



# Influence of aerosols on snow cover during 2003 to 2021 over Northern Pakistan

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## Abstract

Rapid urbanization, industrialization, and transportation of aerosols from other regions are contributing remarkably to atmospheric pollution in Pakistan. This study investigates the influence of aerosols on snow cover in Northern Pakistan from 2003 to 2021. The present study acquired snow cover data from the Famine Early Warning Systems Network (FEWS-NET), Land Data Assimilation System (hereafter FLDAS), and dust aerosols (dust extinction Aerosol Optical Depth (AOD) and dust surface mass concentration) from Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA 2) over Northern Pakistan. The longest distribution (2003–2021) of MERRA 2-AOD ( $>0.05$ ) was observed over the Hindu Kush and the Himalaya ranges. The highest seasonal distribution of dust surface mass concentration was observed in the monsoon and pre-monsoon seasons, whereas the lowest concentrations occurred during winter and post-monsoon seasons. A positive correlation of  $>0.15$  over the Kashmir and  $\sim 0.13$  over the Himalaya range was observed between snow cover and dust surface mass concentration. Moreover, the highest positive correlation of  $>0.69$  between snow cover and precipitation was also observed over the Karakoram range. The MERRA 2-AOD, MERRA 2 dust surface mass concentration, and FLDAS snow cover depict statistically insignificant trends from 2003 to 2021.

**Keywords** Remote sensing · Aerosols · Snow cover · Climate change · Northern Pakistan

## Introduction

The Earth's environment has continuously been destroyed due to increased population density accounting for enhanced pollutants emission. The atmospheric composition changes because of emissions from industrial activities and the burning of fossil fuels which emit aerosols and greenhouse gases (Dey et al. 2004; Tariq et al. 2015; Mahapatra et al. 2019; Nichol et al. 2020; Mhawish et al. 2020; Mehmood et al. 2021). Atmospheric aerosols are microscopic solid or liquid particles and have impact on visibility, air quality, human health, ecosystems, and climate change (Bilal et al. 2021; Mhawish et al. 2021; Qayyum et al. 2021, 2022; Tariq et al. 2021; Ali et al. 2022). Moreover, aerosols can affect the climate and radiative processes, directly by absorbing and scattering the radiation (Miller and Tegen 1998), while indirectly changing the precipitation and modifying the micro-physical properties of clouds (Kumar et al. 2011). However, the spatio-temporal distribution of aerosols suspended in the atmosphere is highly inconsistent. Therefore, it is very important to acquire an

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in-depth understanding of aerosol characteristics, spatiotemporal distribution, and physical properties.

In many regions, dust is a major component of atmospheric aerosols and has attracted the great attention of the scientific community (Ge et al. 2010; Tariq et al. 2021). The emission of dust aerosol particles suspended in the Earth's atmosphere is from drylands through the wind erosion process. The physical processes including dust emission and transport are linked to the atmosphere, hydrosphere, and cryosphere (Niemand et al. 2012). Global dust aerosol sources are primarily located in areas such as the Sahara Desert, the Sistan region, Central Asia, Africa, the Middle East, India, North America, Arabia, and Australia, which provide a lot of aerosols to the atmosphere. The dust aerosols can influence the hydrological cycle, air quality, health, visibility, monsoon system, and meteorological variables (Tegen et al. 2004; Alam et al. 2014; Cao et al. 2014). Thus, it is important to accurately find out the sources and amount of dust aerosol emissions in the atmosphere for evaluating the aerosol effects on climate change.

Pakistan is located in South Asian region and is famous for the highest mountain peaks in the world. The Himalayas, Hindukush, and Karakoram are the world's most famous mountain ranges situated in Pakistan and are also occupied by more than 5000 glaciers. The snow-pack and glacial extent of Pakistan is continuously decreasing due to global warming and climate change (Zeb et al. 2019). Moreover, the temperatures in the northern region of Pakistan are continuously rising which resulted in the fast melting of snow (Rasul et al. 2008; Adnan et al. 2017; Zeb et al. 2019). The water in the winter season is preserved as snow and starts melting in summer due to the rise in temperatures and feeds the rivers.

Recent studies have examined the optical properties of aerosols over Northern Pakistan (NP) using both satellite and ground-based measurements (Zeb et al. 2019; Nasir et al. 2019). However, these studies have used limited datasets and selected portions of NP. In the present study, we used the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA 2) reanalysis and Famine Early Warning Systems Network (FEWS-NET), Land Data Assimilation System (hereafter FLDAS) data to assess the spatial pattern of atmospheric aerosols, especially the dust particles and their influence on snow cover over the entire NP. Moreover, this study also evaluates the spatial correlation of dust aerosols with snow cover and meteorological parameters from 2003 to 2021.

## Material and methods

### Study area

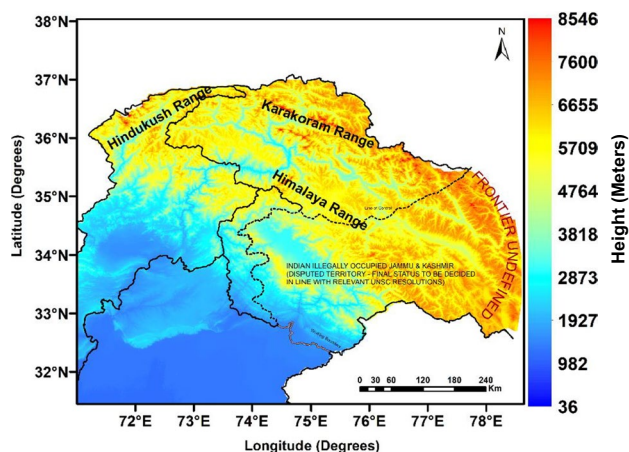
The present study is focused on the northern portion of Pakistan (Fig. 1). The northern portion of Pakistan is

the most spectacular region consisting of world-famous mountain ranges, namely; the Hindukush, the Himalayas, and the Karakoram. An ancient trading route (Karakoram Pass, 5575 m) between Pakistan and China was named because of this mountain range. The glacier part of northern Pakistan spreads over an area of 16,933 km<sup>2</sup>. This portion also includes world-famous peaks such as Karakorum 2 (K2). One-half of the summits in this region are above 4500 m, while more than 50 peaks are above 6500 m. The meteorological conditions of this region were classified into four distinct seasons: winter, pre-monsoon, monsoon, and post-monsoon.

## Material used

### MERRA 2 reanalysis

The MERRA 2 data was developed by NASA and is the updated form of MERRA (Rienecker et al. 2011). MERRA 2 is considered the first satellite-based reanalysis data which assimilates aerosol properties. The interaction between the atmospheric aerosols and the climatic variables on the Earth is represented by MERRA 2. The MERRA 2 aerosol model is developed based on assimilation from different satellite products from the MODIS, MISR, and Advanced Very High-Resolution Radiometer (AVHRR) and in-situ observational systems such as Aerosol Robotic Network (AERONET) (Gelaro et al. 2017). Recent studies have also compared MERRA 2-AOD with AERONET-AOD and found satisfactory results (Ali et al. 2022). In this study, dust extinction AOD dust surface mass concentration, total surface precipitation, and surface albedo with a spatial resolution of 0.5° × 0.625° over NP from 2003 to 2021 were



**Fig. 1** Map of the Northern region of Pakistan. The background image represents the elevation in meters with dark red depicting more elevated areas and lighter colors representing less elevated areas

acquired from Giovanni and can be accessed at (<https://giovanni.gsfc.nasa.gov/>). Moreover, a recent study conducted by Khan et al. (2021) in Pakistan also utilized MERRA 2 data to assess the spatial and temporal variations of aerosols from 1980 to 2018.

**Other datasets**

The other datasets used in this study are temperature at a spatial resolution of 1° × 1° from Atmospheric Infrared Sounder (AIRS), short wave net solar radiation at 0.5° × 0.5° from Global Land Data Assimilation System (GLDAS), sensible heat flux at 0.5° × 0.5° from GLDAS, and snow cover at 0.1° × 0.1° from FLDAS. These datasets can be accessed from Giovanni online interface. Recent studies have also used some datasets from these sources (Rana and Siddiqui 2023; Tariq et al. 2023)

**Methodology**

To examine the influence of aerosols over the snow-covered region of Pakistan and to find an association of aerosol with meteorological parameters and snow cover, the following methodology was adopted in the present study:

- (i) The MERRA 2 AOD, dust surface mass concentration, and snow cover datasets were used to assess the mean annual spatial distributions over NP from 2003 to 2021.
- (ii) The seasonal distribution of dust surface mass concentrations and snow cover were also examined over NP from 2003 to 2021.
- (iii) The mean annual spatial correlation analysis was performed to understand the correlation of snow cover with meteorological parameters and dust surface mass concentration over NP from 2003 to 2021. To develop a correlation between different resolution datasets, the fine spatial resolution data were gridded to the coarse resolution.
- (iv) The monthly variations of AOD retrieved from MERRA 2 were also assessed over NP from 2003 to 2021.
- (v) The long-term variations in aerosols and snow cover over NP are examined using the non-parametric analysis (the Mann-Kendall test (Mann, 1945) associated with Sen’s slope). The non-parametric MK test is less sensitive to outliers and more reliable for data that is not regularly distributed. Moreover, the rank is calculated using Equation (1) and the  $sgn(x_j - x_i)$  is the function sign calculated using Equation (2).

$$\tau = \frac{2}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j=i+1}^n sgn(x_j - x_i) \tag{1}$$

$$sgn(x_j - x_i) = \begin{cases} +1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases} \tag{2}$$

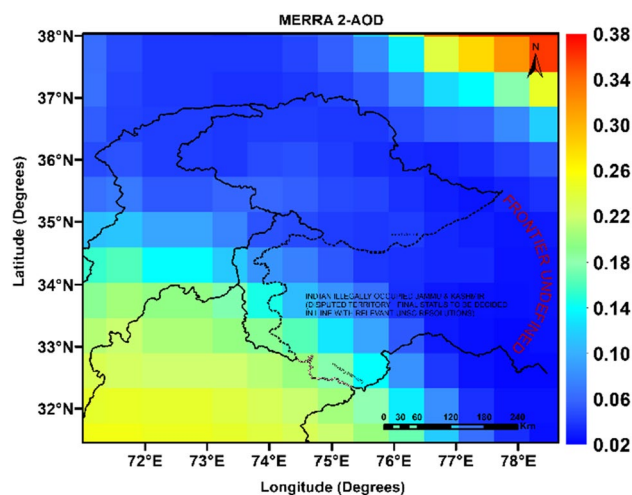
whereas the Sen technique determines the median of these slopes by computing the slope of time-series among the data pairs and is calculated using the equation (3).

$$\text{Slope} = m \frac{x_i - x_j}{i - j} \tag{3}$$

**Results and discussion**

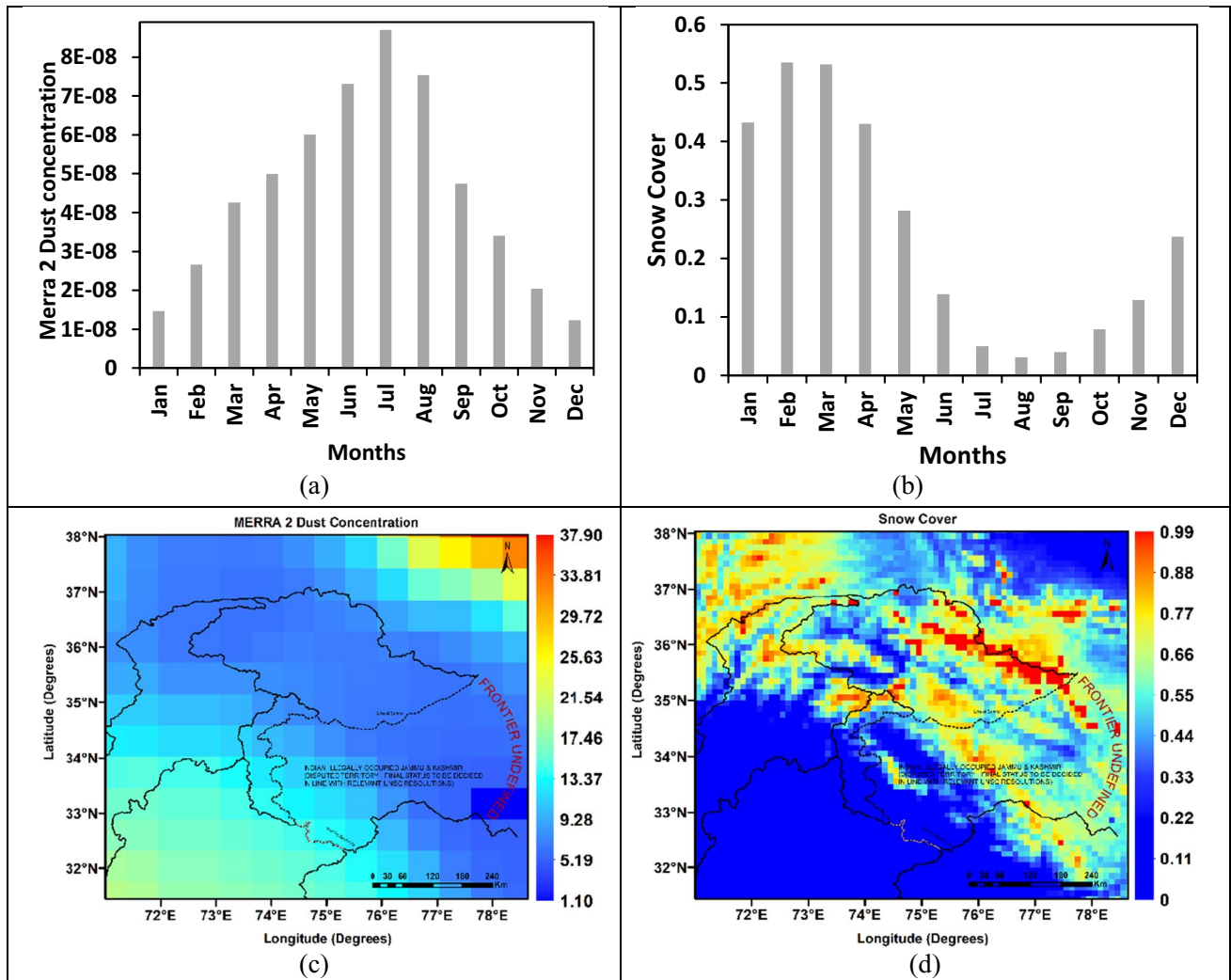
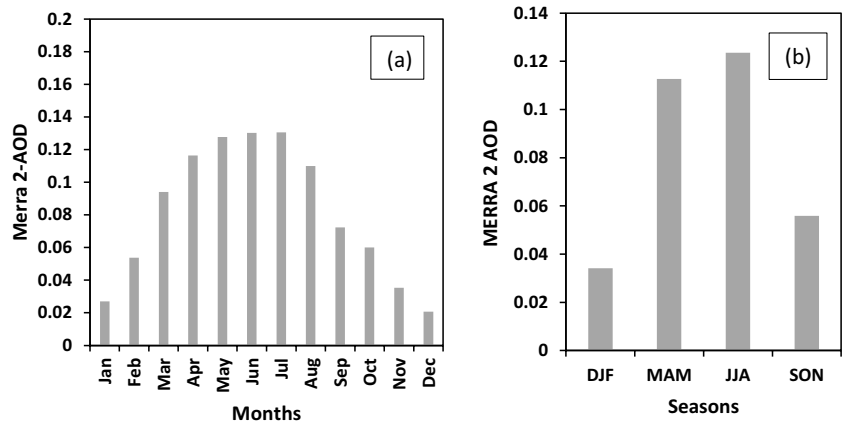
**Spatial distribution**

Figure 2 represents the mean annual spatial distributions of AOD retrieved from MERRA 2 over NP from 2003 to 2021. The major causes of air pollution in Pakistan are urbanization, population density, and automobile emissions which lead to high aerosol loadings. Also, the sources of aerosols can be linked with coal, biomass, and fossil fuel burning, as well as the long-range transportation of dust aerosols. The MERRA 2-AOD of >0.05, 0.05, and >0.05 were observed over the Hindukush, Karakoram, and Himalaya ranges, respectively, from 2003 to 2021. The north-eastern and central NP regions receive moderate annual aerosol concentration, whereas low values persist in the Gilgit and Kashmir region as shown in Fig. 2. The aerosol concentrations over northeastern and central NP were attributed to the anthropogenic emissions and changes in meteorological parameters (e.g., wind patterns). These concentrations were lower than that were noticed over

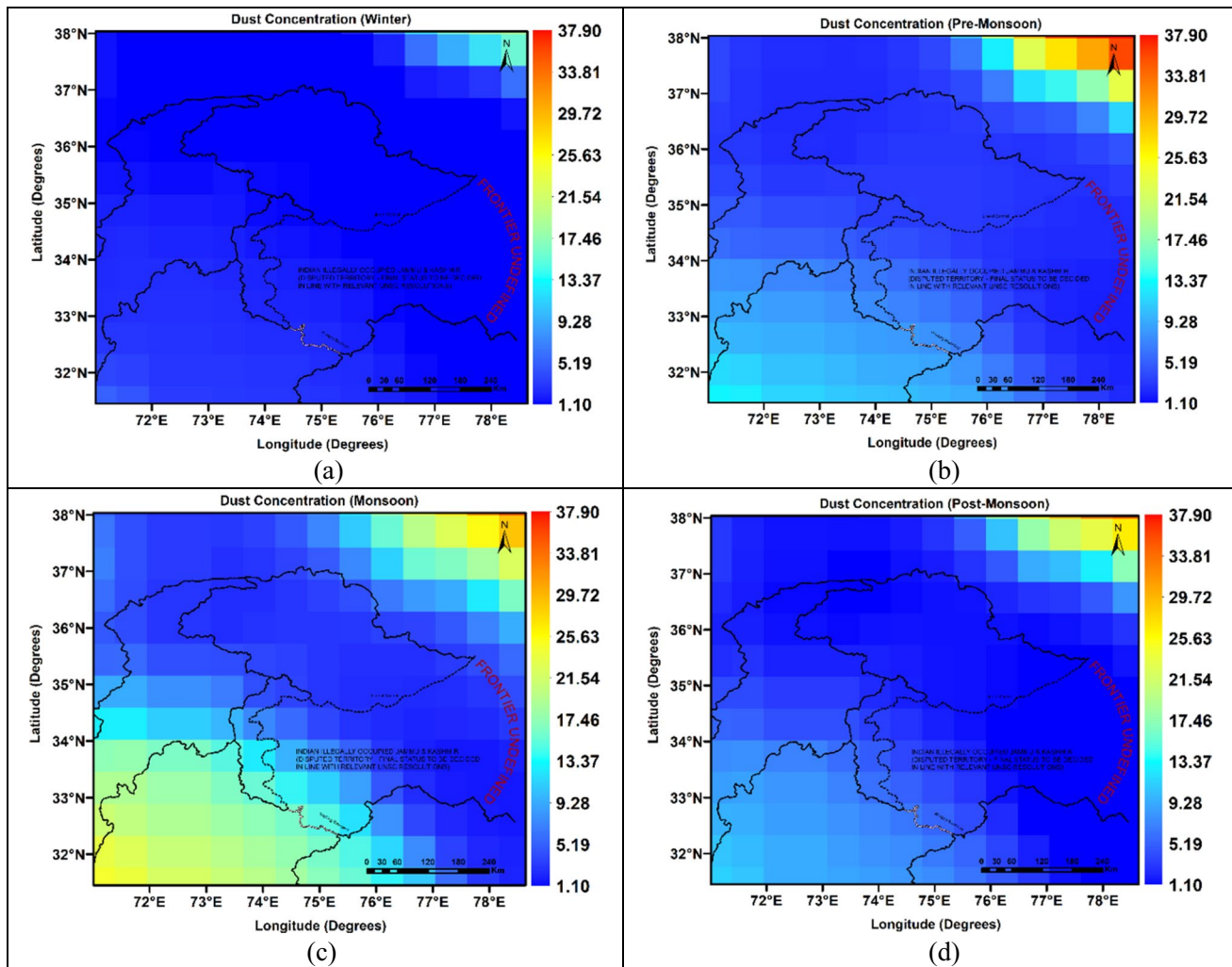


**Fig. 2** Mean annual spatial distributions of AOD over NP acquired from MERRA 2 retrievals during 2003–2021

**Fig. 3** Monthly and seasonal variations of AOD over Northern Pakistan acquired from MERRA 2 retrievals during 2003–2021



**Fig. 4** Monthly variations of **a** dust surface mass concentration ( $\text{Kg m}^{-3}$ ) and **b** snow cover (fraction), and spatial distributions of **c** dust surface mass concentrations ( $\times 10^{-8} \text{ Kg m}^{-3}$ ) and **d** snow cover (fraction) from 2003 to 2021 over the NP



**Fig. 5** Spatial distributions of dust surface mass concentration ( $\times 10^{-8} \text{ Kg m}^{-3}$ ) during **a** winter, **b** pre-monsoon, **c** monsoon, and **d** post-monsoon seasons over NP from 2003 to 2021

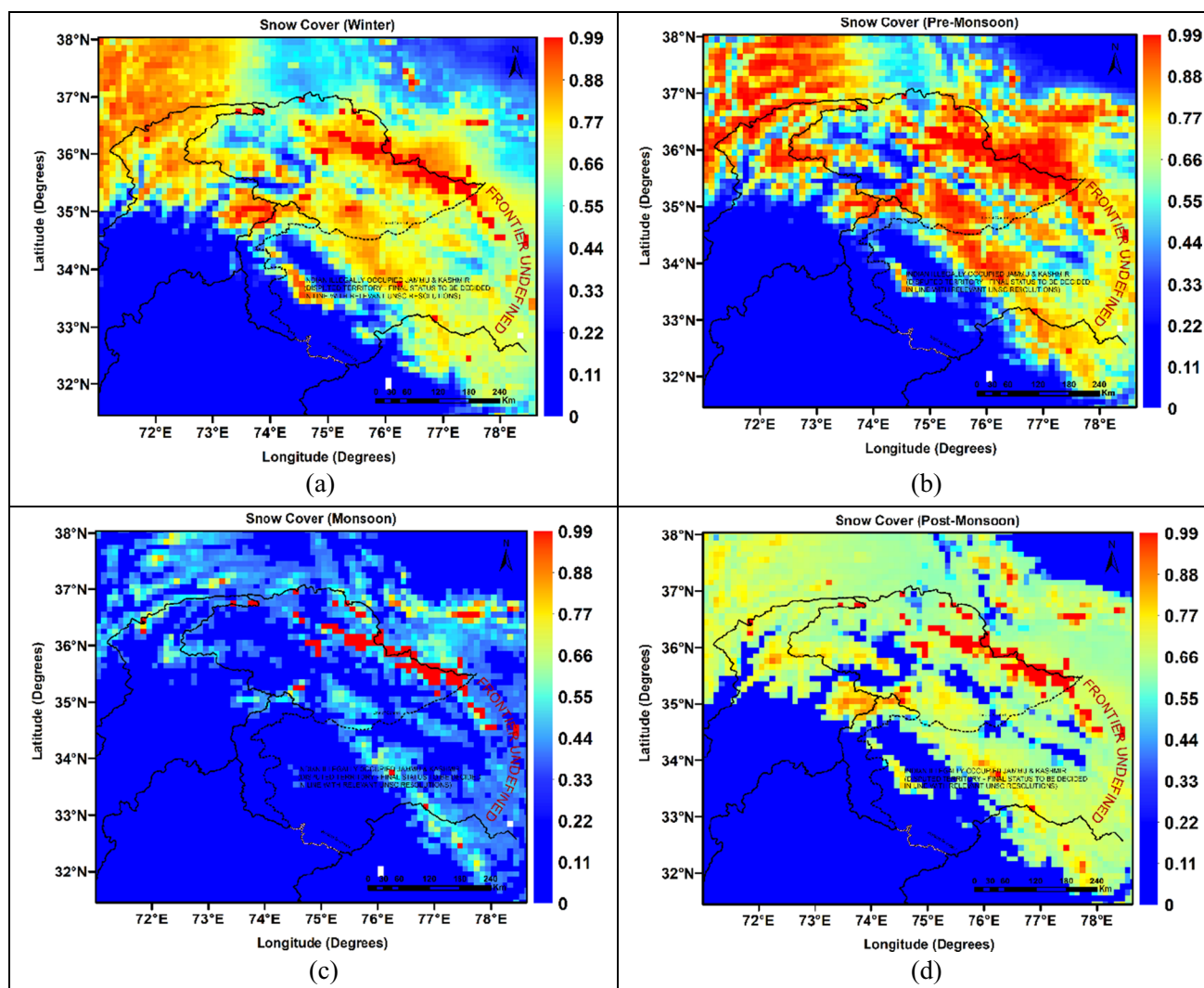
other parts of Pakistan like Punjab and Sindh which experienced high AOD of  $>1.0$  in July (Bilal et al. 2021). A rise in MERRA 2 AOD over the northwestern and southern Kashmir regions was observed from 2003 to 2021. Overall, little variation in MERRA 2-AOD values was noticed over NP. The AOD over the NP region is attributed to anthropogenic, natural sources or can be a combination of both sources.

### Monthly variations

The monthly variations of MERRA 2 AOD over NP from 2003 to 2021 are shown in Fig. 3a. The AOD retrieved from MERRA 2 reanalysis data has the highest AOD of 0.13 in July and the lowest in December over NP from 2003 to 2021 as shown in Fig. 3a. High AOD in the

summer season is mainly attributed to the hygroscopic aerosols growth due to high relative humidity (Bilal et al. 2021). Moreover, local aerosol sources can also be a possible reason for high aerosol concentration over NP. Figure 3 b shows seasonal variations of MERRA 2 over NP from 2003 to 2021. The highest average values of AOD observations acquired from MERRA 2 were observed in summer. Furthermore, the MERRA 2 AOD was found to be higher in monsoon (0.123) followed by pre-monsoon (0.112), post-monsoon (0.055), and winter (0.034), respectively.

Figure 4 a shows dust surface mass concentration over the NP region from 2003 to 2021. The highest dust concentrations were observed in July, while the lowest concentrations was seen in December over NP from 2003 to 2021. The findings depict that dust surface

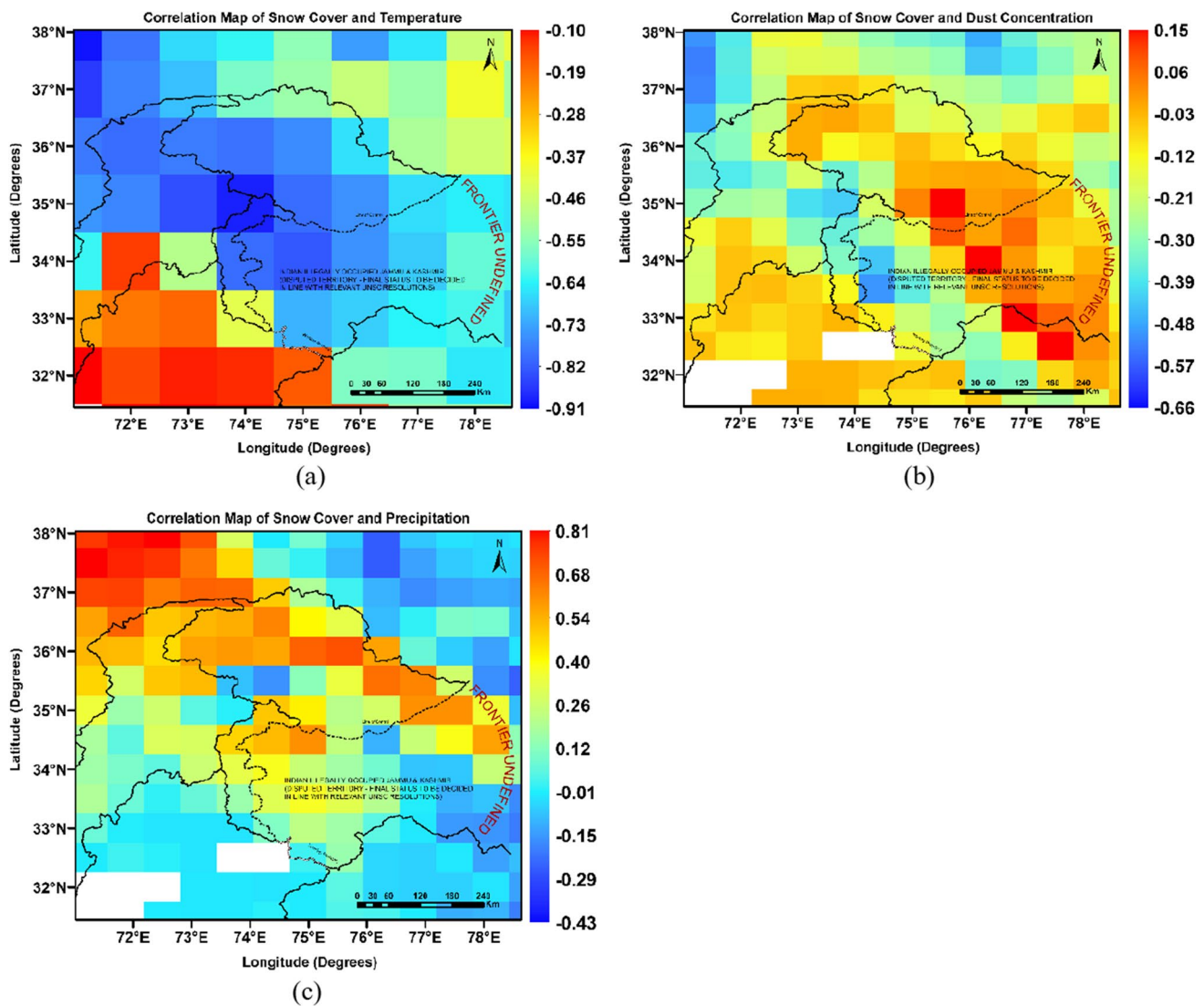


**Fig. 6** Spatial distributions of snow cover during **a** winter, **b** pre-monsoon, **c** monsoon, and **d** post-monsoon seasons over NP from 2003 to 2021

mass concentration is high in monsoon, followed by pre-monsoon, post-monsoon and winter. High concentration of dust in the monsoon season is because of high wind speed and high temperature. The lower dust concentrations in December is because of reduced surface emissions from primary atmospheric aerosols over NP. Figure 4b shows the monthly variations of snow cover over NP during the period 2003–2021. The highest snow cover of 0.53 was observed in February, while the lowest of 0.03 was seen in August over NP. The rapid variation in snow cover was observed from February to August due to the temperature rise. Snow cover is mainly located in northwestern Pakistan, Gilgit, and Kashmir as shown in Fig. 4d. The monthly variations of dust concentration are in opposite behavior to snow cover.

### Seasonal distribution

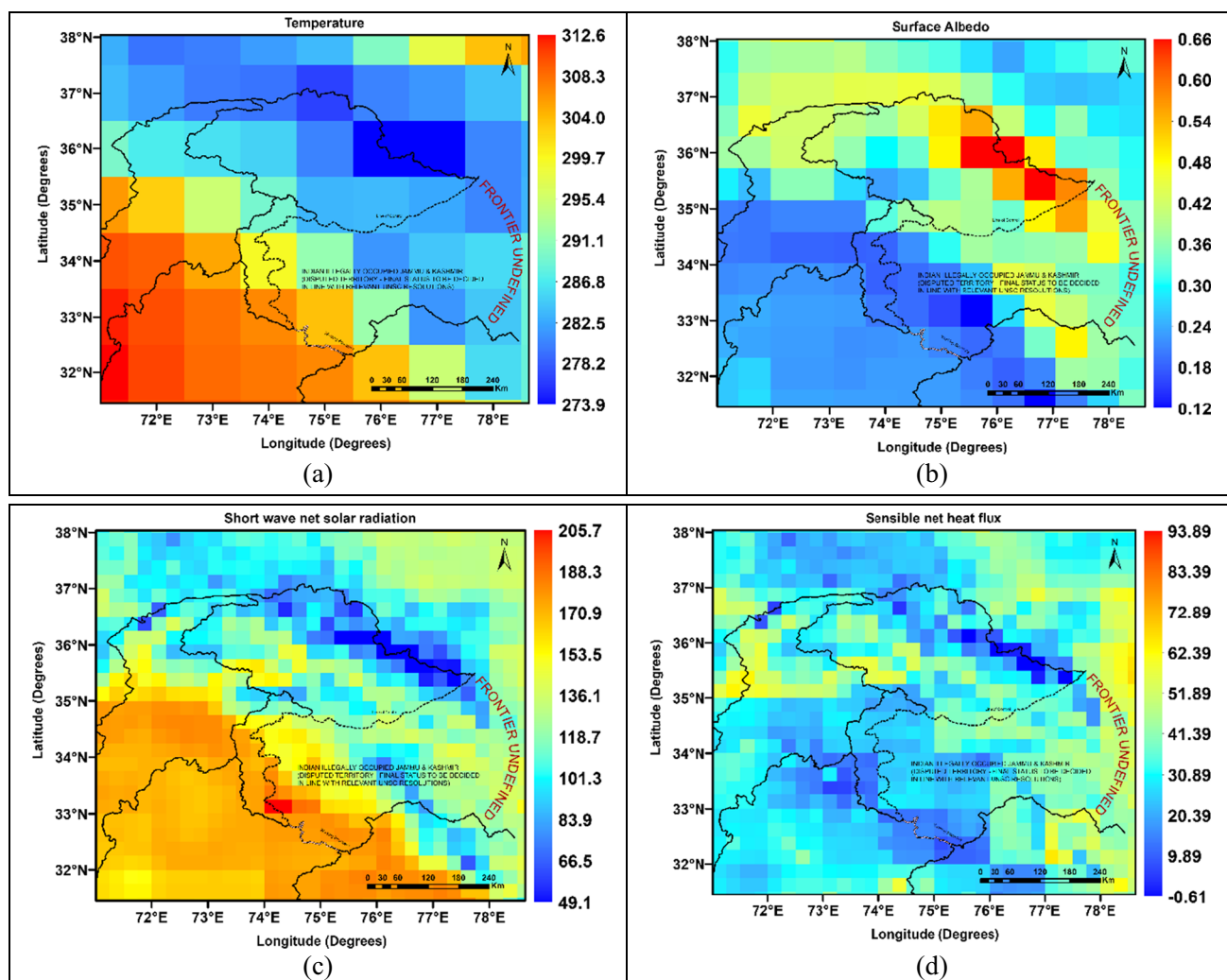
Figure 5 shows the variations of seasonally averaged dust surface mass concentrations over NP. The spatial variations of pre-monsoon and monsoon dust surface mass concentrations are almost similar for NP from 2003 to 2021. However, a detailed look shows that the MERRA 2 dust surface mass concentration is somewhat higher over the Himalaya, Karakorum, and Hindukush range in the monsoon and pre-monsoon seasons, whereas in contrast, over areas with lower dust surface mass concentration values from MERRA 2 were observed in winter and post-monsoon season. The low aerosol concentrations in the winter and post-monsoon season are because of the washout processes of aerosols from the environment that occurs due



**Fig. 7** Spatial correlation of Snow cover with **a** temperature, **b** dust surface mass concentration, and **c** precipitation over NP from 2003 to 2021

to the heavy rain and reduced surface emissions. It can be seen from Fig. 5b that the dust surface mass concentration starts building up from March over the NP region. The dust surface mass concentration varies from east to west, with the highest seasonal mean concentrations in Kashmir and lower values over the northwestern areas, as well as in a few portions of Gilgit in pre-monsoon (Fig. 5b) and monsoon (Fig. 5c). The high aerosol concentrations in spring and summer season are due to high temperatures, high wind speeds, and long-range transport of aerosols (Alam et al. 2011). Zeb et al. (2019) found high AOD in spring over glacier portions of northern Pakistan. The authors reported that the dust aerosols were prominent in spring and summer, while anthropogenic aerosols were in autumn and winter.

The seasonal snow cover from 2003 to 2021 is shown in Fig. 6. The spatial pattern of snow cover in NP is significantly different in all seasons. In winter, the high snow cover was identified over the Hindukush ( $>0.80$ ), Karakoram ( $\sim 1.0$ ), and Himalayas ( $>0.83$ ) ranges as shown in Fig. 6a. However, in Hindukush, Karakoram, and Himalayas ranges, the monthly averaged snow cover varied greatly. The winter season weather pattern is also strongly influenced by the atmospheric circulation, which is main the factor for great snowiness. The snow cover has somehow similar pattern in the pre-monsoon season with high values over the Hindukush, Karakoram, and Himalayas from 2003 to 2021, and lower values were observed over central Gilgit and a few parts of Kashmir as shown in Fig. 6b. The maximum values of snow cover were mainly observed over the Karakoram



**Fig. 8** Mean annual Spatial distribution of **a** temperature (K), **b** surface albedo, **c** shortwave net solar radiation ( $\text{Wm}^{-2}$ ), and **d** sensible net heat flux ( $\text{Wm}^{-2}$ ) over NP from 2003 to 2021

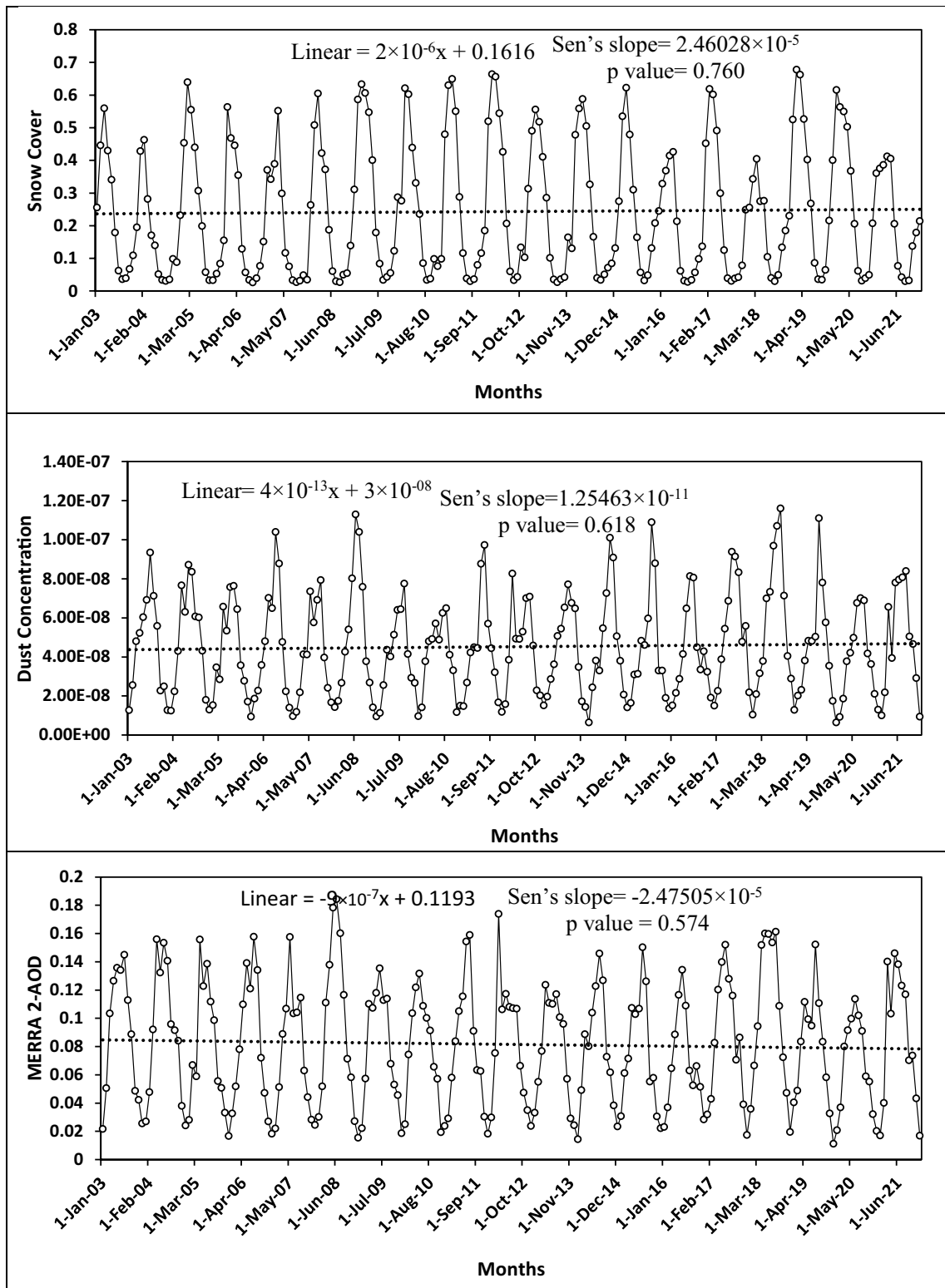
ranges. There was very little snow cover in NP in monsoon due to the rise in temperature. The Karakoram range still shows high snow cover values in monsoon as shown in Fig. 6c. In the post-monsoon season, the snow cover values started rising again due to the change in temperature and atmospheric conditions. Overall, more snow cover was observed in winter and pre-monsoon over the three mountain ranges and nearby areas.

### Spatial correlations

The spatial correlation of snow cover with temperature, dust surface mass concentration and precipitation over NP from 2003 to 2021 is shown in Fig. 7. The aerosol's influence on snow cover in the NP region was examined using the mean spatial correlation analysis between dust surface

mass concentration and snow cover. All three mountain ranges including adjoining regions of NP show a negative correlation value between snow cover and temperature (Fig. 7a). In Fig. 7b, a positive correlation value between snow cover and dust surface mass concentration was examined over a few parts of NP, with the highest value of a  $>0.15$  over the Kashmir and  $\sim 0.13$  over the Himalaya range. The negative correlation between snow cover and dust surface mass concentration was observed over the Hindukush and Karakoram range as shown in Fig. 7b. The precipitation and temperature are two major factors which influence the snow, while the dust concentration indirectly affects it by utilizing the surface temperature. Figure 7c shows the correlation map between snow cover and precipitation over NP from 2003 to 2021. The positive correlation between snow cover and precipitation was seen over the three mountain





**Fig. 9** Time series and trend analysis for monthly, FLDAS snow cover, MERRA 2 dust surface mass concentration, and MERRA 2-AOD over NP from 2003 to 2021

**Table 1** Mann-Kendall test and Sen's slope results of monthly averaged AOD, dust surface mass concentration and snow cover over NP from 2003 to 2021

Products	Z-values	P values	Sen's slope
MERRA 2-AOD	−0.56196	0.57413	$-2.47505 \times 10^{-05}$
MERRA 2 dust concentration	0.49769	0.61869	$1.25463 \times 10^{-11}$
FLDAS snow cover	0.30486	0.76046	$2.46028 \times 10^{-05}$

ranges and a few portions of Kashmir. The highest correlation of  $>0.69$  between snow cover and precipitation was also observed over the Karakoram range, while the lowest correlation was seen in the southern part of Gilgit. Moreover, Fig. 8 shows the mean annual spatial variations of temperature, surface albedo, shortwave net solar radiation and sensible net heat flux.

### Monthly trend analysis

Figure 9 and Table 1 show the results of trend analysis for FLDAS snow cover, MERRA 2 dust surface mass concentration, and MERRA 2-AOD over NP from 2003 to 2021. To assess the detailed pattern of long-term trends in aerosols and snow cover over NP, we have used the MK trend test and Sen's slope. The MERRA 2-AOD ( $p$ -value: 0.57413, Z-statistics:  $-0.56196$ , and Sen's slope:  $-2.47505 \times 10^{-05}$ ), MERRA 2 dust surface mass concentration ( $p$ -value: 0.61869, Z-statistics: 0.49769, and Sen's slope:  $1.25463 \times 10^{-11}$ ), and FLDAS snow cover ( $p$ -value: 0.76046, Z-statistics: 0.30486, and Sen's slope:  $2.46028 \times 10^{-05}$ ) depicts statistically insignificant trends over NP from 2003 to 2021.

### Conclusions

The multiple modelled and reanalysis datasets were used to investigate the influence of aerosols over snow cover in the northern areas of Pakistan from 2003 to 2021. The highest mean annual MERRA 2-AOD of  $>0.05$ , 0.05, and  $>0.05$  was observed over the Hindukush, the Karakoram, and the Himalaya range, respectively, from 2003 to 2021. The mean annual spatial correlations of snow cover with dust surface mass concentration and meteorological parameters (temperature and precipitation) were also assessed over the northern region. The highest seasonal dust surface mass concentrations over the Himalaya, Karakoram, and Hindukush ranges were observed in the monsoon and pre-monsoon seasons, whereas an opposite pattern of snow cover was observed over NP with the highest snow cover in winter and pre-monsoon. Furthermore, the long-term trends in the variation of aerosols and snow cover were also examined from 2003 to 2021 using the Mann-Kendall test and Sen's slope.

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**Author contributions** Writing — review and editing: Shahid Parvez, Zia Ul-Haq, and Fazzal Qayyum; conceptualization: Shahid Parvez and Zia Ul-Haq; visualization: Shahid Parvez, Syeda Aadila Batool, and Fazzal Qayyum; methodology: Shahid Parvez, Salman Tariq, Asim Daud Rana, Khalid Mahmood, and Fazzal Qayyum; supervision: Shahid Parvez and Zia Ul-Haq.

**Data Availability** The datasets can be availed from the Giovanni websites (<https://giovanni.gsfc.nasa.gov/giovanni/>).

**Code availability** Not applicable.

### Declarations

**Ethics approval** Not applicable.

**Consent to participate** All the authors have participated and reviewed this manuscript for publication.

**Consent for publication** Not applicable.

**Conflict of interest** Not required.

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