A CASE STUDY OF DUST STORM EVENTS IN PAKISTAN USING NORMALIZED DUST DETECTION INDEX

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ABSTRACT: Currently dust storms are among the most prevalent global environmental issues. They are the early warning indicators for desertification and climate change. The study intends to analyse dust event in Pakistan using normalized dust detection index (NDDI), brightness temperature (BT) and MODIS data of aerosol optical depth (AOD), deep blue angstrom exponent (AE), aerosol index (AI) and HYSPLIT mass trajectory methods. It also highlighted the relationship between NDDI, BT and AOD. The threshold value of NDDI was 0.19 - 0.36 and BT ≤ 310.5 K. Data from CALIPSO, NCEP/NCAR reanalysis datasets were used to validate research's findings. The results found NDDI and BT value for Pakistan and track the movement of dust storm from west to east especially at the height of 5-10km. Dust storms are inversely proportional to relative humidity and pressure.

A case study of Dust Storm Events in Pakistan using Brightness Temperature and NDDI

Key words: NDDI; Dust storms; Brightness temperature; MODIS; HYSPLIT

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Abbreviations:

NDDI	Normalized Dust Detection Index
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory Model
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
AOD	Aerosol Optical Depth
AE	Angstrom Exponent
	NCEP/NCAR National Centre for Environmental Prediction / National Centre for Atmospheric Research
BT	Brightness Temperature

INTRODUCTION

Dust storms are complex local systems developed under certain meteorological conditions controlled by soil moisture, vegetation land-use and land cover changes; deforestation and drought conditions (Qu *et al*., 2006, Yue *et al*., 2017). They are among the dominant environmental issues of recent times which humans are encountering specially in arid areas (Gui *et al*., 2022) while arid topographical depressions (Papi *et al*., 2022) with sparse rainfall (100 – 250 mm)(Khamooshi *et al*., 2016a, Filonchyk, 2022), and low vegetation cover acts as their sources. The terminology of dust storm is used for entrainment of huge amount of finer dust particles in lower air which travel long distances specifically in urban areas (Sissakian *et al*., 2013).

Pre-monsoon dust events in Indo-Gangetic plain have been under observation since eighties due to their heating affect upon Himalayan glaciers (Sarkar *et al*., 2019). The common causes for their development are thunder storms and atmospheric depression assisted by soil moisture (Sissakian *et al*., 2013, Sarkar *et al*., 2019, Eshghizadeh and Environment, 2021) along with vegetation cover, wind speed and direction, climate change, drought and poor farming practices (Papi *et al*., 2022). Specially in South West Asia sub-tropical jet stream and polar front jet stream are the main reasons of their development (Sissakian *et al*., 2013). They escalate in pre-monsoon season (March–May) by south - westerly winds of arid Arabia (Saeed *et al*., 2014, Basha *et al*., 2015, Jish Prakash *et al*., 2015, Sarkar *et al*., 2019). According to researchers, 20% of global dust storms occur in Iraq, Iran and Saudi Arabia, due to their prolonged summer season (Najafi *et al*., 2014, Albarakat and Lakshmi, 2019), which entrap large amount of sand and dust in boundary layer (Albarakat and Lakshmi, 2019).

Dust storms trend has increased in the recent past. They are indicators of desertification and often considered as the early warning of environmental depravation (Yue *et al*., 2017). Intensity of dust storms facilitates the desertification process by transporting and depositing sediments, resulting in loss of crops, damaged infrastructure and uninhabitable environment (Fernandes *et al*., 2019, Fernández *et al*., 2019, Eshghizadeh and Environment, 2021, Rashki *et al*., 2021). They play an important role in amplifying climate change process (Xie *et al*., 2010, Karimi *et al*., 2012) their radiative properties are of special significance due to their duel role in heating and cooling affect of radiation (Rezaei *et al*., 2019, Filonchyk *et al*., 2021). Over deserts, air borne dust creates a cooling effect day time; by absorbing terrestrial and cosmic radiation, the effect is reversed at night due to the increased downward energy flux, hence cause a change in earth's energy budget (Prakash *et al*., 2014, Francis *et al*., 2022). It also has a direct affect upon clouds and their optical properties. Extreme dust events prove to be injurious for air quality, even at distant places from the main source region (Wang *et al*., 2010, Wang *et al*., 2011, Francis *et al*., 2022).

Due to limitation in the ground observations, remote sensing has become a valid and vital tool for dust storm monitoring (Azimzadeh *et al*., 2022). Use of remote sensing has facilitated the process of detection and classification of dust events (Ginoux *et al*., 2010, Wang *et al*., 2011, Jebali *et al*., 2021) and facilitated model simulation for authentic results.

This study intends to investigate the characteristics of the dust storm incidents that took place in different parts of Pakistan in a week due to the occurrence of high dust storm activity. The atmospheric conditions and dust pathways were observed to identify source regions of dust storms. NDDI model was applied for dust storm detection and their source routing. Brightness temperature was used to evaluate the relationship between NDDI, brightness temperature and Aerosol Optical Depth (AOD).

MATERIALS & METHODS

Study area: Pakistan; located in the west of South Asia with world's fifth largest population cluster of almost 20 million inhabitants. It has an area of 796096 km². It shares its borders with India in the East, China to the Northeast, Afghanistan to the West, Iran to the Southwest and 1046 km long coastline to the South facing Arabian Sea.

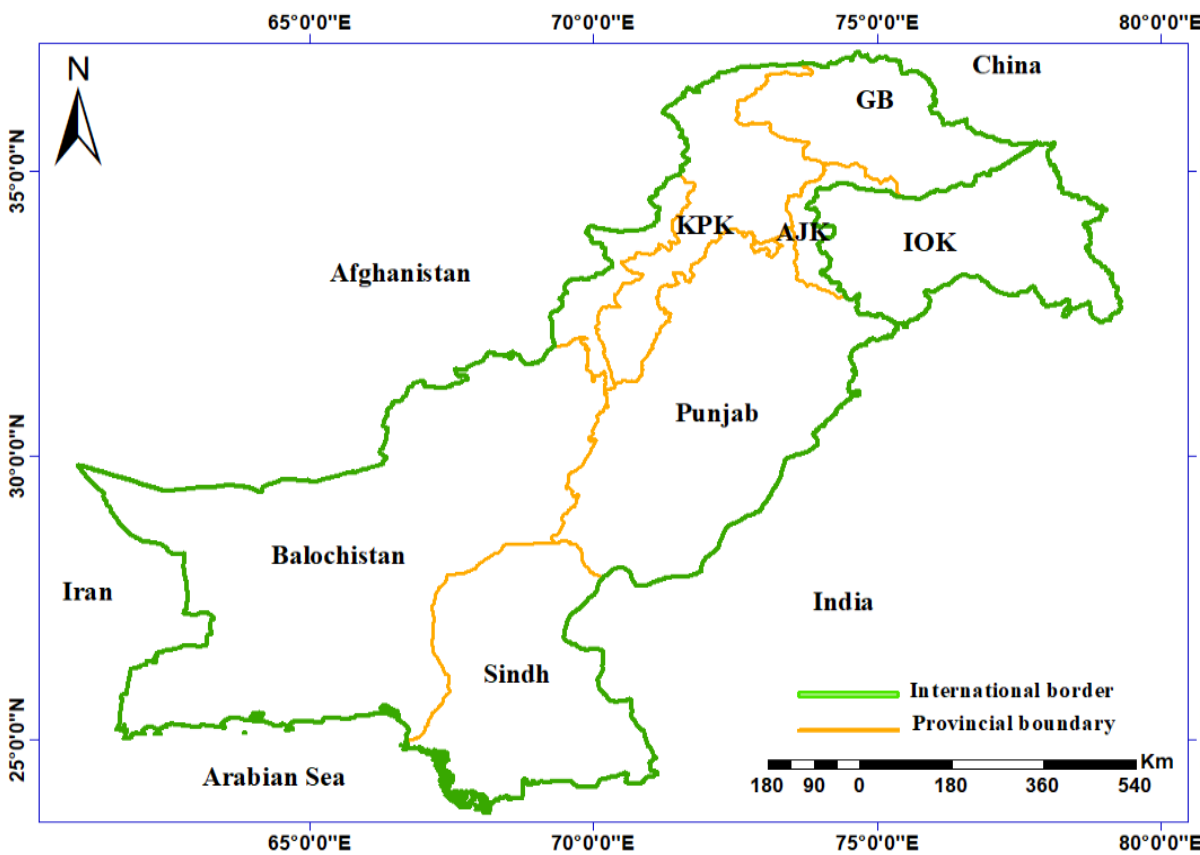

Figure 1 Location Map of Pakistan

Pakistan exhibits a diverse landscape with mountains plateau, plains and deserts with distinct weather conditions (Alam *et al*., 2011). Pakistan is largely an arid country surrounded by arid deserts, plateaus and salt lakes of India, Afghanistan and Iran.

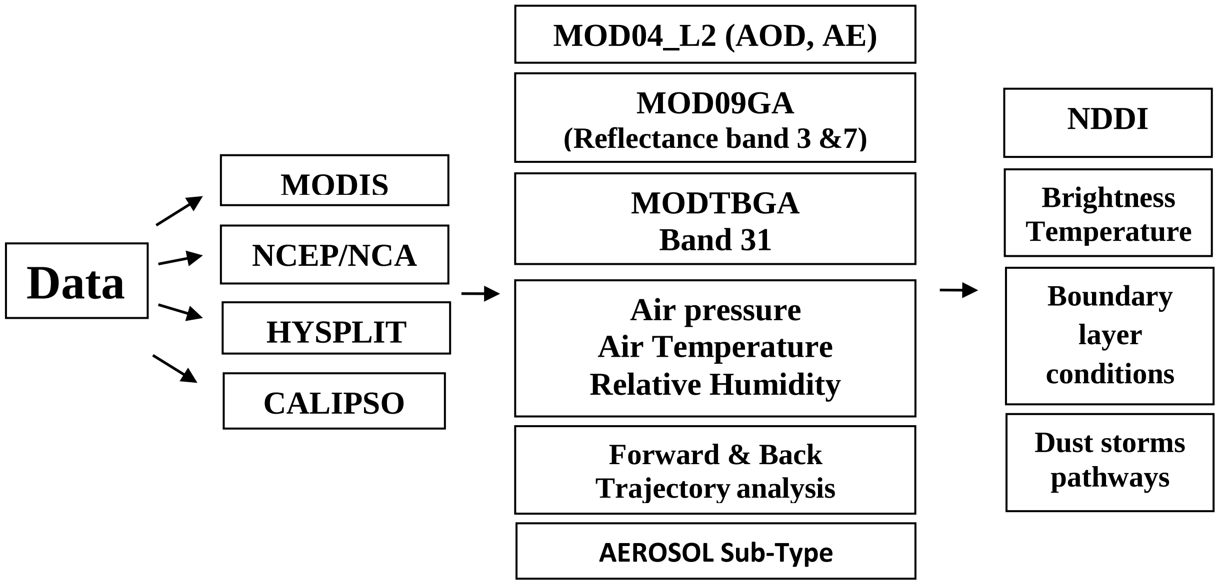

Figure 2 Research Design

This study examined the dust events occurred in Pakistan from 18 -23 May, 2021. The study period was selected due to the occurrence of many dust storms throughout the country, especially in Karachi on 18 May 2021.

Satellite observations: Remote sensing techniques play an important role in monitoring and analysing dust storms. Due to its efficiency and limitations of ground based environmental and climatic observations remote sensing have become an important approach (Wang *et al*., 2011, Albarakat *et al*., 2018, Albarakat and Lakshmi, 2019, Rezaei *et al*., 2019, Eshghizadeh and Environment, 2021, Rashki *et al*., 2021, Azimzadeh *et al*., 2022). The research involved different satellite observations from MODIS, OMI, HYSPLIT and NCEP/NCAR reanalysis datasets.

Moderate Resolution Imaging Spectro-radiometer (MODIS): MODIS surface reflectance Daily L2G Global (MOD09GA) and band 31 of daily thermal BT datasets were used to calculate the spectral reflectance for NDDI. The threshold value of NDDI was set as 0.05 for clouds and water bodies, and 0.19 - 0.36 for dust storms. The threshold of BT of 310.5 K was used to determine dust aerosols (Karimi *et al*., 2012, Park *et al*., 2014, Albarakat and Lakshmi, 2019, Eckardt *et al*., 2020). MOD04_L2 data was used for aerosol optical depth and angstrom exponent for accuracy and validation of NDDI results.(Penning de Vries *et al*., 2015, Rezaei *et al*., 2019, Gui *et al*., 2022, Rashki *et al*., 2021). AOD > 0.3, AE < 0.75, AI <0.7 from OMI were considered to show the presence of dust aerosols even on brighter surfaces (Bibi *et al*., 2017, Parolari *et al*., 2016, Albarakat and Lakshmi, 2019, Rezaei *et al*., 2019).

Normalized Dust Detection Index (NDDI): NDDI depend upon visible bands of MODIS (MOD09GA V006). The mechanism depends upon the reflectance of dust in different bands which varies with wavelength, generally increase between 0.4 – 2.5 µm. Its lowest value lies in band 3 and highest in band 7.

$$\mathbf{NDDI = (B7\text{-}B3) / (B7+B3)} \qquad \textbf{(i)}$$

The $\rho 2.13\mu m$ and $\rho 0.469\mu m$ were reflectance observations in band 7 and 3 respectively. The NDDI values for clouds are “0”, for dust it was “0.19 – 0.36” and for surface feature its value was below the dust value threshold. Many researchers have used different threshold values for dust detection through NDDI such as 0.5 (Park *et al*., 2014), 0.26 (Samadi *et al*., 2014), 0.22 (Butt and Mashat, 2018), 0.18 (Albarakat and Lakshmi, 2019).

Brightness temperature (BT): (Qu *et al*., 2006) used band 31 of MODIS brightness temperature to identify ground and airborne dust with a threshold of 275 K, (Butt and Mashat, 2018)(290K) (Samadi *et al*., 2014, Albarakat and Lakshmi, 2019). The threshold varies with different environments (Albarakat and Lakshmi, 2019, Bahrami *et al*., 2020). The study involves MODBGA V006 for BT with a threshold of 310.5K for dust storm areas, values above this shows ground sand and dust (Yue *et al*., 2017, Albarakat and Lakshmi, 2019).

HYSPLIT Trajectory model: HYSPLIT **(**Hybrid Single Particle Lagrangian Integrated Trajectory Model**)** model was used to trace dust storm's propagation. The model was run for 72 hour with 6 hour time interval at 500 and 1000m above ground for 18 and 21may 2021 for forward and back trajectories (Rashki *et al*., 2017, Yue *et al*., 2017, Wang *et al*., 2022). Visibility, wind speed, velocity, rainfall and humidity data was retrieved at 500 hap from NCEP/NCAR.

RESULTS AND DISCUSSION

Normalize Dust Detection Index (NDDI): The NDDI analysis was run and mapped with the threshold value of 0.19 - 0.36 for dust storms. The results revealed a trend of high NDDI values in Pakistan throughout the study period. The map shows the movement of dust storm from southern areas of Pakistan (Makran coast and Karachi, Thatha) to upper Sindh on 18 May 2021 and further north, blowing dust in most of the areas of Punjab and a few areas of KPK. Until 20th May 2021, the effects of dust storm had penetrated to the whole country and the high values of AOD and NDDI were observed. On 21st May 2021, another wave of dust approached the country from the south and south - west Baluchistan, which travelled north to Punjab specially and KPK. Areas of central and south Punjab and upper Sindh were most affected by the dust storm; as well as some south and south - western areas of Baluchistan.

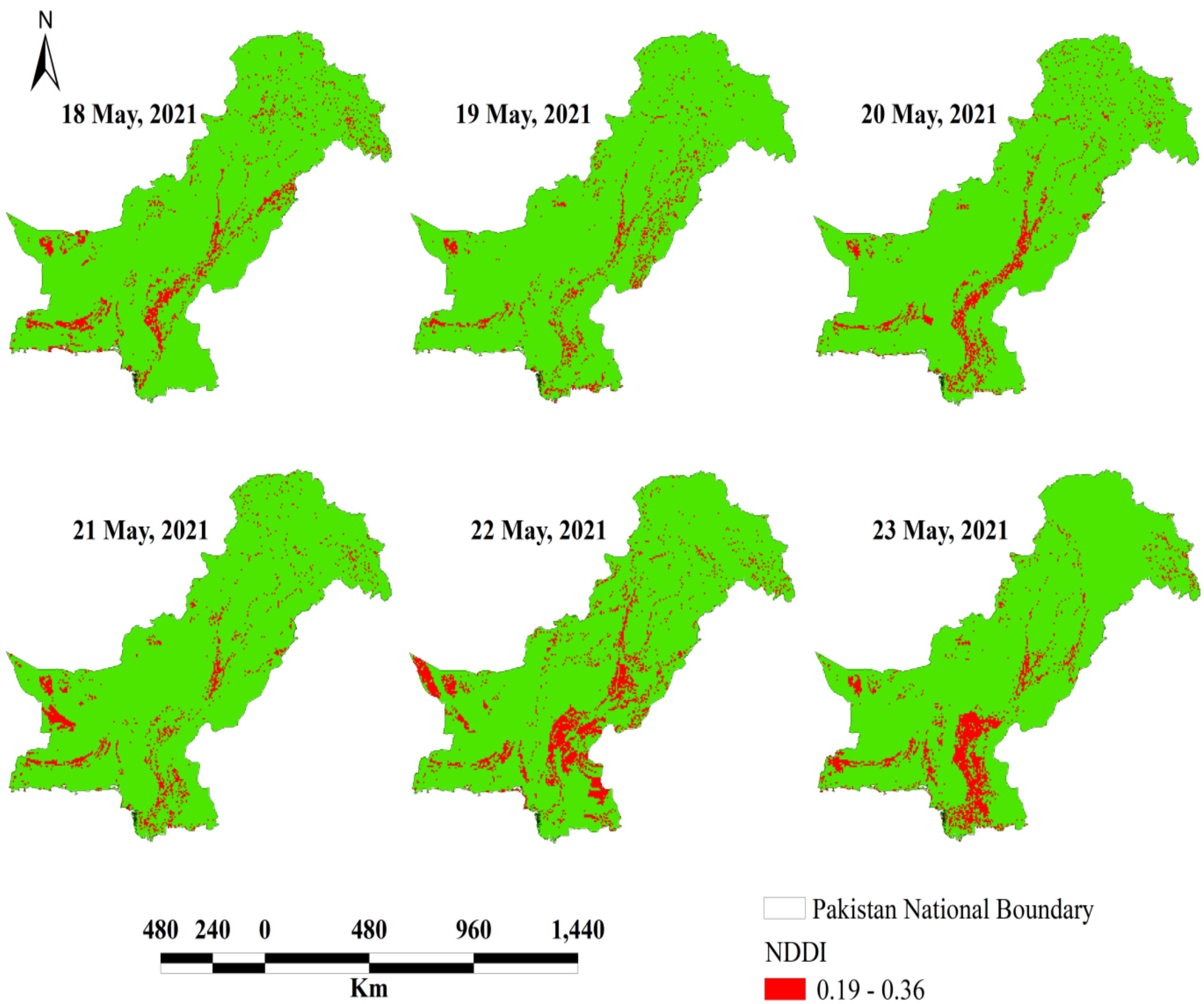

Figure 3 Dust storm detection using NDDI

The meteorological data indicated the presence of low-pressure area in the north Punjab creating steep pressure gradient in areas around it (Himalayan foothill). The winds rush from high-pressure areas to low pressure areas (Hamidi *et al*., 2014, Rashki *et al*., 2014, Khamooshi *et al*., 2016a, Dar *et al*., 2022). A noticeable decrease in the relative humidity was observed during the event. The foothill areas of Himalayas are one of the major hotspot for aerosols (Hamidi *et al*., 2014, Basha *et al*., 2015, Rashki *et al*., 2015, Khamooshi *et al*., 2016b).

Brightness Temperature: The brightness temperature map validates the NDDI results. The threshold value for BT was ≥ 310.5 K, areas having brightness temperature below 310.5K were considered to have high concentration of dust aerosols, which reduced the temperature from the surroundings by reflecting and absorbing the incoming solar radiation. A strong negative correlation existed between NDDI and brightness temperature. Higher NDDI values and low brightness temperature highlights the area with dust storm. The brightness temperature value of less than equal to 310.5 K shows the presence of dust aerosols.

Aerosol Optical Depth (AOD): A higher AOD value was observed in the study area during the dust event (Sarkar *et al*., 2019). Areas of Central Punjab, Central Sindh and a few areas of Baluchistan experienced higher AOD values throughout the study period. There was a strong positive correlation between NDDI and AOD values in the areas of dust storm occurrence (Yue *et al*., 2017).The AOD values during the dusty days remained high but they were especially high (0.6 – 0.8) on 19th, 20th and 22nd May 2021 in eastern parts of Pakistan. The intensity of AOD started to increase in Punjab from 18th to 20th may which showed a marked decrease on 21st May 2021 and again a rise was monitored all over Pakistan which affect many districts of Pakistan even on 23rd may 2021.

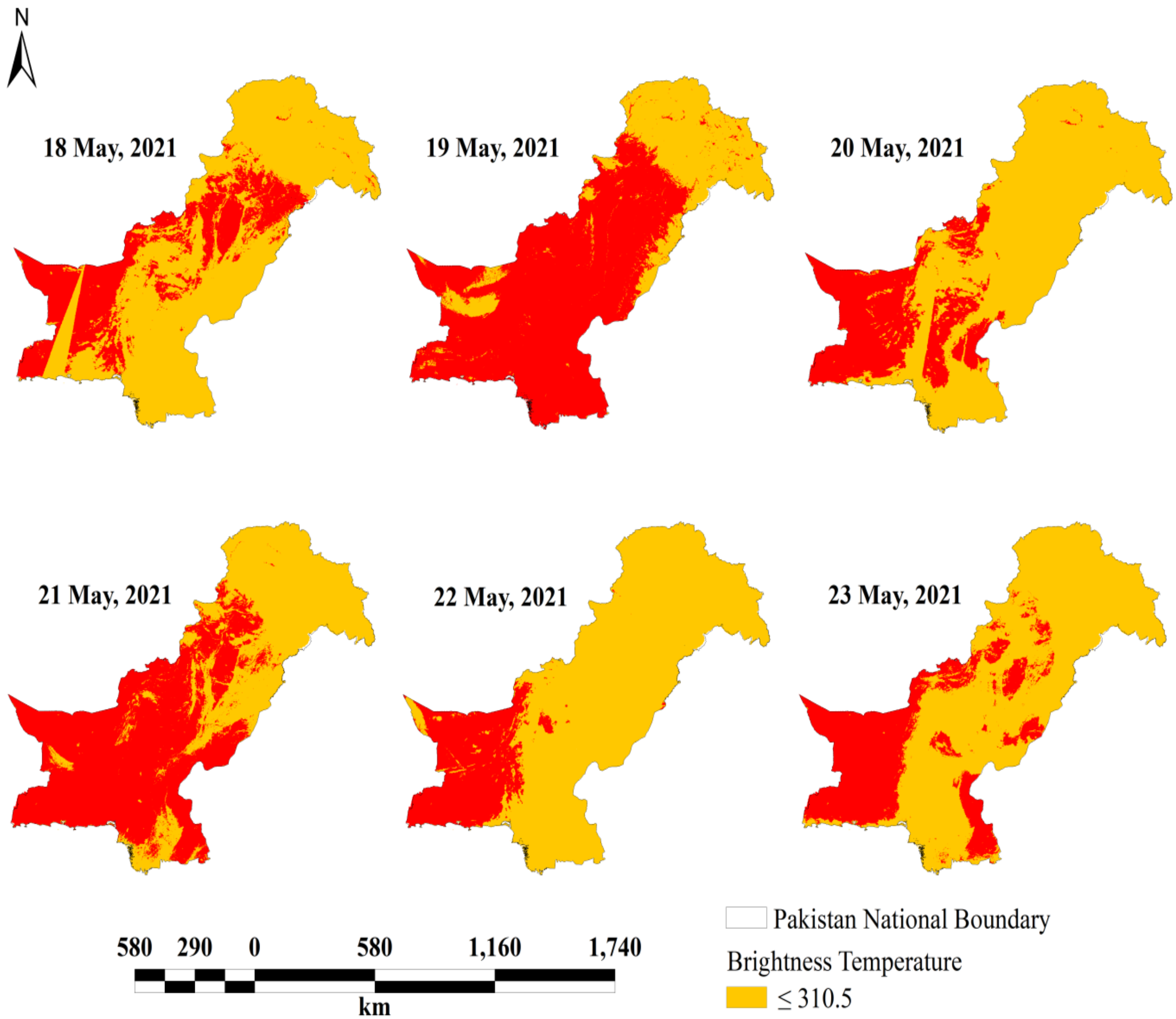

Figure 4 Spatial distribution of Brightness Temperature using MODTBGA dataset

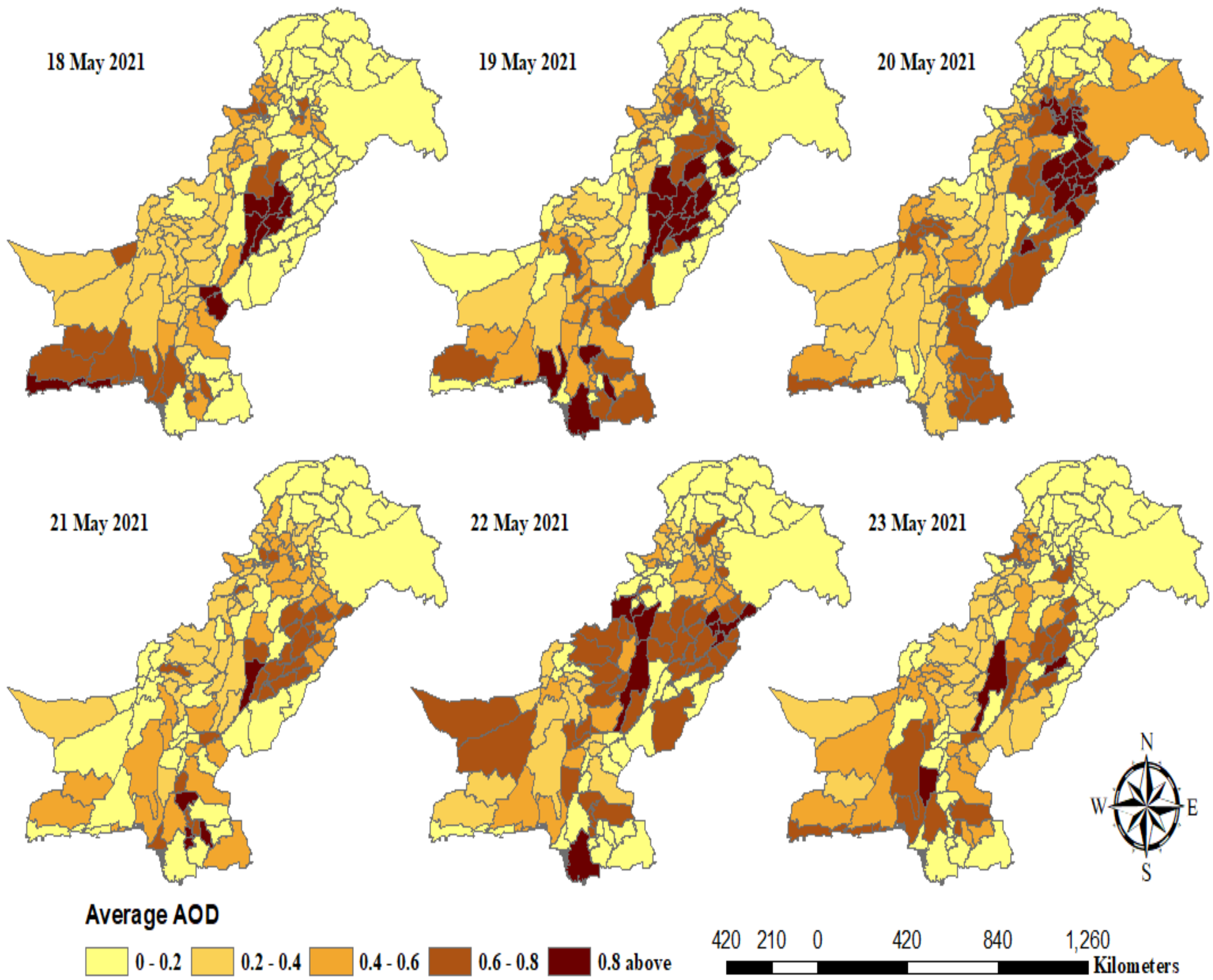

Figure 5 Spatial distribution of AOD using MOD04_L2 data

As a general trend the areas of central Punjab, lower Sindh and southern Baluchistan showed higher aerosol optical depth. The districts of Muzaffargarh, Multan, Leiah, Bhakkar, Jhang, Khanewal, Sargodha, Toba Tek Singh, Faisalabad, Sahiwal, Vehari, Khanewal, Gujrat, Gujranwala, R. Y. Khan, Khushab and Chiniot in Punjab; Badin, Ghotki, Sukkur and Mirpur Khas in Sindh; Lasbella, Makran and Awaran in Balauchistan and Malakand and Khyber Agency in KPK, possessed the higher levels of aerosols during the study period. The coastal areas of Pakistan experienced higher levels of AOD due to its location for the air masses coming from Arabian Peninsula (Sarkar *et al*., 2019). One reason for higher levels of AOD is development of low-pressure area and abundance of loose particle in the vicinity such as Thal, Cholistan and Tharparkar deserts and source trajectories of air masses. The area upon which an air mass travels influences its properties. Air masses have a west and southwest to east and northeastern trend. The dusty air masses from west enter KPK and Baluchistan, cross the central mountains of Sulaman and Kirthar range and change their direction northwards due to the presence of southerly trajectories from Arabian sea, which gather more dust while moving over arid areas of Sindh and South Punjab.

HYSPLIT mass trajectory analysis: Heights of the trajectories in the figure 6, reflect the interaction of air masses with boundary layer. The HYSPLIT model was run for six cities of Pakistan (Lahore, Karachi, Quetta, Peshawar and the capital city of Islamabad). The trajectories were taken for Federal and Provincial Capitals. Results revealed that the sources of the trajectories were in Central Asia to the West, Arabian Peninsula and horn of Africa to the south and south-west. From there dusty winds are blown and enter Pakistan in two branches; western and southern. According to the HYSPLIT back and forward trajectory analysis, the western branches affect the areas of KPK and Baluchistan and spread towards east and northeast.

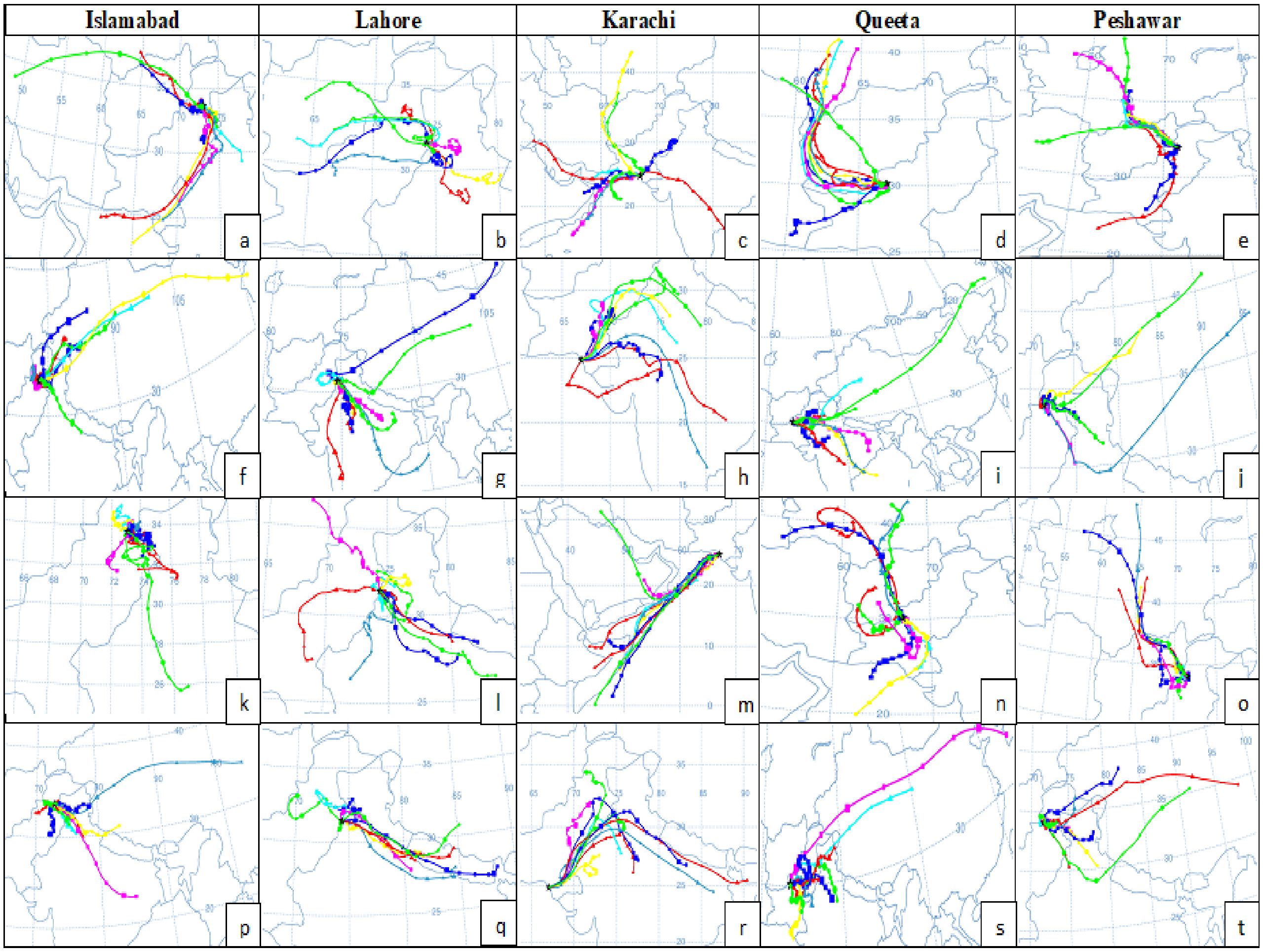

Figure 6 shows HYSPLIT trajectories for the study period. Fig a, b, c, d, e and f, g, h, I, j shows backward and forward trajectories for 18 May 2021 respectively. Fig k,l,m,n,o and p,q,r,s,t shows backward and forward trajectories for 21st May 2021respectivey.

While the dusty air masses coming from the Arabian Peninsula and Africa travel north from Sindh from south and affect areas of Punjab from where it disperses into North and Central India; few of its branches travel north into China and some even further to Russia (Sarkar *et al*., 2019). Most of the air masses travelled between 500 and 1000 m height. They initiated at 500 m and remained mostly between 100m height while a few reached to the height of 3000 m above sea level. The model traced low-pressure areas in the Himalayan foothills as the main cause (Hamidi *et al*., 2014, Rashki *et al*., 2015, Khamooshi *et al*., 2016a).

Backwards trajectories on 18 may 2021 were concentrated at west and south-west are among the world's most arid areas, especially Iran that is famous for dust storms, which further moved to north and northeast direction. On 22nd May 2021, dust sources for cities vary considerably; Islamabad and Lahore had most of the tributaries coming from south - east (the Rajasthan desert). Karachi has major contribution of tributaries from south-west (east coast of Arabian Peninsula and north - eastern part of Africa commonly known as horn of Africa), one of the most arid areas of world. Quetta and Peshawar both have their sources in Afghanistan and Turkmenistan in the west and north - west.

Cloud Aerosol Lidar and Infrared Path Finder satellite Observation: CALIPSO data was used to validate the presence of dust storm in the study area. The data confirms the dust aerosol as the major sub type of aerosol in the study period at 5 – 12 km of height. The presence of dust aerosol is especially high on 21 and 22 May 2021 (fig 7a & 7b).

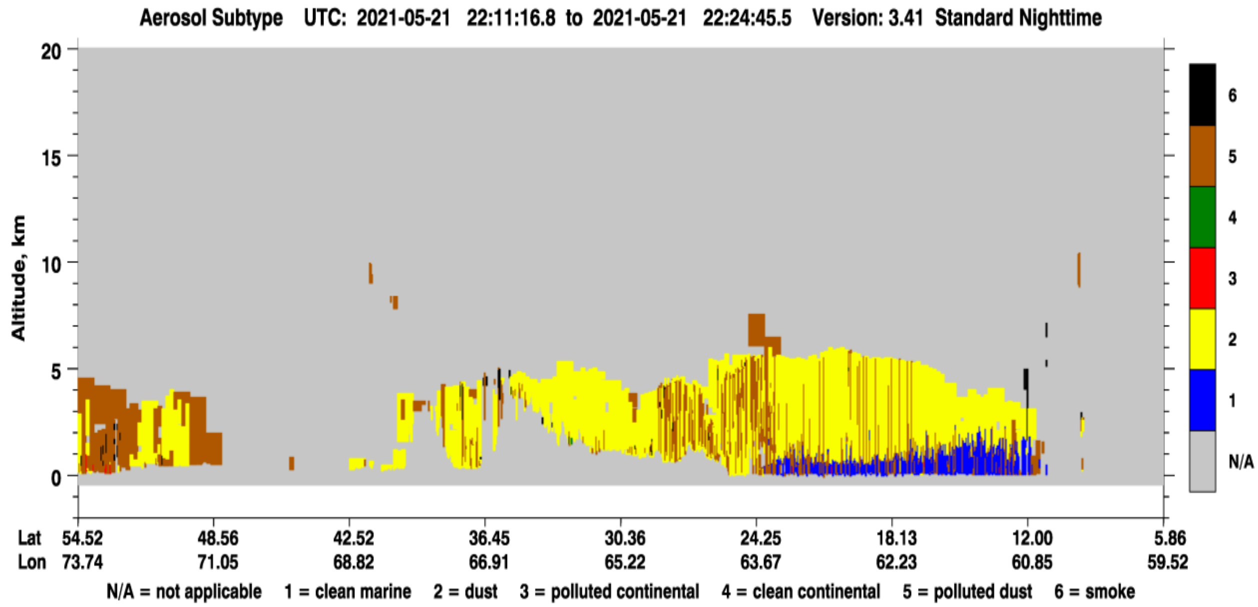

Figure 7a Aerosol subtype by CALIPSO (21 May 2021)

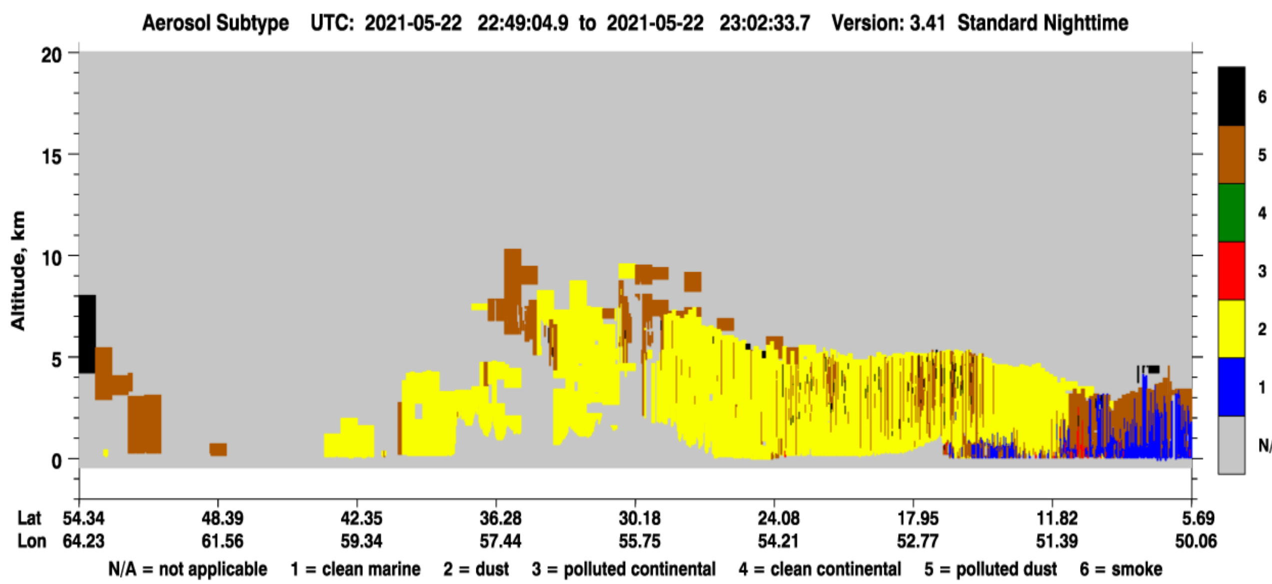

Figure 7b Aerosol subtype by CALIPSO (22 May 2021)

Conclusion: The study investigated the occurrence of dust storms through NDDI and brightness temperature model. The model proved 0.19 - 0.36 as the threshold value to detect dust storm. HYSPLIT analysis states the sources of the dust storms in the Rajasthan desert to East and Afghanistan and Iran (dusht-e-loot) in the west. Tributaries after entering Pakistan travel across local dust sources of Dusht-e-Kharan in Balochistan, Tharparkar in Sindh, and Cholistan, Nara, Thal deserts in Pakistan. From their initiating point, they propagate North (Northern Punjab) due to the development of low-pressure areas in the foothills of Himalayas. Development of low-pressure area, decreasing relative humidity and increase in aerosol optical depth was observed during the dust event. Air pressure and relative humidity showed an inverse relation. The brightness temperature threshold of < 310.5K, also go hand in hand with the NDDI results showing a strong negative correlation. In addition, the AOD values remain high in the dust storm days in study area. maximum AOD value is observed in Central Punjab (around Cholistan and Thal desert) northern Sindh (adjoining point of Tharparkar and Cholistan) and Makran coast in Balochistan which moved north to northern Punjab due to the development of low-pressure area. The strong positive correlation between the NDDI and AOD depicts the abundance of dust particles in the air. The CALIPSO data also confirms the presence of abundant dust particle in the area during the investigated period. The study successfully highlighted the dust-affected areas during this dust event and analysed the different parameters to locate their sources and causes.

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