



Three Pathways of Eastward Transport of North African Dust: Synoptic Patterns and Impacts on Air Quality in China

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Abstract. The long-range eastward transport of North African dust substantially influences China's climate, environment, and human health. However, the circulation mechanisms that modulate its pathway variability and downstream impacts remain poorly understood. In this study, we investigated the synoptic patterns along three distinct eastward transport pathways of North African dust and their impacts on air quality in China using reanalysis and observations. Results show that seasonal variations in dust activity and the position of the westerly belt govern the eastward transport of North African dust, with transport peaking in April and spring accounting for 56.3% of the annual dust mass potentially available for eastward transport. Among the three transport pathways, the northern pathway transports dust northward into Europe, followed by eastward advection through the mid- and high-latitude westerlies following pre-trough uplift. In contrast, the middle pathway features Mediterranean uplift and northeastward deflection. Mid-latitude westerly transport is modulated by western Mediterranean cyclonic activity, a southward-extending trough, and the blocking and splitting effects of the European high-pressure system. The southern pathway transports dust eastward along lower latitudes and around the southern Tibetan Plateau toward southern China. This pathway is guided by southward displaced lower-latitude westerlies, the European cold trough, and Himalayan topographic deflection. These dust plumes produce maximum $\text{PM}_{2.5}$ anomalies of $54.1\text{--}202.4\ \mu\text{gm}^{-3}$ decreasing from north to south across China. These findings may support early warnings of the eastward transport of North African dust to East Asia—an overlooked issue that is becoming increasingly critical as aerosol levels decline in China.



1. Introduction

Dust aerosols have significant impacts on climate, environment, and human health (Jickells et al., 2005; De Longueville et al., 2010; Kok et al., 2023). They can modulate the radiation budget of the Earth-atmosphere system through the absorption and scattering of solar and terrestrial radiation (Huang et al., 2014; Lin et al., 2026). Dust aerosols act as ice-nucleating particles that influence cloud properties (Chen et al., 2024), thereby affecting precipitation (Zhang et al., 2015; Seinfeld et al., 2016; Patel et al., 2019). Airborne dust particles are an important source of elements such as iron and carbon (Fung et al., 2000; Pabortsava et al., 2017). The transport of nutrients and trace elements by dust can regulate chemical processes in both continental and marine ecosystems (Yu et al., 2015; Li and Wang, 2024). In addition to these ecological impacts, transported dust particles can serve as carriers for certain viruses (Acosta-Martínez et al., 2015) and have significant adverse effects on cardiovascular and respiratory health (García-Pando et al., 2014; Goudie, 2014; Crooks et al., 2016).

North Africa is the largest contributor to the global dust emission, accounting for 58% of the total global dust emissions and 62% of the total global dust loading in the atmosphere (Tanaka and Chiba, 2006; Laurent et al., 2008). Annually, approximately 60% of these dust emissions are estimated to be scavenged over the African continent (Dalmeida, 1986). Some of the dust can be transported westward across the Atlantic Ocean by the trade winds, and reaching the Americas (Gläser et al., 2015; Barkley et al., 2022), or northward to Europe under specific synoptic conditions (Francis et al., 2022). Previous studies have shown that the North African dust can also be transported eastward (Ganor and Mamane, 1982; Huang et al., 2025). It not only reaches the coast of the Mediterranean Sea but can also be transported to East Asia and even deposited in the North Pacific Ocean (Park et al., 2005; Hsu et al., 2012).

Severe dust storm events over North Africa have received extensive attention due to their direct impacts as natural hazards and their ease of identification. The Sahara Desert and the Sahel region are the primary dust emission areas in North Africa, with sandstorm events occurring most frequently in spring (Wang et al., 2011). Generally, the development of cyclones over the central Sahara, accompanied by anticyclones over the Atlantic Ocean and monsoon troughs in tropical regions, is responsible for large-scale continental dust storms in North Africa (Shao et al., 2010). Mediterranean cold-core cyclones and Sharav cyclones are the dominant synoptic drivers of North African dust outbreaks in the eastern Mediterranean (Bodenheimer et al., 2019). Besides closed low-pressure systems over the eastern Mediterranean, 500 hPa deep troughs extending into North Africa are also important synoptic circulation patterns associated with dust storms (Karami et al., 2024). Overall, dust activity is closely associated with synoptic-scale disturbances such as lows, troughs, cyclones, fronts, and low-level jets (Knippertz and Todd, 2012). These systems can enhance low-level convergence and upward motion, strengthen horizontal pressure gradients, and increase near-surface wind speeds, thereby favoring dust emission and vertical uplift (Kok et al., 2012; Al-Mutairi et al., 2023). Existing studies have extensively investigated the circulation patterns and mechanisms of North African dust storms, although not all of these events lead to eastward dust transport. Previous studies have shown that Saharan dust transport is governed by the pressure gradient between the North African high-pressure belt and the low-pressure belt over the southern Sahara. An additional gradient between



the Azores High and downstream low-pressure systems promotes the eastward transport of Northeast African dust toward Asia (Awad and Mashat, 2014). Although long-range dust transport is closely
80 related to the configuration of high and low pressure systems, such pressure patterns alone cannot fully characterize the circulation features governing eastward dust transport. Seasonal migration of the Intertropical Convergence Zone, associated precipitation patterns, low-level jet intensity, and the development of mid- to upper-tropospheric westerlies all play important roles in dust emission, uplift, and downstream transport (Washington and Todd, 2005; Engelstaedter et al., 2006). However, the
85 dominant factors governing the eastward transport of North African dust remain poorly understood. In particular, the synoptic circulation patterns associated with different dust transport scenarios have not been comprehensively considered.

Dust from North Africa can be distributed in the upper troposphere and carried eastward throughout the year, with its impacts on East Asia and the North Pacific receiving increasing attention
90 in recent years. From March to April, dust from North Africa and the Middle East can be transported eastward by the westerlies to East Asia, where it mixes with local East Asian dust (Sugimoto et al., 2019). Further research revealed that multi-source mixed dust transported to northwestern China shows clear differences between aged long-range transported dust and fresh local dust, with North African and Middle Eastern dust contributing up to 58% of the local aerosol loading (Zhou et al., 2024). The impact
95 of the dust transported from Africa extends beyond these regions. Previous studies of dust events in Hong Kong during 1996–2007 indicated that approximately 83% of these events were influenced by long-range transported Saharan dust (Lee et al., 2010). Source attribution for extreme spring dust events in Japan further suggests that North Africa and the Middle East are the dominant source regions (Tanaka et al., 2005). Some studies have examined the climatological characteristics and interannual
100 variability of eastward Saharan dust transport, estimating an annual Saharan dust flux of 33.05 Tg to East Asia. They further suggest that approximately 24.3% of dust events in East Asia may be associated with Saharan dust (Liu et al., 2022). Based on both case observations and simulations, these studies have described the transport processes and climatological characteristics of eastward transported dust in terms of its temporal evolution and spatial extent. However, specific and quantitative assessments of
105 the environmental impacts of North African dust transport to East Asia remain limited. Moreover, the affected regions and magnitude of these impacts warrant further investigation.

Given these knowledge gaps, this study aims to investigate the corresponding synoptic circulation patterns and downstream environmental impacts along three eastward transport pathways of North African dust based on reanalysis datasets, and lidar observations. In Section 2, the data and methods
110 employed in this study are described in detail. The long-term statistics and representative case studies of the eastward transport of North African dust are presented in Section 3. Section 4 discusses the dominant synoptic circulation patterns associated with eastward North African dust transport, their differences, and the associated downstream environmental impacts. Finally, Section 5 summarizes the main findings and presents the conclusion of this study.

115 2. Data and methods

2.1 Study area



North Africa hosts the Sahara, the world's largest hot desert, which covers more than a quarter of Africa and has expanded notably in the past (Thomas and Nigam, 2018), providing an abundant source of dust. The region is highly vulnerable to climate change and characterized by scarce water resources. The emission of Saharan dust is associated with different weather systems and mechanisms. Over the past four decades, the average annual temperature has increased at a rate of 0.36 °C per decade (Hadjinicolaou et al., 2023). The increase in surface air temperature, accompanied by enhanced atmospheric instability, is likely to generate more dust (Zhou et al., 2023b). The Saharan heat low, which is widely distributed in North Africa, is associated with 55% of dust emissions in terms of the spatial mean (Fiedler et al., 2014; Wang et al., 2017). The northward shift of the convective region in North Africa during summer and its eastward shift in winter, along with changes in the position and intensity of the subtropical highs, regulate dust loading over North Africa (Francis and Fonseca, 2024). In addition to climatological changes and large-scale weather systems, the breakdown of the nocturnal low-level jet and cold pool outflows from deep convection are primary mesoscale meteorological drivers of dust events (Harrison et al., 2019). The combined effects of these factors favor frequent dust activity over North Africa during spring and summer, enabling dust lifted into the middle and upper troposphere to be transported eastward.

2.2 Reanalysis data

The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) is a global reanalysis dataset produced by the Global Modeling and Assimilation Office (GMAO) of NASA. Building upon the MERRA dataset, MERRA-2 incorporates the Goddard Chemistry, Aerosol, Radiation, and Transport model (GOCART) online into the Goddard Earth Observing System Model, Version 5 (GEOS-5) modeling system (Molod et al., 2015). Additionally, it assimilates bias-corrected aerosol optical depth (AOD) from AVHRR and MODIS, MISR AOD over bright surfaces, and AERONET AOD (Gelaro et al., 2017). MERRA-2 contains more than 40 years of global meteorological data spanning 1980 to the present, with spatial resolutions of 0.625° longitude and 0.5° latitude. The variables are provided on the native vertical grid (at 72 model layers or 73 boundaries), or interpolated to 42 standard pressure levels. Depending on the dataset, the temporal resolution typically ranges from 1 to 3 h. In MERRA-2, dust aerosols are represented by five bins, with corresponding dry effective radii of 0.73, 1.4, 2.4, 4.5 and 8 μm, respectively.

Data used in this study, including the dust aerosol optical depth (DAOD), dust mixing ratio (DMR), temperature, wind direction and wind speed, were derived from MERRA-2. To better demonstrate the dust transport process, DMR was converted into dust mass concentration (DMC) (Song et al., 2024), and the dust flux rate (DFR) (Han et al., 2022; Ying et al., 2022) was calculated:

$$m_d(z) = \alpha_d(z) \frac{P}{RT} \quad (1)$$

$$R_U = \int_{z_1}^{z_2} m_d(z) U(z) dz \quad (2)$$

$$R_V = \int_{z_1}^{z_2} m_d(z) V(z) dz \quad (3)$$

where, α_d is DMR at altitude z ($\text{kg} \times \text{kg}^{-1}$), P and T are pressure (hPa) and temperature (K), respectively, R is the specific gas constant ($287.058 \text{ J} \times \text{kg}^{-1} \times \text{K}^{-1}$), m_d is DMC at altitude z ($\text{kg} \times \text{m}^{-3}$), U and V



155 ($\text{m}\times\text{s}^{-1}$) represent the zonal and meridional wind speed at altitude z , respectively, R_U and R_V
 ($\text{kg}\times\text{m}^{-1}\times\text{s}^{-1}$) denote the zonal and meridional DFRs, respectively, with positive values representing
 eastward and northward transport and vice versa. Meanwhile, dust mass was calculated from the
 eastward dust flux at 3–10 km along the cross section from 3.5°N , 48°E to 53°N , 10°E , to minimize the
 influence of dust from the Middle East and other source regions and to estimate dust with potential for
 160 eastward transport.

The ERA5 atmospheric reanalysis data is the fifth-generation reanalysis product launched by the
 European Centre for Medium-Range Weather Forecasts (ECMWF). It can provide stratified and surface
 data spanning 1940 to the present (Bell et al., 2021). The ERA5 pressure-level data product has a
 spatial resolution of $0.25^\circ\times 0.25^\circ$ and provides hourly data at standard pressure levels. Compared with
 165 its predecessor, ERA-Interim, ERA5 has been greatly improved in terms of spatiotemporal resolution
 and assimilation methods (Hersbach et al., 2020). The temperature, geopotential, and horizontal wind
 direction and speed of ERA5 are used in this study to characterize atmospheric circulation types. The
 temperature is further converted to potential temperature.

2.3 Observational data

170 Multiple lidar datasets were employed to support the identification of eastward transported dust
 cases and the analysis of dust geometric and optical properties. These include observations from the
 Barcelona station (41.386°N , 2.117°E , 125 m ASL) and SEDE_BOKER station (30.855°N , 34.782°E ,
 480 m ASL) (Welton et al., 2000) in MPLNET, the Sainshand station of Mongolia in AD-Net (47.92°N ,
 106.90°E , 1320 m ASL) (Sugimoto et al., 2015), and the Dunhuang station (40.1°N , 94.6°E , 1085 m
 175 ASL) and Yunnan University station (24.83°N , 102.85°E , 1920 m ASL) of China. The 532 nm
 attenuated backscatter coefficient and volume depolarization ratio from these observations were used to
 identify dust layers. In addition, the Vertical Feature Mask derived from Cloud-Aerosol Lidar and
 Infrared Pathfinder Satellite Observations (CALIPSO) was applied to assist in the dust identification
 and classification of dust in this study (Winker et al., 2009). The particle depolarization ratio and color
 180 ratio retrieved from the Level 2 5-km Aerosol Layer product, combined with HYSPLIT trajectories,
 were adopted to screen mid- and upper-level dust aerosols and verify the evolutionary characteristics of
 dust physical properties.

In this study, PM_{10} and $\text{PM}_{2.5}$ data were obtained from the China National Environmental
 Monitoring Centre and used to evaluate the impact of eastward transported dust on air quality in China.
 185 As this study targets dust deposition from distant sources, urban areas with PM_{10} concentrations
 exceeding $500\ \mu\text{g}\text{m}^{-3}$ were considered to be substantially affected by local or nearby dust sources,
 following the criteria of a previous study (Zhou et al., 2023a). To exclude such interference,
 observations during each study period, as well as those from one day before and after each event, were
 excluded from the research scope. Combined with HYSPLIT simulation results, the periods influenced
 190 by North African dust over East Asia were determined based on the screened eastward dust transport
 cases. The monthly background concentrations averaged over the past three years were subtracted from
 the original PM_{10} and $\text{PM}_{2.5}$ concentrations to obtain anomaly disturbances for impact assessment.



2.4 HYSPLIT trajectory model

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT), developed by the Air Resources Laboratory (ARL) of the National Oceanic and Atmospheric Administration (NOAA), is one of the most widely used models for atmospheric trajectory and dispersion calculations. The model combines the Lagrangian and Eulerian approaches (Stein et al., 2015). HYSPLIT model supports various simulations related to the atmospheric transport and dispersion of pollutants or harmful substances, including radioactive materials, volcanic ash, wildfire smoke, and dust, as well as the deposition of these substances on the Earth's surface (Rolph et al., 2017). In this study, the HYSPLIT model was used to simulate the forward trajectories of dust plumes, and backward trajectory analysis was further employed to verify the lidar observations.

3. Results and discussion

3.1 Spatiotemporal evolution of dust over the dust belt

Monthly changes in the spatial distribution of dust aerosol optical depth (DAOD) over the dust belt from 2006 to 2023 are shown in Fig. 1. Here, the DAOD over Africa was mainly examined. In winter, the regions with high DAOD were primarily located in Nigeria and its adjacent regions. With the onset of spring, these areas gradually shifted toward Niger. By May, they expanded to cover Mali, southern Algeria, and the Bodélé Depression in Chad. During summer and autumn, the regions with high DAOD were relatively stable and were primarily located in the western part of the Sahel. Overall, regions with high DAOD shifted markedly northward with the seasons and corresponded well with previously identified dust emission sources (Evan et al., 2015; Mokhtari et al., 2015). The westward shift of regions with enhanced DAOD from spring to summer may be related to the Saharan heat low and transport of dust toward the Americas during summer (Meng et al., 2017; Wang et al., 2017). In terms of DAOD magnitude, the multi-year monthly average DAOD in the major dust source regions and dust active areas of North Africa and the Middle East remained consistently above 0.4 throughout the year. During the period of frequent dust events from February to August, DAOD can exceed 0.8. Although dust emissions in North Africa peak in summers, dust activities are present in North Africa almost throughout the year (Chappell et al., 2023).

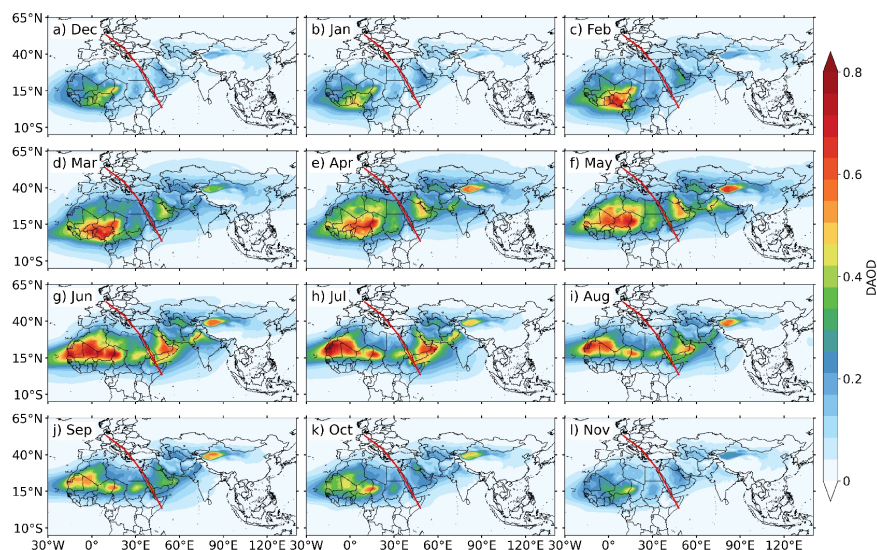


Fig. 1. The multi-year monthly mean climatology of dust aerosol optical depth (DAOD) derived from MERRA-2 for 2006–2023. The red line indicates the vertical profile path shown in Fig. 3.

Given the typically high altitude of intercontinental dust transport, the dust distribution at 500 hPa can partly reflect dust transport patterns. Here, the DMR at 500 hPa was selected to represent the transport characteristics of dust (Fig. 2). Some differences in dust distribution in the middle and upper troposphere were observed. In autumn and winter, the DMR over Africa was extremely low and its spatial extent was much smaller than that of DAOD. This suggests that effective long-range transport is constrained by circulation, uplift, and transport conditions despite ongoing dust activity over North Africa. During spring and summer, particularly from May to August, elevated DMR was increasingly widespread and pronounced. Geographically, the regions characterized by elevated DMR gradually shifted from the southern Sahara Desert towards Western Sahara, coinciding with the westward transport of Saharan dust toward the Americas (Gläser et al., 2015). Meanwhile, elevated DMR over the Middle East also shifted southward, a pattern closely associated with regional dust emission and transport processes (Jin et al., 2018), and the emission and transport of African dust towards the Arabian Sea (Kalenderski and Stenchikov, 2016). The Northern Hemisphere dust belt stretching from the Mediterranean region to the mid- to high latitudes of East Asia is clearly discernible. DMR indicates stronger mid- and upper- tropospheric dust activity over North Africa in spring and summer than in autumn and winter, consistent with the DAOD derived seasonal variability in dust emission and transport. However its spatial distribution differs slightly from the dust activity pattern at 500 hPa. Combined with the 500 hPa wind field, these results indicate that the westerly belt is displaced southward in winter, affecting regions north of 20°N, and its intensity reaches the annual maximum. In spring, the westerly belt gradually shifted northward and was split by the high topography of western and eastern Asia. In summer, the westerly belt further shifted northward, beyond 40°N, while the westerlies at middle and high latitudes weakened markedly. In autumn, the westerly belt shifted southward again and gradually strengthened. Variations in the wind field generally correspond to



differences in dust distribution.

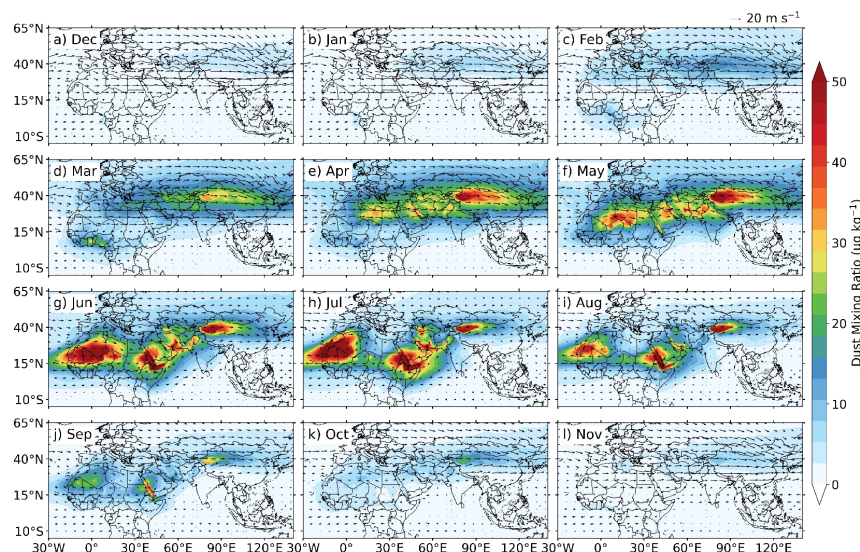


Fig. 2. The multi-year monthly mean climatology of dust mixing ratio (DMR) and wind speed and direction at 500hPa derived from MERRA-2 for 2006–2023.

Based on the horizontal distribution of dust, within an same period, a region defined by coordinates ranging from 3.5°N, 48°E to 53°N, 10°E was selected (Fig. 1). This region starts from Germany, spans across Europe, the Mediterranean Sea, and the Red Sea, and terminates at Somalia. The purpose was to illustrate the monthly average vertical distribution characteristics and transport dynamics of dust. In Fig. 3a1–a12, the vertical distribution of DMR was mainly confined to 10°N–34°N, and its seasonal variation was generally consistent with the horizontal distribution. From winter to spring, both the dust concentration and its vertical extent gradually increased, reaching their maxima in summer, and then decreased rapidly in autumn, with the weakest intensity and narrowest spatial extent occurring in November. In contrast, the horizontal extent of dust influence was highest in spring. The center of dust plumes in summer was located slightly farther south than in other seasons, possibly reflecting the influence of dust activity over the Red Sea and the Middle East, as well as the seasonal northward migration of the Intertropical Convergence Zone and its modulation of near-surface winds (Doherty et al., 2014).

DFR effectively characterizes dust transport. Its U and V components indicate that the region affected by eastward transported dust was displaced northward relative to the DMR distribution (Fig. 3a1–a12) and exhibited distinct temporal variability. In winter, particularly from December to January (Fig. 3b1–b3, c1–c3), eastward dust transport was very weak, with only a slight northeastward dust transport occurring in February. In spring (Fig. 3b4–b6, c4–c6), strong northeastward dust transport flux occurred at altitudes of 2–7 km between 25°N and 40°N. From March to May, the intensity of eastward dust transport changed only slightly, and most eastward transported dust trajectories were concentrated in the vicinity of the region spanning from the northern Red Sea to the southeastern



Mediterranean. However, the intensity of northward transport gradually decreased, with its latitudinal position shifting southward. In summer, when dust activity was most frequent, eastward dust transport was significantly weakened, while a northward dust transport channel appeared at altitudes of 4–6 km near 25°N (Fig. 3b7–b9, c7–c9). Meanwhile, strong southwestward dust transport from the Middle East occurred within 10°N–20°N. Southward transport extended up to 6 km, with eastward transport below 4 km and westward transport at 4–6 km. This suggests strong dust transport from the Middle East toward southern North Africa under the influence of the trade winds. In autumn, the low-latitude southwestward dust transport gradually weakened and disappeared (Fig. 3b10–b12, c10–c12). Eastward transport near 25°N was also very weak, and the corresponding northward transport weakened and eventually vanished. These results are generally consistent with previous findings on the frequency of Saharan dust events affecting East Asia (Liu et al., 2022). Saharan dust influence in winter is reported to be only slightly less frequent than in spring; weaker winter dust emissions may explain the lower overall intensity of eastward transport. In terms of the amount of eastward transported North African dust, the dust mass with potential for eastward transport showed pronounced seasonal variability, increasing from winter to spring and then gradually decreasing thereafter. On the monthly scale, the dust mass reached its minimum in December at 0.92 Tg and peaked in April at 11.03 Tg. On the seasonal scale, the corresponding dust masses in winter, spring, summer, and autumn were 6.12, 29.56, 11.47, and 5.32 Tg, respectively. Spring accounted for approximately 56.3% of the annual total, making it the dominant season for eastward North African dust transport, while February–July contributed 82.3% of the annual eastward transported dust.

Driven by the seasonal migration of solar heating, the mid-latitude 500 hPa westerly belt in the Northern Hemisphere generally shifts poleward in summer. In contrast, during winter and spring, the westerly belt shifts equatorward, allowing 500 hPa troughs to penetrate more readily into the Mediterranean and North Africa, thereby enhancing surface low-pressure development, cold frontal activity, and finally associated dust processes. The seasonal north-south migration of intertropical convergence zone and wind belts positions the mid- to upper-level westerly circulation near the source regions during winter and spring (Schneider et al., 2014). This circulation pattern facilitates the long-range transport of dust. The northward movement of the Northeast Trade Winds in summer increases dust emissions from the Sahara and facilitates the westward transport of dust (Engelstaedter and Washington, 2007). Overall, the distributions of dust and dust transport flux indicate that February to July is the primary period for the eastward transport of North African dust. Dust concentration and eastward transport flux are not fully synchronized in time. The more frequent eastward dust transport in spring is mainly attributed to the favorable alignment between the westerly belt and North African dust source regions, while seasonal shifts in the wind belts lead to distinct transitions in dust transport pathways. In summer, stronger dust activity is accompanied by trade winds that favor westward dust transport. Dust transport pathways over North Africa exhibit strong seasonal variability, while eastward dust transport is mainly regulated by spring dust activity and the westerly belt.

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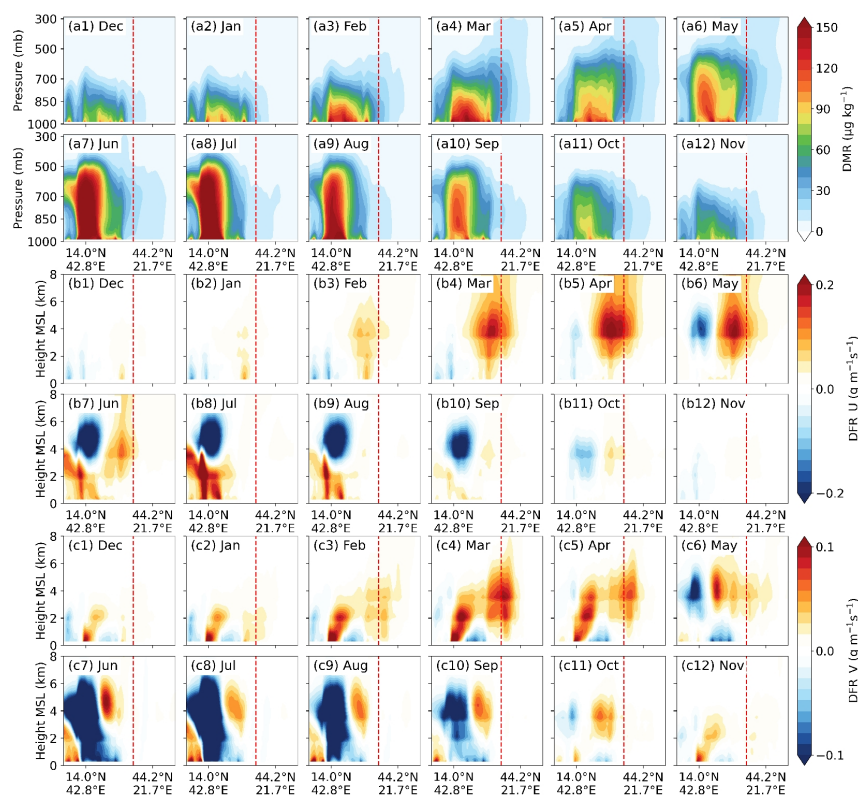


Fig. 3. Monthly mean vertical distribution of dust mixing ratio (DMR; a1–a12) and zonal (DFR_U) (b1–b12) and meridional (DFR_V) (c1–c12) components of dust flux rate (DFR) derived from MERRA-2 for 2006–2023. Regarding DFR, positive values indicate eastward or northward transport, and negative values indicate westward or southward transport. The red dotted line indicates the boundary between the Mediterranean Sea and Europe.

3.2 Cases of different long-range transport pathways

Considering the distribution of DMR at 500 hPa over the period from 2006 to 2023, three non-consecutive yet highly representative dust transport cases with unique transport pathways and potentially distinct synoptic characteristics were selected for in-depth analysis. Based on previous studies (Huang et al., 2025), this study selected a representative North African dust transport event from March 18 to 22, 2022, whose pathway is consistent with the Northern Hemisphere dust belt, as a case of the middle transport pathway. To compare the circulation characteristics and differences under distinct transport conditions, two additional eastward transport events with the northernmost and southernmost trajectories were selected as the northern and southern pathway cases, occurring from 6 to February 10, 2021 and from March 20 to 24, 2019, respectively (Fig. 4). The three cases showed clear differences in dust activity intensity and transport scale. The extreme dust event in the middle pathway case produced approximately 6.38 Tg of dust with potential for eastward transport, whereas the northern pathway case produced only 1.43 Tg. In the southern pathway case, continuous dust emissions contributed to a cumulative transported dust mass of 2.89 Tg. The dust source regions of the cases were kept as close as possible to minimize the influence of other factors. This study compares the



initial synoptic conditions of transport pathways to identify their similarities, differences, and possible causes. The subsequent circulation evolution over Central and East Asia, after pronounced downstream transport has been established, is beyond the scope of this discussion.

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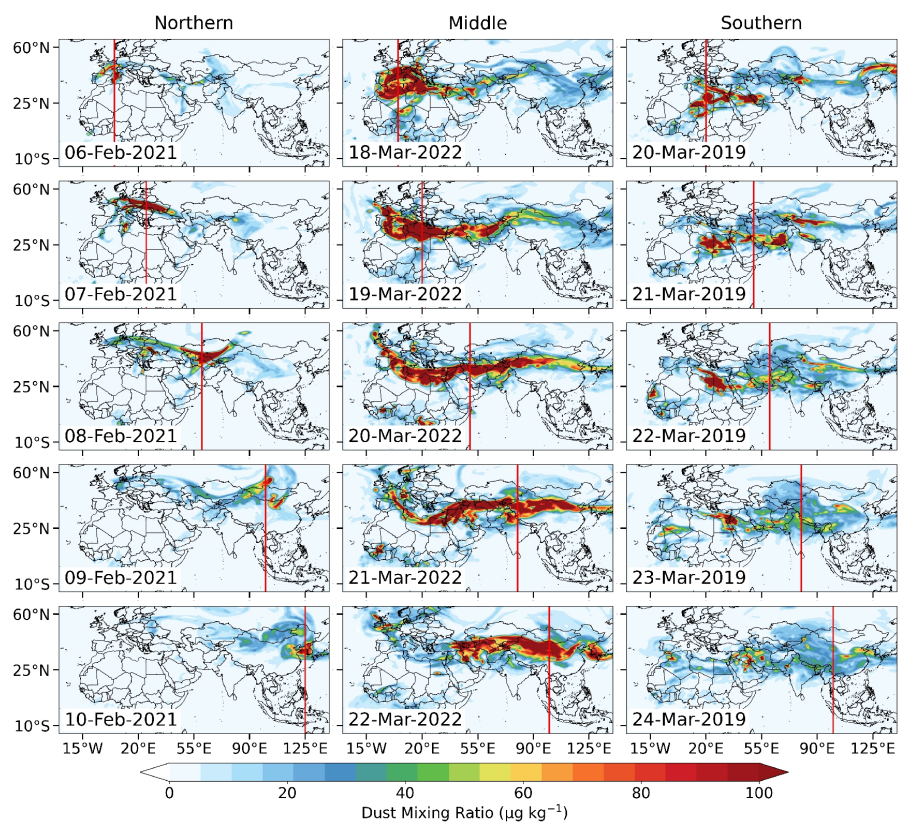
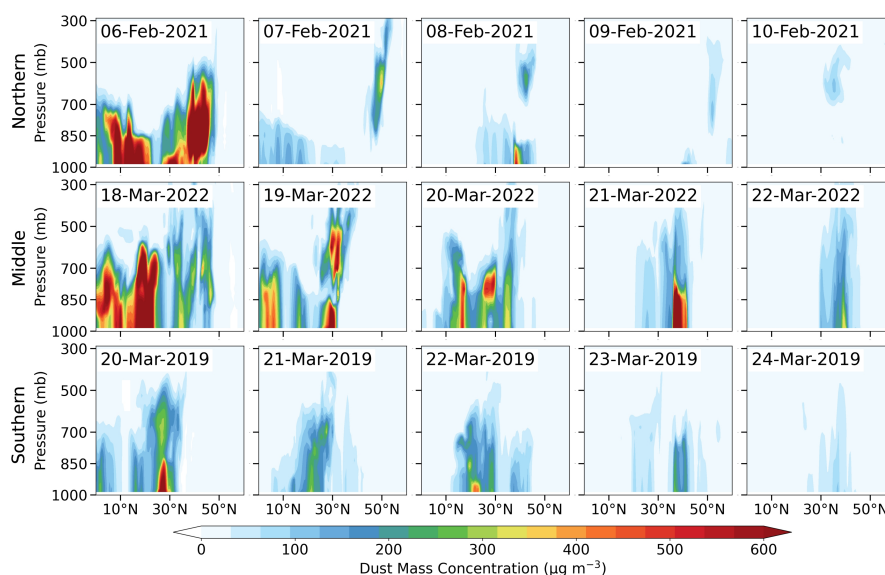


Fig. 4. The spatial distribution of dust mixing ratio (DMR) at 500 hPa for three dust transport cases derived from MERRA-2. The red line indicates the location of the cross-section shown in Fig. 5.



340 **Fig. 5. Zonal cross-sections of the three dust transport cases derived from MERRA-2.**

3.2.1 Northern pathway: February 6–12, 2021

In recent winters and springs extreme North African dust transport events to Europe have been observed, and their impacts on air quality and environmental conditions have been comprehensively documented using multiple approaches (Rodríguez and López-Darias, 2024; Xu-Yang et al., 2025).
 345 However, through case-based research, this study reveals that these events may have an impact extending beyond Europe and the western Mediterranean Basin. In some cases, North African dust reaching Europe is not fully deposited there but continues to be transported eastward, affecting East Asia and northern Asia and potentially reaching the Pacific Ocean. A dust storm event occurred over North Africa from February 6 to 12, 2021, during which the dust plume was initially transported
 350 northward to Europe and subsequently eastward toward East Asia. Figs. 4 and 5 illustrate the three-dimensional evolution of the dust-affected region during this case. The dust plume reached Europe on February 6, where it was mainly concentrated in the lower to middle troposphere, with dust concentrations exceeding $500 \mu\text{g m}^{-3}$. The plume shifted slightly southward and was transported southeastward to West Asia before turning northward again, thereby affecting northern East Asia and reaching the eastern coastal region of China on February 10. During transport, the dust plume was
 355 clearly evident near 500 hPa, while its concentration gradually decreased with time (Fig. 5), indicating that gravitational settling played a significant role during the transport process.

At 850 hPa (Fig. 6a–b), the Algerian source region is influenced by a trough to its north and is also located near the western flank of the warm high-geopotential region over North Africa. Therefore, a
 360 pronounced horizontal gradient in geopotential height and potential temperature was established between these two systems. This indicates a strong low-level baroclinic zone or frontal structure which favors the development of strong near surface winds. In addition, the relatively high potential temperature over the Sahel reflects a warm, dry, and thermally unstable lower tropospheric

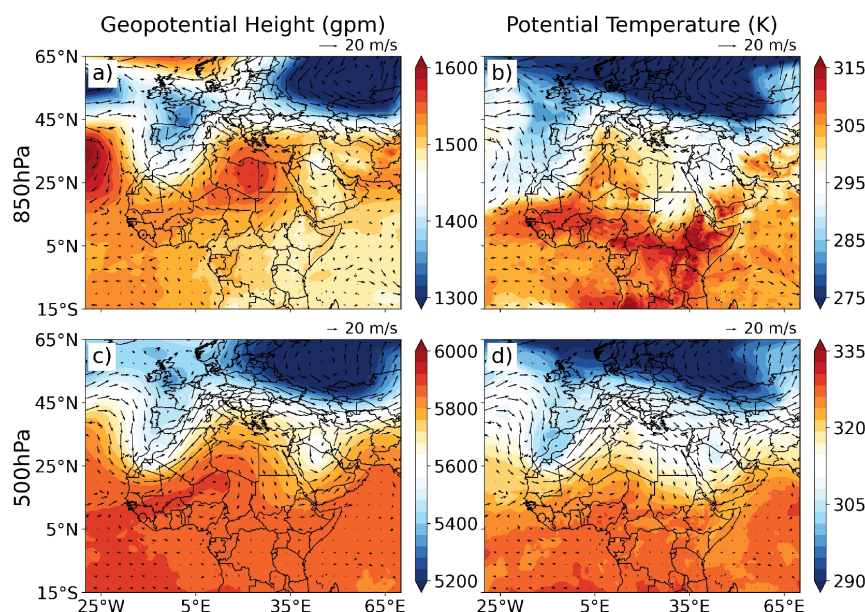


environment, which generally favors boundary layer development and enhanced turbulent mixing, thereby facilitating the upward transport of dust emitted near the surface. As shown in Fig. 6c–d, the circulation at 500 hPa was characterized by a “two trough and one ridge” pattern. The Algerian source region was located ahead of the southward extending trough over the northeastern Atlantic and Iberian Peninsula sector and near the North African high-geopotential ridge. The associated southwesterly flow and dynamic lifting ahead of the trough favor the northward transport of low-level dust into the western Mediterranean and its subsequent injection into the free troposphere. The elevated geopotential height and potential temperature over North Africa indicate a warm, dry, and deep middle tropospheric thermal background. Meanwhile, the strong gradient between the eastern Mediterranean trough and the North African high-geopotential region enhances pre-trough ascent and dust uplift, thereby developing a favorable westerly transport pathway over the Mediterranean (Salvador et al., 2014). As depicted in Fig. 9f, North African dust was transported northward from approximately 2 km into the western Mediterranean by low-level southerly to southwesterly flow. It was subsequently lifted into the middle troposphere and embedded in the mid-latitude westerlies at approximately 4–5 km, enabling further transport toward inland Europe and downstream regions. Elevated potential temperature, strong surface heating, and a warm, dry boundary layer over the source region enhanced turbulent mixing, while stronger low-level winds promoted dust emission. The southerly to southwesterly flow along the western flank of the North African high-geopotential region and south of the trough provided a northward transport pathway. After entering the free troposphere near 500 hPa, the dust was advected eastward from Europe toward East Asia by the mid-latitude westerlies.

As shown in Fig. 9a, observations from the Barcelona site of MPLNET confirm a dust event over Spain on February 5–6. MERRA-2 and CALIPSO observations further indicate a North African origin. After impacting Europe, the dust plume transported eastward and was observed by the Sainshand site of AD-net in Mongolia (Fig. 9a, b). The depolarization ratio showed much more pronounced variation. Near the source area, a dust plume depolarization ratio of up to 0.34 was observed in Barcelona. However, aerosol plumes with strong backscatter intensity at approximately 3 km were observed over Mongolia on February 10. Their backward trajectory originated from North Africa, although their depolarization ratios were only slightly higher than 0.1. In this case, the particle depolarization ratio of dust decreased along the transport pathway from 0.32 over the source region to 0.26 over northeastern China (from CALIPSO), and the color ratio of dust layer also exhibited a similar overall decreasing trend. This indicates that dust aging intensified during transport, accompanied by a reduction in coarse dust particles and a possible decrease in the overall particle size. Previous studies have shown that the depolarization ratio of pure dust particles at 532 nm wavelength in the source region near the Sahara is 0.31 (Freudenthaler et al., 2009), while the depolarization ratio of dust reaching Central Europe can be as low as 0.1 to 0.25 due to the effects of mixing, sedimentation and aging during the dust transport process (Müller et al., 2003). During long-range transport, dust plumes are progressively diluted, particle concentrations decrease, and coarse particles are preferentially removed, resulting in weakened total backscatter intensity. The dust layer may also mix with dust from other source regions, which can further modify the optical properties of the plume. In addition, differences in lidar retrieval algorithms and instrumental characteristics among different stations may also affect the derived parameters. These



factors can substantially influence the volume depolarization ratio. By contrast, the particle
 405 depolarization ratio from CALIPSO is less affected by molecular scattering. Therefore, the observed
 differences between dust volume and particle depolarization ratios, as well as their deviations from
 previous studies, were considered reasonable.



410 **Fig. 6. Geopotential height (a, c) and potential temperature (b, d) at 850 hPa and 500 hPa at 12:00 (UTC) on February 6, 2021.**

3.2.2 Middle pathway: March 15–24, 2022

The dust event from March 15 to 24, 2022 followed the typical eastward transport pathway and represents a middle pathway case in this study. However, this event was characterized by a relatively
 415 long duration and high intensity (Fig. 4). Since March 15, dust emission and uplift persisted over the source region. The dust activity observed on March 18 suggests that cyclonic activity over the western Mediterranean substantially influenced dust evolution and transport pathways. Favorable synoptic conditions for dust emission and uplift lasted for several days, providing a continuous supply of transportable dust and resulting in an extensive dust transport belt. The dust concentrations at 700–500
 420 hPa in the middle case (Fig. 5) were higher than those observed in other cases. Although the plume mixed with dust from a Taklimakan Desert dust storm during downstream transport (Li et al., 2026), the North African dust could still be distinguished by its higher altitude distribution.

As shown in Fig. 7a–b, at 850 hPa, western and central Europe were dominated by high geopotential height, while relatively high potential temperature persisted over the lower latitudes of
 425 North Africa. These features resulted in a pronounced meridional thermal gradient over southern Europe and the Mediterranean. Although the high geopotential system over Europe is mainly characterized by stable subsidence, its southern flank can enhance the horizontal thermal and pressure



gradients and strengthen the low-level wind field near the Mediterranean, thereby favoring the dust transport toward the Mediterranean along the southern edge of the high pressure system. At 500 hPa (Fig. 7c–d), the mid-latitude circulation was influenced by the ridge over North Africa and the western Mediterranean, as well as by shallow troughs on both sides, although the variation in the westerly flow was relatively weak. A region of high geopotential height persisted from western Europe to central Europe, and the troughs on its two flanks produced a local saddle pattern with weak gradients. This ridge of high geopotential height partly blocked and split the mid-latitude westerlies, allowing the westerly flow to extend toward the Mediterranean and the northern margin of North Africa. Cold air advection over eastern Europe promoted the development of a trough, guided the westerlies toward lower latitudes, and further caused a local northward deflection of the dust transport pathway behind the trough. The mechanism was similar to the promoting effect of the Mediterranean low pressure on the transport of North African dust to the Middle East, as previously reported by (Karami et al., 2024). As indicated by air trajectory (Fig. 9f), after emission, the dust did not move directly eastward but underwent rotational uplift and development under the influence of low pressure system or trough near the northern side of the source region. After entering the westerly flow near 500 hPa and the transport pathway south of the downstream trough, the dust was transported eastward on a large scale along the mid-latitude westerly belt at altitudes above 8 km.

As shown in Fig. 9c, the dust was lifted and transported to the eastern Mediterranean. Observations from the SEDE_BOKER station in the southeastern Mediterranean indicated that the dust was mainly distributed at altitudes of 2–6 km, with some portions reaching up to 9 km, and the volume depolarization ratio reached up to 0.3. In contrast, eastward-transported dust in the middle and upper troposphere was observed at approximately 5–8 km at the Dunhuang site in China (Fig. 9d), with some dust plumes extending up to 9–10 km. Compared with several days earlier, the depolarization ratio had decreased substantially, with the lidar volume depolarization ratio reaching 0.2 and the CALIPSO particle depolarization ratio reaching 0.19.

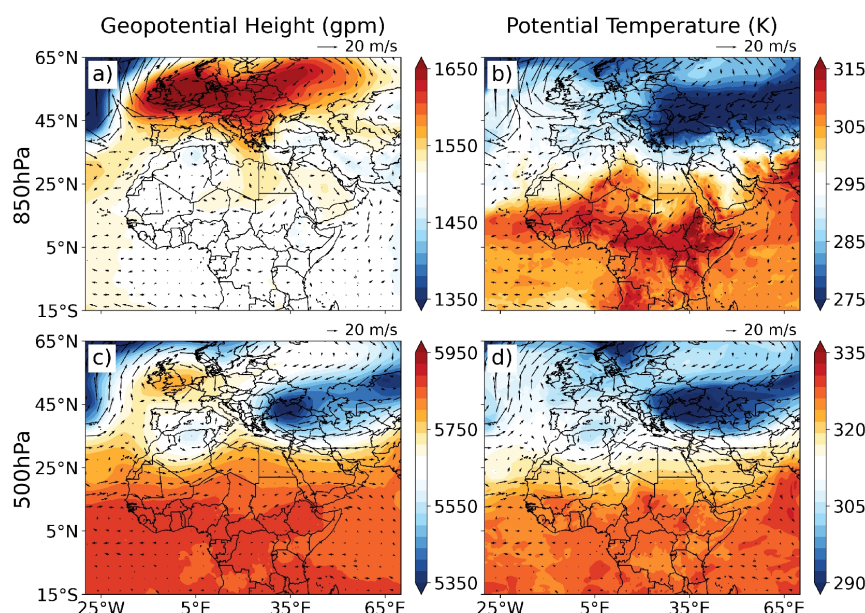


Fig. 7. Geopotential height (a, c) and potential temperature (b, d) at 850 hPa and 500 hPa at 12:00 (UTC) on March 18, 2022.

3.2.3 Southern pathway: March 18–25, 2019

Previous studies have generally divided eastward dust transport into two branches: dust from North Africa and the Middle East is either transported northward to East Asia or settles south of the Himalayas under the topographical influence of the Tibetan Plateau (Lau and Kim, 2006). Some cases have demonstrated that the dust can continue to be transported eastward, affecting southern China and even Hong Kong (Lee et al., 2010). Because this transport pathway is uncommon, the March 18–25, 2019 case shown in Fig. 4 was selected to examine the associated synoptic characteristics. This case was characterized by intermittent dust plume transport, with the broadest meridional extent among the three cases after the plume entered Asia. Compared with the other cases, dust concentration near 500 hPa was markedly lower (Fig. 5). After the dust was transported south of the Tibetan Plateau, its concentration decreased sharply as the transport range expanded. Part of the dust was transported to India, while the topographical influence of the Himalayas largely prevented further large-scale dust transport (Prasad and Singh, 2007). Only a fraction of the dust at high altitudes could continue eastward, which may explain the limited number of reported cases of this type of transport.

From the perspective of circulation patterns, at 850 hPa (Fig. 8a–b), the high-geopotential-height region over northern Africa was not pronounced. Instead, the region was primarily controlled by the high geopotential system over western Europe and the warm region over North Africa, indicating a warm and dry lower troposphere and strong thermal mixing within the boundary layer. The high-geopotential-height region near the northeastern Atlantic and western Europe may be associated with the northeastward extension of the Azores High ridge. This configuration favors enhanced low-level winds and dust emission, but limits the further poleward dispersion of dust, causing dust



activity to be more confined to the southern side of the Mediterranean. At 500 hPa (Fig. 8c–d), no pronounced geopotential height difference was observed over North Africa. The southward extension of the cold trough over Europe strengthened the westerly belt over North Africa in the middle and lower latitudes to some extent, but its position showed no substantial change. Compared with the previous two cases, the westerly belt was located slightly farther south, with a relatively uniform airflow field between 15°N and 30°N. This pattern allowed dust to be transported eastward along lower latitudes. Therefore, after dust over the Sahara was emitted and lifted, the high geopotential ridge promoted its transport mainly by enhancing the thermal and pressure gradients and the low-level wind field along its southern flank. As a result, the dust was transported along the peripheral flow of the low-level cyclone and reached 30°N on March 20 (Fig. 9f). In contrast, the mid-level cold trough over Europe influenced the transport pathway by shifting the westerly belt southward. Under the influence of the Himalayas, the dust plume then descended in altitude and was diverted southward, before being transported to southern China.

The southern transport case was supported by lidar observations from Yunnan, China (Fig. 9e). The dust layer was located only 3–4 km above the ground, with a lidar volume depolarization ratio of 0.13 and the CALIPSO particle depolarization ratio of 0.17, both lower than those observed in the other cases. Influenced by the Intertropical Convergence Zone, variations in wind belts, and seasonal factors, low-latitude dust was rarely lifted extensively into the middle and upper troposphere and transported along an eastward pathway. In reality, most North African dust is transported toward the Indian Ocean or the Arabian Peninsula, and seldom crosses mountains and plateaus to affect southern China. Therefore, the southern transport pathway is relatively rare.

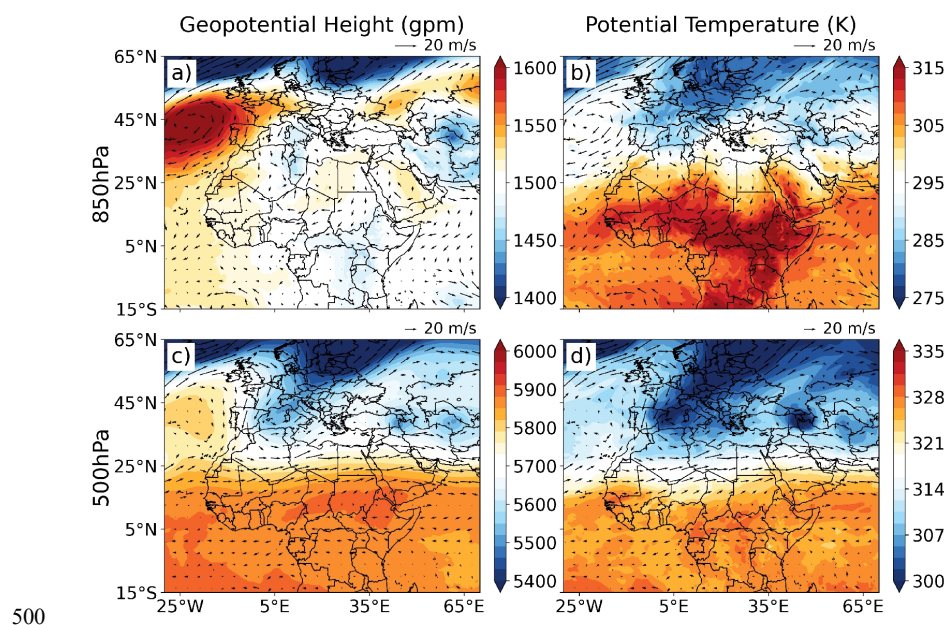
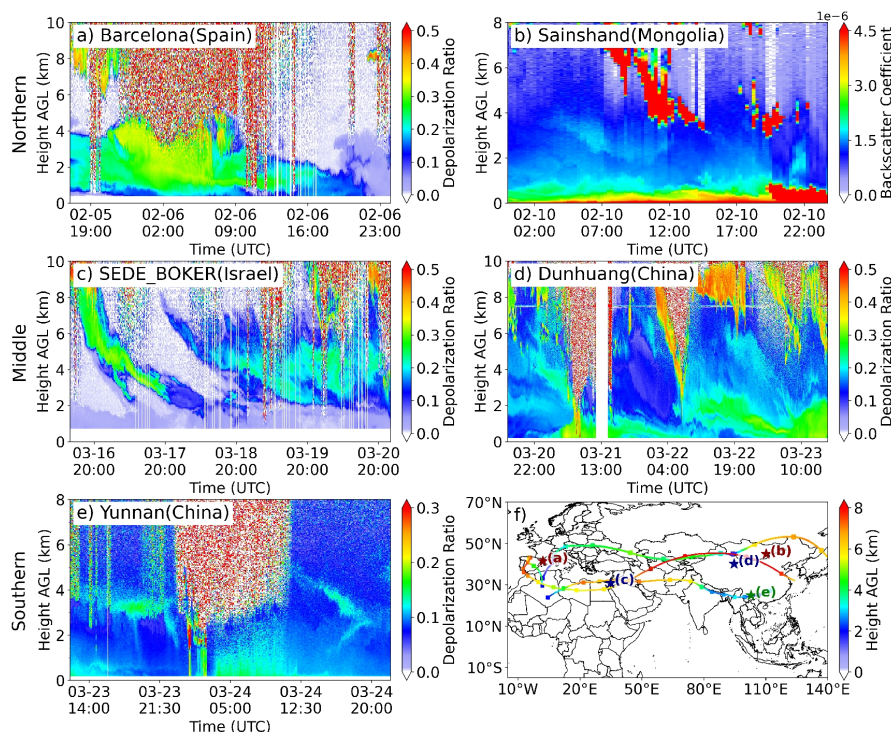


Fig. 8. Geopotential height (a, c) and potential temperature (b, d) at 850 hPa and 500 hPa at 12:00 (UTC) on March 19, 2019.



505 **Fig. 9.** Time-height cross-section of dust transport processes along the pathways at selected sites: (a) Barcelona, Spain; (b) Sainshand, Mongolia; (c) SEDE_BOKER, Israel; (d) Dunhuang, China; and (e) Yunnan, China. Station locations are denoted by pentagrams in (f), among which red, blue and green sites correspond to the northern, middle and southern pathway cases, respectively. The forward trajectories in (f) are simulated using the HYSPLIT model for the three cases.

510 **4. Synoptic Patterns and Air Quality Impacts**

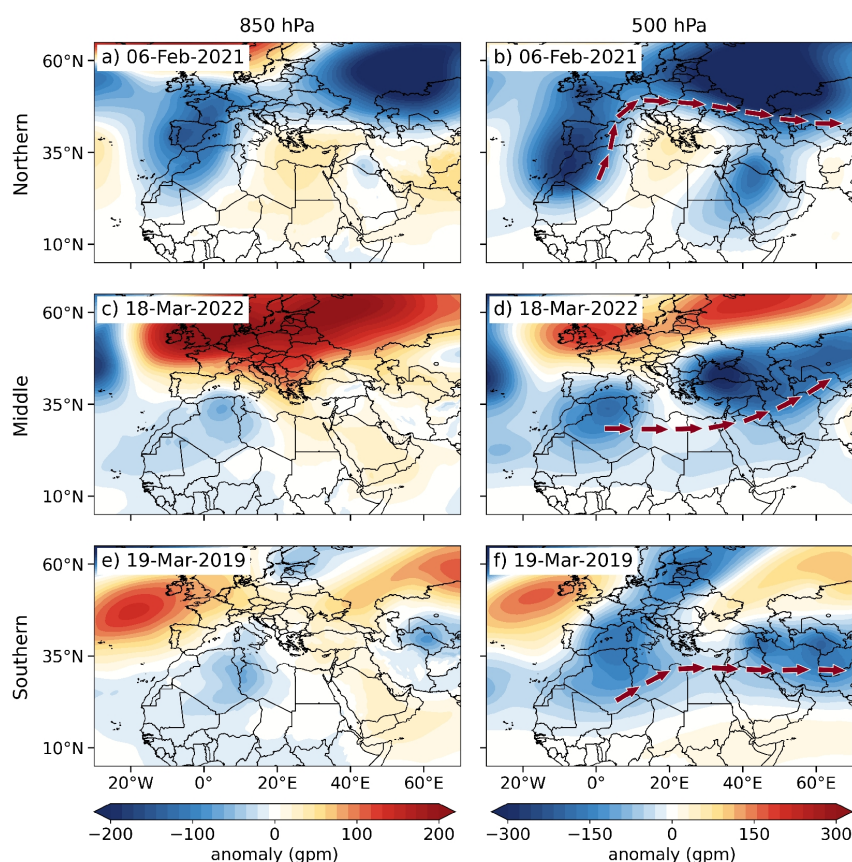


Fig. 10. Geopotential height anomalies for the three dust transport cases relative to the 1994–2023 multi-year climatological mean. Panels (a–b), (c–d), and (e–f) represent the northern, middle, and southern pathway cases, respectively, at 850 and 500 hPa. The red arrows indicate the dust transport pathway.

Based on the transport pathways and synoptic characteristics of the three cases, their circulation patterns were compared with the multi-year climatology, to identify the associated circulation anomalies. The emission and uplift of dust are modulated by weather systems operating at various scales within the near-surface layer, whereas the transport process is predominantly governed by the westerlies in the middle and upper troposphere. In the northern pathway case (Fig. 10a), negative anomalies at 850 hPa were present from North Africa to western Europe and over Siberia, while a positive anomaly appeared over the Mediterranean region. In contrast, pronounced negative geopotential height anomalies were observed at 500 hPa with a broader spatial extent (Fig. 10b). A slightly negative anomaly was also evident over the Middle East (Fig. 10b). Compared with 850 hPa, the negative anomaly gradient at 500 hPa was stronger, whereas the positive anomaly was relatively weaker. A pronounced negative anomaly at 500 hPa was observed, with its spatial distribution corresponding to the trough and low-pressure system in this case. This abnormal distribution facilitated the transport of dust to high latitudes through atmospheric rivers (Francis et al., 2022). The periphery of this negative anomaly coincided with the dust transport pathway. In the middle pathway case, a



prominent positive anomaly was observed across Europe at 850 hPa (Fig. 10c), which was associated
 530 with the cold high-pressure system resulting from the accumulation of cold air. At 500 hPa, western
 Europe and Siberia exhibited positive anomalies, while northwestern Africa and Western Asia
 displayed negative anomalies of comparable magnitude (Fig. 10d). Collectively, this configuration
 reveals two dipole patterns. In the southern pathway case, a pronounced positive geopotential height
 anomaly was observed at lower levels, whereas the negative anomaly was relatively weak (Fig. 10e).
 535 The positive anomaly was mainly located from the northeastern Atlantic to western Europe, with its
 center shifted northeastward relative to the typical Atlantic high pressure system. Meanwhile, the
 positive anomaly over northern Eurasia extended southwestward. At 500 hPa, the negative anomaly
 became markedly stronger and extended from Europe to northwestern Africa, where it connected with
 the negative anomaly over western Asia (Fig. 10f). Compared with the middle pathway case, this
 540 negative anomaly covered a wider area over North Africa and its downstream transport regions,
 particularly over western Asia and the Middle East. Its position was generally shifted southward,
 with the southern edge reaching approximately 25°N, broadly consistent with the latitude of dust transport
 along the southern pathway.

Overall, the three cases exhibited pronounced negative anomalies at 500 hPa over the
 545 Mediterranean and Europe, while the 850 hPa anomalies were relatively weak and only locally positive.
 This may be attributed to the combined effect of cyclonic and anticyclonic circulations and the increase
 in the temperature gradient with cold air at the upper level and warm air at the lower level. Moreover,
 the negative anomalies at 500 hPa all coincided with the dust transport pathway and the westerly belt.
 The differences in the dust transport along the westerly belt can be attributed to the influence of the
 550 synoptic system on the position of the westerly belt. The Mediterranean cyclone system, driven by the
 temperature contrast between the coastal areas of North Africa and the Mediterranean Sea, is generally
 considered an important mechanism contributing to regional dust transport (Flaounas et al., 2015).
 However, sufficiently intense troughs or low pressure systems extending southward into lower latitudes
 can strengthen the low-level wind field, induce upward motion, and modulate the position of the
 555 mid-level westerly belt. Their role in North African dust emission and long range transport should
 therefore not be overlooked. In addition, the case analysis suggests that European circulation
 configurations partly regulate the eastward transport of North African dust, and monitoring key
 circulation patterns may provide useful guidance for the early warning and forecasting of its
 downstream impacts.

560 Fig. 11 illustrates the environmental impacts of eastward transported North African dust on parts
 of China. Among three cases, the PM₁₀ anomaly exhibited the largest variation in the northern transport
 case, with maximum values of 236.1 $\mu\text{g m}^{-3}$ in Hebei (North China) and 245.8 $\mu\text{g m}^{-3}$ in Heilongjiang
 (Northeast China) on February 12, 2021. PM_{2.5} anomalies also remained relatively high during the
 same period. For the middle transport case, PM₁₀ showed almost no positive anomaly relative to the
 565 dust influenced background, whereas PM_{2.5} exhibited peak positive anomalies of 79.7 $\mu\text{g m}^{-3}$ in Henan
 (Central China) and 64.8 $\mu\text{g m}^{-3}$ in Shanxi (North China) on March 22, 2022. In the southern transport
 case, Yunnan (Southwest China), identified as an affected region confirmed by both observations and
 simulations, showed maximum PM₁₀ and PM_{2.5} anomalies of 77.1 $\mu\text{g m}^{-3}$ and 54.1 $\mu\text{g m}^{-3}$, respectively,



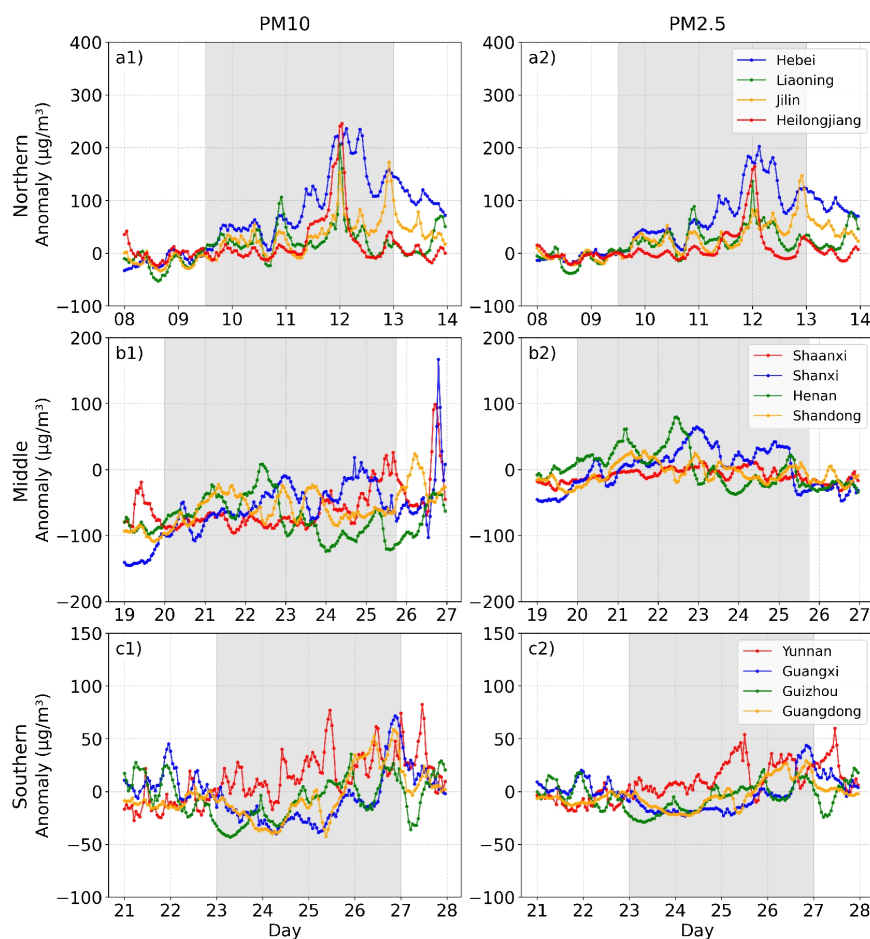
on March 25, 2019. The regions surrounding Yunnan, Guangxi also exhibited high positive anomalies
 570 on March 26, while the relatively low anomalies in Guangdong and Guizhou indicated a limited dust
 influence. A comparison of PM_{10} and $PM_{2.5}$ anomalies across the same cases indicated that $PM_{2.5}$
 anomalies were more pronounced than those typically observed during dust events. This indicates that
 the near surface environmental impact of eastward transported North African dust over East Asia
 mainly results from the deposition of fine particles from the elevated dust plume. In three cases, the
 575 dust plumes did not show pronounced intrusion into the planetary boundary layer. PM_{10} anomalies in
 three cases were much smaller than those induced by dust from East Asian sources (Pan et al., 2025).
 Even the large-scale extreme dust event like the middle transport case had a limited environmental
 impact because the dust was transported at exceptionally high altitudes. In contrast, the northern and
 southern transport cases exhibited greater environmental impacts despite lower dust loading and lower
 580 transport altitudes. Therefore, the altitude of long-range transported dust plumes is also an important
 influencing factor. Changes in $PM_{2.5}$ concentrations corresponded with dust transport events, indicating
 that fine particles play a dominant role in the downstream environmental impacts of eastward
 transported North African dust.

In recent years, China has made continued progress in air pollution prevention and control, with
 585 anthropogenic emissions from coal combustion, industrial activities, vehicle exhaust, and fugitive dust
 effectively reduced nationwide (Cheng et al., 2019; Geng et al., 2024). The environmental status
 reports released by the Ministry of Ecology and Environment of China indicate that the annual mean
 $PM_{2.5}$ concentration across 339 prefecture-level and above cities decreased by 28.6% cumulatively
 since the beginning of the 13th Five-Year Plan period, reaching $29.3 \mu g m^{-3}$ in 2024. The contribution of
 590 local anthropogenic emissions to particulate matter pollution has gradually declined, accompanied by
 substantial improvements in air quality (Cheng et al., 2021). Against this background, long-range
 transported dust may not substantially alter annual mean PM levels, but under specific springtime
 circulation conditions, its relative contribution may become more prominent, influencing regional PM
 anomalies, the vertical distribution of dust aerosols, and the regional radiation budget (Zhu et al., 2026).
 595 In particular, when North African dust is transported to China, its deposition and mixing with local
 pollutants may increase uncertainties in air quality assessment and forecasting. Therefore,
 strengthening monitoring and early warning of long-range transported dust during spring is essential
 for improving China's ability to identify and forecast cross-regional dust transport and its associated
 climatic and environmental impacts.

600 Despite these findings, this study has several limitations that should be acknowledged. The
 circulation pattern analysis was mainly based on three typical cases. Although these cases capture the
 differences among the northern, middle, and southern transport pathways, their representativeness
 requires validation using a large number of cases and long-term statistical analysis. In addition,
 eastward transported North African dust passes through multiple potential dust source regions, and
 605 reanalysis data, trajectory simulations, and observations alone make it difficult to accurately distinguish
 the contributions of dust from different sources. Furthermore, the assessment of environmental impacts
 is affected by local emissions, dust activity, and observational uncertainties; therefore, the observed PM
 anomalies cannot be fully attributed to North African dust. Future studies should combine source



attribution, model simulations, and additional observations to further quantify the transport of North
 610 African dust and its impacts over China.



615 **Fig. 11. PM10 and PM2.5 anomalies over China associated with North African dust transport processes. The anomaly background fields are defined as the averages of the monthly mean PM10 and PM2.5 concentrations for the event year and the preceding and following years. Shading indicates the potential influence period, from the entry of the dust plume into China to its deposition or departure from the region.**

5. Conclusion

In summary, this study investigated the spatial distribution of North African dust from 2006 to
 620 2023, as well as the circulation characteristics, regulating mechanisms, and downstream air quality
 impacts associated with its three long-range eastward transport pathways. The peak of North African
 dust emissions did not coincide with peak eastward transport, and the dust transport pathways exhibited
 pronounced seasonal variability. The southward displacement of the westerly belt in winter and spring
 favored dust uplift and its injection into the middle and upper tropospheric westerly circulation.



Therefore, February to July was the main period for eastward transport of North African dust, contributing 82.3% of the annual eastward transported dust. In addition spring was the most favorable season for long range transport toward East Asia, providing 29.56 Tg of dust with potential for eastward transport. Variations in North African dust transport toward East Asia among the three transport pathways were primarily regulated by the short term intensity and position of the westerly belt, which were influenced by large scale circulation systems such as cyclones and trough ridge systems. Specifically, in the northern pathway case, the strong pressure gradient between the North African high pressure system and the European low pressure system facilitated the northward transport of dust into the middle and high latitude westerlies. In the middle pathway case, cyclonic activity over the eastern Mediterranean resulted in the northeastward deflection of dust, developing a more common eastward transport pattern. In the southern pathway case, weather systems exerted weaker disturbances on the westerlies, while southwesterly flow guided the dust toward India and southern East Asia. Meanwhile, the northern Saharan dust source region was typically influenced by upper level troughs or high and low pressure systems. The guiding effect of pressure gradients and the uplift associated with low pressure systems were crucial for dust emission, uplift, and transport, indicating that strong cyclonic activity may be an important condition for widespread dust uplift and eastward transport. In addition, during eastward transport events of North African dust, variations in lidar depolarization ratios may be more pronounced than those observed during other types of dust events. However, when differences in environmental conditions are relatively small, the degree of dust aging may be less pronounced than that reported in previous studies. The near surface environmental impacts of eastward transported North African dust vary among transport pathways. Because of their lower transport altitudes, the northern and southern pathway cases produced more evident PM anomalies, including PM₁₀ maxima of 245.8 and 77.1 μgm^{-3} , respectively, whereas the higher altitude middle pathway case had a relatively limited near surface influence, with a weak PM₁₀ response but pronounced PM_{2.5} anomalies of up to 79.7 μgm^{-3} . Although long range transported dust in the middle and upper troposphere had a relatively small effect on the near surface environment, its regulatory role in various atmospheric processes should not be overlooked.

Finally, through an in-depth analysis of case characteristics across different transport pathways, this study provides new insights into the mechanisms and patterns of eastward dust transport. Circulation characteristics may provide a useful basis for predicting or classifying dust transport pathways. Because eastward transported North African dust passes through multiple dust source regions, reanalysis data alone make it difficult to accurately distinguish the contributions of dust from different source regions, which may affect the assessment of downstream environmental impacts. This study does not include long term numerical simulations but instead validates the transport processes based on observations. Future studies should integrate more advanced dust source attribution methods, additional representative transport cases, and high-resolution numerical simulations to further quantify eastward dust transport and its downstream impacts.

Data availability

The MERRA-2 reanalysis data are available from the NASA Earthdata at



665 <https://disc.gsfc.nasa.gov/datasets?project=MERRA-2>. The air quality data are sourced from the China
National Environmental Monitoring Centre at <https://www.cnemc.cn>. The ERA-5 reanalysis data can
be obtained from the ECMWF at
<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>. The CALIPSO
data are available from the NASA Earthdata at
<https://www.earthdata.nasa.gov/data/platforms/space-based-platforms/calipso>.
670 The HYSPLIT data are accessible through the NOAA at <https://www.arl.noaa.gov/hysplit/>. The
MPLNET data are available at <https://mplnet.gsfc.nasa.gov/links>. The AD-Net data are available at
<https://www.lidar.nies.go.jp/AD-Net/>.

Authors' contributions

DW and TZ conceived and designed the study. DW performed the data analysis, software development,
675 and wrote the original manuscript. TZ supervised the research, acquired funding, and contributed to
manuscript revision. XL, YG, and WF contributed to data processing, software development, and
manuscript revision. ZL, QG, and KZ contributed to methodology development and analysis. ZH
reviewed and edited the manuscript.

Declaration of competing interest

680 The authors declare that they have no known competing financial interests or personal relationships
that could have appeared to influence the work reported in this paper.

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970