Postprint: Spatiotemporal Variation of Aeolian Dust in Egypt, North Africa

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Abstract

Through analysis of meteorological observation data and satellite remote sensing data from Egypt, North Africa during 1990–2020, this study investigates the spatiotemporal variation characteristics of wind-eroded dust and elucidates the primary influencing factors. The results demonstrate that: the frequency of dust weather events in Egypt over the past 30 years varied between 20–65 $d \cdot a^{-1}$, exhibiting an overall decreasing trend; the annual average concentration of Total Suspended Particulates (TSP) fluctuated between 400–1200 $g \cdot m^{-3}$, representing a relatively high intensity level among global arid regions; blowing sand events occurred most frequently, followed by floating dust, dust storms, and severe dust storms; the number of blowing sand days in spring and summer accounted for over 60% of the total annual dust weather days; ambient TSP concentration was highly correlated with the frequency of dust weather events; surface wind speed in Egypt showed a decreasing trend over the past 30 years, with wind erosion serving as a key factor affecting regional air quality; the frequency of dust weather events exhibited a significant negative correlation with the Atlantic Multidecadal Oscillation (AMO) index, with a correlation coefficient of approximately -0.67. This study provides theoretical basis and data support for comprehensively understanding the spatiotemporal variation characteristics of wind-eroded dust and preventing dust storm disasters in Egypt, North Africa.

Full Text

Spatiotemporal Variability of Eolian Dust in Egypt, North Africa

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Abstract: Based on meteorological observation data and satellite remote sensing products from 1990–2020, this study investigates the spatiotemporal variability characteristics of eolian dust in Egypt and identifies the primary influencing factors. The results show that dust weather occurrence frequency in Egypt varied between 20~65 $d \cdot a^{-1}$ over the past 30 years, exhibiting an overall decreasing trend. Annual average total suspended particulate (TSP) concentrations fluctuated between 400~1200 $g \cdot m^{-3}$, representing relatively high intensity levels among global arid regions. Blowing dust occurred most frequently, followed by suspended dust, dust storms, and severe dust storms. Spring and summer blowing dust days accounted for over 60% of annual total dust weather days, with ambient TSP concentrations highly correlated with dust weather frequency. Over the past 30 years, surface wind speed in Egypt showed a decreasing trend, yet wind erosion remains a critical factor affecting regional air quality. Dust weather frequency demonstrated a significant negative correlation with the Atlantic Multidecadal Oscillation (AMO) index, with a correlation coefficient of approximately -0.67. This study provides theoretical basis and data support for comprehensively understanding the spatiotemporal characteristics of eolian dust in Egypt and for preventing dust storm disasters.

Keywords: Egypt; eolian dust; spatiotemporal variability; environmental evolution

Introduction

Desertification represents a severe ecological and environmental issue of global concern that directly impacts the sustainable socioeconomic development of human societies. Approximately 900–3300 Mt of surface soil material is eroded, transported, and deposited by wind annually worldwide, with the resulting eolian dust consisting primarily of fine particulate matter that constitutes one of the most critical environmental problems affecting regional and global scales. Dust activity and material transport processes caused by soil wind erosion severely affect desertification progression in arid and semi-arid regions while exerting significant influences on regional climate change, ground-level solar radiation intensity, topographic evolution, and human health, closely linking these activities to global environmental change. Consequently, scientific research on eolian dust has garnered widespread international attention.

The Sahara region in North Africa releases approximately 1000 Mt of dust into the atmosphere annually, accounting for about 50% of global dust emissions. Egypt, located on the edge of the Sahara Desert, ranks among the countries most severely affected by desertification worldwide. In recent years, as environmental problems caused by eolian dust have received increasing attention, scholars have conducted extensive research on dust weather in Egypt using multi-source observation data. Previous studies have identified eastern Egypt as one of the four major dust source regions in North Africa, with spring being the most frequent season for dust storms and April–May representing the peak period. Research using MODIS data has revealed that most high-intensity dust events in Egypt originate from dust storms in the western desert, while analyses of atmospheric aerosols in Cairo have shown that high wind speeds lift large quantities of relatively loose dust particles, severely impacting atmospheric particulate matter concentrations. Investigations of spatiotemporal variability of dust storms in North Africa have indicated a significant upward trend in dust storm frequency in Egypt, with temperature and wind speed identified as the most prominent influencing factors. Other studies have demonstrated that Egyptian dust weather is closely related to the Atlantic Multidecadal Oscillation (AMO), with Atlantic sea surface temperature anomalies causing further abnormal variations in wind speed, precipitation, and temperature in Egypt, thereby exerting significant modulating effects on decadal climate variability. However, most previous research on Egyptian dust weather has focused on Cairo and parts of the Nile Delta. With the emergence of land reclamation projects in Egypt's western desert, more in-depth studies on the spatiotemporal variability of eolian dust across the entire country and in geographically distinctive typical cities have become necessary.

As an important country along the "Belt and Road" initiative, Egypt faces harsh arid natural conditions and extremely severe wind-sand disasters. Eolian dust has caused significant negative impacts on local infrastructure including major transportation routes and key engineering projects. Therefore, thoroughly understanding and mastering the spatiotemporal patterns of eolian dust and the current status of desertification in Egypt not only helps clarify regional resource and environmental issues but also strengthens the foundation for China-Africa technical cooperation. Based on satellite remote sensing products and meteorological observation records from 30 cities in Egypt from 1990–2020, this study analyzes the spatiotemporal variability characteristics and patterns of eolian dust in Egypt, elucidates the primary influencing factors, and focuses on four typical representative cities—Mersa Matruh, Kharga, Hurguada, and Cairo—to analyze interannual variation characteristics of dust frequency in different regions of Egypt, providing theoretical basis and data support for research on national-scale spatiotemporal variability and dust storm disaster prevention.

1.1 Study Area Overview

Egypt is situated on the edge of the Sahara Desert dust source region (Fig. 1), adjacent to the Mediterranean Sea and Red Sea, characterized by perennial hot, dry, and rainless conditions severely affected by desert and Gobi dust materials. Egypt has an annual average temperature of 20–25°C, multi-year average precipitation of less than 50 mm, annual evaporation exceeding 2600 mm, and annual average relative humidity below 50%. The northern coastal area and Nile Delta belong to the subtropical Mediterranean climate zone, while southern regions exhibit tropical desert climate. Over 90% of Egypt consists of arid desert areas, with most terrain at 100–700 m elevation. The western region connects to the Libyan Desert dominated by shifting sand surfaces, the Red Sea coast and Sinai Peninsula feature mainly hilly mountains, and the eastern Arabian Desert consists of gravel deserts and exposed bedrock. The western desert surface soil is relatively loose with very low vegetation coverage, experiencing long-term wind erosion and dust impacts with numerous dust days, particularly during spring.

1.2 Data Sources and Methods

Daily routine meteorological element data and dust weather process records from 1990–2020 were obtained from the National Meteorological Center through the Global Telecommunication System, comprising data from 30 Egyptian surface meteorological stations. Meteorological elements included visibility, wind speed, temperature, and precipitation with observation intervals of 3 hours. Satellite remote sensing spatial imagery for Egypt's desert regions was sourced from MODIS products. Dust weather was classified according to World Meteorological Organization standards based primarily on horizontal visibility into four types: suspended dust, blowing dust, dust storm, and severe dust storm. Horizontal visibility <10 km indicates suspended dust; 1–10 km indicates blowing dust; 200–1000 m indicates dust storm; and <200 m indicates severe dust storm. Total suspended particulate (TSP) concentration data were calculated and statistically derived from visibility data using conversion formulas. The formula is as follows:

$$C = 3802.29 \times DV^{-0.84} + 7.62 \times DV^{-0.11} \text{ (for } DV < 3.5 \text{ km)}$$
$$C = 542 \times DV^{-0.84} \text{ (for } DV \geq 3.5 \text{ km)}$$

where C represents TSP concentration and DV represents visibility.

2.1 Interannual Variation Characteristics of Dust Weather Frequency in Egypt

Dust weather frequency can characterize regional wind-sand activity intensity. Fig. 2 shows interannual variation characteristics of dust weather frequency in Egypt from 1990–2020. The highest annual average dust weather frequency occurred during 1990–1995 at approximately 65 $\mathrm{d \cdot a^{-1}}$, followed by a sharp decline to 27 $\mathrm{d \cdot a^{-1}}$. Subsequently, dust frequency exhibited small fluctuations, reaching a minimum of 23 $\mathrm{d \cdot a^{-1}}$ in 2010 before returning to relatively high dust intensity levels in recent years. Overall, dust weather frequency in Egypt showed a decreasing trend over the past 30 years, generally varying between 20–65 $\mathrm{d \cdot a^{-1}}$, representing relatively high intensity among global arid regions. High-frequency eolian dust weather alters underlying surface characteristics, thereby affecting precipitation and temperature variations. Dust weather frequency demonstrated a significant negative correlation with the Atlantic Multidecadal Oscillation (AMO) index, with a correlation coefficient of approximately

-0.67 (Fig. 3). High-frequency dust weather directly impacts desertification processes and exacerbates aridity in Egypt.

To understand interannual variation characteristics of dust weather frequency in different regions of Egypt, four typical stations were selected: Mersa Matruh, Hurguada, Cairo, and Kharga. Statistical analysis of interannual variation characteristics for four weather phenomena—suspended dust, blowing dust, dust storm, and severe dust storm—from 1990–2020 revealed distinct regional differences (Fig. 4). Among these cities, Kharga showed the highest proportion of blowing dust weather with an annual average of approximately 60%, followed by Mersa Matruh, Hurguada, and Cairo at around 40%. This likely relates to local geographical location and high-wind weather conditions. Kharga, the most developed oasis city in Egypt's western desert, experiences severe impacts from desert and Gobi dust materials coupled with frequent high-wind events, resulting in relatively high blowing dust frequency. Additionally, suspended dust frequency at the four typical stations remained relatively stable at low levels over the past 30 years.

2.2 Temporal Variation Characteristics of Ambient TSP Concentrations in Egypt

Fig. 5 illustrates interannual and intra-annual variations of TSP concentrations in Egypt. At the beginning of the 21st century, annual average concentrations fluctuated between 500–800 $\text{g} \cdot \text{m}^{-3}$ and gradually decreased, likely related to changes in suspended and blowing dust days. Seasonally, spring TSP concentrations showed high values fluctuating around 800 $\text{g} \cdot \text{m}^{-3}$, maintaining relatively high levels. From May onward, high-concentration TSP areas gradually contracted, reaching minimum values in September before increasing again during autumn and winter. Spring high TSP concentrations correlated highly with dust frequency. According to local environmental monitoring stations, average TSP concentration during dust weather could reach 1315 $\text{g} \cdot \text{m}^{-3}$, while concentrations in other months averaged 542 $\text{g} \cdot \text{m}^{-3}$, indicating that extreme dust weather TSP concentrations are generally higher than non-dust periods.

2.3 Analysis of Influencing Factors

2.3.1 Wind Speed

Wind erosion represents the power source for dust emissions and transport. Fig. 6 shows interannual variation trends of maximum wind speed and intra-annual distribution ratios of different wind force levels in Egypt. Over the past 30 years, Egypt's maximum average wind speed was approximately 5.9 $\text{m} \cdot \text{s}^{-1}$, with wind force levels 3–4 dominating at 60% of the annual total. Spring and summer blowing dust days accounted for over 60% of total annual dust weather days. Although spring and winter precipitation gradually increased, maximum monthly precipitation intensity remained below 1.1 $\text{mm} \cdot \text{d}^{-1}$. Despite precipitation increases in spring and winter, wind erosion intensity remained high with average wind speeds around 5.6 $m \cdot s^{-1}$, while autumn and winter wind erosion intensity significantly decreased to approximately 5.6 $m \cdot s^{-1}$. Although wind speed showed a decreasing trend, wind erosion remains a key factor affecting air quality. Wind erosion transports desert dust particles through atmospheric circulation to Egypt, representing the primary source of atmospheric particulate pollutants. The correlation coefficient between TSP concentration and dust storm frequency reached 0.71, indicating a significant positive relationship. As dust weather frequency increases, ambient TSP concentrations rise markedly, with frequent dust weather and relatively high TSP concentrations exacerbating aridity in Egypt.

2.3.2 Precipitation

Wet removal of aerosols by precipitation constitutes an important atmospheric deposition process for dust aerosols. Fig. 7 shows interannual and intra-annual variations of precipitation in Egypt. Egypt experiences long-term drought with irregular interannual precipitation variation. Maximum annual precipitation reached 526 mm in 1994, while minimum annual precipitation was only 41 mm in 2010. Overall, average annual precipitation in Egypt has remained below 185 mm since 1990, with atmospheric dry deposition dominating due to small total precipitation. Intra-annual precipitation variation is extremely irregular with strong seasonal characteristics: daily average precipitation is lowest in summer at less than 0.1 $mm \cdot d^{-1}$, gradually increasing from September, with winter precipitation reaching 1.1–1.2 $mm \cdot d^{-1}$, the highest monthly values of the year. Precipitation variation in Egypt is closely related to AMO phases: when AMO is in its cold phase, it increases winter precipitation in Egypt, while warm phases reduce summer precipitation. Precipitation variation is extremely irregular both intra-annually and interannually, with maximum precipitation periods (January–February) playing a key role in desertification impacts.

2.3.3 Temperature

Fig. 7 also displays interannual and intra-annual temperature variations in Egypt. Annual temperatures range between 11–31°C, with summer temperatures significantly higher than winter and maximum values occurring in July. Overall, temperatures in Egypt have shown a slow increasing trend over the past 30 years, likely related to AMO warm phases and increased greenhouse gas forcing. AMO warm phases affect atmospheric circulation, causing tropospheric temperature increases in North Africa, strengthening thermal differences between land and sea, and ultimately enhancing summer winds in Egypt. Increased anthropogenic activities have exacerbated greenhouse gas forcing, with their combined effects leading to the observed warming trend. Temperature increases enhance surface evaporation, causing greater water loss that is unfavorable for desertification reversal. Combined with wind field analysis, prevailing northeasterly and easterly winds in winter create relatively stable atmospheric stratification with dominant downdrafts and clear, dry weather that intensifies desertification processes.

Conclusions

Based on daily routine observation data from Egyptian ground meteorological stations and satellite remote sensing products from 1990–2020, this study analyzed spatiotemporal variability characteristics and patterns of eolian dust in Egypt and discussed the impacts of wind speed, precipitation, and temperature on regional wind-sand activities. The main conclusions are:

1) Eolian dust weather frequency in Egypt varied between 20~65 $d \cdot a^{-1}$ over the past 30 years, showing an overall decreasing trend with fluctuations, representing relatively high intensity among global arid regions. Dust weather frequency is significantly negatively correlated with the Atlantic Multidecadal Oscillation (AMO) index (correlation coefficient -0.67). Due to geographical location and high-wind weather influences, distinct regional differences exist in dust weather frequency variation characteristics across Egypt.

2) Blowing dust days in spring and summer accounted for over 60% of total annual dust weather days, with wind force levels 3–4 dominating at 60% of the annual total. Ambient TSP concentrations are positively correlated with dust storm frequency (correlation coefficient = 0.71). Wind-eroded dust particles from the Sahara Desert transported through atmospheric circulation constitute the primary source of atmospheric particulate pollutants in Egypt.

3) Wind speed in Egypt showed a significant decreasing trend over the past 30 years, likely related to changes in pressure gradient force due to altered circulation patterns and increased surface roughness from land use changes. Wind erosion remains a key factor affecting air quality in oasis areas. Precipitation variation is extremely irregular both intra-annually and interannually, with maximum precipitation periods playing a crucial role in desertification impacts. Temperature showed a slow increasing trend, related to AMO warm phases and increased greenhouse gas forcing.

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Note: Figure translations are in progress. See original paper for figures.