The Circumglobal Transport of Massive African Dust and Its Impacts on the Regional Circulation in Remote Atmosphere

Hongru Bi, Siyu Chen, Daizhou Zhang, Yong Wang, Litai Kang, Khan Alam, Mingjin Tang, Yu Chen, Yue Zhang, and Danfeng Wang

ABSTRACT: Atmospheric dust from North Africa, the largest and most persistently active dust source over the world, spreads widely in the Northern Hemisphere and plays essential roles in the Earth environment evolution. During 7–24 June 2020, an extremely strong dust event occurred with its westward spreading modulated by the North Atlantic Oscillation (NAO) and its eastward spreading regulated by European blocking, ultimately resulting in the circumglobal transport of African dust. The Mediterranean low pressure linked to the European blocking dipole was the key to facilitating the eastward transport of dust. This record-breaking African dust episode caused a notable diurnal precipitation decrease of 0.98 mm day$^{-1}$ over northeastern India and a decrease of 1.55 mm day$^{-1}$ over central North America, which was ascribed to the effect of dust-induced radiative heating on large-scale circulation. It triggered a Rossby wave train and caused anomalous high pressure over northeastern India, which weakened the India summer monsoon and consequently inhibited the occurrence of precipitation. Dust-induced radiative heating also supported the stability in the anomalous warm high over North America, further repressing import of moisture from Atlantic. Ambient moisture and atmospheric instability also presented consistent variation over North America and India characterized as strengthen descending motion and sharply reduced moist convection. This study reports, for the first time, the strong modulation of regional circulation by circumglobally transported African dust, especially in Asia and North America. The new aspects on the unexpected consequences on moisture convection indicate broader roles that the dust may play in the global climate change.

SIGNIFICANCE STATEMENT: This study elucidated the circumglobal transport of African dust and revealed its modulation to large-scale circulation with the consequent impact on regional precipitation in remote downstream regions. The circumglobal transport of African dust was represented in two pathways, with its westward spreading modulated by the North Atlantic Oscillation and its eastward spreading regulated by European blocking. The dust-induced radiative heating triggered a Rossby wave train and caused anomalous anticyclones dominating central North America and northeastern India, ultimately resulting in a notable diurnal precipitation decrease of 0.98 and 1.55 mm day$^{-1}$ over northeastern India and central North America, respectively. These results highlight broader roles that African dust may play in the global climate change in the future.

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Corresponding author: Siyu Chen, chensiyu@lzu.edu.cn
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North Africa accounts for the largest source of global dust emissions, with annual dust emission fluxes varying from 400 to 2,200 Tg yr\(^{-1}\) (Huneeus et al. 2011). In particular, dust released from the Sahara Desert contributes approximately 50% of the world’s atmospheric mineral dust (Wagner et al. 2009; Heinold et al. 2013). Case studies of North African dust storms have found that dust particles from there can move thousands of kilometers across continents and oceans and therefore have drastic consequences for the climate, environment, and ecosystems (Prospero and Mayol-Bracero 2013; K. Yu et al. 2015; Chen et al. 2017a; Weinzierl et al. 2017; Chen et al. 2018; Thomas and Nigam 2018; Zeng et al. 2020). The dust provides nutrients for the Amazon rainforest and feeds the growth of the marine phytoplankton in the North Atlantic and the Mediterranean Sea (Gallisai et al. 2014; H. Yu et al. 2015; Ravelo-Pérez et al. 2016), which plays a key role in controlling the chemical composition of marine and terrestrial ecosystems and hence the global carbon cycle (Conway and John 2014). In addition, substantial evidence also indicates the relevance between episodes of Saharan dust storms and the frequency of tropical cyclones and hurricanes (Evan et al. 2006; Bretl et al. 2015; Dai et al. 2022), which threatens public health and economic well-being in large population centers and industrial areas of southern Europe and West Africa.

At present, efforts have been made to explore the effect of Saharan dust on the West African monsoon and Sahel precipitation based on different climate models (Rosenfeld et al. 2001; Wu and Lin 2014; Su and Fung 2015; Evan et al. 2016; Gu et al. 2016; Zhao et al. 2020). It is elucidated that the response of monsoon precipitation to African dust is dependent on the strength of dust radiative forcing, and a strong forcing may weaken the monsoon intensity by cooling in the lower troposphere and warming in the upper troposphere (Solmon et al. 2008; Kim et al. 2010; Zhao et al. 2011). Except for local effect, numerous studies have focused on the westward transport of Saharan dust particles to the Caribbean Sea, the southern United States, and northeastern South America through trans-Atlantic transport (Doherty et al. 2008; Schepanski et al. 2009; Mulitza et al. 2010; Kim et al. 2014; Prospero et al. 2014) and demonstrated the potential modulation of various atmospheric phenomena on the westward transport of Saharan dust plumes (Evan et al. 2006; Francis et al. 2020). It is related to the location and the intensity of the midtropospheric African easterly jet (AEJ), the North Atlantic subtropical high (NASH), the Caribbean low-level jet (CLLJ), the intertropical convergence zone (ITCZ), and the subtropical high off the coast of West Africa (Moulin et al. 1997; Doherty et al. 2008; Fontaine et al. 2011; Bercos-Hickey et al. 2020; Pu and Jin 2021; Ramírez-Romero et al. 2021; Li and Wang 2022).
The importance of Saharan dust to the atmospheric loading over Asia and western North America is further highlighted (Park et al. 2005; Tanaka et al. 2005; McKendry et al. 2007; Yu et al. 2021; Asutosh et al. 2022), which affects precipitation distribution over East Asian coastal areas and the western United States by changing cloud microphysical properties (Creamean et al. 2013; Kalenderski and Stenchikov 2016; Zhang et al. 2017), and also stimulates ocean productivity in the North Pacific due to more than 50% contribution of Saharan dust to overall dust deposition (Hsu et al. 2012). The eastward transport of African dust is mainly concentrated in the middle to upper troposphere along the prevailing westerly. Previous studies paid more attention to quantifying the contribution of Saharan dust to atmospheric loading over East Asia. It accounts for 31%–58% of dust concentration at 300 hPa over the Tibetan Plateau (TP) (Mao et al. 2019). The long-term modeling from 2007 to 2020 further indicated that about 35.8% of dust loading in the upper troposphere in Northern China in spring is attributed to the Sahara Desert, comparable to the contribution from dust sources over East Asia (Liu et al. 2022). The result implies the long-distance transport of African dust has more profound effects on remote atmospheric environment at a global scale.

At present, the modulation of atmospheric factors on trans-Atlantic transport of African dust has been clearly clarified. The contribution of Saharan dust to atmospheric loading over East Asia is also clearly quantified in a climatological view. However, fewer studies have characterized the circumglobal transport of African dust in details and revealed the potential atmospheric feedback process. There is also no attempt made to illustrate whether the effect of Saharan dust to regional circulation in remote atmosphere is more likely to increase or decrease precipitation in downstream regions by modulating ambient moisture and atmospheric instability, which is also crucial to better predicting the dust-induced precipitation variability over the coming decades.

During 7–24 June 2020, a super-Saharan dust episode was witnessed with aerosol optical depth (AOD) intensity 60%–70% larger than climatology mean during June 2002–22 (Figs. S1 and S2 in the supplemental material). This record-breaking African dust storm swept across the Caribbean Basin, the Gulf of Mexico, and the southern United States, which raised widespread concern in the scientific community for its severity and considerable impacts on the atmospheric environment. The physical mechanism affecting the emission and westward propagation of African dust has been extensively investigated (Francis et al. 2020; Pu and Jin 2021; Yu et al. 2021; Asutosh et al. 2022). The intense dust storm was attributed to an anomalous subtropical high off the coast of West Africa, exceptionally strong surface winds, and reduced vegetation coverage in the dust source regions (Francis et al. 2020; Pu and Jin 2021). Pu and Jin (2021) further examined the atmospheric circulation extremes and noted that a strong African easterly jet, westward extension of the North Atlantic subtropical high (NASH), and intensified Caribbean low-level jet were essential for the westward transport of African dust plumes.

Note that this massive African dust plume was quite different from previous dust events. The favorable atmospheric circulation pattern not only resulted in trans-Atlantic transport of African dust, but also supported dust plumes proceeding into the northern slope of the TP in the upper troposphere and entering China, the Korean Peninsula, and Japan, ultimately achieving the circumglobal transport of Saharan dust. Thus, the purpose of this study is to investigate the potential physical mechanism that results in circumglobal transport of African dust and its impact on large-scale circulation and precipitation in the downstream regions, based on multiple satellite and ground observations as well as simulations from the Weather Research and Forecasting Model coupled with the Chemistry module (WRF-Chem).

**Model configuration and methodology**

WRF-Chem is configured to conduct a 19-day simulation of African dust in the Northern Hemisphere from 6 to 24 June 2020. Sensitivity experiments are designed to investigate the
impact of African dust on the temporal and spatial variation of precipitation, especially over India and North America, by modulating ambient moisture and atmospheric instability. More details of the model are given in the first subsection. The observations from satellites, including Moderate Resolution Imaging Spectroradiometer (MODIS), Multiangle Imaging Spectroradiometer, and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), and ground-based AERONET are then applied to analyze the transport of African dust in details. Next, reanalysis data from ERA5 are utilized to identify the atmospheric circulation favoring the circumglobal transport of African dust. Finally, the composite analysis is further utilized to reveal the main atmospheric factors in driving the circumglobal transport of African dust in a climatological view.

**WRF-Chem model and simulation setup.** The model utilized in this simulation is WRF-Chem V3.9.1. The model domain is centered at (10°N, 0°) with 435 latitude × 180 longitude grid points (54°S–64°N, 179.8°W–179.8°E). The horizontal grid increment is 80 km in both directions. There are 35 vertical levels up to 100 hPa. The simulations are conducted for 19 days from 0000 UTC 6 June 2020 with the first 24 h as the spinup time to allow the model to adjust to the initial and lateral boundary conditions. The simulations are focused on the dust process over North Africa during 7–24 June 2020. Boundary and initial conditions are obtained from the NCEP (National Centers for Environmental Prediction) FNL global reanalysis data, which are available for every 6 h and 1° spatial resolution. The SST datasets are also from NCEP FNL global reanalysis data.

The settings in the model are listed in Table 1. The Thompson scheme and the Yonsei University (YSU) scheme are adopted to simulate microphysical processes and the planetary boundary layer, respectively (Hong et al. 2006). The Monin– Obukhov scheme and the Noah scheme are used to parameterize surface layer physical processes and the interaction with the land surface (Chen and Dudhia 2001; Pahlow et al. 2001; Chen et al. 2010). The Rapid Radiative Transfer Model for General Circulation Models (RRTMG) scheme is applied to simulate the transfer of both longwave and shortwave radiation (Mlawer et al. 1997). The Model for Ozone and Related Chemical Tracers (MOZART) chemistry mechanism and the Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) aerosol mechanisms are utilized in the aerosol module (Ginoux et al. 2001). The natural dust emission scheme used in WRF-Chem is the GOCART aerosol scheme, which is typically used for the simulation of global dust processes (Ginoux et al. 2004; Huneeus et al. 2011; Hu et al. 2019). In the GOCART model, the dust emission flux $F_p$ is expressed as

$$F_p = \begin{cases} 
C S_p U^2 (U - U_t)(D_p \theta_s) & U > U_t(D_p \theta_s) \\
0 & U \leq U_t(D_p \theta_s)
\end{cases}$$

where $C$ is a proportionality constant (0.8 μg s² m⁻⁵), $S$ is a unitless erodibility value showing the availability of particles to be entrained, $S_p$ is the mass fraction of dust emitted from soil separate classes (sand, silt, and clay) of size group $p$ at the soil surface, $U$ is the horizontal wind speed at 10 m, $U_t(D_p \theta_s)$ is the threshold 10 m wind speed, $D_p$ is the particle diameter of size $p$, and $\theta_s$ is the degree of saturation measuring soil moisture. There are five noninteractive dry size bins selected in WRF-Chem to compute the sources and sinks of dust, including 0.1–1, 1–2, 2–3, 3–6, and 6–10 μm, with corresponding effective radii of 0.73, 1.4, 2.4, 4.5, and 8.0 μm, respectively. The SW refractive index of dust is a constant value of 1.53 + 0.003i following Zhao et al. (2010). In the model, anthropogenic emissions are from the Emissions Database for Global Atmospheric Research (EDGAR; Janssens-Maenhout et al. 2012), which offers various pollutants emissions, including CO, CH₄, SO₂, NOₓ, NMVOCs, NH₃, PM₂.₅, PM₁₀, BC, and OC.
In this study, a control simulation (CTRL) and two sensitivity simulations (SEN1_AFD_Only and S_SEN2_AFD_OFF) were carried out (Table 2). In the CTRL experiment, all kinds of aerosols in the study area were considered equivalent to real atmospheric processes. In the SEN1_AFD_Only experiment, the dust emitted from Africa was singled out by setting the wind erosion equal to zero in other regions in order to quantify the contribution of African dust to atmospheric loading in different areas in the Northern Hemisphere. The SEN2_AFD_OFF was an experiment with the dust emission from Africa closed. The atmospheric feedback induced by the African dust event was investigated based on the differences between the CTRL experiment and the SEN2_AFD_OFF experiment.

Satellite observations. The Moderate Resolution Imaging Spectroradiometer (MODIS) is an important sensor operating on board the polar-orbiting National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) (Salomonson et al. 1989). It provides aerosol parameters and related atmospheric, biological, and physical processes with high-resolution (250 m at nadir), multichannel (36 channels between 0.412 and 14.2 μm), and wide coverage (2,330 km). The aerosol characteristics from MODIS can be retrieved by two methods, including Dark Target (DT) and Deep Blue (DB) algorithms (Kaufman and Tanré 1998). The aerosol optical depth (AOD) product that combines DT and DB algorithms has the capability of retrieving AOD with a relatively high accuracy (Levy et al. 2013). In this study, the daily global MODIS product MOD08_D3 is utilized with a spatial resolution of 1° × 1°. It provides the AOD at 550 nm combined with DT and DB algorithms (http://modis-atmos.gsfc.nasa.gov/).

MISR is a satellite instrument designed to observe the radiation reflected by Earth’s atmosphere and surface with relatively high spatial resolution, which can classify AODs according to different particle types and provide detailed information on aerosol particle properties (Kahn et al. 2001). MISR instrument is designed to provide complete near-global coverage.
coverage in a 9-day cycle (Diner et al. 1998). In this study, the MISR level 3 global data with a spatial solution of 0.5° × 0.5° is utilized to identify the AOD distribution.

The CALIPSO satellite was launched on 28 April 2006 and offers the vertical structure of clouds and aerosols by using the cloud–aerosol discrimination (CAD) algorithm. It can detect aerosols both under clear-sky conditions and beneath thin cloud layers. It can further categorize aerosol types as smoke, dust, polluted dust, clean continental, and polluted continental (Winker et al. 2007; Guo et al. 2017). The CALIPSO level 2 vertical feature mask (VFM) provides the feature classification of aerosols and clouds, the dust vertical distribution, and the dust-layer height. The vertical and horizontal resolutions of VFM products are 30 and 333 m from the ground up to 8.2 km altitude, 60 m and 1 km for 8.2–20.2 km, and 180 m and 5 km for 20.2–30.1 km (Winker et al. 2007; Liu et al. 2009). In this paper, the CALIPSO VFM and AOD retrieved by CALIPSO observation are adopted.

**AERONET ground-based observations.** The Aerosol Robotic Network (AERONET) is a ground-based remote sensing aerosol network established by the NASA (Holben et al. 1998). It provides a long-term accessible dataset of global aerosol optical properties by using sun-sky radiometers (Dubovik et al. 2000; Gobbi et al. 2007). In this study, the data of AOD at 500 nm and Ångström exponent (440–870 nm) is obtained from version 3.0 with quality level 2.0, which is cloud-screened and quality assured. The Ångström exponent usually varies between 0 and 2, with a value less than 0.6 as an indicator of coarse dust particles (Schuster et al. 2006).

**ERA5 data.** In this study we use ERA5 to analyze the dynamic factors related to the dust episode. ERA5 is the latest fifth-generation reanalysis global atmosphere dataset from the European Centre for Medium-Range Weather Forecasts (Hersbach et al. 2020; Jiao et al. 2021). It provides an estimation of the atmospheric, land, and oceanic climate variables with high spatial and temporal resolution. We adopted hourly ERA5 mean sea level pressure (MSLP; unit: hPa), winds at 10 m, the temperature at 2 m, boundary layer height, and vertical velocity.

**Composite analysis.** To reveal whether North Atlantic Oscillation (NAO) and the Mediterranean low pressure are the main atmospheric factors in driving the circumglobal transport of African dust in a climatological view, the AOD index during 2002–20 is selected to composite the corresponding circulation fields. In this study, the AOD index is calculated as the area-averaged AOD over grid boxes within 10°–20°N, 30°–15°W, with its value exceeding/less than 0.5 standard deviation chosen to construct the related anomalous field of circulation pattern at 500 and 850 hPa. It can characterize high dust loading over North Africa. The two-sided $t$ test is further chosen to test the statistical significance of the composite anomalies.

**Results**

We first explore the spatial and temporal characteristics of “Godzilla” African dust episode and analyze the dynamic factor driving the intense dust emissions. The following subsection focuses on the three-dimensional transport of the African dust and the physical mechanism. Finally, the effect of the dust on atmospheric circulation and the moisture convection over India and North America is investigated.

**Circumglobal transport of the dust.** The extremely strong dust episode that occurred in North Africa was captured by a daily natural-color image from the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the NOAA-20 satellite on 7 June 2020 (Fig. S1). It caused durable and nonnegligible impacts within several days in the Northern Hemisphere and...
thus was dubbed the “Godzilla” African dust episode. This event was the most exceptional dust storm since 2002 (Fig. S2; Pu and Jin 2021; Yu et al. 2021), with dust emissions extending from central North Africa to the coast of West Africa (Fig. 1a, Fig. S3). The Godzilla African dust episode was also observed on 7 June based on the mean cross sections of zonal MODIS AOD$_{550\text{nm}}$, with a magnitude of AOD$_{550\text{nm}}$ in the range of 0.4–0.75 along the coast of west Africa (Fig. S4a). With the intensification of dust emissions, the daily average magnitude of AOD$_{550\text{nm}}$ increased to much larger than 0.8 in the dust source regions after 7 June.

Based on the combined view of the large-scale circulation fields (Fig. S5) and daily MODIS AOD anomalies relative to 2002–20 climatology mean (Fig. S6), the westward spreading of Godzilla African dust from Atlantic to Caribbean was clearly captured. Noted the westward transport of dust plume initially stalled over the eastern Atlantic Ocean from 7 to 17 June (Fig. S4b) due to an anomalous northward shift of the NASH affected by circumglobal wave train (Francis et al. 2020). After 18 June, the dust plume which stagnated in the eastern Atlantic in the past 11 days moved westward due to the southward shift of the NASH, the anomalous westward extension of the Saharan subtropical high pressure, and the North African easterly jet (Pu and Jin 2021). The eastward transport of African dust to East Asia was also identified.

Fig. 1. (a) The simulated dust emission flux (unit: $\mu$g m$^{-2}$ s$^{-1}$) (SEN1_AFD_Only experiment), and the spatial distribution of AOD$_{550\text{nm}}$ (b) observed by MISR and (c) simulated by WRF-Chem (CTL experiment) in the Northern Hemisphere during 7–24 Jun 2020. The blue dashed box in (b) shows the range of zonal and meridional cross sections of dust loading, and the green and yellow dots are the AERONET sites. (d) The simulated mean cross sections of zonal dust loading (longitude averaged over 15°W–25°E) and (e) the meridional dust loading (latitude averaged over 5°–50°N) during 7–24 Jun 2020 (SEN1_AFD_Only experiment). (f) The AOD (bars) and Ångström exponent (line) at seven sites observed by AERONET as labeled in (b) as yellow dots, which includes Ragged_Point site (13.165°N, 59.432°W), Guadeloupe site (16.225°N, 61.528°W), Cape_San_Juan site (18.384°N, 65.620°W), NEON_GUAN site (17.970°N, 66.869°W), Dushanbe site (38.553°N, 68.858°E), Beijing-CAMS site (39.933°N, 116.317°E), and Xitun (24.162°N, 120.617°E) site.
by the anomalous MODIS AOD over North China Plain after 20 June (Figs. S6c,d), when there were no strong positive anomalies of AOD over other dust sources. Overall, the spatiotemporal variation of AOD revealed by satellite retrieval was reproduced reasonably by the WRF-Chem model (Figs. 1b,c, Fig. S7). Based on the zonal cross sections of dust loading, it was clearly seen that dust aerosol over North Africa rapidly accumulated over dust source regions on 7 June 2020 and reached a maximum on 17 June with dust loading exceeding $2.3 \times 10^6 \mu g m^{-2}$ (Fig. 1d). The accumulated dust aerosols were partly transported westward across the Atlantic to the North America after 18 June, and partly spread eastward traveling across East Asia to Pacific. After 20 June, the African dust swept across the Northern Hemisphere and realized circumglobal transport (Fig. 1e).

In addition to satellite observations, AERONET ground-based observations (stations marked with green or yellow dots in Fig. 1b) also provided additional pieces of information about this dust storm (Fig. 1f, Fig. S8). The AOD$_{500nm}$ observed by AERONET increased at several stations located in the Caribbean Basin after 20 June with a decline in the Ångström exponent, verifying dust particles transporting to Caribbean Basin and southern United States. More AERONET sites were further added along the eastward transport pathway of African dust over Mediterranean Basin, western Europe, and the Middle East (Fig. S8). Obviously, the value of AOD in western Europe was relative higher during the period of 14–20 June (Fig. S8a). The rapid increase in AOD$_{500nm}$ and decline in the Ångström exponent could also be observed over the Mediterranean Basin after 19 June (Fig. S8b), when the observation sites (Dushanbe, Beijing, and Xitun) over East Asia showed a slight increase in AOD$_{500nm}$ and a decline in the Ångström exponent over the northern TP and eastern China after 20 June (Fig. 1f). It further indicated that dust particles of this extremely strong dust event spread not only westward across the Atlantic to North America, but also eastward to East Asia and even to the North Pacific. All these observational facts and modeling indicated that Godzilla African dust was characterized by circumglobal transport. Furthermore, to improve the reliability for the dust transport from Africa toward East Asia, the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT-4) was further utilized (Fig. S9). It was found that the dust-loaded air parcel trajectories from HYSPLIT-4 well supported the results regarding dust transport from North Africa directly to East Asia.

The dominant factors affecting dust emissions were further examined. During the Godzilla African dust episode, the ascending motion represented a strong potential to accelerate the development of the boundary layer height (BLH) and further lifting of the dust plumes (Figs. S10a,b). The continuous growth of the northeasterly wind was associated with the anomalously high mean sea level pressure (MSLP), which intensified the wind erosion over western North Africa centered over $18^\circ$–$30^\circ$N (Fig. S10c). In addition, the raising of temperature at 2 m near the dust source also intensified the meridional temperature gradient between the warm Sahara and cool Guinean coast (Fig. S10d), which further enhanced the Saharan high and African easterly jet (Pu and Jin 2021), and favored the circumglobal transport of Godzilla African dust.

**Mechanism of the eastward transport.** During Godzilla African dust episode, the contribution of the African dust to the dust loading in different areas in the Northern Hemisphere was quantified based on SEN1_AFD_Only experiment (Fig. 2a). Overall, the effect of African dust on dust loading was most pronounced in the Atlantic, central Europe, and the southern United States (Fig. 2a), with the magnitude of dust loading up to $3.1 \times 10^5$, $6.6 \times 10^4$, and $3.4 \times 10^4 \mu g m^{-2}$, respectively (Fig. 2b). The contribution of African dust to the dust loading in the Korean Peninsula and eastern China solely accounts for $1.9 \times 10^4$ and $4.3 \times 10^3 \mu g m^{-2}$, respectively. The simulated dust transport flux was further utilized to reveal the dynamic variation of African dust transport (Fig. 2c, Fig. S11), which clearly captured dust aerosols...
spreading westward in a continuous plume from the coast of North Africa into the Caribbean Basin and eastward traveling across East Asia and proceeding into the Pacific. The eastward transport of African dust was mainly concentrated in the middle to upper troposphere along the prevailing westerly, with dust transport flux at 500 hPa noticeably larger than that at 850 hPa along with the north side of the Siberian high pressure (Fig. S12). The elevated African dust plumes were further lifted by the dynamic forcing of the Tibetan Plateau and proceeded into northern China and the Pacific (Fig. 2c). The westward transport of African dust mainly occurred in the lower and middle troposphere and was distributed in the range of 15°S–30°N (Fig. S12b).

The details of the three-dimensional transport process simulated by the WRF-Chem model presented consistent distribution with the result retrieved by CALIPSO (Figs. 2d,e, Figs. S7 and S13). Overall, the elevated dust from North Africa was more conducive to long-distance transport in the upper troposphere and accounted for larger contribution to atmospheric dust loading over East Asia and South Asia compared to dust from the Arabian Peninsula (Fig. S14), which was mainly concentrated on lower altitude of 1–4 km (Fig. S15). Vertically extended
dust layers (orange color) over North Africa were clearly captured by CALIPSO sensors along CALIPSO orbital track on 7 June 2020 (Fig. 2e), which was dispersed mainly in two pathways. The thick dust plume that moved westward was further transported to the Atlantic with dust aerosols lifted to 6–8 km during 7–17 June (Fig. 2e, Fig. S13). It reached the Caribbean Basin and the southern United States after 20 June, with the top of the dust plumes descending to approximately 4 km. The dust plumes that moved eastward, proceeding to the far northern part of India. It was not just constrained to a narrow latitude range and further extended to the TP, with the top of dust layer lifted to the upper troposphere over the northern slope of the TP (Figs. 2d,e).

During the Godzilla African dust episode, the WRF-Chem model well reproduced the spatial and temporal evolution of meteorological fields, which was characterized by NASH, European blocking dipole, and NAO positive phase, when the high temperature further extended from North Africa to the Middle East and northern India (Fig. 3a, Figs. S16 and S17). This evolution of the main modes of meteorological fields was also in an extremely abnormal state compared to long-time climatological mean from 2002 to 2020 (Figs. S18 and S19). The persistence of NASH at 850 hPa resulted in strong low-level easterly winds, associated with NAO positive phase, favoring the dust outflow from the West African coast to the eastern United States (Figs. 2c and 3b). The West Siberia high linked to the European blocking dipole dominated the transport of dust plumes at latitudes higher than 30°N, where dust plumes proceeded to Europe and Inner Mongolia and traveled over the Pacific Ocean along the prevailing westerly jet (Figs. 2c and 3b). The northwesterly winds behind the Mediterranean low bypassed eastern North Africa and converged with southwest monsoon, which resulted in the dust plume from North Africa being transported eastward farther into northeastern India at latitudes lower than 30°N (Fig. 2c). In addition, the north–south pressure gradient induced by the positive NAO phase drove the mean winds and strengthened the westerly jet (Figs. 3b,c). It accelerated the downstream propagation

![Fig. 3. Spatial distribution of geopotential height fields (shading; unit: gpm) and wind vectors (unit: m s⁻¹) at (a) 500 and (b) 850 hPa during 7–24 Jun 2020; the zonal symmetry of geopotential height and wind mean state are removed. (c) Vertical cross sections of vertical circulation (latitude averaged over 0°–50°N) during 7–24 Jun 2020, which is multiplied by a factor of −120 to enhance the visual interpretation of wind vectors. (d) Spatial distribution of geopotential height fields and wind vectors anomalies at 500 hPa in the composites with strong AOD index (exceeding 0.5 standard deviation); the zonal symmetry of geopotential height and wind mean state are removed, and the black dots represent the grid points that passed 90% confidence level according to a two-tailed $t$ test.](image-url)
of Rossby waves and was conducive to the activation of blocking circulations in European areas and the redistribution of downstream blocking dipoles, consequently sustaining the transport of the dust to the east.

To reveal whether NAO and the Mediterranean low pressure were the main atmospheric factors in driving the circumglobal transport of African dust in a climatological view, the AOD index was further chosen to characterize high dust loading and construct the composite fields of anomalous circulation with 0.5 standard deviation as criterion, which was calculated as regionally-averaged AOD over grid boxes within 10°–20°N, 30°–15°W in June 2002–20. The result exhibited significant relationships between large-scale atmospheric circulation patterns and AOD (Fig. 3d, Fig. S20). During high AOD index cases, the positive phase of NAO and the Mediterranean low were steadily maintained (Figs. S20a,b), which presented a reversal of the anomaly signals with low AOD index cases (Figs. S20c,d). It suggested that the synergistic effect of NAO and Mediterranean low pressure played a vital role in modulating the circumglobal transport of African dust in the Northern Hemisphere.

Effect on regional circulation in remote areas. The circumglobal transport of Godzilla African dust had significant effects on large-scale circulation (Figs. 4a,b) and consequently regional precipitation in some remote downstream regions (Figs. 4c,d). During Godzilla African dust episode, the WRF-Chem model well captured the spatial pattern of precipitation over North America and India compared to observations obtained from the Climate Prediction Center (CPC) Global Precipitation product (Figs. S21a,b and S22a,b). Based on the differences of CTRL and SEN2_AFD_OFF experiment, it was found that the influence of African dust on precipitation was significant over North America and India during 7–24 June 2020, with the results passing 90% significance level. The decrease of regionally-averaged daily precipitation induced by dust was up to 0.98 mm day$^{-1}$ over northeastern India (19°–25°N, 75°–88°E) and 1.55 mm day$^{-1}$

Fig. 4. (a) The climatological mean geopotential height fields (shading; unit: gpm) and wind vectors (unit: m s$^{-1}$) at 850 hPa from 1991 to 2020; the zonal symmetry of geopotential height and wind mean state are removed. (b) Dust-induced variation of circulation field at 200 hPa and variation of daily precipitation (shading; unit: mm day$^{-1}$) over (c) India and (d) North America (CTRL minus SEN2_AFD_OFF experiment) during 7–24 Jun 2020. The black dots represent the grid points that passed 90% confidence level according to a two-tailed $t$ test, and the green box stands for the areas located at southeastern India and central North America. (e),(f) The dust-induced variation of relative vorticity over (e) India and (f) North America during 7–24 Jun (CTRL minus SEN2_AFD_OFF experiment).
over central North America (35°–45°N, 105°–75°W), respectively (Figs. 4c,d). This variation of precipitation was attributed to the modulation of dust radiative forcing to the atmospheric stability and subsequently regional circulation in remote atmosphere (Figs. S23–S25).

The African dust resulted in significant warming within atmosphere and radiative cooling at surface as indicated by the vertical profiles of net radiative heating rate and dust concentration (Fig. S26). It caused large heating within the dusty layer (1–5.5 km) near dust source areas due to strong absorption to the incoming solar radiation. Simultaneously, the high pressure systems over western Europe and North America were also in an extremely abnormal state compared to long-time climatological mean from 2002 to 2020 (Fig. S18), when the long-distance transport of African dust to Europe and North America further heated the atmosphere and thus allowed for the higher temperatures in this region (Fig. S24). It resulted in strengthening of anticyclonic circulation anomalies and supported the stability in the anomalous warm highs over western Europe and North America, which was unfavorable for moisture transport from Atlantic to central North America. Dust-induced radiative heating near dust source areas also resulted in anomalous Rossby wave trains (Fig. 4b, Figs. S25a–c). It supported energy dispersion eastward to southern Asia and caused anomalous high pressure over northeastern India. The strengthening of high pressure further weakened the monsoon trough and suppressed moisture transport from the Indian Ocean to the Indian subcontinent, resulting in reduction of monsoon rainfall over northeastern India (Figs. 4a,c). The regression pattern of circulation at different levels and area-averaged AOD index (over grid boxes within 8°–35°N, 15°W–25°E) also showed anomalous high pressure over central North America and northeastern India, verifying the effect of African dust on large-scale circulation (Figs. S25d–f).

The changes of ambient moisture and atmospheric instability caused by dust aerosols further verified the response of precipitation over North America and India to African dust. The dust-induced negative relative vorticity inhibited the precipitation forming by suppressing vertical circulation and moist convection (Figs. 4e,f), which was characterized by strong descending motion (Figs. 5a,c) and sharply reduced relative humidity (Figs. 5b,d). The potential physical mechanism that modulated the precipitation variability over northeastern India was

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Fig. 5. The dust-induced variation of (a) vertical circulation (multiplied by a factor of 500 to enhance the visual interpretation of wind vectors) and (b) relative humidity over India (latitude averaged over 18°–25°N) during 7–24 Jun 2020. (c),(d) As in (a) and (b), but for North America (at 40°N). The terrain is filled in black.
consistent with the related atmospheric feedbacks over central North America at local scale (Fig. 5). Furthermore, the modeled decrease of precipitation induced by dust over central North America also had a highly coherent pattern with the anomalies of daily precipitation obtained by CPC (Figs. S21c,d), and the regression pattern of precipitation and area-averaged MODIS AOD over grid boxes within 8°–35°N, 15°W–25°E (Fig. S27b). It indicated that the African dust was the key to effectively inhibiting the occurrence of precipitation over central North America. But there was no consistent spatial pattern between the simulated variation of precipitation induced by dust and the anomalies of daily precipitation over northeastern India (Figs. S22c,d), indicating the long-term variation of monsoon precipitation over India was more probably dominated by other atmospheric factors.

Conclusions and discussion
This study is the first attempt to explore the circumglobal transport of massive African dust in June 2020 and its potential physical mechanism. It provides a complete picture of the long-range transport of African dust, and its subsequent effect on weather change in the Northern Hemisphere (Fig. 6). The observations from multiple satellite and ground-based platforms and modeling of WRF-Chem model have provided a comprehensive view of the three-dimensional transport process of African dust. The main channel for dust transport from North Africa to East Asia was through the northern slope of the TP in the middle and upper troposphere, which was revealed by CALIPSO retrievals and further validated by ground-based AERONET observations and HYSPLIT model.

WRF-Chem model provides reliable spatial and temporal patterns for the physical process of African dust, and the simulation of AOD also presents a good agreement with MISR observation and CALIPSO retrievals. But there are still some discrepancies in the simulated AOD, which presents a negative bias over the Atlantic but positive bias over eastern North Africa. It was because the simulated high pressure over the Atlantic was relatively easterly around 20°–35°N, 10°–45°E (Fig. S7). It further changed pressure gradients east of 10°E longitude and consequently triggered a stronger eastward transport of dust from the West African coast to eastern North Africa and limited dynamic transport of African dust westward, ultimately resulting in an overestimation of AOD over eastern North Africa and an underestimation of AOD over the Atlantic. Furthermore, the incorrect explanation in terms of the contribution of submicron dust particles in the Mie calculations of aerosol optical properties also results in

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Fig. 6. Schematic diagram of Godzilla African dust transport and its relationship with precipitation over North America and India. The dust concentration (SEN1_AFD_Only experiment) and variation of daily precipitation in the inner plots (CTRL minus SEN2_AFD_OFF experiment) is from the simulation of the WRF-Chem model.
bias between simulation and observation (Ukhov et al. 2021). As exemplified in this study, the contribution of African dust only accounted for a small fraction of the dust loading over East Asia, but the eastward transport of African dust would be one of the nonnegligible factors in driving weather and climate change over East Asia and South Asia in the coming decades (Park et al. 2005; Tanaka et al. 2005; McKendry et al. 2007; Mao et al. 2019; Yu et al. 2021; Asutosh et al. 2022). It was found that the Mediterranean low pressure linked to the European blocking dipole lent strong support to the eastward propagation of African dust. The NAO phase also created large-scale meteorological conditions favorable for sustaining European blocking by intensifying the prevailing westerly winds and accelerating the downstream dispersion of Rossby waves.

The essential role of African dust in affecting large-scale circulation and subsequently precipitation variability in a remote region was revealed. The radiative heating of African dust strengthened anticyclonic circulation anomalies and supported the stability in the anomalous warm highs over central North America, which was characterized by the extending of anomalous high pressure from the Atlantic to central North America. This variation embraced almost the entire troposphere and further resulted in drier atmosphere and less precipitation over this region. The radiative heating of African dust also affected the upper-tropospheric Rossby wave in the Northern Hemisphere. It induced an intensified anticyclone over northeastern India, which repressed the import of moisture from the Indian Ocean and resulted in the decrease of precipitation over northeastern India. The ambient moisture and atmospheric instability in remote downstream regions also represented consistent variation. It was characterized by strengthened descending motion and sharply reduced relative humidity over the rainfall band over central North America and northeastern India. But due to the uncertainty of simulation, the effect of dust-induced radiative forcing on weather processes over India would be amplified to some extent than what would have happened, when the effect of African dust on North America would be underestimated due to limited westward transport of dust compared to observation.

The GOCART scheme has been acknowledged as one of the most popular aerosol modules (Ginoux et al. 2001; Chen et al. 2017b; Rizza et al. 2018; LeGrand et al. 2019; Bukowski and van den Heever 2020). It takes the advantage of being able to effectively simulate atmospheric constituents in multiple regions by using observed meteorological fields (Ginoux et al. 2001), even though there is the absence of data regarding soil composition, soil aggregate strength, and terrain roughness at microscale or macroscale. The GOCART scheme also presents well performance in terms of a quasi-global simulation of dust physical process as clarified by Hu et al. (2016). Compared to the GOCART scheme, the Shao dust emission scheme shows better performance in simulating dust emission and transport over East Asia (Shao 2001; Shao et al. 2011; Wu and Lin 2013; Su and Fung 2015; Zhao et al. 2020). Thus, the GOCART scheme is chosen to simulate the spatiotemporal variation of African dust and reveal its circumglobal transport. In addition, this study mainly focuses on the variation of large circulation caused by African dust and its effect on regional precipitation in downstream regions. The dust-induced modulation of large circulation to cloud microphysics is not studied, which is also the key to regulating the intensity and duration of precipitation. Thus, further research is needed to investigate the simultaneous responses of cloud microphysics to African dust based on more granular simulations.

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**Data availability statement.** The AOD used in this paper is acquired from MODIS, which is available at https://ladsweb.modaps.eosdis.nasa.gov/search/order/1/MOD08_D3–61. The OMI/Aura and CALIOP/CALIPSO data are provided by the NASA team. The AERONET datasets can be obtained from http://aeronet.gsfc.nasa.gov/. The MISR level 3 global data products can be obtained at https://l0dup05.larc.nasa.gov/L3Web/download. The ERA5 data are available at https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset. We gratefully acknowledge NASA for providing the reliable data used in this study. We sincerely thank the AERONET team for their efforts in establishing and maintaining instrumentation, as well as processing the data used in this study. We sincerely thank the reviewers and the editor for their valuable suggestions that have helped to improve the manuscript.
References


