data

AOD and AE

In 1999, Moderate-resolution Imaging Spectro-radiometer (MODIS) sensor Aqua satellite was launched (Salomonson et al., 1989). It has 36 spectral bands along with high radiometric resolution at 12 bits to monitor aerosols, cloud cover, and global radiation budget on daily basis (Kaufman et al., 1997). For retrieval of aerosols over land and ocean, two different algorithms are used; deep blue and dark target (Kaufman et al., 1997). In our study, we have used a MODIS Aqua sensor with a combined dark target and deep blue AOD monthly product at 0.55 micron (MYD08_M3v6.1) with 1°×1° spatial resolution from Giovanni (https://giovanni.gsfc.nasa.gov/giovanni/) . Similarly, for AE, we have used MODIS Aqua sensor with Deep Blue Angstrom Exponent for land (0.412-0.47 micron) monthly product (MYD08_M3v6.1) with 1°×1° spatial resolution from same site Giovanni . Version 6 of AOD and AE is the latest and most improved product that provides improved cloud masking and atmospheric profile algorithms.

$PM_{2.5}$

The atmospheric composition analysis (ACA) (https://sites.wustl.edu/acag/datasets/) website will be used for the collection of data for $PM_{2.5}$. The version V4.GL,03 $PM_{2.5}$ along with the resolution of 0.01°× 0.01°, ranging from the year 1998 to 2020 will be downloaded (Hammer et al., 2020)

Population Density data

Data for population density will be obtained from "The Center of International Earth Science Information Network at Columbia University (CIESIN) (https://sedac.ciesin.columbia.edu/data/collection/gpw-v4/documentation). They provide a global dataset consisting of different spatial resolutions. We will use a population density dataset with a resolution of 2.5 ×2.5 (5 km × 5 km) for 2000, 2005, 2010, and 2020.

NDVI, soil moisture, evapotranspiration, and meteorological parameters.

Data for a meteorological and topological parameter was obtained from Atmospheric Infrared Sounder (AIRS, Kim, 2003) for relative humidity at 925hPa. Similarly, data for precipitation rate, NDVI, surface wind speed, and surface temperature was obtained from the Tropical Rainfall Measuring Mission (TRMM, Robertson, et al., 2003), Moderate-resolution Imaging Spectro-radiometer (MODIS) sensor Terra satellite (Terra, Fensholt, et al., 2009) and MERRA 2 Model respectively (Schubert et al., 2012.). Data for soil moisture and evapotranspiration was collected from Global Land Data Assimilation System (GLDAS, Rodell et al., 2007) All the data was collected from the site of Giovanni(https://giovanni.gsfc.nasa.gov/giovanni/). Details of all the data sets are given below in Table 2.

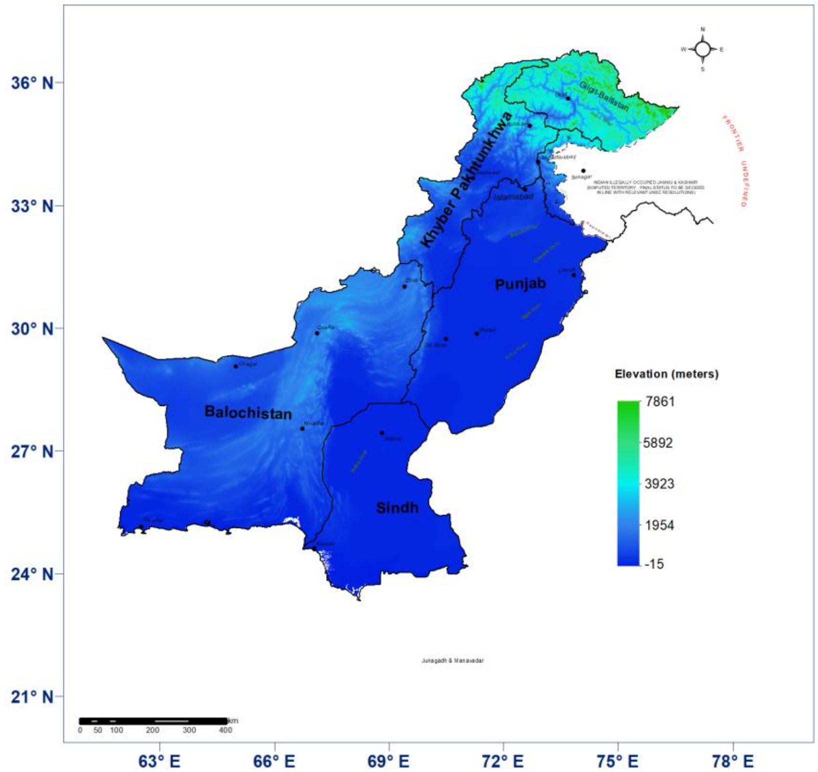


Fig. 1. Study area map of Pakistan

Working in Arc Gis software

We have downloaded data of AOD at 550nm and AE from the year 2002 to 2021 over different seasons; winters, premonsoon, monsoon, and post-monsoon. These data sets were utilized to observe the spatial variability of AOD and AE over different seasons among all provinces of Pakistan.

Furthermore, seasonal data sets were also downloaded for NDVI, soil moisture, evapotranspiration, and other meteorological parameters Similarly, data for population density and PM2.5 was also downloaded. Data were downloaded in the form of TIFF (tagged image file format) and later on imported into the software

Arc Gis software was used to carry out all the analysis. After downloading data, the resolutions of the data sets were equalized by using a resampling tool in the data management category of Arc Gis. Furthermore, a correlation between AOD and the rest of the parameters along with health risk analysis was carried out in the Arc Gis software. Finally, correlation maps were exported from the Arc Gis software, and the results were compared.

For health risk evaluation we have utilized the unsupervised trend clustering method to analyze PM2.5 longer-term variation over provinces of Pakistan. Unlike previous unsupervised classification methods, in which spectral band data is used. Here extended application of unsupervised classification is used by using images obtained from the site. Instead of including previous knowledge regarding the features of the image, spectral characteristics of the spectral bands are used as they play an important role in the identification of the class and classification of the image. Therefore, an image of each year was stacked to extract similarities among different years. This method of unsupervised classification utilizes an algorithm to identify unknown pixels and categories on the basis of natural clustering or grouping available in the image and categorized into different categories. Extensively used algorithms for clustering methods are K means and the Iterative Self-Organizing Data Analysis Technique Algorithm (ISODATA) that were utilized for unsupervised classification in order to do image segmentation. ISODATA is mostly used in the remote sensing applications. It involves three steps initiating from randomly selecting cluster center within the image and then assigning pixels to the cluster closer to it and then updating the new cluster by its means value. This helped in obtaining different classes.

Table 2

Details of the dataset used in the study.

Product name	**Sensor/model**	**Retrieval time (day/ night)**	**Spatial resolution (degrees)**	**Product name/ version / level**	**Units**
AOD (MYD08_M3 v6.1)	MODIS-Aqua	Daytime	1°×1°	Version 6/ level 3	Unit less
AE (MYD08_M3 v6.1)	MODIS Aqua	Daytime	1°×1°	Version 6/ level 3	Unit less
Precipitation Rate (TRMM_3B43_v7)	TRMM	Daytime	0.25°× 0.25°	Version 7/ level 3	mm/day
Surface wind speed (M2TMNXFLX v5.12.4)	MERRA-2 Model	Daytime	0.5°× 0.625°	Version 5	ms^{-1}
Relative Humidity (AIRS3STM v6.0)	AIRS	Daytime	1°×1°	Version 7/ level 3	Percent
Surface Temperature (FLDASNOAH01CGLMOO1)	FLDAS	Daytime	1°×1°	Version 6/ level 3	Kelvin
NDVI (MOD13C2v006)	MODIS- Terra	Daytime	0.5°×0.5°	Version 6/ level 3	NDVI
Soil moisture content (GLDAS_NOAHO25_Mv2.1)	GLDAS	Daytime	0.25°	Version 2	Kgm^{-2}
Evapotranspiration (GLDAS_NOAHO10_Mv2.1)	GLDAS	Daytime	0.25°	Version 2	$Kgm^{-2}S^{-1}$
$PM_{2.5}$	MODIS+MISR + Sea WiFS combined with GEOS chem transport model	Daytime	0.5°× 0.5°	Version 4	µg/mg^3

Chapter: 4 Results

Fig. 2 presents the spatial distribution of AOD and AE over all provinces of Pakistan. The higher values of AOD were observed in Punjab and Sindh with peak values of approximately 0.55 and 0.48 respectively, extended into the southern region. similarly, AE distribution among provinces of Pakistan was in such a way that the approximate value of AE was 1.06 in eastern Pakistan, 1.15 in northern Pakistan, 0.89 in southern Pakistan, and 0.82 in western Pakistan.

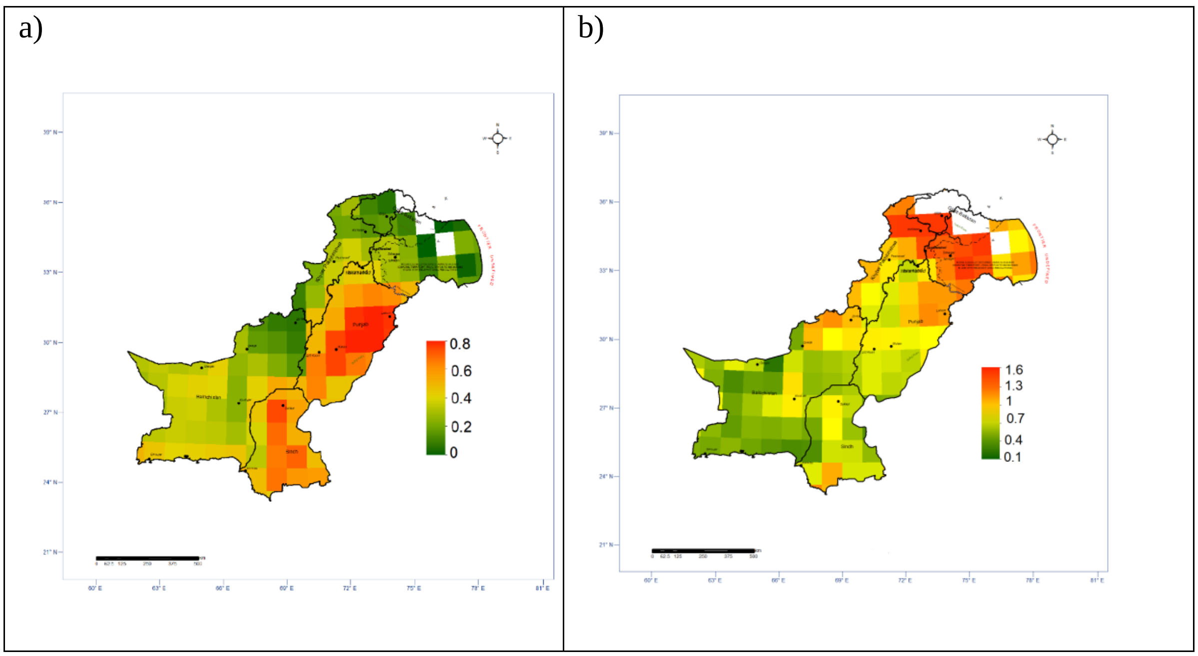


Fig. 2. Spatial distribution of (a) AOD (2002-2022) and (b) AE (2002-2022) in Pakistan.

Fig.3 shows the seasonal variation of AOD in Pakistan from 2002 to 2022. Data had been collected for four seasons; winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and autumn (September, October, and November).

Seasonal variation of AOD showed that peak occurrences of AOD were found in summer and spring, while lower AOD was found in autumn and winter among all provinces of Pakistan.

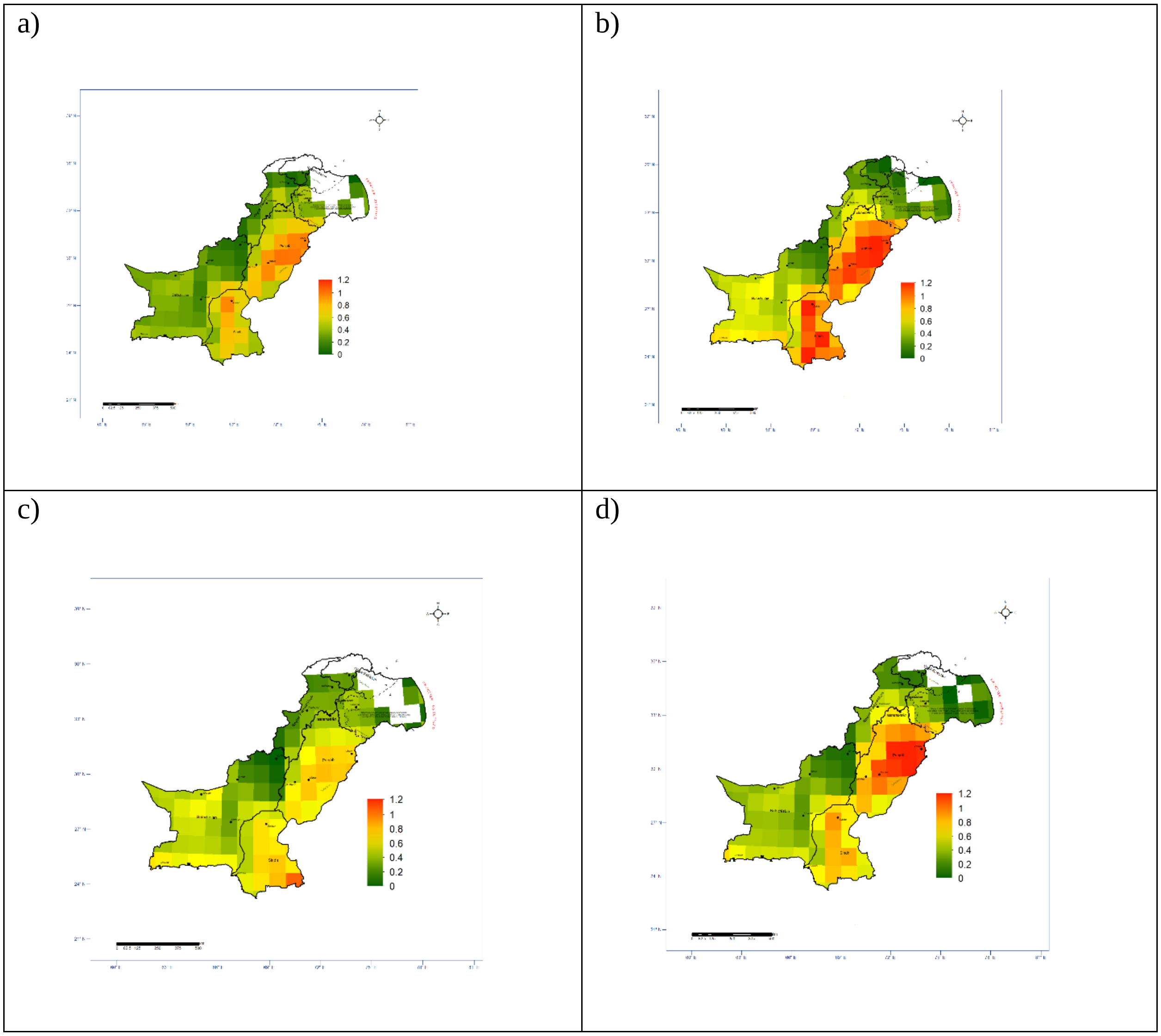
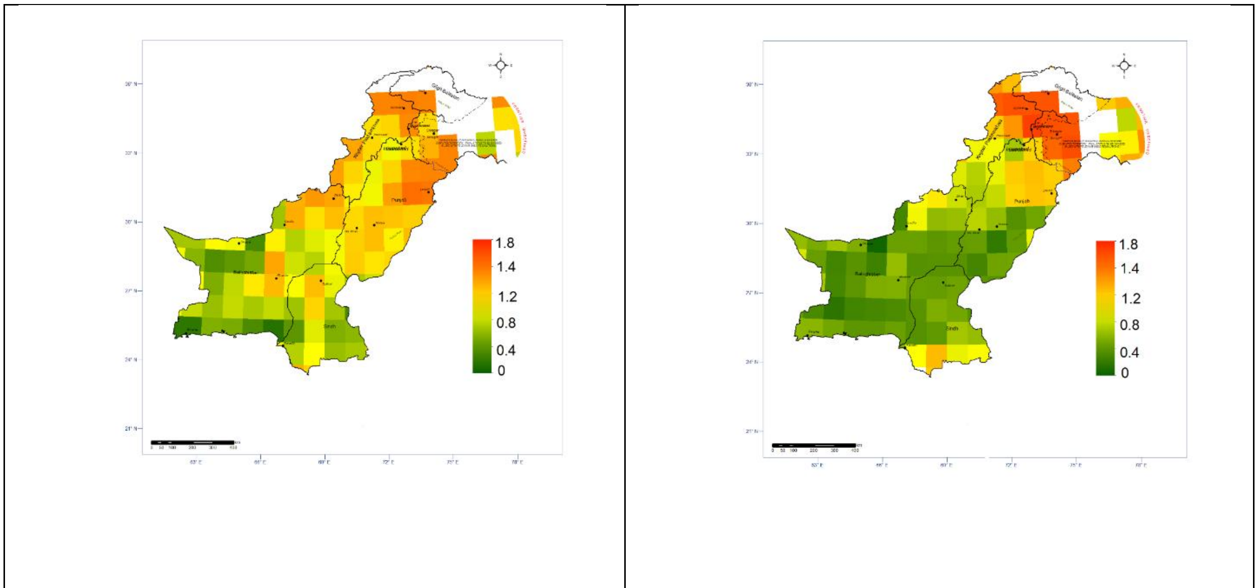


Fig.3. **Seasonal variation of AOD (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.**

Fig.4 shows the seasonal variation of AE from 2002 to 2022. AE is an indicator for the size distribution of aerosols. The size of aerosol in the winter trend from maximum to minimum value was recorded as follows; Punjab (1.3), Khyber Pakhtunkhwa (1.2), Sindh (0.5), and Balochistan (0.4).

a)	b)



c) d)

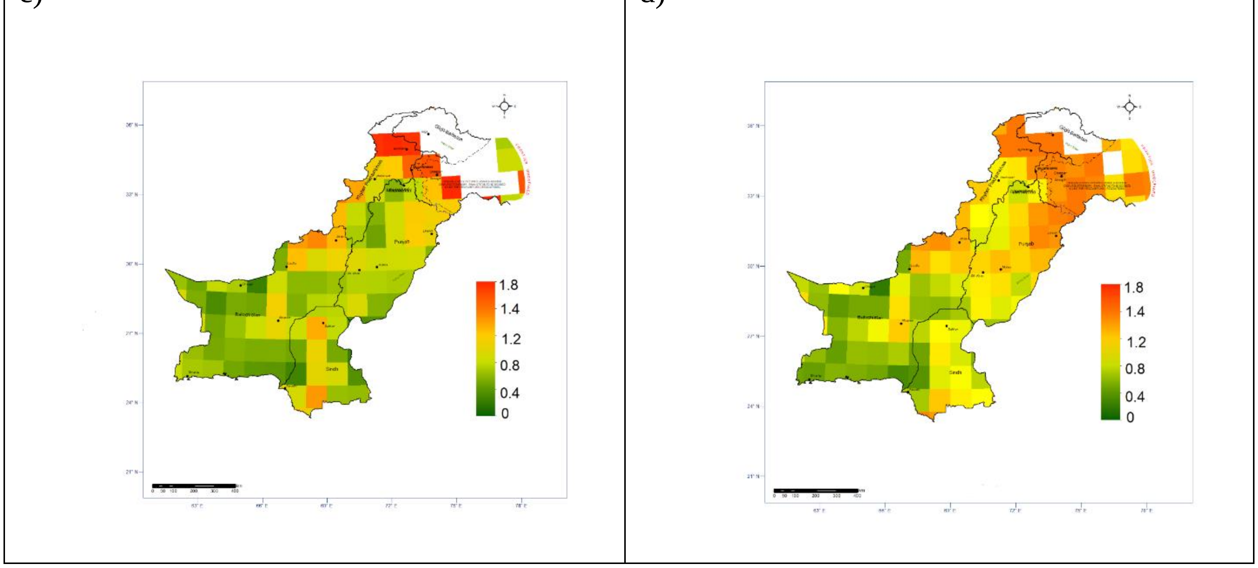


Fig.4 Seasonal variation of AE (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Seasonal variation of NDVI

Fig.5 shows seasonal variation of NDVI during the winter season, Punjab (0.6) and few areas of Sindh (0.6), and Khyber Pakhtunkhwa (0.3) show moderate amounts of NDVI. However, in the summer, the area of Jammu Kashmir (0.8) and northern Khyber Pakhtunkhwa (0.8) shows the highest index of NDVI.

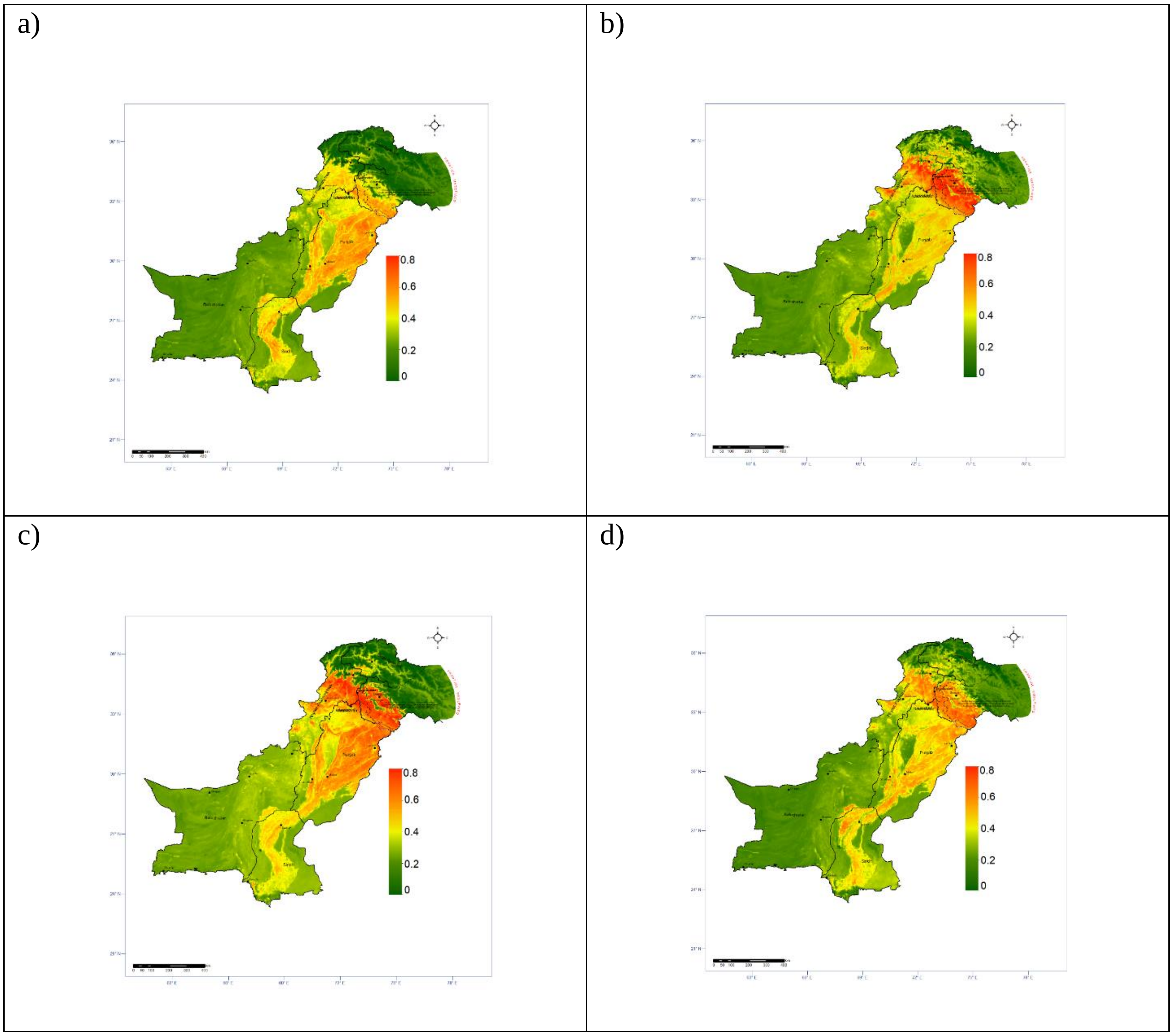


Fig.5 Seasonal variation of NDVI (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Seasonal variation of wind speed

According to fig.6. during winter and spring seasons highest wind speed is found to be in the areas of Balochistan (10-12). Similarly, high wind speed is found to be in Sindh (12) during the spring season.

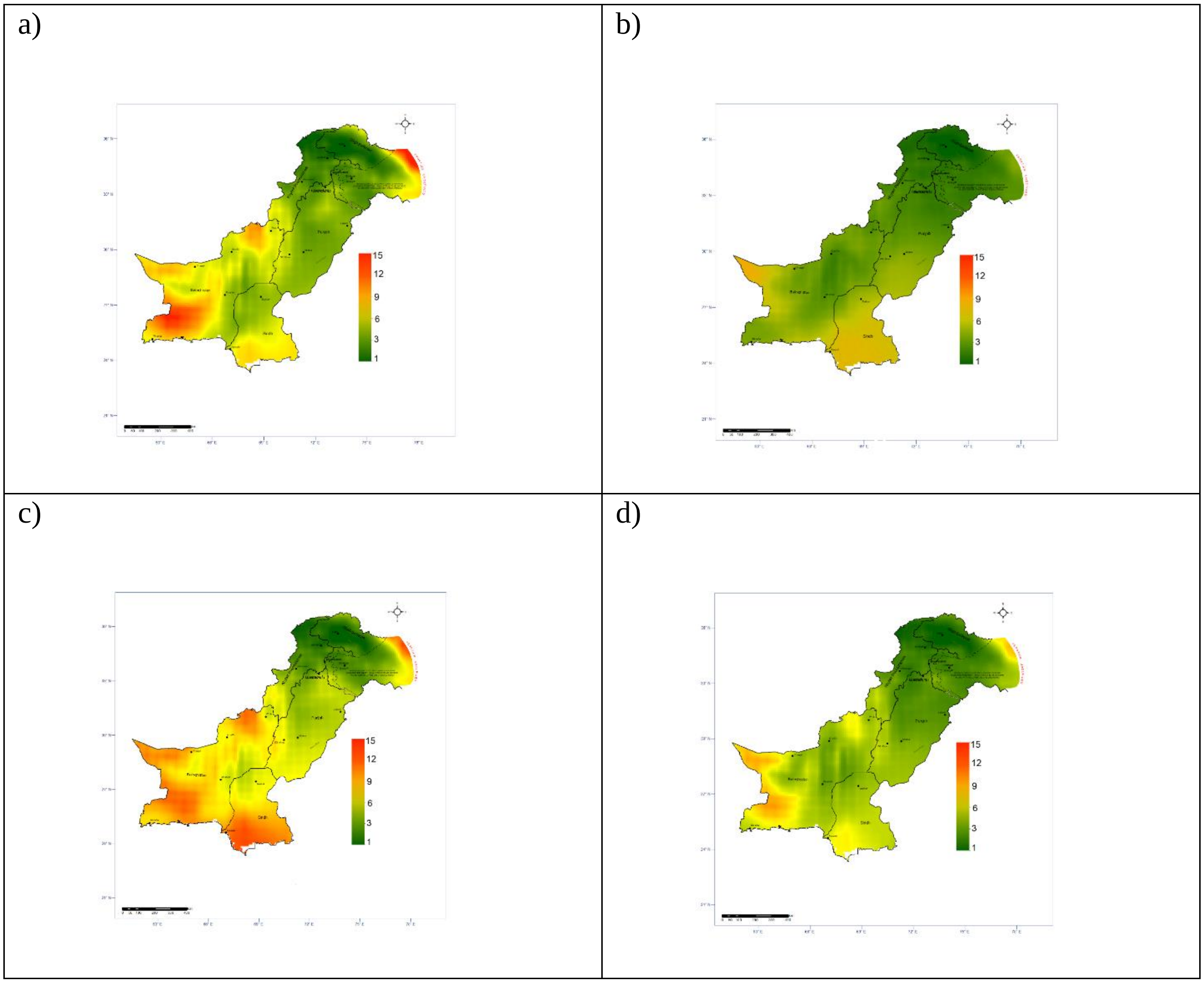


Fig.6 Seasonal variation of windspeed (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Seasonal variation in temperature

According to fig.7, in all seasons temperature is found to be high in Punjab (300-320 k) and Sindh (300 k) areas. Balochistan (310-320 k) has the highest temperature value during the summer and autumn seasons.

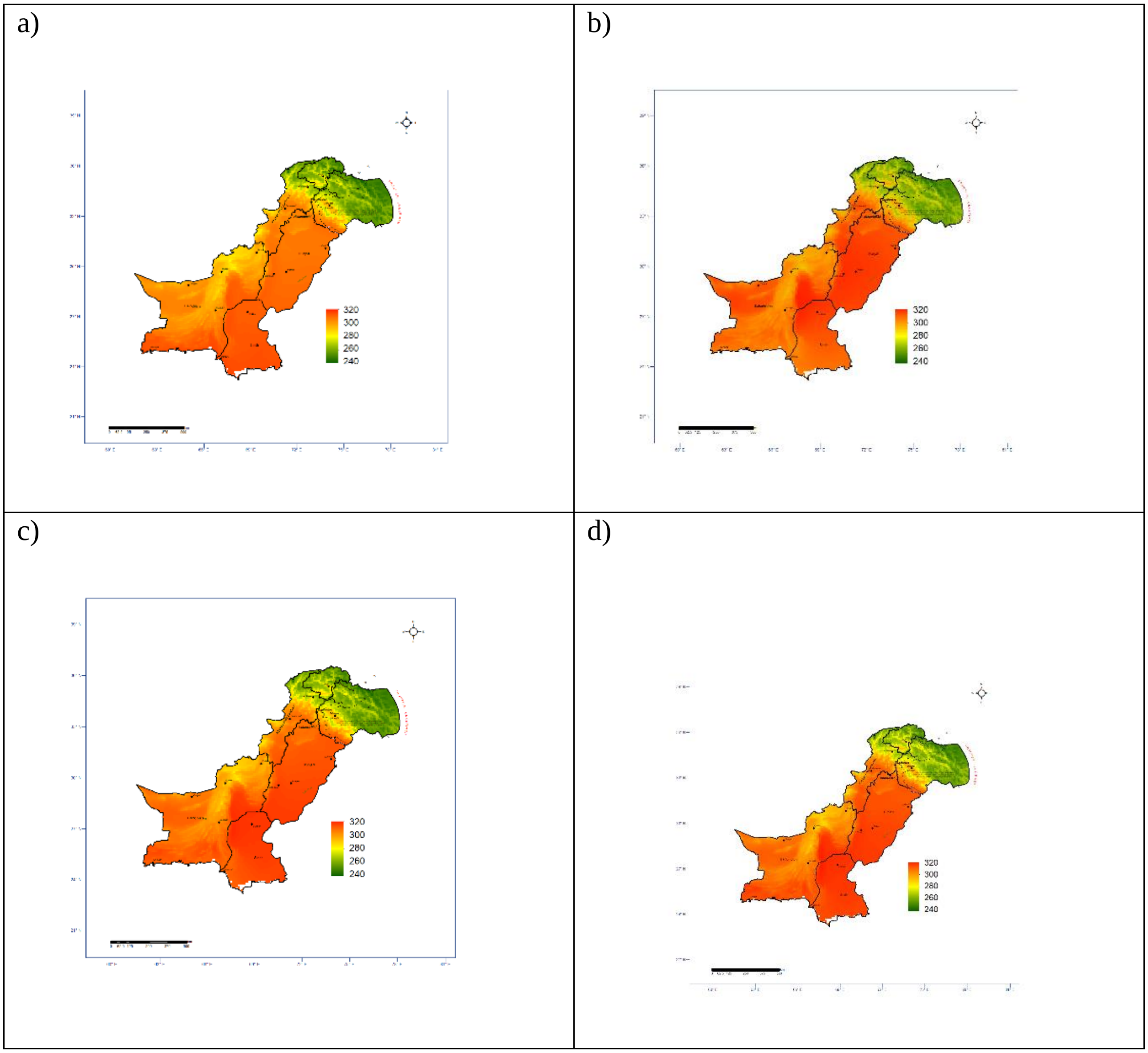


Fig.7 Seasonal variation of temperature (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Seasonal variation of relative humidity

According to fig.8, the relative humidity is found to be highest in northern Khyber Pakhtunkhwa (70) and Jammu Kashmir (70) areas only during winter and spring seasons.

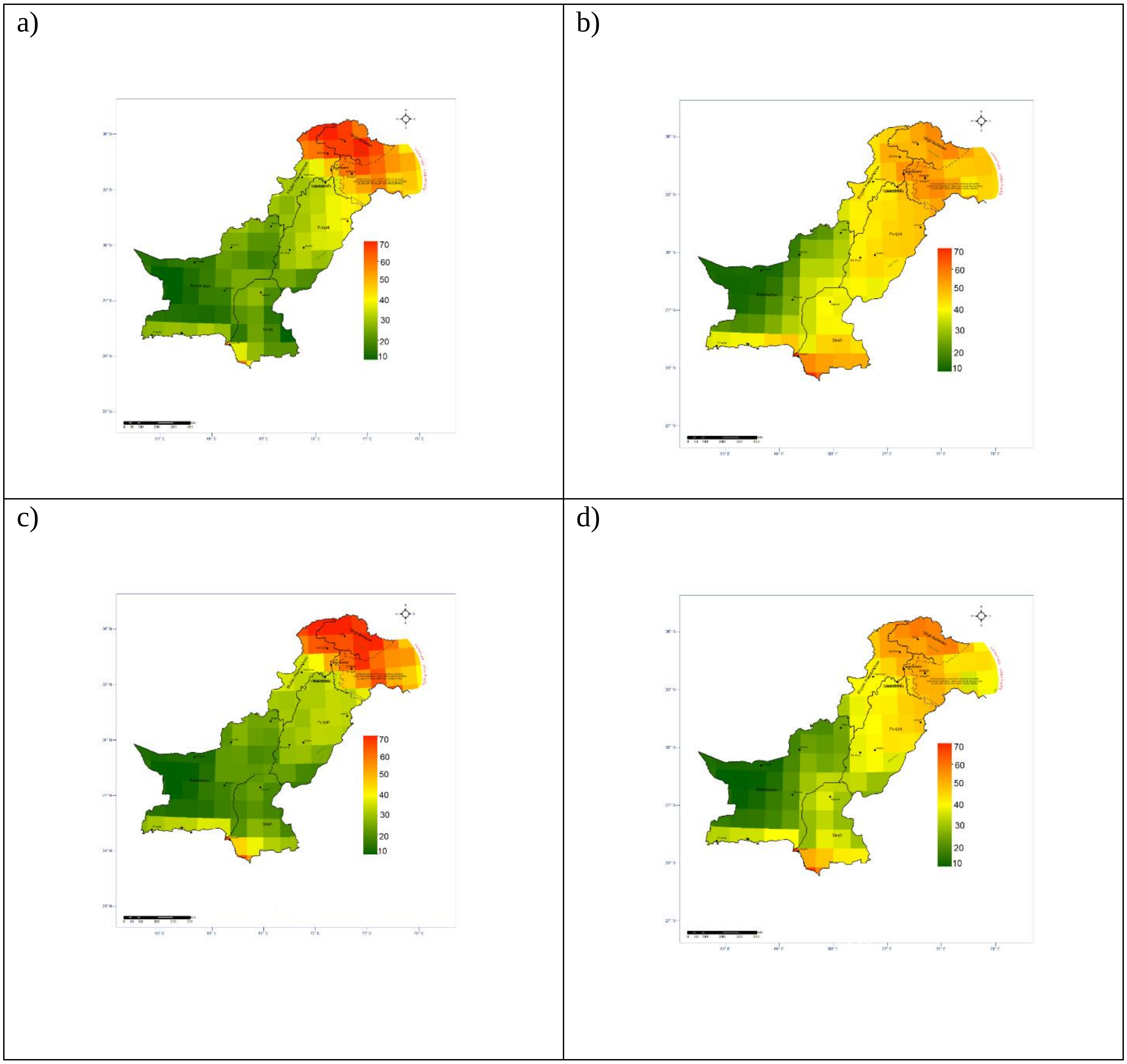


Fig.8. **Seasonal variation of relative humidity (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.**

Seasonal variation of precipitation

According to fig.9. highest ranges for the precipitation rate are found in northern Khyber Pakhtunkhwa (0.8), near Quetta (0.4), and southern Jammu Kashmir (0.8) during the winter season.

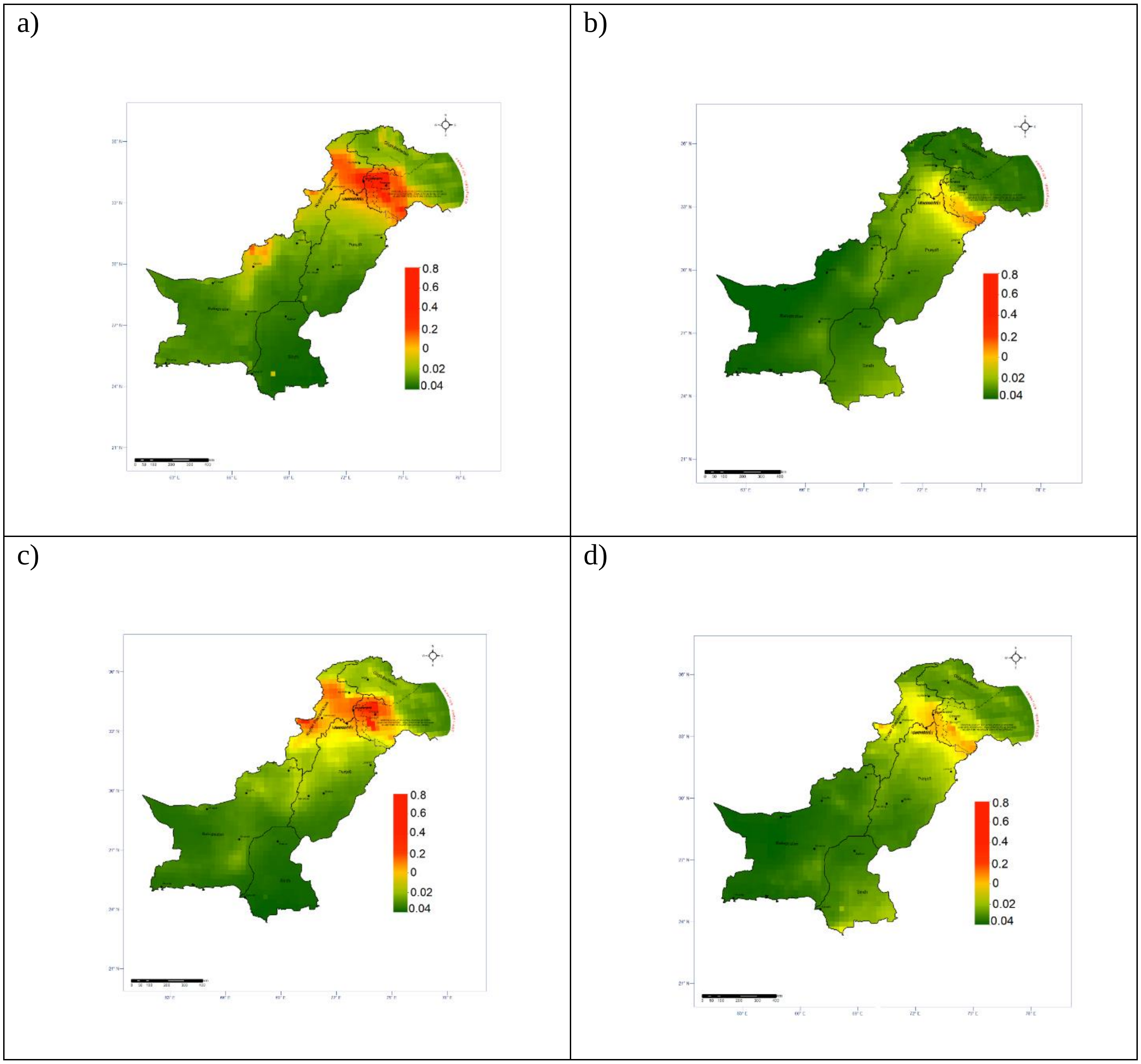


Fig.9. **Seasonal variation of precipitation (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.**

Seasonal variation of soil moisture

According to fig.10. in all seasons of Pakistan, the highest soil moisture content (280) is found to be in northern Jammu Kashmir only.

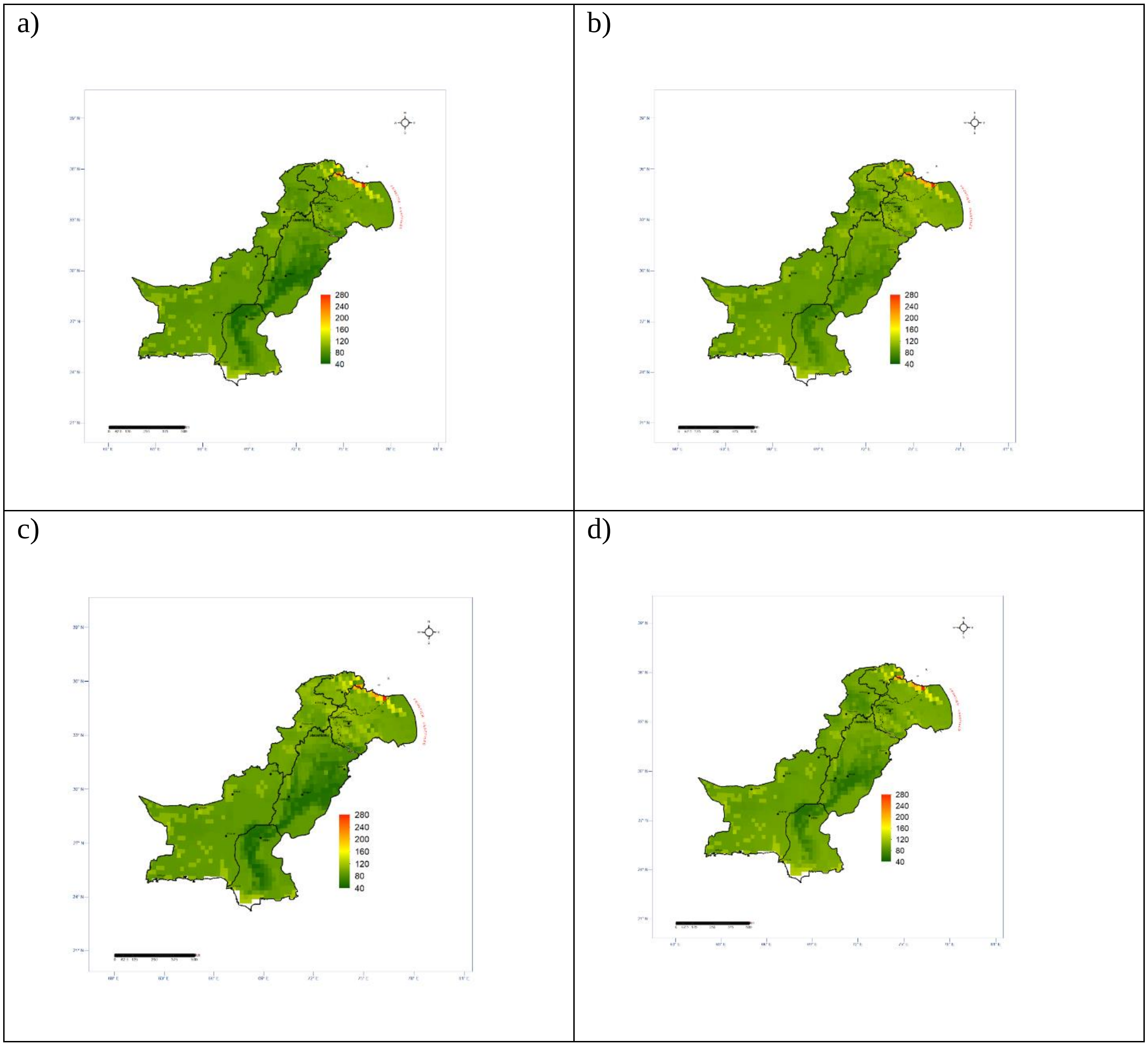


Fig.10. **Seasonal variation of soil moisture (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.**

Seasonal variation of evapotranspiration

According to fig.11. during winter and summer seasons, a high rate of evapotranspiration ($4.7e^{-005}$) is found to be in northern Punjab, all over Khyber Pakhtunkhwa, and in southern Jammu Kashmir in summer.

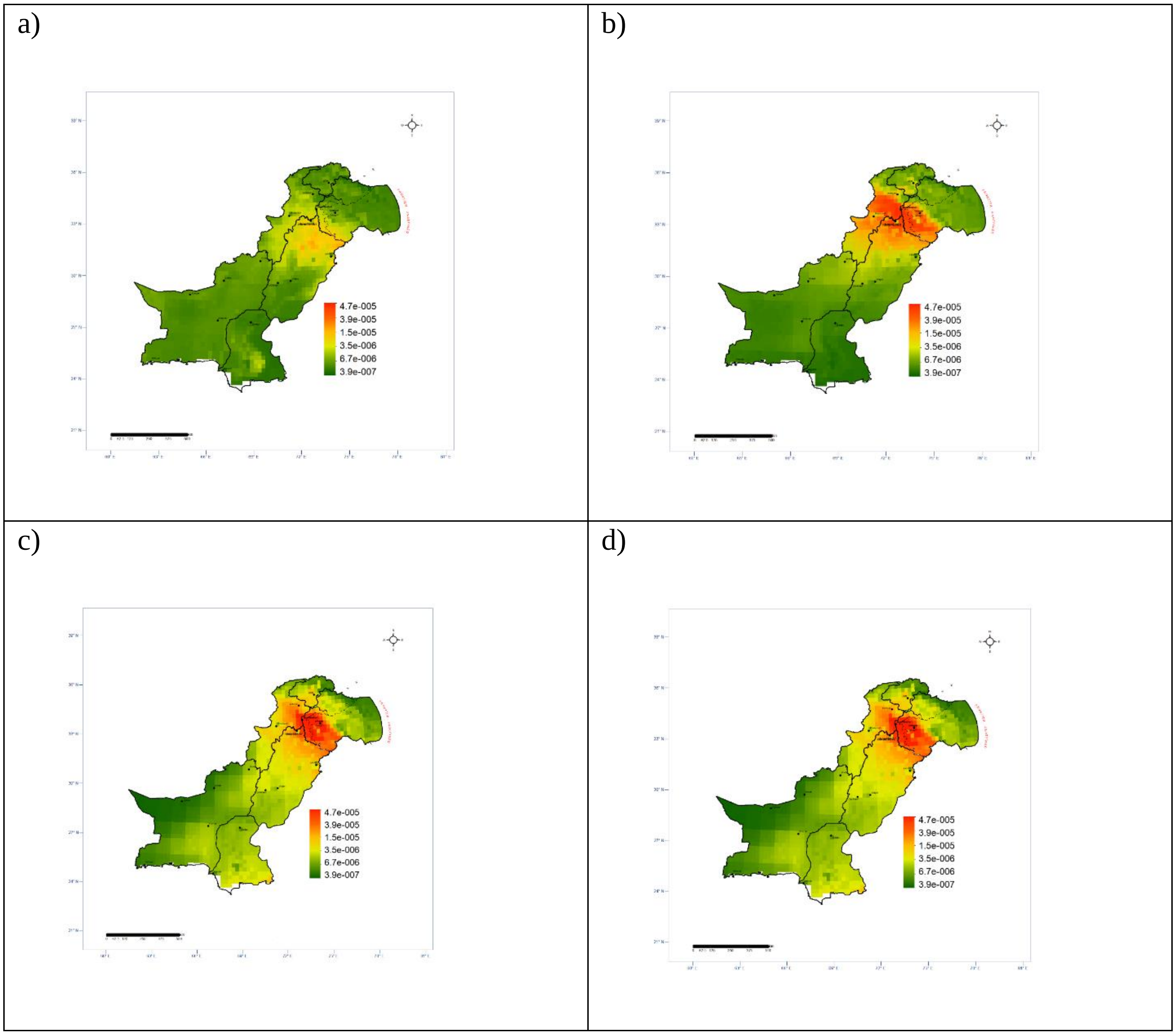


Fig.11. **Seasonal variation of evapotranspiration (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.**

Seasonal correlation of AOD with NDVI, soil moisture, evapotranspiration, and meteorological parameters.

AOD and AE

Correlation between AOD and AE derived from Aqua- MODIS over Pakistan has been shown in fig.12.

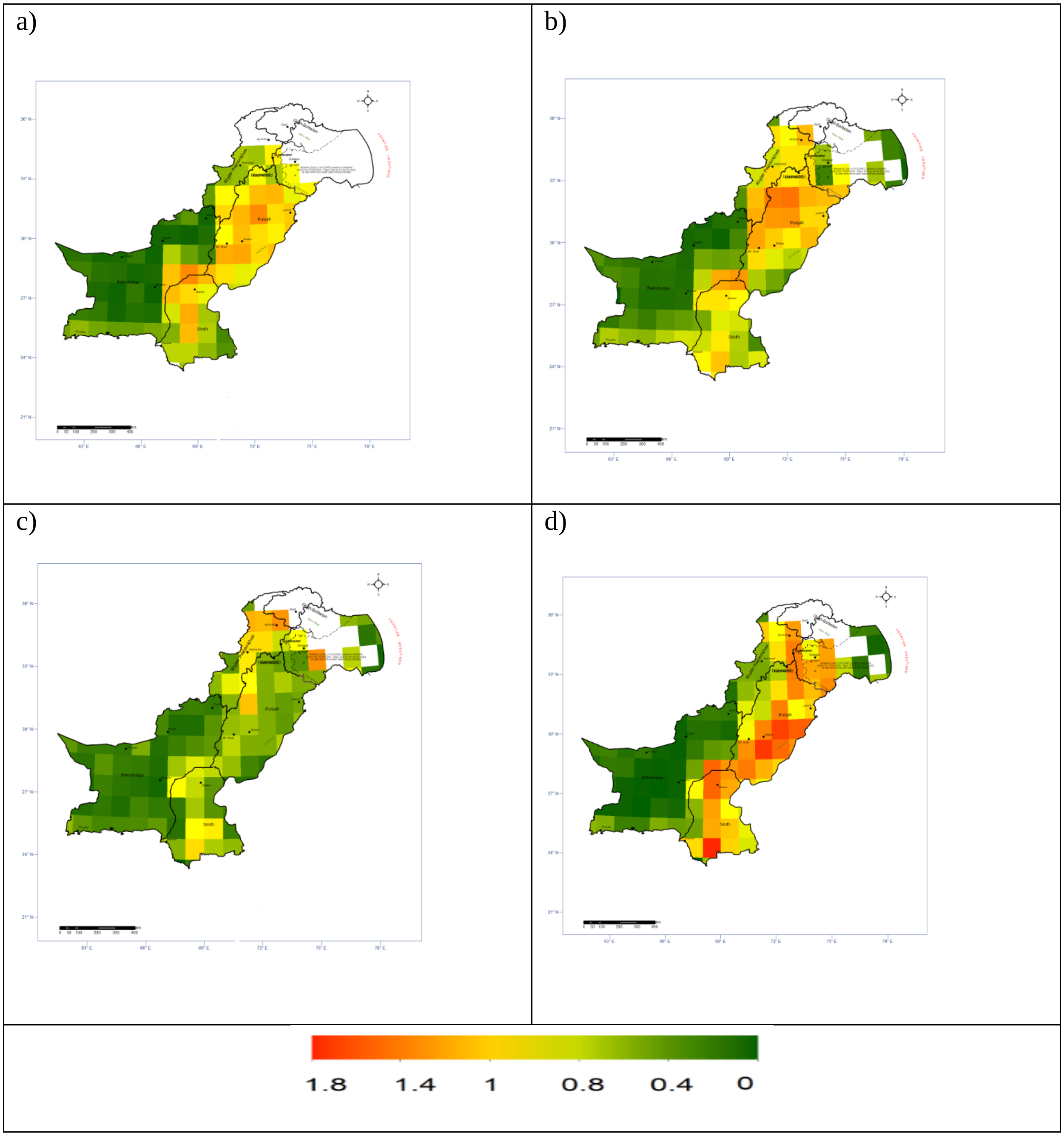


Fig.12 Seasonal correlation between AOD and AE (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Fig.13 shows a correlation between AOD and NDVI. Results show that an increase in NDVI decreases aerosol dispersal and a decrease in NDVI increases aerosol dispersal so these two parameters have indirect relation in all seasons except spring and autumn.

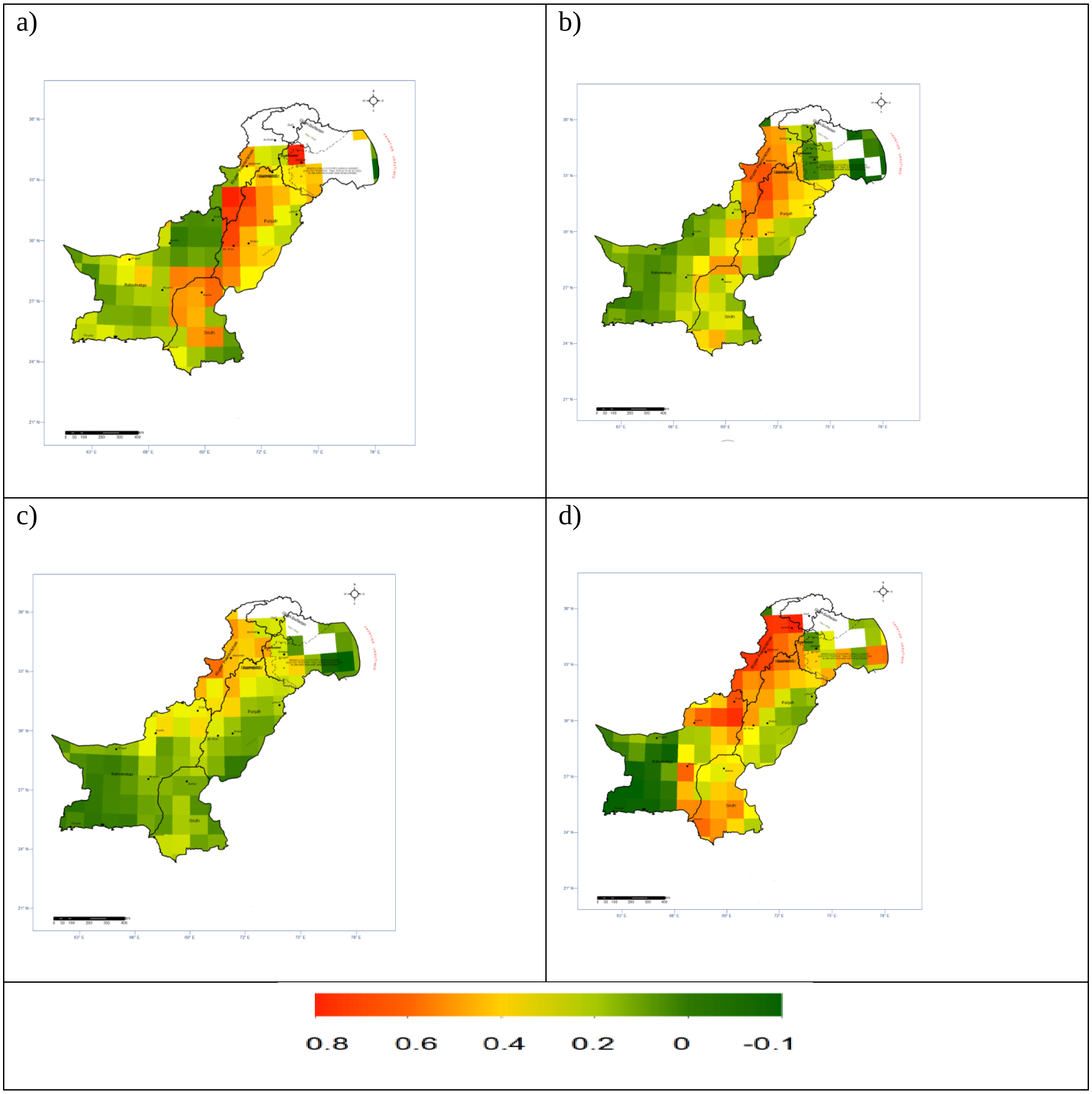


Fig. 13 Seasonal correlation between AOD and NDVI (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Fig. 14 shows the correlation between AOD and windspeed. Results show that wind and AOD have a direct relationship between them in all seasons. An increase in wind speed increases aerosol burden whereas, a decrease in windspeed decreases aerosol burden.

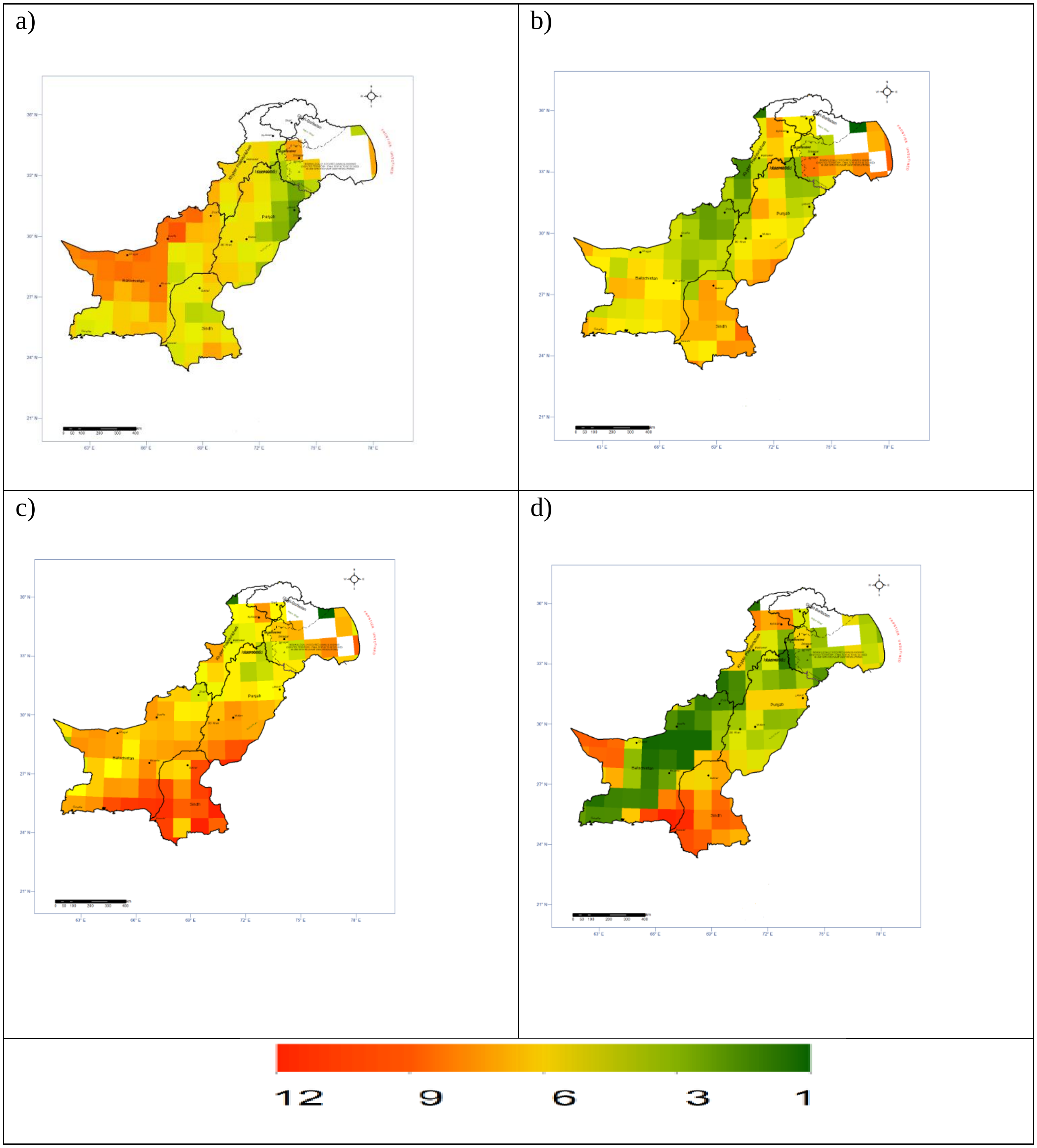


Fig.14 Seasonal correlation between AOD and Windspeed (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Fig. 15 shows the correlation between AOD and temperature. Results show that AOD and temperature have a direct relationship between them in all seasons. An increase in temperature increases the aerosol burden and vice versa.

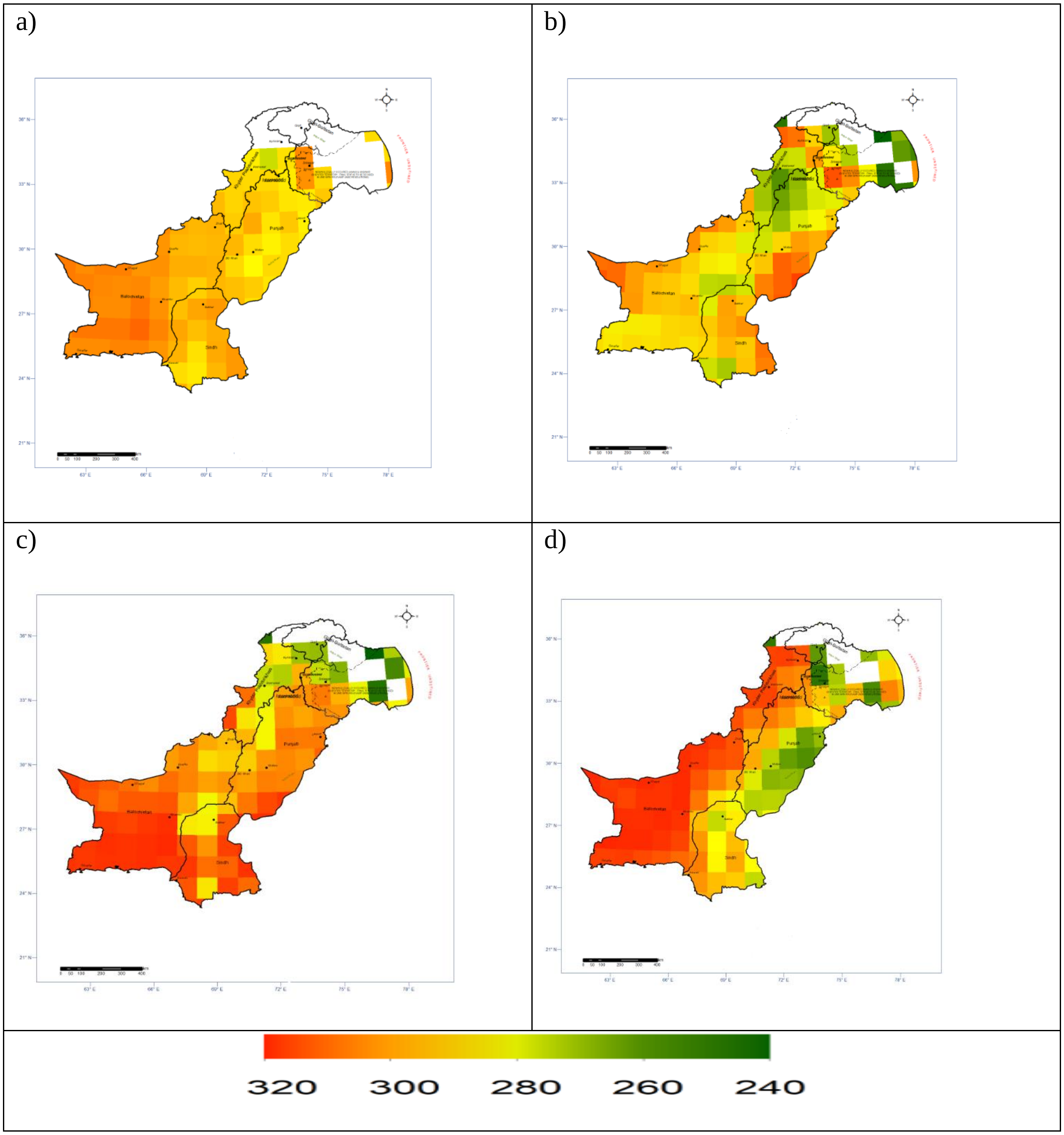


Fig. 15 Seasonal correlation between AOD and Temperature (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

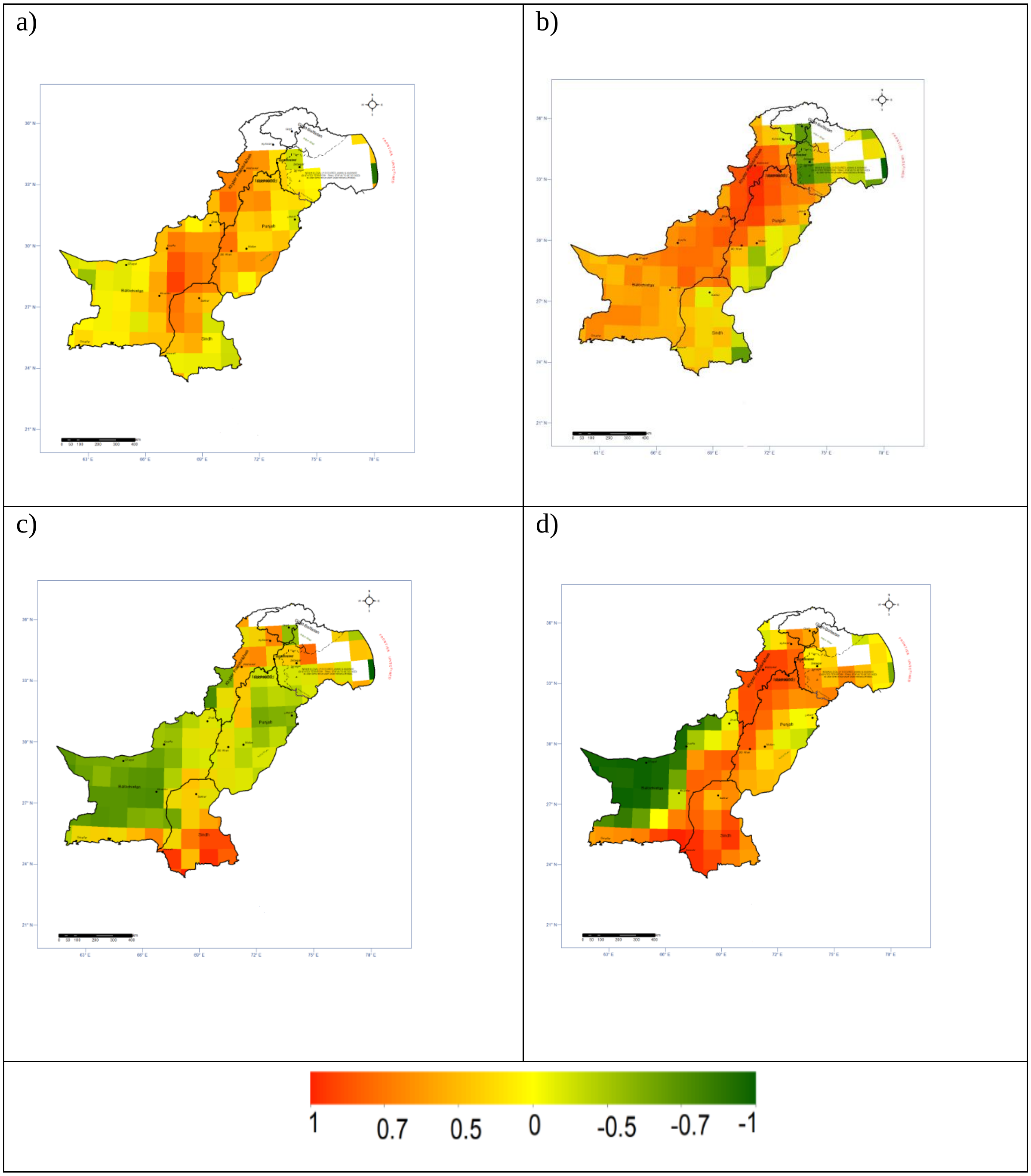


Fig. 16 shows a correlation between AOD and relative humidity (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Results show that AOD and relative humidity shows direct relation in the summer and winter season. However, in autumn and spring AOD and relative humidity shows an indirect relationship between them.

Fig.17 shows the correlation between AOD and precipitation. Results show that AOD and precipitation have an indirect relationship between them in all seasons except in the spring season because in the spring season relationship between AOD and precipitation is direct.

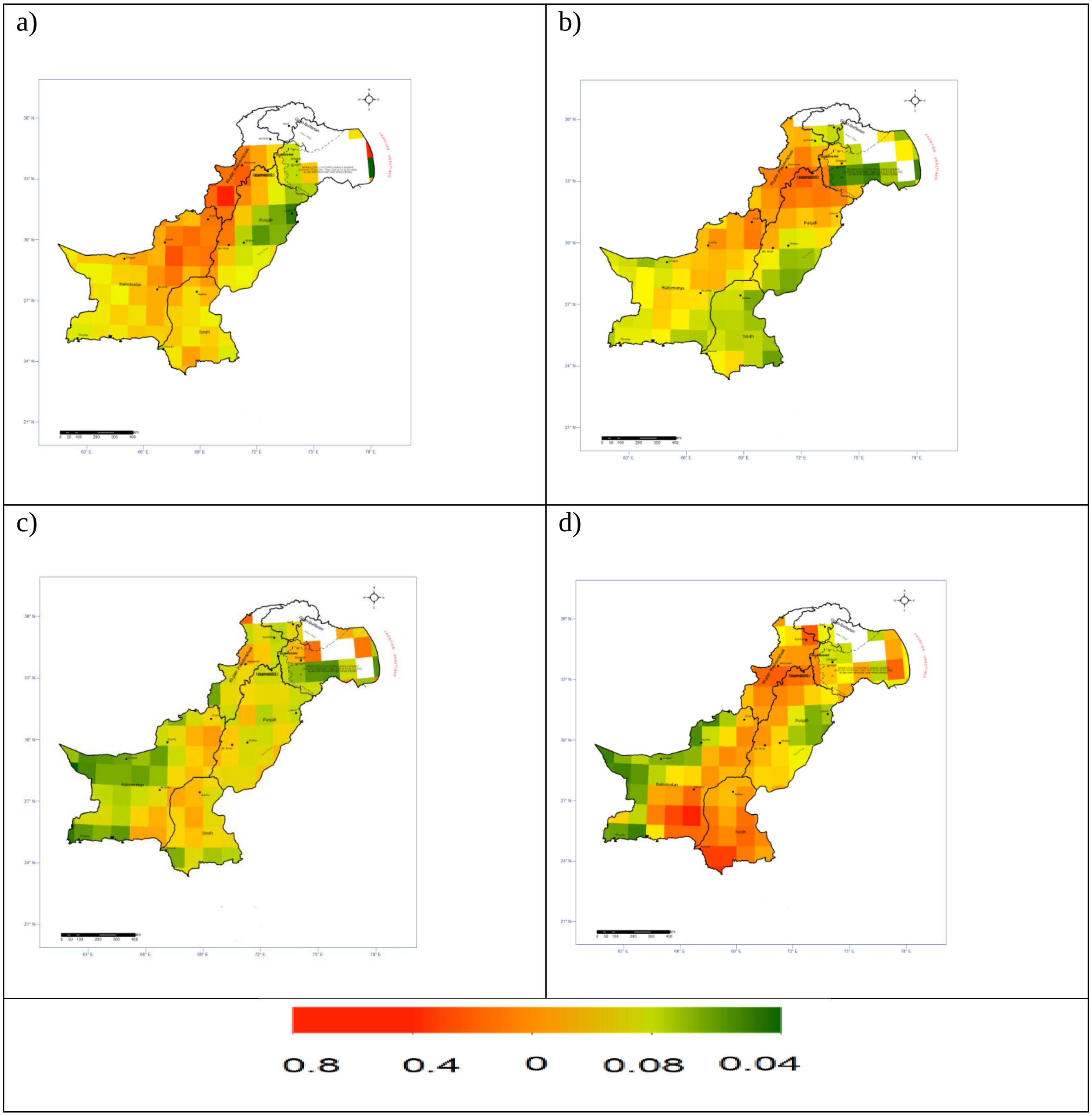


Fig 17. Seasonal correlation between AOD and Precipitation (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Fig. 18 shows a correlation between AOD and soil moisture. Results show that AOD and soil moisture have an indirect relationship in all seasons. An increase in AOD is due to low soil moisture content and a decrease in AOD is due to moderate to high moisture content.

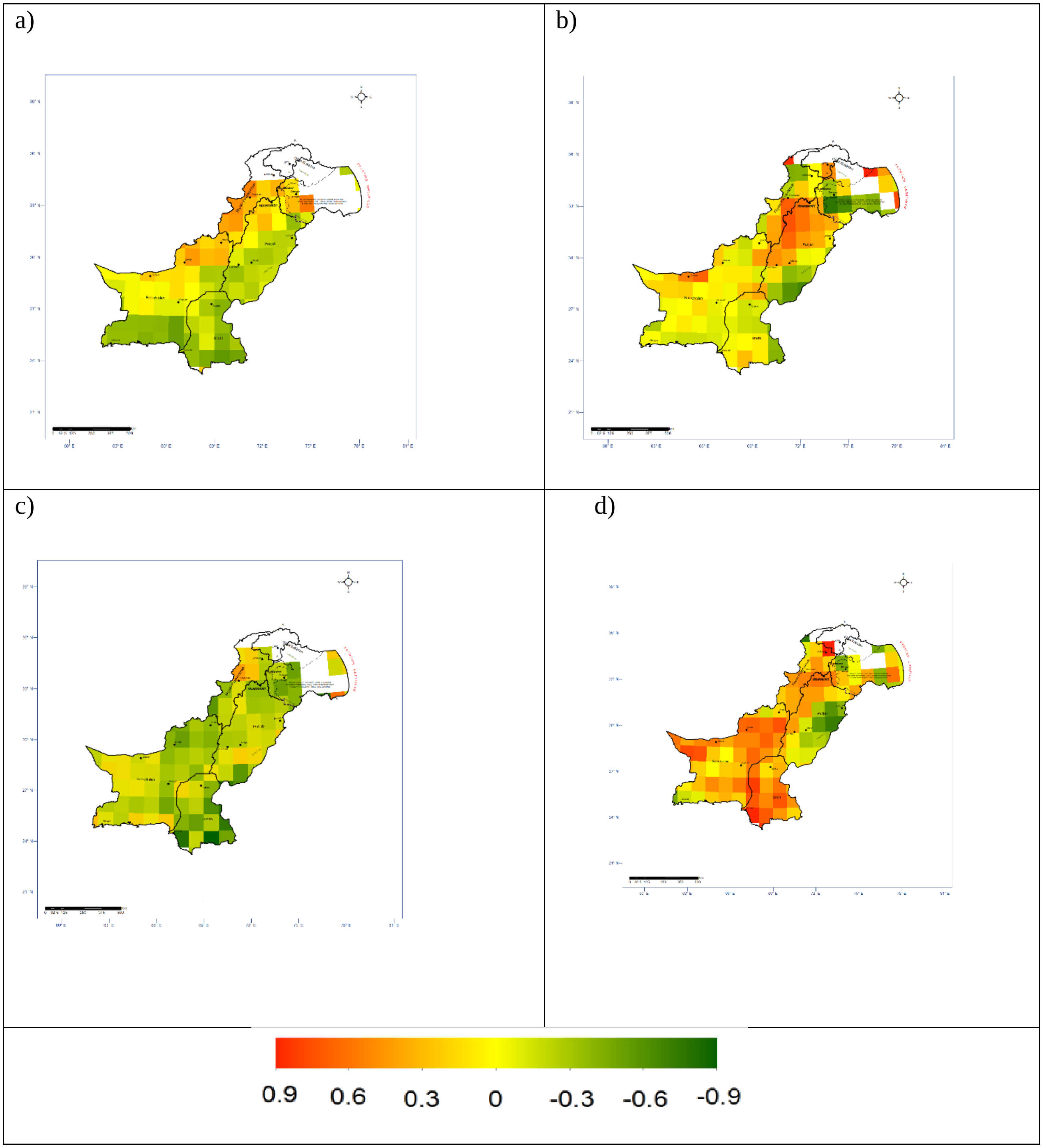


Fig.18 Seasonal correlation between AOD and soil moisture (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

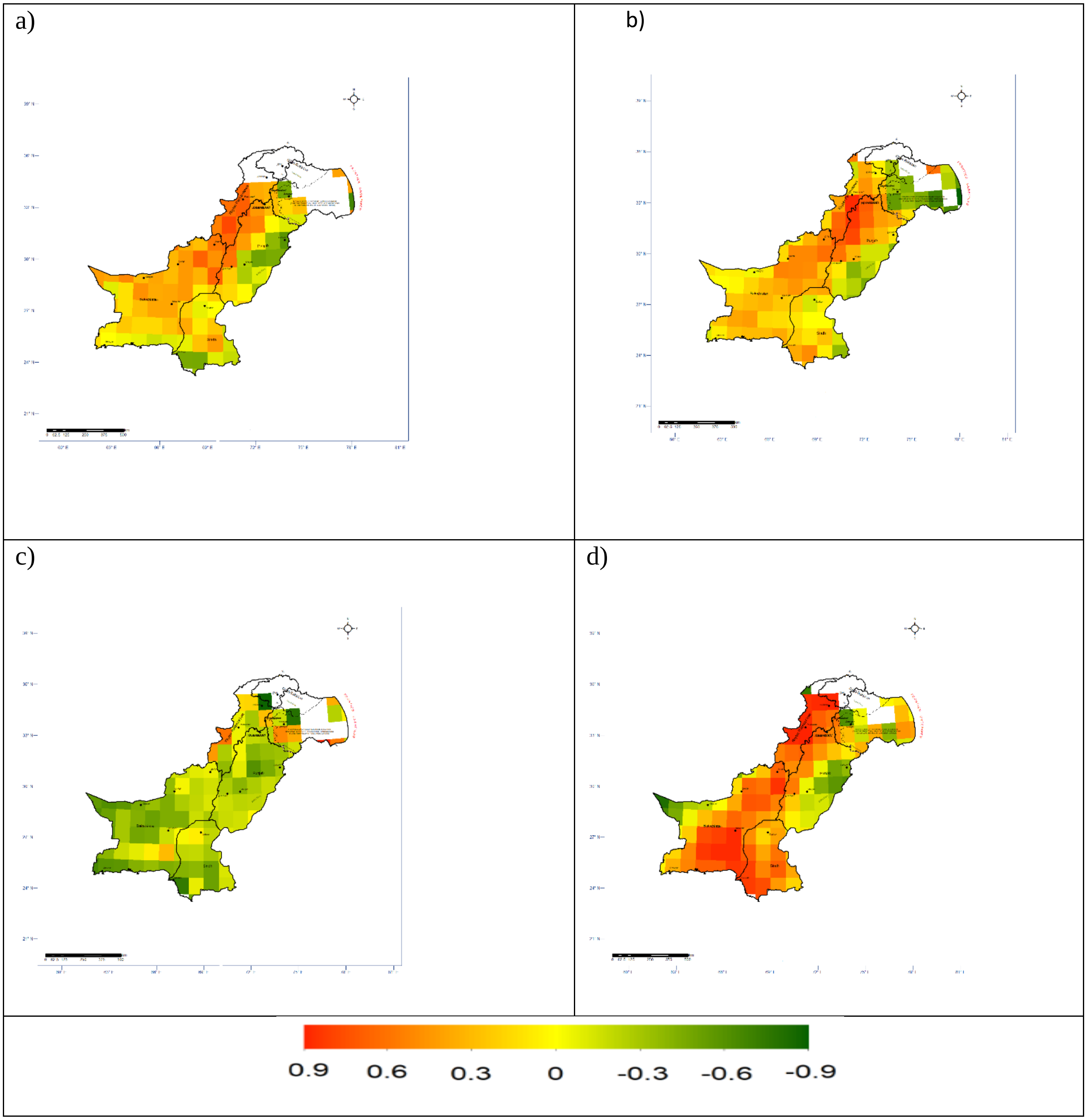


Fig. 19. Seasonal correlation between AOD and evapotranspiration (a) Winter, (b) Summer, (c) Spring, (d) Autumn in Pakistan.

Fig.19 shows a correlation between AOD and evapotranspiration. Results show that AOD and evapotranspiration have an indirect relationship between them in summer and winter. However, the spring and autumn scenario is entirely different AOD and evapotranspiration have a direct relationship between them.

Zoning control for PM2.5 concentrations

Fig. 20. Shows the control zoning classification of $PM_{2.5}$ concentration in Pakistan. It shows strict control areas and maintains optimal areas and resilient areas. Similarly, fig. 21 shows the medium growth class-covered regions in Pakistan from 1998 to 2020.

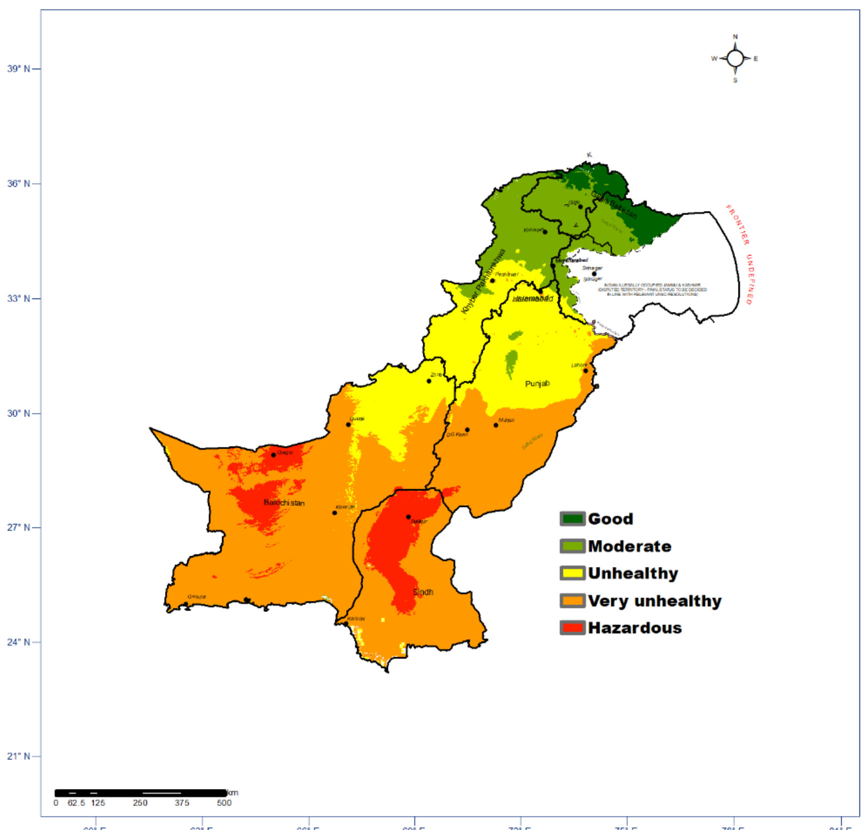


Fig. 20. Control zoning classification of $PM_{2.5}$ concentration over Pakistan

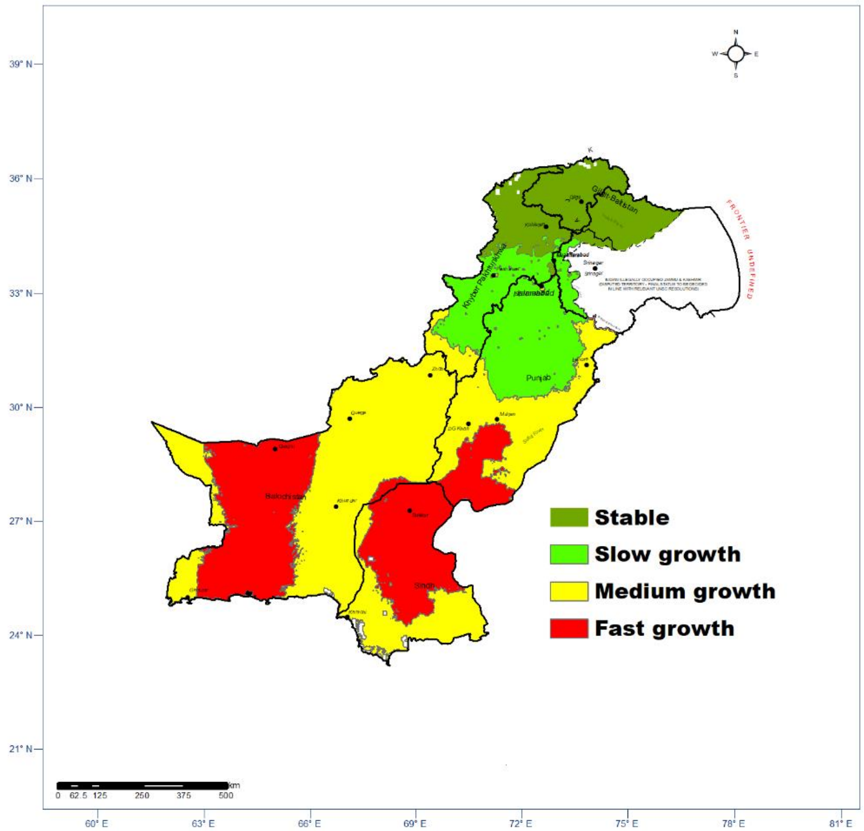


Fig.21. PM2.5 concentration variation trend classification over Pakistan from 1998 to 2020.

Fig. 22 shows the health risk evaluation that was conducted by classifying health risks by computing PM2.5 and population density in Pakistan. The unsupervised classification method made 5 different categories.

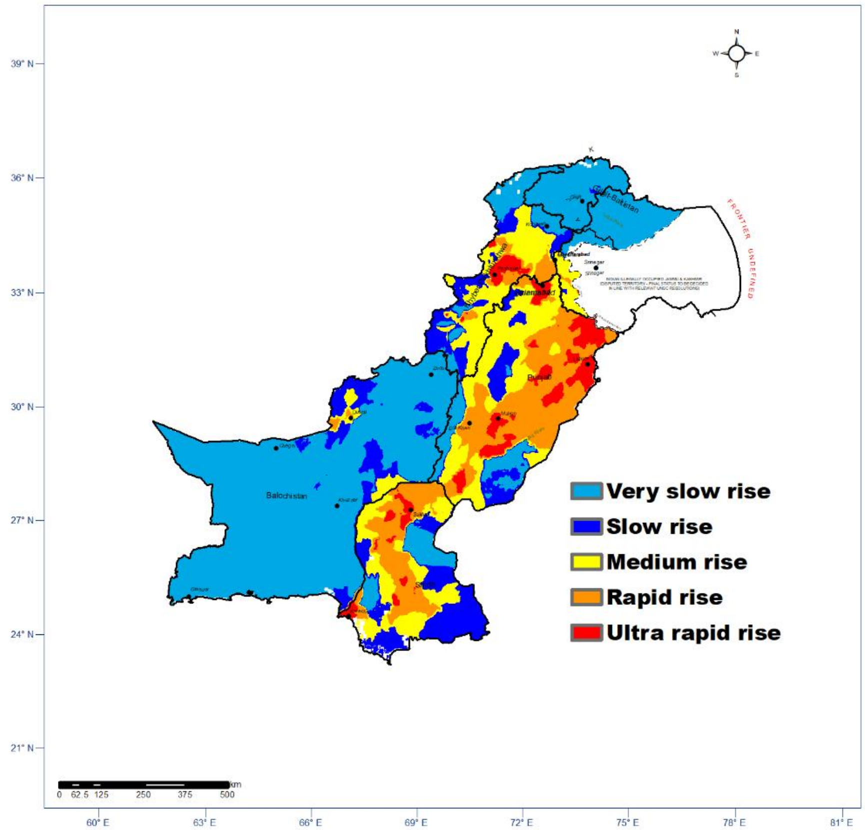


Fig.22. Health risk classification on the basis of population density and $PM_{2.5}$ concentration over Pakistan.

Chapter: 5 Discussion

Fig. 3 presents the spatial distribution of AOD and AE over Pakistan. The higher values of AOD were observed in Punjab and Sindh with peak values of approximately 0.55 and 0.48 respectively, extended into the southern region. Ashraf et al. (2013) pointed out that Punjab had the highest rate of aerosol loading which badly impacted the visibility of Punjab. Alam, Qureshi, et al. (2011) pointed out that higher values of AOD were found over southern areas of Pakistan (including Sindh, and Balochistan) due to an increase in population and urbanization along with an increase in the rate of industrialization. Furthermore, the increase in the flux of aerosols in the region of Punjab and Sindh was contributed by dust and desert aerosol transported from Thar and Cholistan desert through wind currents (Tariq & Ali, 2015). Similarly, low values of AOD (approximately 0.23) were observed in KPK which is in northern areas of Pakistan. Alam, et al. (2011) reported northern western areas of Pakistan faceless flux of AOD due to less population and more agricultural land for cultivation.

By contrast, AE distribution among provinces of Pakistan was in such a way that the approximate value of AE was 1.06 in eastern Pakistan, 1.15 in northern Pakistan, 0.89 in southern Pakistan, and 0.82 in western Pakistan. AE was high in Punjab and Khyber Pakhtunkhwa (approximately 1.06 and 1.15), indicating that there was an increase in aerosol burden as fine mode fraction aerosol particles were increasing in these regions. The dominance of fine-mode aerosols in Khyber Pakhtunkhwa and Punjab indicated a large number of biomass burning and related anthropogenic activities, especially in winter. Ali, et al. (2014) contributed while studying aerosol properties over the eastern region of Pakistan that AE values in Sindh were found to be smaller than that of Punjab indicating that Sindh has less polluted air as compared to Punjab. Sindh contains a large number of coarse-mode particles instead of fine-mode particles that originate from the Thar and Sahara regions. Similarly, our study showed elevated values of AE for Khyber Pakhtunkhwa and Punjab while the lower value of AE for Sindh and Balochistan proved less fine mode particles in Sindh and Balochistan (approximately 0.89 and 0.82 respectively).

Annual variation between AOD and AE among provinces of Pakistan has represented in Fig.3. Results indicated that AOD peaks were accountable for anthropogenic activities and the movement of dust particles from nearby deserts. AE was relatively low in the Sindh and Balochistan regions of Pakistan, which showed that fine mode particles had not played an influential role in aerosol extinction so, coarse particles played a more crucial role. Similarly, the impact of a dust particle on aerosol extinction was more in Khyber Pakhtunkhwa and Punjab. Therefore, we have discussed in detail the seasonal spatial distribution of AOD and AE in all provinces of Pakistan in section 3.2 of this paper. Fig.4 shows seasonal variation of AOD showed that peak occurrence of AOD was found in summer and spring, while lower AOD was found in autumn and winter among all provinces of Pakistan. In spring, peak values were found to be in Punjab (0.45) and Sindh (0.43). Further, an increasing trend for AOD was recorded in summers for all provinces of Pakistan with peak values in Punjab (0.8) and Sindh (0.7). In autumn and winter, AOD decreased significantly across all the provinces of Pakistan with the highest value (0.54) for autumn and approximately 0.48 for winter. These seasonal variations indicated that in summers severe aerosol extinction events occurred. Higher AOD values in summers in Punjab (0.84) and Sindh (0.84) contributed to various anthropogenic activities such as industrial and fossil fuel burning, several open burning sources, smoke coming from forest fires, and water-soluble agricultural aerosols (Alam et al., 2014)

We also recorded the seasonal spatial distribution of AE. Fig.5 shows the seasonal variation of AE from 2002 to 2022. AE is an indicator for the size distribution of aerosols. The size of aerosol In the winter trend from maximum to minimum value was recorded as follows; Punjab (1.3), Khyber Pakhtunkhwa (1.2), Sindh (0.5), and Balochistan (0.4). Similarly, in spring highest value of AE was in Khyber Pakhtunkhwa (1.6) followed by Punjab (0.4), Sindh (0.3), and Balochistan (approximately 0.4). During summers, the AE value was highest for Khyber Pakhtunkhwa (1.8) followed by Punjab (1), Sindh (0.8), and Balochistan (0.6). For autumn highest value for AE was in Khyber Pakhtunkhwa (1.5) followed by Punjab (1.4), Sindh (0.8-0.4), and Balochistan (0.8-0.4). These results indicated that the value of AE remained above 1 throughout all the seasons in Khyber Pakhtunkhwa followed by the highest value in Punjab (approximately 1.3), especially in winter. Alam et al., 2014b reported that fine-mode aerosol concentration in winters increased because the temperature dropped down below the freezing point so wood was the only cheap source of getting heat. People survive by burning wood that contributes to biomass aerosols. Another study confirms the fact that the burning of wood, dung, and coal in winter contributes to fine aerosol particles (Ali, Tariq, Mahmood, Daud, & Batool, 2014).

Fig.6. shows seasonal variation of NDVI during the winter season, Punjab (0.6) and few areas of Sindh (0.6), and Khyber Pakhtunkhwa (0.3) show a moderate amount of NDVI. However, in the summer, the area of Jammu Kashmir (0.8) and northern Khyber Pakhtunkhwa (0.8) shows the highest index of NDVI. Similarly, in the spring season Punjab (0.7) southern Jammu Kashmir (0.8), and northern Khyber Pakhtunkhwa (0.8) shows the highest range of NDVI over there. In the autumn season, Punjab (0.6), a few areas of Sindh (0.6), northern Khyber Pakhtunkhwa (0.7), and southern Kashmir (0.7) show the highest NDVI index. Whereas, Balochistan (0.2) and some areas of Jammu Kashmir (0-0.1) have the lowest amount of NDVI throughout all the seasons almost. Whereas

According to fig.7. during winter and spring seasons highest wind speed is found to be in the areas of Balochistan (10-12). Similarly, high wind speed is found to be in Sindh (12) during the spring season. During the season wind speed is found to be lower (1-3) in areas of northern Khyber Pakhtunkhwa (1-3), Punjab (3), and a few areas of Sindh also (4). During the summer season, windspeed is found to be in Balochistan (5-6) also.

According to fig.8. in all season's temperature is found to be high in Punjab (300-320 k) and Sindh (300 k) areas. Balochistan (310-320 k) has highest temperature value during summer and autumn season. For Khyber Pakhtunkhwa temperature during winter season is (290 k), spring season (280 k) and autumn season (275 k). Low temperature is found to be in area of Jammu Kashmir (240-260) only in all seasons.

According to fig.9. the relative humidity is found to be highest in northern Khyber Pakhtunkhwa (70) and Jammu Kashmir (70) areas only during winter and spring seasons. Similarly, moderate (30-45) relative humidity is found to be in Sindh, Punjab, and Khyber Pakhtunkhwa in the summer and autumn seasons. The lowest value (10-20) for relative humidity is found to be all over Balochistan in all seasons and Sindh during the winter and spring season.

According to fig.9. highest ranges for the precipitation rate are found in northern Khyber Pakhtunkhwa (0.8), near Quetta (0.4), and southern Jammu Kashmir (0.8) during the winter season. Similarly, in the spring season precipitation rate is found to be moderate to high in Khyber Pakhtunkhwa (0.1) and near Srinagar (0.4). During the summer and autumn seasons low to moderate precipitation is found to be in northern Punjab (0.1) and Khyber Pakhtunkhwa (0.1). however, in all seasons precipitation remained moderate (0.02-0.1) in Punjab and lowest (0.02-0.05) in Balochistan.

According to fig.10. in all seasons of Pakistan, soil moisture remained low to moderate (120-150) in all seasons in Balochistan, Khyber Pakhtunkhwa, and some areas of Sindh. The lowest range of soil moisture content (40-60) is found in majorly in Punjab and Sindh in all seasons. Similarly, the highest soil moisture content (280) is found to be in northern Jammu Kashmir only.

According to fig.11. during winter and summer seasons, the lowest evapotranspiration rate is found to be all over Balochistan ($3.9e^{-007}$), Sindh ($3.9e^{-007}$), and southern eastern Punjab (6.7^{e-006}). However, a moderate evapotranspiration rate is found to be in northern Punjab ($1.5e^{-005}$) in winter. In summer high rate of evapotranspiration ($4.7e^{-005}$) is found to be in northern Punjab, all over Khyber Pakhtunkhwa, and in southern Jammu Kashmir. Similarly, in the case of Jammu Kashmir high rate of evapotranspiration ($4.7e^{-005}$) is found in the spring and autumn season also. A moderate range ($3.5e^{-006}$) of evapotranspiration is found to be in all of Punjab, Khyber Pakhtunkhwa, and a few cities of Sindh during the autumn and spring season. Similarly, the lowest value ($3.9e^{-007}$) is found to be in Balochistan during the autumn and spring season.

Correlation between AOD and AE derived from Aqua- MODIS over Pakistan has been shown in fig.12. During the winter season, a very weak positive correlation can be observed in Punjab (1.4), Sindh (1.2), and a few areas of Balochistan (1) including cities i.e., Multan (1.2), Lahore (1.2), DG khan (1.3) and Sukkur (1.3). A weak positive value indicates the presence of a high value of AOD (1) and a high value of AE (1.2) according to fig. 4 and 5. High burden of fine-mode aerosols is present in these regions due to industrial and biomass burning (Mhawish et al., 2021). Similarly, a strong negative correlation between AOD and AE can be observed in Balochistan (0.2). It includes areas of Quetta (0.2), Zhob (0.2), chagai (0.2), and Khuzdar (0.2). According to fig 4 and 5, a high value of AOD (0.9) and a low value of AE (0.8) in these regions indicate the present burden of coarse mode aerosols especially dust aerosols (Ali et al., 2020). During the summer season, a weak positive (1) correlation between AOD and AE has been observed in Khyber Pakhtunkhwa (1), Punjab (greater than 1), and Sindh (1). AOD is higher (1.2) during the summer season followed by a high value of AE (1.2) (fig 4 and 5) indicating the presence of a high burden of aerosols having fine size. Similarly, a strong negative correlation (0.2) is observed between AOD and AE in Balochistan and a few areas of Jammu Kashmir. Cities that face negative correlation include Srinagar (0.1), Khuzdar (0.1), Quetta (0.1), Zhob (0.2), and chagai (0.1). These areas have a high aerosol burden but a low value of AE indicating the presence of coarse mode particles. (Ali et al., 2014) conducted a similar study in which they reported that Balochistan has high AOD due to high temperatures in summer and high dust storm frequency.

During the spring season, a very weak positive correlation has been observed in northern Khyber Pakhtunkhwa (1) Jammu Kashmir area (1), and near Dera Ismail khan (0.9) in Punjab. These areas face a low burden of aerosol (0.7) with the presence of coarse mode particles indicating a low value of AE (0.6) (fig 4 and 5) except Khyber Pakhtunkhwa where burning coal in the spring season produces fine mode particles (1.2). (Alam et al., 2011) conducted a similar study in which they reported that Khyber Pakhtunkhwa faces a high burden of fine-mode aerosols in spring due to the burning of coal. Similarly, a strong negative correlation can be observed in Balochistan (0.2-0.4) and some areas of Sindh (0.5). It includes cities i.e., Zhob (0.3), Quetta (0.2), Chagai (0.3), Khuzdar (0.3), and Karachi (0.5). A negative correlation during the spring season validates the presence of coarse mode particles (0.8) followed by low aerosol burden (0.6) (fig 4 and 5). Increased traffic and industries are responsible for the contribution of dust in the atmosphere of Quetta and Sindh (Sami et al., 2006). Moreover, during the autumn season, a strong positive correlation can be observed in Punjab (1.4-1.6) and a few areas of Sindh (1.4-1-6). These areas include cities like Multan (1.8), DG Khan (1.4), and areas around Lahore (1.2). A strong positive correlation indicates the presence of a high burden of aerosol (high AOD) followed by the presence of a fine and mixed type of aerosols indicating a high value of AE (fig 4 and 5). This season shows the prevailing dust aerosols over industrial, biomass, and urban aerosols (Ali et al., 2014). Similarly, a strong negative correlation has been observed in Balochistan (0.1) and a few areas of Khyber Pakhtunkhwa (0.3) showing low aerosol burden in Balochistan followed by the presence of coarse mode aerosols over there due to the presence of dust aerosols (Zhang et al., 2020)Whereas, in Khyber Pakhtunkhwa area AOD is low (0.5) with the presence of fine mode aerosols (1.2) according to fig. 4 and 5.

According to fig.13 during the winter season, a strong positive correlation can be observed in western Punjab (0.7) and southern Khyber Pakhtunkhwa (0.8). According to fig 4 and 6 in Khyber Pakhtunkhwa, the aerosol burden is low (0.2) so the NDVI index is in the medium range (0.4) whereas in Punjab aerosol burden is medium (0.7) so the NDVI index is higher over there. Forest degradation and deforestation in Khyber Pakhtunkhwa have decreased vegetation that plays role in acting as barriers to the movement of aerosols (Munawar et al., 2015). Despite the high NDVI index in Punjab, smoke from traffic and industries contribute to the aerosol contribution followed by the rise in dense fog in winter (Yasmeen et al., 2013). Similarly, a strong negative correlation can be observed in Balochistan (-0.1), especially in areas of Gwadar, Quetta, and Zhob along with some cities in western Khyber Pakhtunkhwa (0.1) and southern Sindh (0.1). Aerosols burden is found to be low in winters in Balochistan (0.3) as well as in southern Sindh (0.2) and western Khyber Pakhtunkhwa (0.4) followed by a low level of vegetation (0.1-0.2) in these areas (fig 4 and 6). During the summer season, a weak positive correlation can be found in Khyber Pakhtunkhwa and western Punjab. It includes Islamabad (0.9) and Peshawar (0.9). according to fig. 4 and 6, Khyber Pakhtunkhwa has a medium aerosol (0.6) burden due to low vegetation (0.2) is present.

Punjab has a high urbanization rate that reduces the vegetation index and high employment rates in Punjab increases the demand for land (Mazhar et al., 2021). Similarly, western Punjab has a high aerosol (0.8) burden and low NDVI index (0.2) according to fig 4 and 6 which shows an indirect relation between the two parameters. A negative correlation can be observed in Kashmir (0.7) where the aerosol burden is found to be low (0.4) because the NDVI level is high (0.8) (fig 4 and 6). Mountainous areas have less increased vegetation that plays a great role in acting as a barrier for aerosol dispersal (Alam et al., 2011).

During the spring season, a weak positive correlation (1) between NDVI and AOD can be observed in Khyber Pakhtunkhwa (0.5-0.7). According to fig 4 and 6, the NDVI level is low (0.3-0.5) and the aerosol burden is moderate (0.6) in Khyber Pakhtunkhwa. Similarly, a medium negative correlation can be observed in the area of Balochistan (-0.1), southern Punjab (0), and Kashmir (-0.1) which includes cities like Zhob (-0.1), and Quetta (-0.1). According to fig 4 and 6, the aerosol burden is low (0.1-0.4) in areas of Punjab (0.3), Balochistan (0.3), and Kashmir whereas, the NDVI index is also low (0.4) in the above-mentioned areas except for Kashmir (0.7). The vegetation index is found to be very low in Balochistan because it is a deserted area and receives very less rainfall (M. Ashraf et al., 2022). Punjab is found to have a rapid rate of urbanization and a high rate of industrialization which leads to an increase in land use over there (Ali et al., 2014). Similarly, during the autumn season, a strong positive correlation between AOD and NDVI can be observed in Khyber Pakhtunkhwa (0.8) and northern Balochistan (0.7). According to fig. 4 and 6, in Khyber Pakhtunkhwa NDVI is moderate (0.4-0.6) and the aerosol burden is low (0.2). However, in the case of Balochistan aerosol burden (0.3) and NDVI (0.2), both are low due to less rainfall and low windspeed in northern Balochistan during the autumn season which causes less dispersal of aerosols in the northern region (Ali et al., 2020). A strong negative correlation can be observed in western Balochistan (-0.1) in fig.13. It can be observed in fig. 4 and 6 that western Balochistan has low NDVI (0.1) and moderate aerosol burden (0.7). Western Balochistan faces severe evapotranspiration that makes the air less humid contributing to a reduction in vegetation (Zhang et al., 2020). All these results show that an increase in NDVI decreases aerosol dispersal and a decrease in NDVI increases aerosol dispersal so these two parameters have indirect relation in all seasons except spring and autumn.

According to fig.14, during winters weak positive (9) correlation can be observed in the northwestern region of Balochistan including the cities; chagai (9), Quetta, and Khuzdar. According to fig. 4 and 7, the aerosol burden is low (0.4) and windspeed is moderate (7 ms^{-1}) in these above-mentioned regions. Whereas we can observe a weak negative correlation between AOD and windspeed in northern eastern Punjab (3) where the aerosol burden is found to be higher (0.8) in Punjab and windspeed is slower (3 ms^{-1}). Smog episodes in Punjab hold the aerosols in the atmosphere and reduce the speed of wind (Khokhar et al., 2016). (Li et al., 2021) contribute in their study that in winter, low wind speed in the above areas shows that the aerosol in the atmosphere settles down on the land under the action of gravity. During the summer season, a weak positive relationship between windspeed and AOD is found to be in the area of Jammu Kashmir (8) (fig. 14). AOD (0.2) and windspeed (3 ms^{-1}) both are found to be low in the Jammu Kashmir area according to fig 4 and 7. Similarly, a negative correlation can be observed in northern Balochistan (4) including Quetta, Zhob, Khuzdar, and the southern region of Khyber Pakhtunkhwa (2) but according to fig. 4 and 7 aerosol burden is observed to be lower (0.2) in northern Balochistan and southern Khyber Pakhtunkhwa similarly, wind speed is also low (5 ms^{-1}). Slow winds in northern Balochistan and southern Khyber Pakhtunkhwa followed by low to moderate temperature causes relatively weak vertical convection thus having low aerosol burden (Zhang et al., 2020b).

During the spring season, a strong positive correlation is observed in southern Punjab (10), almost all the areas of Sindh (12), and a few areas of Balochistan (11). The aerosol burden is found to be moderate (0.7) in respective areas in Punjab, Sindh, and Balochistan. Similarly, windspeed is also moderate (<6 ms^{-1}) according to fig. 4 and 7. An extremely weak negative relation is found to be in northern Punjab in Islamabad (4). According to fig. 4 and 7 low aerosol (0.4) burden and windspeed (3 ms^{-1}) in found in northern Punjab. In spring aerosol burden is found to be moderate because frequent dust storm events occur in which wind helps to transport the aerosols from Thar, Thal, and surrounding arid areas to Sindh, Balochistan, and Punjab (Zhang et al., 2020b). The temperature in northern Punjab is low to moderate in spring along with wind speed due to which aerosol burden is low over there.

During the autumn season (fig. 14) positive relationship between AOD and windspeed is found in areas of western southern Balochistan (10) and almost the whole of Sindh (9). According to fig. 4 and 7 aerosol burden (0.4) and windspeed (9 ms^{-1}) both are low in the above regions. Similarly, strong negative relation is observed in northern southern Balochistan (1) and southern Khyber Pakhtunkhwa (1). According to fig. 4 and 7 aerosol burden (0.3) and windspeed (3 ms^{-1}) both are low. Pakistan faces low AOD during post-monsoon due to fewer dust storms in this season and low windspeed does not allow the movement of aerosols.

All these results show that wind and AOD have a direct relationship between them in all seasons. An increase in wind speed increases aerosol burden whereas, a decrease in windspeed decreases aerosol burden.

According to fig. 15 during the winter season, a weak positive correlation (310) is observed between AOD and temperature in western southern Balochistan (300) and Srinagar (310). According to fig.4 and 8, it can be observed that aerosol burden (0.4) is low and temperature is normal (200 K). It covers Zhob (310 K), chagai (300 K) and Khuzdar (300 K). similarly, in winter aerosol burden (0.2) and temperature (50 K), both are low in Srinagar. Relative humidity remains low in desert areas so, fewer aerosols are present in the respective area at low temperatures, especially in Balochistan (Khan, 2021). Ramachandran & Cherian, (2008) conducted a study that showed that the Kashmir and Srinagar areas have relatively lower annual AOD because of less traffic and less industrialization as compared to the rest of the areas.

A weak negative correlation is found to be in northern Khyber Pakhtunkhwa i.e area of Mardan. Aerosols are found to be moderate in concentration (0.6) over there but the temperature is also low to moderate (180 K) (fig. 4 and 8). Tariq et al., (2021) conducted a similar study in which AOD is moderate to high in winter because people burn wood, biomass, and coal to overcome cold in winter and for cooking purposes in Khyber Pakhtunkhwa

During the summer season, a weak positive correlation is found to be in western Balochistan (295), northern southern Sindh (290), eastern southern Punjab (310), and Khyber Pakhtunkhwa northern area of Kohistan (310). According to fig 4 and 8, the aerosol burden is higher (greater than 1) along with temperature (greater than 250 K) in Sindh and Punjab areas. However, in Balochistan aerosol burden is moderate to high (0.8) along with moderate temperature (200 K). During summers soil moisture is deficit in Balochistan and a drought situation occurs that enhances the aerosol burden over there (Ullah et al., 2022). Similarly, a Negative relationship between AOD and temperature is found to be in northern western Punjab (270) and southern western Khyber Pakhtunkhwa (260) including cities i.e Islamabad (270), Dera Ghazi Khan (278), Peshawar (260) along with few areas in Jammu Kashmir (240). According to fig 4 and 8, a low to moderate amount of aerosol burden (0.6) along with high temperature (250 K) is present in above mentioned areas. Tariq & Ali, (2015) conducted a study in Pakistan in which they found out that in summer high AOD value is to an increase in anthropogenic activities i.e road dust, smoke, dust from heavy machines, and burning of crops that ultimately result in global warming. Aerosols generated from human activities affect the climate by scattering and absorbing the solar radiations reaching the earth (Huang et al., 2006).

During the spring season, a strong positive correlation between AOD and temperature is found to be in Sindh (320), Balochistan (320), and southern Khyber Pakhtunkhwa (310) areas. It includes chagai (310), Khuzdar (320) and sukkur (320). According to fig. 4 and 8, temperature (greater than 180 K) and AOD (0.4) both are found to be low in the above-mentioned areas. Similarly, a negative correlation is found to be in Khyber Pakhtunkhwa (275) and Jammu Kashmir (approximately 260). According to fig. 4 and 8 AOD is low (0.4) and temperature is low to moderate (greater than 150 K) in these regions. Similarly, during the autumn season, a strong positive correlation is found to be in all over Balochistan (320), and Khyber Pakhtunkhwa (320) that includes chagai, Zhob, Quetta, Khuzdar, Peshawar, Mardan, and Kohistan. According to fig. 4 and 8 temperature is low (180 K) and the aerosol burden is also low (0.2). AOD is lowest during the spring, winter, and autumn seasons in above mentioned regions because of weak vertical mixing in the atmosphere and the absence of strong connective winds in the low temperature (Khan et al., 2021).

A negative correlation is observed in southern western Punjab (260) and Gilgit Baltistan (240). According to fig. 4 and 8 temperature (230 K) and AOD (1), both are high in Punjab whereas, in Gilgit Baltistan temperature (160 K) and AOD (0.2) are low. Punjab has high AOD due to the harvesting season of rice in which rice husk contributes to atmospheric pollution in the atmosphere followed by the burning of left-over rice residues (Singh & Kaskaoutis, 2014).

All the above results show that AOD and temperature have a direct relationship between them in all seasons. An increase in temperature increases the aerosol burden and vice versa.

According to fig. 16 during the winter season, a positive correlation (0.7) is found in northwestern Balochistan and Khyber Pakhtunkhwa. According to fig. 4 and 9, both relative humidity (greater than 20 %) and AOD (0.3) are low in the above-mentioned areas of Pakistan. A weak negative correlation is found in Balochistan (-0.5) and Sindh (-0.4). The relative humidity is found to be low (20%) along with low aerosol burden (0.2) (fig. 4 and 9). Low relative humidity in winter along with low temperatures do not trap aerosols in the atmosphere thus reducing the aerosol burden in the atmosphere.

During summers, a positive correlation is found in northwestern Punjab (0.8), furthermore, in Khyber Pakhtunkhwa (0.9). A moderate (40 %) amount of relative humidity is present in the above regions with low AOD (0.6) in Khyber Pakhtunkhwa and moderate to high AOD (greater than 0.8) in Punjab. A negative correlation is found to be in some areas of Punjab (-0.6), Sindh (-0.6), and Gilgit Baltistan (-0.7). High aerosol burden (1) and moderate relative humidity (40 %) in areas of Punjab and Sindh. However, Srinagar, Muzaffarabad, and Gilgit have a low aerosol burden (0.3) and moderate relative humidity (50 %) (fig 4 and 9). Moderate to high relative humidity in summers intensifies the hygroscopic growth of aerosols along with the gas-to-particle conversion process thus increasing AOD (Chen et al., 2015). Northern mountainous areas have suppressed aerosols inflow than the southern areas because of topography, less human activities, decreases in atmospheric pressure, and wind advection (Filonchyk et al., 2019). These are the reasons that despite having moderate humidity aerosol burden is low in Muzaffarabad and Srinagar.

During spring, a strong positive correlation is found in south-eastern Sindh (1) and Srinagar (0.7). According to fig. 4 and 9 relative humidity is low in Sindh (25%) and high in Srinagar (60%) whereas AOD is high (0.8%) in Sindh and low in Srinagar (0.2 %).

A negative correlation is found in southern Khyber Pakhtunkhwa (-0.7), and Balochistan (-0.8). the relative humidity is low (30%) in these areas along with low AOD (0.3). During autumn, a strong positive correlation is found to be in a few areas of Khyber Pakhtunkhwa (1), northern western Punjab (0.8), eastern Balochistan (0.7), and all over Sindh (greater than 0.8). Areas of Peshawar and Khuzdar show relatively low aerosol burden (0.2) with low to moderate (35%) relative humidity over there. However, in Sindh and Punjab, the aerosol burden is high (greater than 0.9) and relative humidity is low (<20%). A negative correlation is found in northwestern Balochistan (-1) so, according to fig. 4 and 9 aerosol burden is low (0.2) along with relative humidity (20 %). During the spring season agricultural harvesting and biomass burning along with emissions from industries is the largest source of increase in aerosol burden. High wind speed during the autumn season helps in the transportation of aerosols thus increasing the aerosol burden (Sharma et al., 2010).

All these results show that AOD and relative humidity shows direct relation in the summer and winter season. However, in autumn and spring AOD and relative humidity shows an indirect relationship between them.

According to fig. 17 during the winter season, a strong positive correlation is found in northern Balochistan (0.4) and Khyber Pakhtunkhwa (0.8). According to fig. 4 and 10, in the winter season aerosol burden is moderate to low (0.2) in Balochistan and Khyber Pakhtunkhwa whereas, the precipitation rate is high in Khyber Pakhtunkhwa (0.2 mm/day) and in Balochistan is low (0.02 mm/day). The droughted land of Balochistan has lost the majority of soil moisture so, very less water evaporation due to which rainfall is very low over there (Ahmed et al., 2016). Whereas, in KPK aerosol burden is low because precipitation washes out aerosols in the atmosphere. A negative correlation is observed in northeastern Punjab (0.004) i.e Faisalabad, Lahore, and Gujranwala. Punjab has low precipitation (0.02 mm/day) and a high aerosol burden (0.8). The precipitation rate is low in Punjab due to the dry climate and short cold season with less humidity Similarly, the high rate of vehicular and industrial emissions along with dust and smoke from burning coal contributes to increasing AOD (Nawaz et al., 2019).

In summer, a weak positive correlation (0.3) is found to be in the northern area of Punjab and the eastern area of Khyber Pakhtunkhwa. According to fig.4 and 10 above areas have low precipitation rates (greater than 0.02 mm/day) and a high burden of aerosol (0.8). Summers remain a deficit of precipitation in especially eastern Khyber Pakhtunkhwa and Punjab due to the rise in temperature which increases aerosol burden also. The fluctuation in precipitation rate is due to changes in EL Nino and La Nina conditions of the southern Pacific Ocean (Mushtaq et al., 2010).

A negative correlation (less than 0.07) is found in a few areas of Punjab, Sindh, and Jammu Kashmir. High aerosol burden (1) with low precipitation (0.02 mm/day) is found in Sindh and Punjab. However, in Muzaffarabad, as well as in Srinagar, the aerosol burden is low (0.4) and precipitation (0.2 mm/day) is found to be high to moderate. Precipitation Is high in Srinagar and Muzaffarabad because they receive winds laden with moisture and rainfall washes out the aerosols present in the atmosphere and due to it temperature fall in summer (Mushtaq et al., 2010.).

During the spring season, a weak positive correlation is found in a few areas of northern eastern Balochistan, northern Sindh, and the area above Srinagar. These areas have a low precipitation rate (0.02 mm/day) and low aerosol burden (0.6) in spring (fig. 4 and 10). Similarly, a Strong negative correlation (0.06) is found in western Balochistan, Srinagar, and Karachi. All these regions have a relatively low aerosol burden (0.5) followed by low precipitation (0.02 mm/day) rate over there except Srinagar which has a high precipitation rate (0.06 mm/day). Areas of Balochistan and Sindh have faced extreme dry events due to a decrease in rainfall in several years due to climate change and due to a decrease in moisture over the years. Northern areas of Pakistan have a high precipitation rate due to humidity, low to moderate temperatures, and high vegetation rates (Salma et al., 2012).

During autumn, a strong positive correlation (greater than 0.4) is found in all of Sindh and Balochistan. In Sindh aerosol burden (0.8) is found to be high whereas, precipitation (0.02 mm/day) is found to be low. In Balochistan precipitation is low (0.04 mm/day) and aerosol burden (0.6) is found to be moderate in the autumn season (fig. 4 and 10). Similarly, a negative correlation (0.04) is found in Balochistan and eastern Punjab (fig. 17). Aerosol burden is moderate in Balochistan (0.7) and high in Punjab (1.2) However, precipitation in low (0.02 mm/day) in both the province (fig. 4 and 10). Significant decrease in evapotranspiration due to the change in the climate of Pakistan due to which temperature keeps on rising resulting in low precipitation (Zahid & Rasul, 2011). The increase in AOD of Pakistan can be due to agricultural harvesting, dust storm activities, industrial activities along with economic developments. (Shahid et al., 2015) conducted a similar study to analyze annual AOD in which they concluded that annual mean AOD was high over Sindh and Punjab followed by Balochistan, Khyber Pakhtunkhwa, Jammu Kashmir, and Gilgit Baltistan. Punjab and Sindh are major economy-producing provinces of Pakistan so this can be the reason for the high AOD over there. Similarly, in Balochistan, thar desert is a major reason for a contribution towards high AOD. (Ali et al., 2020) pointed out in their study that Indian coal-fired power plants are the major sources that are affecting northeast Pakistan. Other reasons can be different sources like vehicular emissions, increased industrial emissions, and locally produced dust (Alam et al., 2011).

All these results show that AOD and precipitation have an indirect relationship between them in all seasons except in the spring season because in the spring season relationship between AOD and precipitation is direct.

According to fig.18 during winters, a positive correlation (0.6) can be observed in northern Balochistan, Srinagar, and Khyber Pakhtunkhwa. A negative correlation (-0.3) can be observed all over Punjab, Sindh, and southern Balochistan. According to fig. 4 and 11 AOD is low (0.4) in Balochistan and Khyber Pakhtunkhwa and higher (0.9) in Punjab and Sindh whereas soil moisture is moderate (120 Kgm^{-2}) in Balochistan and Khyber Pakhtunkhwa and very low (40 Kgm^{-2}) in Sindh and Punjab. Soil moisture is directly linked with precipitation decrease in precipitation in Punjab and Sindh in winters ultimately shows decrease in soil moisture whereas the northern area of Balochistan, Srinagar, and Khyber Pakhtunkhwa have moderate soil moisture due to low temperature that prevents evapotranspiration and high rainfall that add moisture to the soil. Increased AOD in Punjab and Sindh is due to low moisture content in soil (Zahid & Rasul, 2013).

During summers positive correlation can be observed in northern Punjab (0.6) and eastern Khyber Pakhtunkhwa (0.7). whereas, a negative correlation can be observed in southern Punjab (-0.6), northern Khyber Pakhtunkhwa (-0.5), and Srinagar (-0.9). According to fig. 4 and 11, AOD is high (0.9) in Punjab and low (0.4) in Khyber Pakhtunkhwa. Whereas, soil moisture is low to moderate (120 Kgm^{-2}) in Khyber Pakhtunkhwa and Srinagar and lowest in Punjab (40 Kgm^{-2}). During summers soil moisture content in Punjab is low due to the arid climate followed by hot temperatures (above 40 C) that cause excessive evaporation thus losing moisture in the soil that holds up aerosol (Ali et al., 2009)

During spring, a weak positive (0.3) correlation can be observed in western Balochistan and northern Khyber Pakhtunkhwa. Whereas, a strong negative correlation (-0.9) can be observed in Sindh and the southern Punjab area. According to fig. 4 and 11, soil moisture (100 Kgm^{-2}) and AOD (0.2) both are low in Balochistan and northern Khyber Pakhtunkhwa. However, AOD is moderate (0.8) in Sindh and Punjab and soil moisture is very low (40 Kgm^{-2}). Soil moisture is low in Balochistan due to late summer droughts that stress the soil moisture by increasing the evapotranspiration process (Ahmed et al., 2016). Whereas, in Khyber Pakhtunkhwa soil moisture is low due to climate change which has reduced the rate of water received from the hydrological cycle. Zamin et al. (2020) conducted a study in which they reported that swelled and expansive soil followed by desiccation cracks are found in the region of Kohat, Bannu, and Dera Ismail khan of Khyber Pakhtunkhwa

During autumn strong positive (greater than 0.6) can be observed in Sindh and Balochistan. Whereas a negative correlation (-0.7) can be observed in western Punjab and the area of Jammu Kashmir. According to fig. 4 and 11, AOD is low (0.4) in Balochistan and Jammu Kashmir area. Similarly, AOD is higher in Sindh (0.9) and Punjab (1). Soil moisture is low (120 Kgm^{-2}) in Balochistan as well as Jammu Kashmir and very low (40 Kgm^{-2}) in Sindh and Punjab. Soil moisture is low in the above regions due to climate change that makes evapotranspiration excessive leaving behind dry soil. Moreover, AOD is high in Sindh and Punjab due to anthropogenic activities and rice residue burning (Ahmed et al., 2015).

All these results prove that AOD and soil moisture have an indirect relationship in all seasons. An increase in AOD is due to low soil moisture content and a decrease in AOD is due to moderate to high moisture content.

According to fig.19, a positive correlation can be observed in Khyber Pakhtunkhwa (0.8), northern Balochistan (0.7), and western Punjab (0.6). whereas, a negative correlation (-0.5) can be observed in eastern Punjab and southern Sindh. According to fig. 4 and 12, AOD is low (0.4) in Balochistan and Khyber Pakhtunkhwa, and higher (0.8) in Sindh and Punjab. Evapotranspiration is low ($3.9e^{-007}$ $Kgm^{-2}S^{-1}$) in Balochistan, Khyber Pakhtunkhwa, and Sindh. Only Punjab has a high value ($4.7e^{-005}$ $Kgm^{-2}S^{-1}$) for evapotranspiration. Punjab faces high AOD and evapotranspiration due to high temperatures compared to the rest of the provinces. Aerosols emitted from vehicular emissions, industries, and burning of crops along with waste increase the temperature of Punjab by increasing gases in the atmosphere thus increasing the evapotranspiration rate. Amin et al. (2022) have reported in their study that a decrease in rainfall and an increase in temperature have worsened the situation in Punjab by increasing evapotranspiration.

During the summer season, a strong positive correlation (0.9) can be observed in western Punjab and southern Khyber Pakhtunkhwa. Whereas, a negative correlation can be observed in Jammu Kashmir (-0.6) and southern Punjab (-0.3) (fig. 19). According to fig 4 and 12, the AOD burden is high (1.2) in Punjab only however, in Jammu Kashmir and Khyber Pakhtunkhwa it is low (0.4). Evapotranspiration is moderate to high in Jammu Kashmir, western Punjab, and southern Khyber Pakhtunkhwa ($3.9e^{-005}$ $Kgm^{-2}S^{-1}$) and low in southern Punjab ($6.7e^{-006}$ $Kgm^{-2}S^{-1}$). According to Pakistan meteorological department rainfall concentration was intense over Punjab in monsoon but over a few years, it has moved to northern and western Khyber Pakhtunkhwa due to changes in climate patterns. A decrease in rainfall in Punjab increases the evapotranspiration rate (Salma et al., 2012).

During the spring season, a positive correlation can be observed in Srinagar (0.6) and western Khyber Pakhtunkhwa (0.7). whereas, a negative correlation (-0.5) can be observed in northern

Punjab, Balochistan, Khyber Pakhtunkhwa, and Sindh. According to fig 4 and 12, the AOD burden is low (0.4) in Punjab, Balochistan, and Khyber Pakhtunkhwa whereas, in Sindh, AOD remains moderate (0.8). The evapotranspiration rate remains low ($2.7e^{-006}$ $Kgm^{-2}S^{-1}$) in Balochistan and Sindh but high ($4.7e^{-005}$ $Kgm^{-2}S^{-1}$) in northern Punjab and Khyber Pakhtunkhwa. Similarly, Fig 19. shows that during the autumn season, a positive correlation (0.9) can be observed in Balochistan, Khyber Pakhtunkhwa, and Sindh. Whereas, a negative correlation can be observed in eastern Punjab (-0.6), western Balochistan (-0.6), and Srinagar (-0.7). According to fig. 4 and 12, AOD is low (0.4) in Balochistan and Khyber Pakhtunkhwa, moderate (0.7) in Sindh, and high (1) in Punjab. Whereas, evapotranspiration is low to moderate ($3.5e^{-00.5}$ $Kgm^{-2}S^{-1}$) in Balochistan, Punjab, and Sindh. Only Khyber Pakhtunkhwa and Srinagar have a high rate of evapotranspiration ($4.7e^{-0005}$ $Kgm^{-2}S^{-1}$). Khan & Ul Hasan (2017) reported in their study that evapotranspiration in Pakistan increases from northern western regions to southern eastern regions of Pakistan. Temperature is relatively high in northern Punjab and Khyber Pakhtunkhwa during spring and autumn which plays role in increasing evapotranspiration and it is a major reason behind droughts in arid regions.

The above results show that AOD and evapotranspiration have an indirect relationship between summer and winter. However, the spring and autumn scenario is entirely different AOD and evapotranspiration have a direct relationship between them.

It has become essential to design zoning controls based on PM2.5 concentration grades to reduce the hazards linked with exposure to hazardous $PM_{2.5}$ in Pakistan. Therefore, the establishment of contours characterizing geographical coverage was done based on primary and secondary standards of air quality for $PM_{2.5}$ concentration to assist zoning controls.

Fig. 20 Shows those areas in which $PM_{2.5}$ remained exceeding 35 μg/m3 that are considered " very unhealthy areas". Areas in which concertation of $PM_{2.5}$ fell in the range of 70-80 μg/m3 were considered "hazardous areas". Similarly, "moderate" were those areas in which $PM_{2.5}$ concentration fell within range of 15-35 μg/m3.

As shown in Fig.20, a larger area of Pakistan was under a "very unhealthy" as compared to the rest of the zones. "hazardous areas " were heavily polluted regions covering areas of Sindh, central and eastern areas of Balochistan The small region of Khyber Pakhtunkhwa and Punjab were under " unhealthy" range. Similarly, some region of Punjab, Balochistan and Sindh were under " very unhealthy" category.

It is essential to control the $PM_{2.5}$ concentration as the regions covered under the category of "hazardous" are heavily contaminated with toxic particulate matter. These areas are under threat and can be vulnerable for both humans and the environment if not managed properly. The death rate might increase If no proper measures are taken to minimize this hazard.

As illustrated in Fig. 21, the Medium growth class covered regions of Punjab, Balochistan, and Sindh including some cities like Multan, Bahawalpur, Sukkur, Larkana, Hyderabad, Quetta, and Makran. From 1998 to 2020, the northern area of Pakistan (Khyber Pakhtunkhwa) covered a stable type class and very slow growth. Variation in the stable type class and very slow growth showed distribution over hilly areas and forested areas of Pakistan with a smaller population as compared to the rest of the provinces. For slow growth, the larger area was covered by Zhob followed by Hazara, Quetta, and then Malakand. All these cover a larger portion of Khyber Pakhtunkhwa province. Fast growth class has covered a major portion of Balochistan followed by Sindh and Punjab.

The health of humans is significantly impacted due to exposure to the high concentration of $PM_{2.5}$ long period (Peng et al., 2016). To raise awareness regarding exposure to high $PM_{2.5}$ concentrations and its hazardous impact on the health of the environment, it is very essential to assess health risks. A modeling technique was used to compute exposure to $PM_{2.5}$ by using two important parameters; population density and distribution of $PM_{2.5}$ spatially (Kousa et al., 2002)

Health risk evaluation was carried out by classifying health risks that have resulted due to exposure to $PM_{2.5}$ from 2000 to 2020 over all provinces of Pakistan (Fig.22). There were five classes made for the health risk based upon the unsupervised classification method: (1) very slow rise, (2) slow rise, (3) medium-rise, (4) rapid rise, (5) ultra-rapid rise. The very slow rise class was widely dispersed in comparison to the rest of the classes. The ultra-rapid rise was mostly in the region of Punjab, Sindh, and one region of Khyber Pakhtunkhwa. However, the medium and rapid rise has approached over in all provinces of Pakistan. Majorly more area occupied by the medium and rapid rise is of Punjab and Sindh. This showed that it comprised majorly of densely populated areas with high pollution concentrations. The alarming classes of medium rise, rapid rise, and ultra-rapid rise include some cities like Lahore, Karachi, Gujranwala, Faisalabad, Sukkur, Hyderabad, Peshawar, and Gilgit Baltistan which cover almost every province of Pakistan at some points. According to Fig. 22, a more alarming situation is recorded in regions of Punjab followed by Sindh and Khyber Pakhtunkhwa.

Conclusion

In this study, we have analyzed the impact of aerosols on aerosol properties, soil moisture, evapotranspiration, NDVI, and other meteorological parameters in Pakistan. AOD is found to be higher in Sindh (0.48) and Punjab (0.55). similarly, a high value of AE is found to be in Punjab (1.06) and Khyber Pakhtunkhwa (1.15) these results indicate that Punjab and Sindh are badly impacted due to the high burden of aerosols whereas, Punjab and Khyber Pakhtunkhwa face suspended fine mode particles in the atmosphere that are vulnerable for the health of people living there. Furthermore, in the case of NDVI highest value (0.8) of vegetation was found in Jammu Kashmir and Khyber Pakhtunkhwa in winter. Whereas, wind speed is found to be highest during the winter and spring season in Balochistan (10-12) and Sindh (12).

When it comes to seasonal variation of temperature, it is found to be highest in summers in Punjab (300-320K) and Sindh (300K). Similarly, relative humidity is found to be highest in northern Khyber Pakhtunkhwa (70) and Jammu Kashmir (70) areas only during winter and spring seasons. Moreover, the highest ranges for the precipitation rate are found in northern Khyber Pakhtunkhwa (0.8), near Quetta (0.4), and southern Jammu Kashmir (0.8) during the winter season. Similarly, soil moisture remained low to moderate (greater than 120) in all seasons in Balochistan, Khyber Pakhtunkhwa, and some areas of Sindh. A moderate range ($3.5e^{-006}$) of evapotranspiration is found to be in all of Punjab, Khyber Pakhtunkhwa, and a few cities of Sindh during the autumn and spring season.

Correlation results of AOD show that an increase in NDVI decreases aerosol dispersal in all seasons except spring and autumn. Similarly, an increase in precipitation decreases AOD in all seasons except in the spring season. Whereas in the case of windspeed and temperature, AOD has a direct relationship between them in all seasons. An increase in wind speed and temperature increases the aerosol burden and vice versa.

Furthermore, results show that AOD and relative humidity shows direct relation in the summer and winter season. However, in autumn and spring AOD and relative humidity shows an indirect relationship between them. Similarly, soil moisture has an indirect relationship with AOD in all seasons. An increase in AOD is due to low soil moisture content and a decrease in AOD is due to moderate to high moisture content.

Moreover, when it comes to evapotranspiration, results show that an increase in evapotranspiration increases aerosols in the atmosphere and vice versa. Further, results of $PM_{2.5}$ maps show that alarming classes of medium rise, rapid rise, and ultra-rapid rise include some cities like Lahore, Karachi, Gujranwala, Faisalabad, Sukkur, Hyderabad, Peshawar, and Gilgit Baltistan which cover almost every province of Pakistan at some points.

These results clearly show that several different factors play role in increasing and suppressing aerosol burden in the atmosphere. This study also helps the policymakers to take proper decisions in deciding that in which cities of Pakistan there must be more health facilities according to the pollution and vulnerability to health over there.

Limitations

Our study is based on find the aerosol burden and its correlation with few meteorological and topological parameters. It also highlights the hotspots of Pakistan where human health is at more risk. The limitation of our study includes that further surveys must be conducted in hospitals also to find out the number of cases over there due to pollution in the environment. Finding out the figures of patient with allergies and respiratory disorder will help in future studies.

Recommendations

1. More parameters must be added up in future studies to evaluate the role of other parameters in the climatology of aerosols.
2. Ground truthing must be carried out in the future.
3. The government sector must provide proper health facilities to those cities that are having more threats to health.

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