



Simulation of Radiative Redistribution and Photovoltaic Energy Losses during Spring Dust Storms over the Taklimakan Desert

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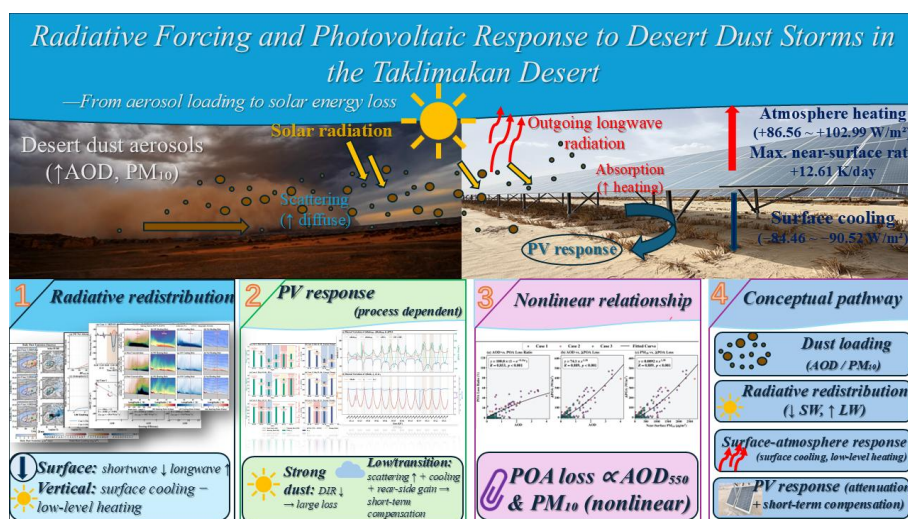
Abstract: Dust aerosols affect the surface radiation budget and photovoltaic (PV) power generation by changing the extinction and scattering of solar radiation. We used WRF-Chem to perform paired simulations with and without dust radiative feedback for three spring 2025 dust storms over Tazhong in the Taklimakan Desert. Dust radiative feedback reduced surface shortwave radiation at Tazhong by 84.46–90.52 W/m² and increased longwave radiation by 33.09–39.72 W/m². The maximum near-surface heating rate reached +12.61 K/day. Surface shortwave radiative forcing showed a significant linear correlation with aerosol optical depth at 550 nm (AOD₅₅₀), with a forcing efficiency ranging from –80.7 to –50.6 W/(m²·τ) per unit AOD₅₅₀. The strong dust event on 26 March reduced daily power generation by 50.96%, while the 3 May and 20 May events reduced it by 18.68% and 1.87%. Under low dust loading and during the onset and dissipation of dust events, enhanced scattering and cooler

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modules slightly raised the plane-of-array (POA) irradiance and power generation of bifacial modules, but these gains could not offset the losses under heavy dust. The POA irradiance loss ratio increased nonlinearly with AOD_{550} and followed power-law relationships with AOD_{550} and near-surface PM_{10} . These relationships may help improve PV power forecasting during dust events at desert PV plants..

Keywords: Taklimakan Desert; WRF-CUACE; dust aerosols; radiative forcing; photovoltaic power generation



Highlights

1) Based on paired WRF-Chem simulations, we quantified the "surface cooling-atmospheric heating" structure of dust radiative feedback and the associated near-surface heating rate.

2) Dust events of different intensities and durations had contrasting effects on POA irradiance and PV power generation..

3) POA irradiance loss followed power-law relationships with AOD_{550} and near-surface PM_{10} , offering potential for estimating irradiance losses under dusty conditions.



50 **1 Introduction**

51 Dust aerosols alter the surface radiation budget by scattering and absorbing solar
52 radiation (Kok et al., 2023; Zaiani et al., 2024; Liu et al., 2024). The Taklimakan
53 Desert, covering approximately $3.376 \times 10^5 \text{ km}^2$, is arid and windy with frequent dust
54 activity, making it a major dust source in East Asia. Observations at the Xiaotang
55 station on the northern margin of the desert show that atmospheric transmittance
56 drops from 0.67 under clear-sky conditions to 0.46 during dust weather, and the
57 probability of daily total radiation falling below 500 W/m^2 exceeds 90% during dust
58 storms (Jin et al., 2021). This demonstrates the substantial weakening of surface solar
59 radiation by dust. The arid region of northwestern China receives abundant sunshine
60 and hosts a core distribution of ground-mounted PV plants. Frequent dust weather
61 directly affects PV power generation by modifying atmospheric optical depth and the
62 composition of incident radiation.

63 PV power generation depends mainly on the intensity of solar radiation reaching
64 the modules and its direct/diffuse composition. Dust not only reduces the total surface
65 solar radiation but also changes the ratio between the direct and diffuse components.
66 Satellite estimates show a dust direct radiative forcing efficiency of -48.6 ± 13.7
67 $\text{W}/(\text{m}^2 \cdot \tau)$ over the Kashgar region of the Taklimakan Desert, whose absolute value is
68 higher than the $-39.6 \pm 10.0 \text{ W}/(\text{m}^2 \cdot \tau)$ at the Tamanrasset site in the Sahara (Tian et
69 al., 2021), indicating that PV plants in this region may face stronger radiation
70 attenuation. The operation of 86 distributed PV plants along the Tarim Desert
71 Highway shows that PV generation in the desert interior is feasible, but also
72 highlights the need to quantify the impact of dust weather on power output. The
73 bifacial glass–glass modules considered in this study receive not only front-side
74 radiation but also ground-reflected and sky-diffuse radiation on their rear side;
75 changes in the direct/diffuse ratio caused by dust may therefore further affect the
76 overall module output through the rear-side light path (Sun et al., 2018; Deline et al.,
77 2019).



78 The regional meteorology–chemistry coupled model WRF-Chem (Weather
79 Research and Forecasting model coupled with Chemistry) can simulate dust emission,
80 transport, and their interaction with radiation, and has been widely used in studies of
81 dust radiative forcing. Previous work has validated the model's ability to simulate the
82 three-dimensional structure and transport flux of dust (Hu et al., 2020; Wulayin et al.,
83 2024) and has reported the magnitudes of shortwave and longwave dust radiative
84 forcing at the surface and in the atmosphere (Wang et al., 2023; Dehshiri et al., 2024).
85 Regarding radiative feedback, Chen et al. (2023) showed that dust radiative feedback
86 substantially intensified a super dust storm, indicating that the two-way interaction
87 between dust and radiation cannot be neglected. Further studies have revealed the
88 adjustments of dust radiative feedback to the boundary layer, wind field, and
89 temperature profile (Liu et al., 2016; Li et al., 2022; Chen et al., 2025). From an
90 energy-application perspective, Bergin et al. (2017) estimated the reduction in solar
91 power generation caused by aerosols, and Song et al. (2025) simulated dust emission
92 trends under future climate scenarios.

93 Despite this progress in understanding dust radiative effects, existing
94 WRF-Chem applications have not yet been directly linked to and quantitatively
95 compared with plant-level observations and actual power output. In addition, the
96 quantification of how dust events of different intensities and durations weaken
97 radiation—and in particular how dust differentially affects the plane-of-array
98 irradiance (POA) of bifacial modules and the resulting power loss—remains limited.

99 Here, we focus on the Tazhong PV plant as the study target and select three dust
100 events in spring 2025 (26 March, 3 May, and 20 May). Using WRF-Chem simulations
101 with and without dust radiative feedback, we quantitatively analyze the dust radiative
102 forcing and its impact on PV power generation, aiming to provide a scientific basis
103 for power forecasting and dust protection of desert PV plants.



2 Data and Methods

2.1 Study area

The Taklimakan Desert (36.83°–41.17°N, 77.67°–88.33°E) is located in the center of the Tarim Basin in Xinjiang, China (Fig. 1), with a total area of about $3.37 \times 10^5 \text{ km}^2$. The region has an extremely arid continental climate, with annual precipitation of less than 100 mm and annual evaporation of 2500–3000 mm. Wind–sand hazards are severe, and dust storms occur frequently in spring and summer. This study focuses on the PV plant at Tazhong (38.97°N, 83.65°E) in Qiemo County. The PV array covers about 2.55 km² and is oriented due south at a fixed tilt angle of about 37°. Straw checkerboard barriers are installed beneath the panels for sand fixation.

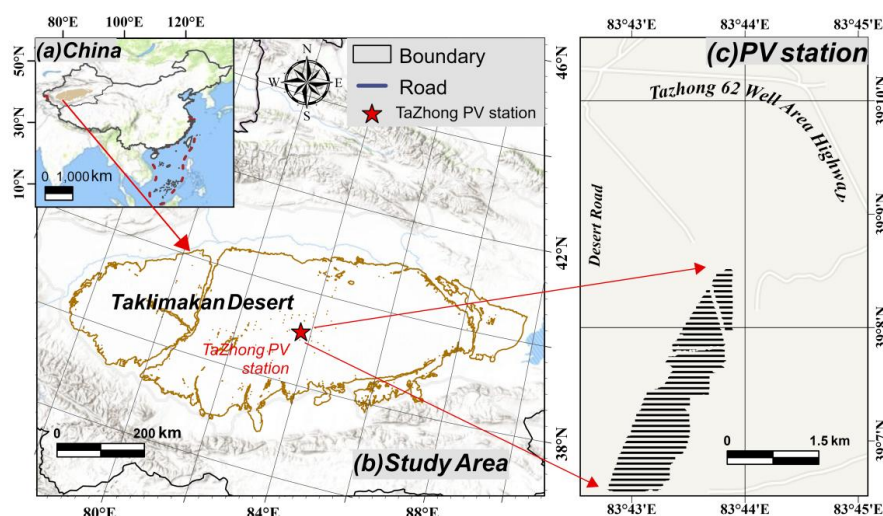


Figure 1 Geographic location of the study area.

Note: The base map was obtained from the National Platform for Common Geospatial Information Services (Tianditu), with map approval number GS(2024)0650 (<https://cloudcenter.tianditu.gov.cn/administrativeDivision>); the base map boundaries were not modified. The vector boundary of the Taklimakan Desert was obtained from the National Cryosphere Desert Data Center (<http://www.ncdc.ac.cn>). The vector data of the Tazhong PV plant were obtained from the global spatiotemporal dataset of PV and wind power (Zeng et al., 2025).



122 2.2 Observational data

123 Surface observations were used to validate model performance. Hourly 2 m air
 124 temperature and 10 m wind speed were obtained from the Tianqing database of the
 125 China Meteorological Administration. Hourly PM_{10} and $PM_{2.5}$ concentrations were
 126 measured by a CCLJP100 atmospheric particulate matter particle size monitor at the
 127 same site, in units of $\mu\text{g}/\text{m}^3$. Downward shortwave radiation ($SW_{\downarrow}$), upward shortwave
 128 radiation ($SW_{\uparrow}$), downward longwave radiation ($LW_{\downarrow}$), and upward longwave radiation
 129 ($LW_{\uparrow}$) were obtained from a four-component radiometer at the Tazhong station, with a
 130 temporal resolution of 1 hour and units of W/m^2 . The original observations at Tazhong
 131 were recorded in local time, which differs from Beijing time (BJT, UTC+8) by about
 132 2 h 25 min. To ensure temporal consistency among observations, model output, and
 133 reanalysis data, all data were converted to Beijing time during preprocessing.

134 2.3 WRF-Chem model setup

135 The WRF-Chem model was used to simulate three dust storm events in spring
 136 2025 (26 March, 3 May, and 20 May). The model used two nested domains (Table 1).
 137 The outer and inner domains had horizontal resolutions of 9 km and 3 km, with grid
 138 dimensions of 279×219 and 264×165 , respectively. The model top is set to 100 hPa,
 139 with 32 sigma levels. Meteorological initial and boundary conditions were taken from
 140 NCEP FNL global reanalysis data, with a 6-hour interval and a horizontal resolution
 141 of 0.25° . Aerosol and chemical processes were treated with the CUACE online
 142 coupling scheme.

143 To isolate the dust radiative feedback quantitatively, a control experiment (CTL)
 144 and a sensitivity experiment (SENS) were designed. In CTL, dust emission, transport,
 145 and aerosol–radiation interactions were enabled, and dust particles participated in
 146 both shortwave and longwave radiative transfer. In SENS, aerosol–radiation
 147 interactions were turned off, so dust did not participate in radiative transfer. The
 148 difference between the two experiments defines the dust radiative feedback:

$$149 \Delta X = X_{CTL} - X_{SENS}$$



150 where X is the corresponding physical variable.

151 **2.4 Aerosol optical depth (AOD) data**

152 Hourly total aerosol optical depth (AOD_{total}) and dust aerosol optical depth
153 (AOD_{dust}) at 550 nm from March to May 2025 were obtained from the NASA
154 MERRA-2 reanalysis via the Google Earth Engine (GEE,
155 <https://code.earthengine.google.com/>) cloud platform. The spatial resolution is
156 $0.5^\circ \times 0.625^\circ$, and the temporal resolution is 1 hour. The data were converted to
157 Beijing time, and the grid cell containing the Tazhong station was extracted for
158 validating the simulated AOD. MERRA-2 AOD_{dust} was used only for model validation
159 and was not included in the subsequent radiative forcing regression analysis.

160 **2.5 Methods**

161 **2.5.1 Dust emission and column mass diagnostics**

162 Based on WRF output variables such as dust concentration, emission flux,
163 column dust mass, and wind fields, the emission intensity, column mass, and transport
164 characteristics of the three dust storm events were diagnosed. When cumulative dust
165 emission variables EDUST1 to EDUST5 (units: kg/m^2) were available in the model
166 output, the daily cumulative dust emission was calculated as the difference between
167 the maximum and minimum cumulative values of each particle size bin on the event
168 day:

$$\Delta EDUST = (EDUST_{max} - EDUST_{min}) \times 1000 \quad (1)$$

169 The resulting values were converted to $g/(m^2 \cdot day)$ (Eq. 1). For the instantaneous
170 emission flux DUST_FLUX ($\mu g/(m^2 \cdot s)$), the flux was integrated over 24 hours (Eq.
171 2):

$$\text{Daily Dust Emission} = \frac{1}{10^6} \sum_{t=1}^{24} (DUST_FLUX_t \times 3600) \quad (2)$$

172 Both quantities characterize the daily cumulative dust emission per unit area.

173 At the time when the simulated near-surface PM_{10} concentration at Tazhong
174 reached its maximum during each dust storm event, the column-integrated dust



loadings for the five particle size bins (DUSTLOAD_1–DUSTLOAD_5, units: $\mu\text{g}/\text{m}^2$) were extracted from the WRF-Chem output at each horizontal grid cell. The total column dust loading was calculated by summing the contributions from all five size bins at each grid cell and converting the resulting values from $\mu\text{g}/\text{m}^2$ to mg/m^2 :

$$L_{\text{dust}}(i, j, t_p) = \frac{1}{1000} \sum_{k=1}^5 \text{DUSTLOAD}_k(i, j, t_p) \quad (3)$$

where L_{dust} is the total column dust loading (mg/m^2). i and j denote the horizontal grid indices, t_p denotes the time when the simulated near-surface PM_{10} concentration at Tazhong reaches its maximum, and k denotes the particle size bin. The 850 hPa horizontal wind components (U850 and V850) at the same time were also extracted to characterize the atmospheric transport of dust.

2.5.2 Surface radiative forcing and forcing efficiency

Surface shortwave, longwave, and net radiative forcings were defined as the differences between CTL and SENS in the corresponding surface net radiation fluxes:

$$\text{DRE}_{\text{sfc}, \text{SW}} = (\text{SWDOWN} - \text{SWUPB})_{\text{CTL}} - (\text{SWDOWN} - \text{SWUPB})_{\text{SENS}} \quad (4)$$

$$\text{DRE}_{\text{sfc}, \text{LW}} = (\text{GLW} - \text{LWUPB})_{\text{CTL}} - (\text{GLW} - \text{LWUPB})_{\text{SENS}} \quad (5)$$

$$\text{DRE}_{\text{sfc}, \text{NET}} = \text{DRE}_{\text{sfc}, \text{SW}} + \text{DRE}_{\text{sfc}, \text{LW}} \quad (6)$$

All radiative forcing terms are expressed in W/m^2 .

To quantify the surface shortwave radiative forcing efficiency per unit AOD, a linear regression was performed during daytime samples that met both of the following criteria: $\text{SWDOWN}_{\text{SENS}} > 10 \text{ W}/\text{m}^2$ and $\text{AOD}_{550} > 0.05$:

$$\text{DRFE}_{\text{sfc}} = \frac{d(\text{DRE}_{\text{sfc}, \text{SW}})}{d\tau_{550}} \quad (7)$$

where τ_{550} , representing AOD at 550 nm, was derived from the vertical integral of the aerosol extinction coefficient output by WRF. The regression slope is the surface shortwave radiative forcing efficiency, in units of $\text{W} (\text{m}^2 \cdot \tau)$ and represents the final fitted value. The MERRA-2 AOD_{dust} was used only to validate the simulated



195 WRF AOD₅₅₀ and was not included in this regression.

196 **2.5.3 Vertical radiative attenuation and atmospheric heating rate**

197 Based on the first law of thermodynamics and the theory of radiative flux
 198 divergence (Hogan et al., 2021; Guan et al., 2010), the net shortwave and longwave
 199 radiative fluxes at different heights were calculated.

200 The net shortwave and longwave radiative fluxes in layer k were calculated as
 201 follows:

$$F_{\text{net,SW}}(k) = F_{\text{SW}}^{\downarrow}(k) - F_{\text{SW}}^{\uparrow}(k) \quad (8)$$

$$F_{\text{net,LW}}(k) = F_{\text{LW}}^{\downarrow}(k) - F_{\text{LW}}^{\uparrow}(k) \quad (9)$$

202 where $F_{\text{SW}}^{\downarrow}(k)$ and $F_{\text{SW}}^{\uparrow}(k)$ denote the downward and upward shortwave
 203 radiative fluxes, respectively, and $F_{\text{LW}}^{\downarrow}(k)$ and $F_{\text{LW}}^{\uparrow}(k)$ denote the downward and
 204 upward longwave radiative fluxes, respectively, in layer k (W/m²).

205 The change in radiative flux caused by dust (ΔF_{net}) is expressed as the difference
 206 between CTL and SENS:

$$\Delta F_{\text{net,SW}}(k) = F_{\text{net,SW}}^{\text{CTL}}(k) - F_{\text{net,SW}}^{\text{SENS}}(k) \quad (10)$$

$$\Delta F_{\text{net,LW}}(k) = F_{\text{net,LW}}^{\text{CTL}}(k) - F_{\text{net,LW}}^{\text{SENS}}(k) \quad (11)$$

207 The shortwave, longwave, and all-wave net radiative heating rates were then
 208 calculated as follows:

$$\text{HR}_{\text{SW}}(k) = \frac{1}{\rho_k c_p} \frac{\Delta F_{\text{net,SW}}(k+1) - \Delta F_{\text{net,SW}}(k)}{Z_{k+1} - Z_k} \times 86400 \quad (12)$$

$$\text{HR}_{\text{LW}}(k) = \frac{1}{\rho_k c_p} \frac{\Delta F_{\text{net,LW}}(k+1) - \Delta F_{\text{net,LW}}(k)}{Z_{k+1} - Z_k} \times 86400 \quad (13)$$

$$\text{HR}_{\text{NET}}(k) = \text{HR}_{\text{SW}}(k) + \text{HR}_{\text{LW}}(k) \quad (14)$$

209 where HR_{SW} , HR_{LW} , and HR_{NET} denote the atmospheric shortwave heating rate,
 210 longwave cooling rate, and all-wave net radiative heating rate, respectively (K/day);

211 $\rho_k = \frac{P_k}{R_d T_k}$ is the air density of layer k (kg/m³), calculated from the actual pressure P_k
 212 and temperature T_k of that layer: $R_d = 287.05$ J/(kg·K) is the gas constant for dry
 213 air; $c_p = 1005$ J/(kg·K) is the specific heat capacity of dry air at constant pressure;



214 $Z_{k+1} - Z_k$ is the geometric thickness of layer k (m); and 86400 is the time
215 conversion factor (converting K/s to K/day).

216 **2.5.4 Surface albedo and rear-side irradiance of bifacial PV**

217 The Briegleb parameterization was used to calculate the desert surface albedo for
218 varying solar zenith angles:

$$\alpha(\theta_z) = \alpha_0 \cdot \frac{1 + c}{1 + 2c \cos \theta_z} \quad (15)$$

219 where $\alpha(\theta_z)$ is the actual albedo at solar zenith angle θ_z ; α_0 is the noon
220 reference albedo, taken as 0.38 (an empirical value for desert surfaces); θ_z is the
221 solar zenith angle; $\cos \theta_z$ is the cosine of the zenith angle; and c is the surface
222 anisotropic scattering coefficient, taken as the classical Briegleb value of 0.4. This
223 equation was used to calculate the ground-reflected gain on the rear side of bifacial
224 modules. In this study, the plane-of-array irradiance (POA) refers to the total
225 tilted-plane irradiance of the bifacial glass–glass modules, i.e., the sum of the
226 front-side and rear-side irradiance. The enhancement of rear-side light reception by
227 dust is inferred indirectly from the increase in the diffuse fraction and the change in
228 surface albedo; the rear-side irradiance component was not separately isolated or
229 quantified in the model.

230 **2.5.5 Photovoltaic generation and bifacial-gain calculation**

231 Photovoltaic generation was computed from the WRF-Chem radiation and
232 meteorological variables, taking a 100 MW centralized PV plant in Qiemu County as
233 the reference and including the bifacial gain. The actual generation (E , in MWh)
234 calculated as follows (Li et al., 2020; Chen et al., 2020; Guerrero-Lemus et al., 2016):

$$E = H \cdot P \cdot \eta \cdot (1 + A_y) \quad (16)$$

235 where H is the theoretical utilization time corresponding to the tilted-plane total
236 irradiance (h), P is the installed capacity (100 MW), η is the system efficiency (83%),
237 and A_y is the bifacial rear-side gain:

$$A_y = Al \cdot bif \cdot \left[H \cdot \left(a - \frac{1}{\sqrt{A}} \right) \cdot \left(1 - e^{-\frac{b \cdot H}{A}} \right) + c \cdot \left(1 - \frac{1}{A^4} \right) \right] \quad (17)$$



where A is the module spacing (8 m), H is the module mounting height (1 m), Al is the surface albedo, and bif is the bifacial factor (0.7); the empirical bifacial-gain coefficients are $a = 1.031$, $b = 8.691$, and $c = 0.125$.

The module operating temperature (T_{cell} , in °C) is estimated from air temperature and radiation:

$$T_{cell} = 1.07 \times T_{air} + 6.12 \quad (18)$$

where T_{air} is the ambient temperature (°C). For high-temperature periods with $T_{cell} \geq 25$ °C, a GHI-based second-order correction is applied:

$$T_{cell} = (T_{air} + 2.64) + 0.017 \times GHI \quad (19)$$

The all-period temperature correction factor c_T is defined as:

$$c_T = 1 - \frac{N_1 + N_2 \times [1 - \gamma(\bar{T} - 25)]}{N_0} \quad (20)$$

where N_1 and N_2 are the number of daytime hours with module temperature below and above 25 °C, respectively; N_0 is the total number of daytime hours in a year; $\bar{T}$ is the mean temperature during hours above 25 °C; and $\gamma = -0.34\%/^{\circ}\text{C}$ is the module temperature coefficient used to account for power losses associated with high temperature.

Table 1 Definitions of observational, model output, and diagnostic variables.

Variable name/abbreviation	Description	Unit
Observations	SW_d / SW_u	Surface downward/upward shortwave radiation W/m ²
	LW_d / LW_u	Surface downward/upward longwave radiation W/m ²
	Wind	Surface wind speed m/s
	PM ₁₀ / PM _{2.5}	Near-surface particulate matter concentration µg/m ³
Model output	GHI (SWDOWN)	Surface downward total shortwave radiation W/m ²
	SWUPB	Surface upward shortwave radiation W/m ²
	GLW	Surface downward longwave radiation W/m ²
	LWUPB	Surface upward longwave radiation W/m ²
	DIR (SWDDIR)	Surface direct downward shortwave radiation W/m ²
	DIF (SWDDIF)	Surface diffuse downward shortwave radiation W/m ²
	OLR	Outgoing longwave radiation at top of atmosphere W/m ²
	EDUST1–EDUST5	Dust emission by particle size bin kg/m ²
	DUSTLOAD_1–DUSTLOAD_5	Column dust mass by particle size bin µg/m ²



	PM ₁₀	Simulated near-surface PM ₁₀	µg/m ³
	Total Dust Loading	Total column dust mass	mg/m ²
	T2	2 m air temperature	K
	WSPD10	10 m wind speed	m/s
	PBLH	Planetary boundary layer height	m
Diagnostic/calculated variables	AOD _{total}	Total aerosol optical depth (MERRA-2, 550 nm)	dimensionless
	AOD _{dust}	Dust aerosol optical depth (MERRA-2, 550 nm)	dimensionless
	AOD ₅₅₀	Aerosol optical depth from vertical integration of WRF extinction	dimensionless
	ΔEDUST	Daily cumulative dust emission	g/m ² /day
	K _d	Diffuse radiation fraction, K _d = DIF/GHI	dimensionless
	DIR/DIF	Direct/diffuse radiation ratio	dimensionless
	DRE _{sfc,SW}	Surface shortwave radiative forcing	W/m ²
	DRE _{sfc,LW}	Surface longwave radiative forcing	W/m ²
	ΔNet _{surf}	Surface net radiative forcing	W/m ²
	DRFE _{sfc}	Surface shortwave radiative forcing efficiency	W/(m ² ·τ)
	F _{net}	Surface net radiation	W/m ²
	SW _{heat_rate}	Shortwave heating rate	K/day
	LW _{cool_rate}	Longwave cooling rate	K/day
	Albedo	Surface shortwave albedo	dimensionless

252 3 Results and Analysis

253 3.1 Model performance and validation of dust event evolution

254 3.1.1 Characteristics of dust events and simulation evaluation

255 Figure 2 shows the observed time series for the three dust storms on 26 March, 3
 256 May, and 20 May. The near-surface PM₁₀ concentration increased rapidly as wind
 257 speed increased. The daily peak PM₁₀ concentrations were 19888.1, 16438.5, and
 258 8745.8 µg/m³, respectively, while the corresponding increases in daily mean PM₁₀
 259 concentration above background levels were 11782.7, 2504.3, and 2602.1 µg/m³,
 260 respectively. The 26 March storm lasted about 22 h. The daily cumulative downward
 261 shortwave radiation ($SW_{\downarrow}$) decreased by 19.08 MJ/m² relative to the background,
 262 corresponding to a reduction of 92%. The downward longwave radiation ($LW_{\downarrow}$)
 263 increased by 5.85 MJ/m², while the change in surface net radiation was −5.42 MJ/m².
 264 The 3 May and 20 May events lasted about 11 h and 6 h, respectively. The $SW_{\downarrow}$
 265 decreased by 20.77 and 13.40 MJ/m² relative to the background, corresponding to
 266 reductions of 77% and 49.8%, respectively. Surface net radiation decreased by 7.69



267 and 4.45 MJ/m², respectively.

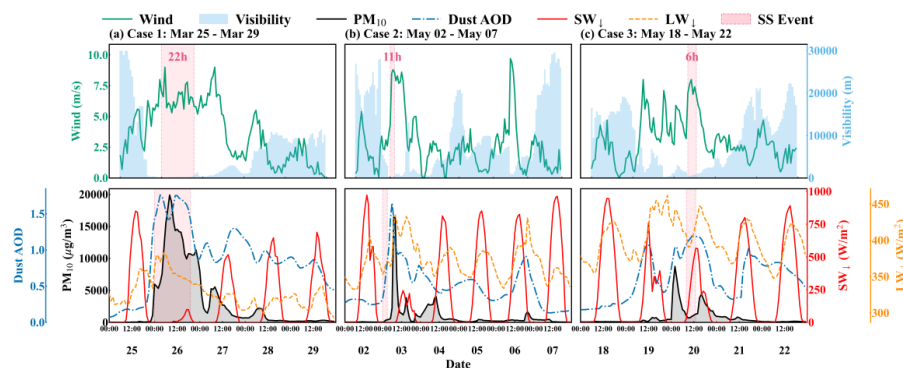


Figure 2 Observed time series of the three dust storm events based on measurements.

Figure 3 shows the WRF-Chem validation results and statistical metrics for the three dust events. The correlation coefficients (R) between the simulated and observed PM_{10} at the Tazhong station were 0.86, 0.27, and 0.26 for the three events, respectively. The correlation coefficients between the simulated AOD_{550} and the MERRA-2 dust AOD (AOD_{dust}) were 0.781, 0.465, and 0.538, respectively. In terms of event evolution, the model reproduced the onset time, magnitude, and duration of the all three dust events. The simulation performed well for the 26 March event, whereas the correlations were lower for the two May events. In terms of magnitude, the simulated peak PM_{10} concentrations were 11004.17, 6365.63, and 4415.80 $\mu\text{g}/\text{m}^3$, respectively. These values were of the same order of magnitude as the observed peaks, indicating that the model captured the relative intensity ranking of the three events. For radiation, the model slightly overestimated the shortwave and underestimated longwave radiation, but captured the abrupt changes in radiation around dust onset and dissipation.

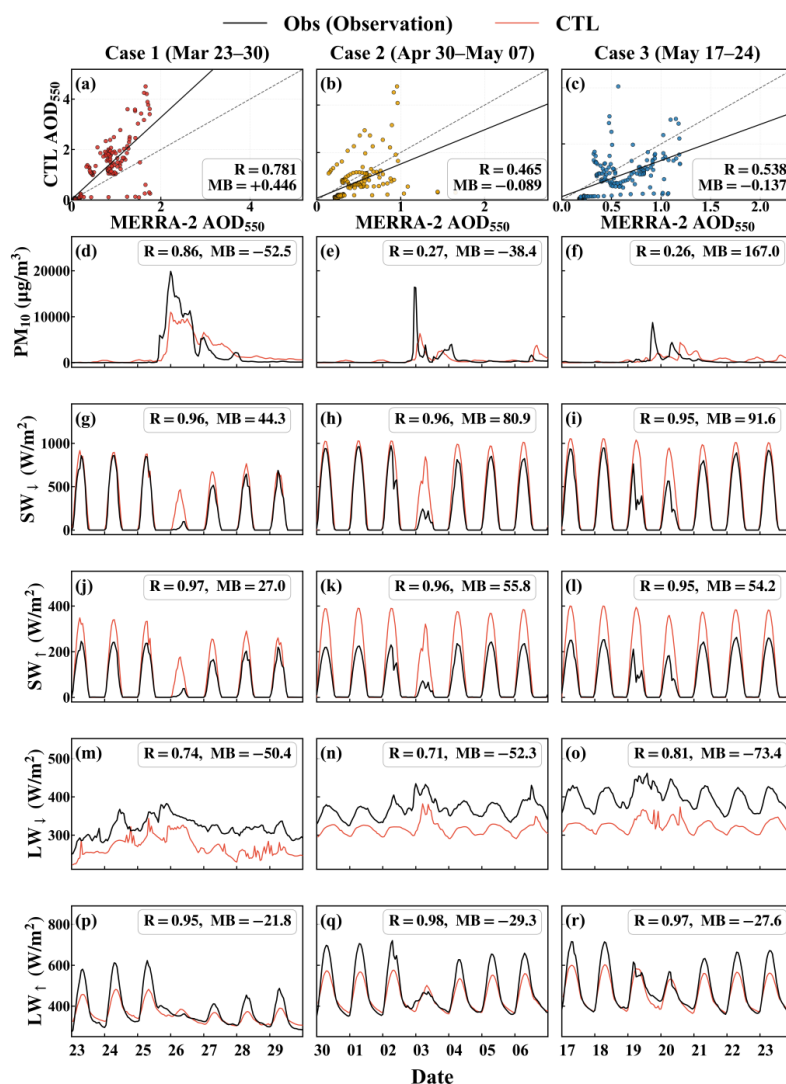


Figure 3 Validation of WRF CTL results against measurements.

3.1.2 Spatial distribution of dust sources and vertical structure of dust

Figure 4 shows the spatial distributions of daily cumulative dust emission ($\text{g}/(\text{m}^2 \cdot \text{day})$) and total dust loading (mg/m^2) for the three dust storms. The two quantities exhibit distinct spatial patterns. For surface dust emission (left column of Fig. 4), the area of strongest emission on 26 March was concentrated along the northeastern edge of the desert, where the maximum daily cumulative emission reached $83.16 \text{ g}/(\text{m}^2 \cdot \text{day})$, compared with $11.04 \text{ g}/(\text{m}^2 \cdot \text{day})$ at the Tazhong station. On



293 3 May, the emission band extended southwest from the northeast part of the desert,
294 with a daily cumulative dust emission of $3.77 \text{ g}/(\text{m}^2 \cdot \text{day})$ at Tazhong. On 20 May, the
295 emission area was more dispersed, with a corresponding value of $3.70 \text{ g}/(\text{m}^2 \cdot \text{day})$ at
296 Tazhong. Dust emissions at Tazhong decreased across the three events, consistent
297 with the simulated peak near-surface PM_{10} concentrations of 11004.17, 6365.63, and
298 $4415.80 \mu\text{g}/\text{m}^3$, respectively. The ranking of these simulated peaks was also consistent
299 with that of the observed peaks (19888.1, 16438.5, and $8745.8 \mu\text{g}/\text{m}^3$, respectively).

300 The total loading at the time of peak near-surface PM_{10} concentration, together
301 with the 850 hPa wind field (right column of Fig. 4), indicates that dust was
302 transported toward the central-eastern basin under the influence of the 850 hPa flow,
303 forming continuous dust belts. On 26 March and 3 May, dust plumes with high
304 column loadings passed directly over the Tazhong station, with column-integrated
305 dust loadings of 6541.35 and $4057.64 \text{ mg}/\text{m}^2$, respectively. On 20 May, surface dust
306 emission was the lowest of the three events. However, under sustained easterly
307 transport and the influence of the western basin's topography, dust converged toward
308 the east, where the regional maximum total dust loading reached $10698.57 \text{ mg}/\text{m}^2$,
309 while the loading over Tazhong was $4508.99 \text{ mg}/\text{m}^2$. These results indicate that
310 near-surface wind erosion controls the emission strength at the source, while dust
311 transport and topography further shape the spatial distribution and accumulation of
312 dust aloft.

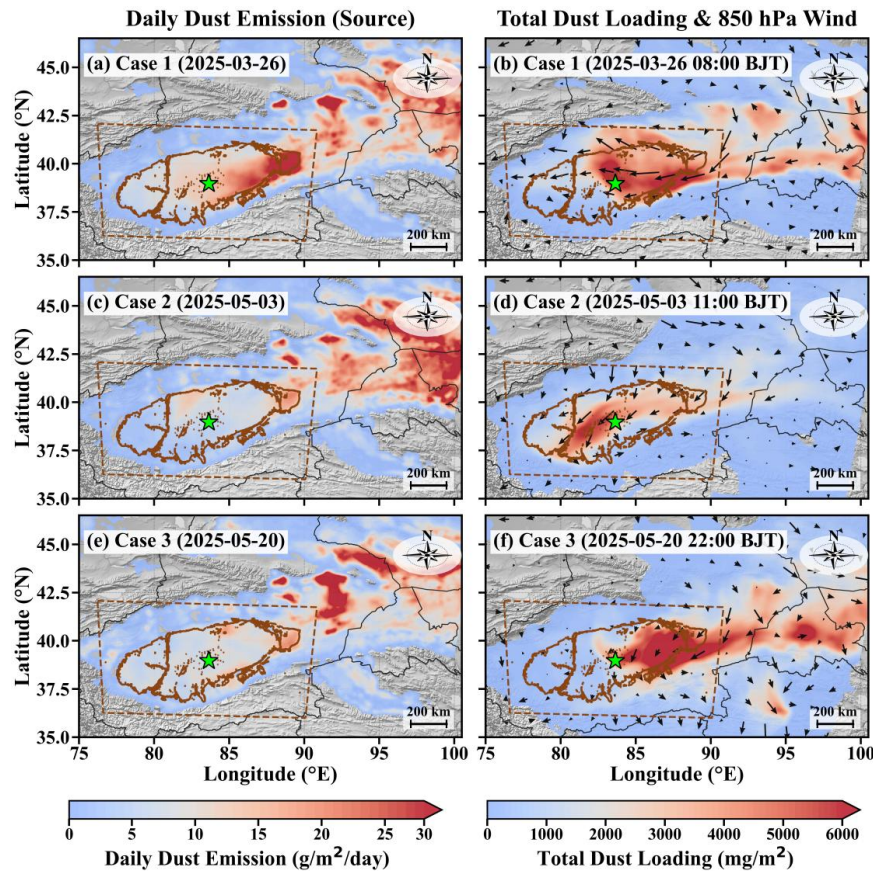


Figure 4 Surface wind erosion source intensity and total column dust mass distribution for the three dust storms.

3.2 Quantitative analysis of dust radiative effects and radiative forcing

3.2.1 Effects of dust on surface radiation components and direct radiative forcing

Figure 5 shows the hourly evolution of the surface radiation components, the diffuse fraction (K_d), the direct-to-diffuse ratio (DIR/DIF), and the simulated dust concentration at the Tazhong station during the three dust storms. In the SENS experiment, in which dust–radiation interaction were disabled, the surface global horizontal irradiance (GHI, i.e., SWDOWN) exhibited a typical single-peak diurnal cycle, with a midday maximum of about 1000 W/m², dominated by the direct component (DIR, i.e., SWDDIR). In the CTL experiment, in which dust–radiation



326 feedback was enabled, surface solar radiation was markedly reduced. The 26 March
327 storm lasted about 22 h. The simulated near-surface PM_{10} concentration peaked at
328 $11004.17 \mu\text{g}/\text{m}^3$, while the peak and mean AOD_{550} values during the dust period were
329 4.505 and 2.560, respectively. The change in direct radiation reached $-817.46 \text{ W}/\text{m}^2$,
330 while diffuse radiation (DIF, i.e., SWDDIF) increased by up to $388.12 \text{ W}/\text{m}^2$. Peak
331 total irradiance decreased by $455.54 \text{ W}/\text{m}^2$, and the mean attenuation of total
332 irradiance over the dust period was 47.8%. On 3 May and 20 May, diffuse radiation
333 increased by up to 566.26 and $528.26 \text{ W}/\text{m}^2$, respectively, while the mean attenuation
334 of total irradiance over the respective dust periods was 30.1% and 23.4%,
335 respectively.

336 Dust markedly changed the composition of the solar radiation reaching the
337 surface. During non-dust background periods, K_d was generally 0.15–0.30, and
338 DIR/DIF could reach 4.5–5.5. After dust onset, K_d rose rapidly and exceeded 0.80,
339 indicating a clear increase in the proportion of diffuse radiation in surface shortwave
340 radiation. During the core period of the 26 March storm, the mean K_d was 0.992, and
341 DIR/DIF approached 0. The mean K_d values over the dust periods on 3 May and 20
342 May was 0.836 and 0.641, respectively. Across the three events, increasing dust
343 loading was associated with stronger attenuation of direct radiation and a shift in
344 surface radiation from a direct-dominated to a diffuse-dominated state. In addition,
345 the simulated near-surface PM_{10} concentration remained at $6008.29 \mu\text{g}/\text{m}^3$ for 6 h
346 after the 26 March storm ended, indicating that surface radiation remained strongly
347 affected during the dust dissipation stage.

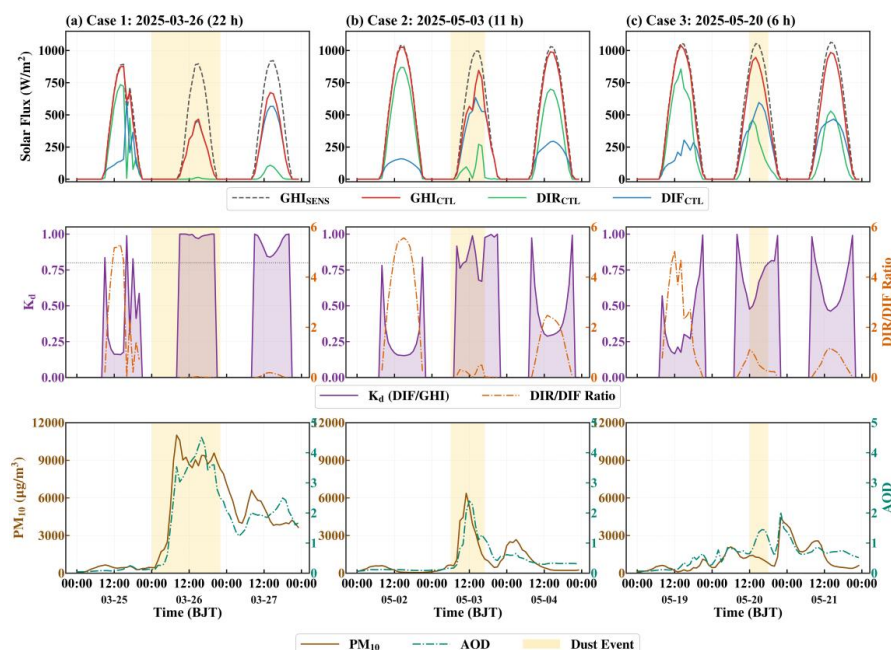


Figure 5 Evolution of surface solar radiation components, scattering characteristics, and dust loading at Tazhong during the three dust events.

Note: Top panels show total radiation (GHI), direct radiation (DIR), and diffuse radiation (DIF) with dust feedback on and off; middle panels show the diffuse radiation fraction (K_d) and direct/diffuse ratio (DIR/DIF); bottom panels show the simulated near-surface PM_{10} concentration and aerosol optical depth (AOD_{550}). The yellow shaded areas indicate dust weather periods.

Figure 6 further shows the surface shortwave and longwave radiative forcing (DRF_{sfc}) during the three dust storms, together with the linear relationships between the surface shortwave radiative forcing ($f_{SW,SRF}$) and AOD_{550} . The slopes of the fitted regression lines represent the surface shortwave radiative forcing efficiencies.

In the shortwave band, dust scattering and absorption reduced the shortwave radiation reaching the surface, making the surface shortwave radiative forcing negative ($DRF_{SW}^{SFC} < 0$). During the 26 March dust storm, the strongest shortwave cooling forcing reached -282.43 W/m^2 , with a daytime mean of -172.91 W/m^2 . The strongest shortwave cooling forcing on 3 May and 20 May was -254.49 and -117.35 W/m^2 , respectively. In the longwave band, dust absorbed surface longwave



radiation and re-emitted part of it downward, resulting in positive surface longwave
 radiative forcing ($\text{DRF}_{\text{SW}}^{\text{SFC}} < 0$). The maximum longwave warming forcing values for
 the three events were 89.11, 77.55, and 51.86 W/m^2 , respectively, while the
 dust-period mean values ranged from 33.09–39.72 W/m^2 .

Daytime regression analyses showed that the surface shortwave radiative forcing
 was significantly and negatively correlated with AOD550 in all three events, with
 absolute correlation coefficients of 0.80–0.92 ($P < 0.001$). The corresponding surface
 shortwave radiative forcing efficiencies ($f_{\text{SW,SRF}}$) were -50.6 , -80.7 , and -71.9
 $\text{W}/(\text{m}^2 \cdot \tau)$ per unit AOD, respectively, indicating that surface shortwave radiative
 forcing decreased by approximately 50.6 – 80.7 $\text{W}/(\text{m}^2 \cdot \tau)$ per unit increase in AOD₅₅₀.
 The absolute forcing efficiencies on 3 May and 20 May were higher than on 26 March,
 possibly related to the higher solar elevation angle and stronger incident shortwave
 radiation in May.

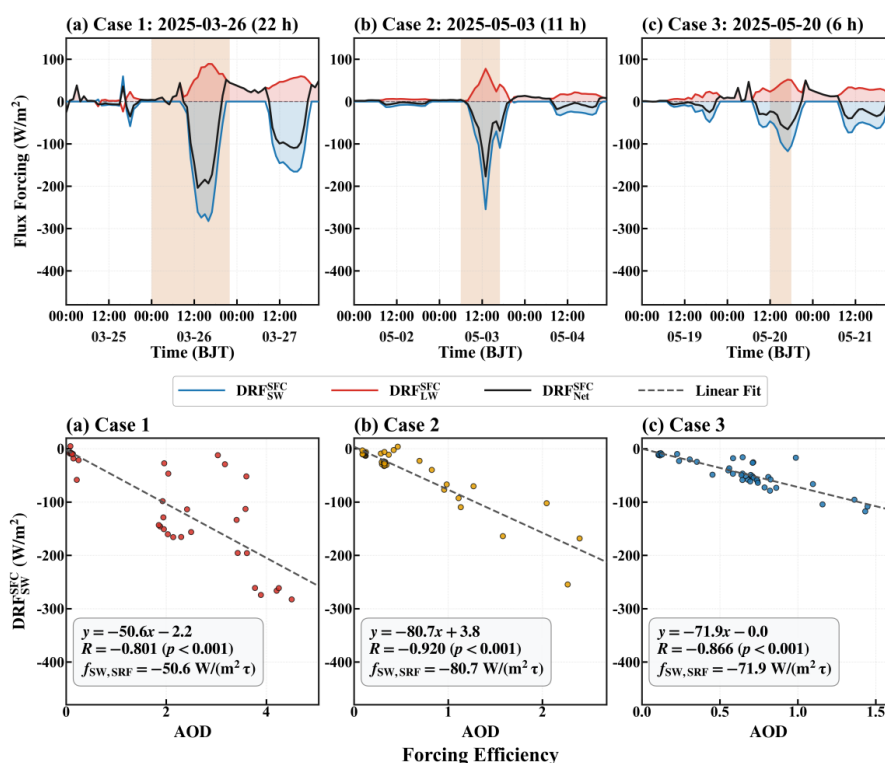


Fig 6 Surface direct radiative effects and shortwave radiative forcing efficiency fits for the three dust



380 storms.

381 Note: Top panels show the hourly time series of surface shortwave radiative forcing, longwave radiative forcing
 382 (DRF_{SW}^{SFC}), and total net direct radiative forcing (DRF_{LW}^{SFC}); the warm sand-colored shaded areas indicate dust
 383 storm periods. Bottom panels show the scatter distribution and linear regression fits of daytime surface shortwave
 384 direct radiative forcing against dust aerosol optical depth (DRF_{Net}^{SFC}) during effective daylight hours; the fitting
 385 equation, radiative forcing efficiency (AOD_{550}), correlation coefficient ($f_{SW,SRF}$), and P value are given in the
 386 boxes.

387 **3.2.2 Spatial distributions of surface and atmospheric dust radiative forcing**

388 Figure 7 shows the spatial distributions of surface and atmospheric radiative
 389 forcing during the three dust storms. Overall, the dust radiative effects were
 390 characterized by reduced surface shortwave radiation, increased surface longwave
 391 radiation, and atmospheric shortwave absorption accompanied by atmospheric
 392 heating.

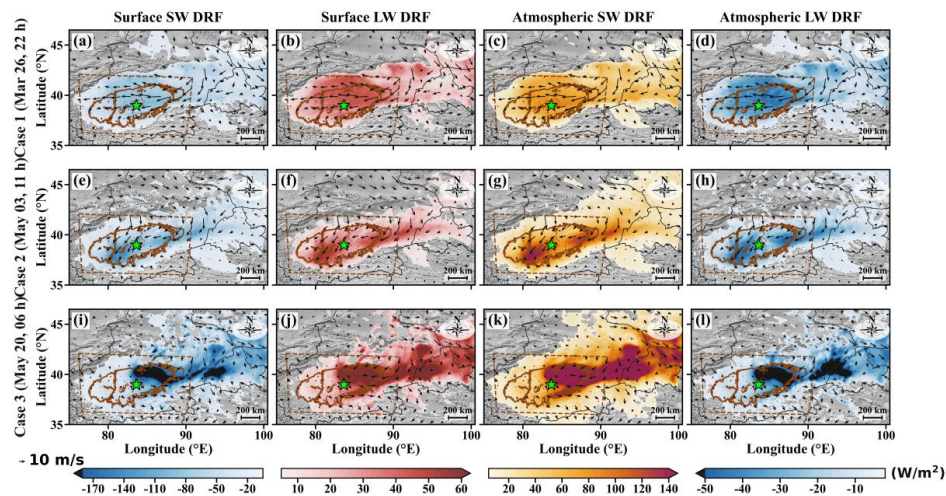
393 The surface shortwave radiative forcing (DRF_{SW}^{SFC} , Fig. 7a,e,i) was negative
 394 across the study region. During the 20 May event, surface shortwave attenuation was
 395 strongest, with the most negative regional value reaching -307.54 W/m^2 and a
 396 regional mean of -19.94 W/m^2 . The most negative regional values on 26 March and 3
 397 May were -105.70 and -154.92 W/m^2 , respectively, with corresponding regional
 398 means of approximately -10.27 and -10.39 W/m^2 . The areas of stronger shortwave
 399 attenuation broadly coincided with the dust transport belt guided by the 850 hPa
 400 easterly flow.

401 The surface longwave radiative forcing (DRF_{LW}^{SFC} , Fig. 7b,f,j) was predominantly
 402 positive. The regional maximum values of surface longwave warming forcing for the
 403 three events were 48.59 , 62.00 , and 110.32 W/m^2 , respectively, while the regional
 404 mean values ranged from 3.99 to 7.56 W/m^2 . The spatial distribution of longwave
 405 forcing was smoother, and its influence extended over a broader area.

406 The atmospheric shortwave radiative forcing (DRF_{SW}^{ATM} , Fig. 7c,g,k) was
 407 predominantly positive, with high-value areas broadly corresponding to regions of



408 strong surface shortwave attenuation. The regional maximum atmospheric shortwave
409 heating values on 20 May, 3 May, and 26 March were 310.36, 161.20, and 91.95
410 W/m^2 , respectively. The corresponding regional mean atmospheric shortwave
411 absorption values were 23.25, 11.13, and 9.87 W/m^2 respectively. The atmospheric
412 longwave radiative forcing ($\text{DRF}_{\text{LW}}^{\text{ATM}}$, Fig.7d,h,l) was predominantly negative, with
413 regional means values ranging from -5.26 to -3.42 W/m^2 . This indicating that the dust
414 layer absorbed longwave radiation from the surface and atmosphere while also
415 emitting longwave radiation, thereby contributing to atmospheric cooling.



416
417 **Figure 7** Spatial distribution of mean radiative forcing and the 850 hPa steering wind field during the
418 three dust storms.

419 Note: From left to right: surface shortwave radiative forcing, surface longwave radiative forcing,
420 in-atmosphere shortwave absorption forcing, and in-atmosphere longwave cooling forcing. The dashed
421 circle marks the Taklimakan Desert boundary, and the star marks the Tazhong station.

422 Table 2 summarizes the event-mean radiative forcing at three spatial scales—the
423 Tazhong station, the regional mean, and the regional extreme—for each of the three
424 dust storms. The comparison indicates that dust-induced surface shortwave attenuation
425 was spatially concentrated. At Tazhong, the event-mean surface shortwave radiative
426 forcing ($\text{DRF}_{\text{SW}}^{\text{SFC}}$) ranged from -90.52 to -84.46 W/m^2 , approximately 4–9 times the
427 magnitude of the corresponding regional means (-19.94 to -10.27 W/m^2). The



strongest regional shortwave attenuation occurred on 20 May, when the most negative regional value reached -307.54 W/m^2 , indicating that the strongest shortwave loss was concentrated in areas with high dust loading.

The spatial variation in surface longwave warming is smaller than that in shortwave attenuation. At Tazhong, the event-mean surface longwave radiative forcing ($\text{DRF}_{\text{LW}}^{\text{SFC}}$) ranged $33.09\text{--}39.72 \text{ W/m}^2$, approximately 5.3–8.3 times the corresponding regional mean. The regional maximum longwave forcing values ranged $48.59\text{--}110.32 \text{ W/m}^2$, with the highest value occurring on 20 May.

The atmospheric shortwave radiative forcing ($\text{DRF}_{\text{SW}}^{\text{ATM}}$) at Tazhong ranged $86.56\text{--}102.99 \text{ W/m}^2$, comparable in magnitude to the corresponding surface shortwave reduction (-84.46 to -90.52 W/m^2). This indicates that a substantial portion of the lost surface solar radiation was absorbed by the dust layer. Meanwhile, the atmospheric longwave radiative forcing ($\text{DRF}_{\text{LW}}^{\text{ATM}}$) at Tazhong ranged from -39.67 to -23.20 W/m^2 , with absolute magnitudes larger than those of the corresponding regional mean values (-5.26 to -3.42 W/m^2). The coexistence of surface cooling and atmospheric heating alters the near-surface thermal structure and may enhance lower-atmospheric stability.

Table 2 Multiscale comparison of dust radiative forcing during the three dust storm events.

Dust event	Spatial scale	Surface shortwave radiative forcing $\text{DRF}_{\text{SW}}^{\text{SFC}}$ (W/m^2)	Surface longwave radiative forcing $\text{DRF}_{\text{LW}}^{\text{SFC}}$ (W/m^2)	Atmospheric shortwave radiative forcing $\text{DRF}_{\text{SW}}^{\text{ATM}}$ (W/m^2)	Atmospheric longwave radiative forcing $\text{DRF}_{\text{LW}}^{\text{ATM}}$ (W/m^2)
Case 1 (26 March; 22h)	Tazhong station	-90.21	+39.15	+86.56	-39.67
	Regional mean	-10.27	+5.28	+9.87	-4.93
	Regional extreme	-105.70	+48.59	+91.95	-50.58
Case 2 (3 May; 11 h)	Tazhong station	-90.52	+33.09	+91.57	-23.20
	Regional mean	-10.39	+3.99	+11.13	-3.42
	Regional	-154.92	+62.00	+161.20	-55.43



	extreme				
	Tazhong	−84.46	+39.72	+102.99	−28.93
	station				
Case 3 (20 May; 06 h)	Regional mean	−19.94	+7.56	+23.25	−5.26
	Regional	−307.54	+110.32	+310.36	−98.93
	extreme				

446 **3.2.3 Vertical structure of dust radiative forcing and atmospheric heating rate**

447 To analyze dust-induced shortwave attenuation at different altitudes and its effect
448 on atmospheric heating, this section examines the vertical radiation budget above the
449 Tazhong station during the three dust storms. The radiative heating rate (K/day)
450 describes the rate of temperature change caused by radiative processes (Huang et al.,
451 2009), while the planetary boundary layer height (PBLH) characterizes the depth of
452 the planetary boundary layer, where near-surface thermal and dynamical processes
453 dominate. Figure 8 shows the event-mean vertical profiles of dust-induced changes in
454 net shortwave radiation, atmospheric shortwave heating rate, and dust mass
455 concentration.

456 Figure 8a shows that shortwave radiation is progressively attenuated by dust as it
457 propagates downward from upper levels to the surface. Above 4 km, where the dust
458 concentration are low, the change in net shortwave radiation is weak, ranging from
459 −0.67 to −0.01 W/m² and remaining close to zero. Once the radiation enters the main
460 dust layer, the attenuation strengthens progressively with decreasing altitude and
461 reaches its largest absolute magnitude near the surface (−90.52 to −84.46 W/m²). On
462 20 May, dust was distributed higher, extending above 3 km, with noticeable
463 attenuation already occurring near 3 km. In contrast, on 26 March, dust was
464 concentrated near the surface, and the attenuation occurred mainly below 1 km.

465 The atmospheric shortwave heating rate and the dust mass concentration show
466 similar vertical distributions (Fig. 8b,c). On 26 March and 3 May, the maximum
467 near-surface heating rates reached 12.61 and 11.49 K/day, respectively, both occurring
468 in the dust-rich near-surface layer. With increasing altitude, dust concentrations and
469 heating rates decreased, with the heating rates declining rapidly toward 0 K/day above



the corresponding PBLH (0.40–2.18 km). These results indicate that the vertical extent of the dust layer directly determines the altitude range of atmospheric shortwave absorption and heating.

The vertical structures of the three events differ markedly. On 26 March and 3 May, dust was concentrated at low levels, with the maximum heating rate occurring near the surface. On 20 May, dust was lifted above 3 km, and the heating extended to higher altitudes. The radiative influence of the latter event therefore extended beyond the boundary layer into the free atmosphere above.

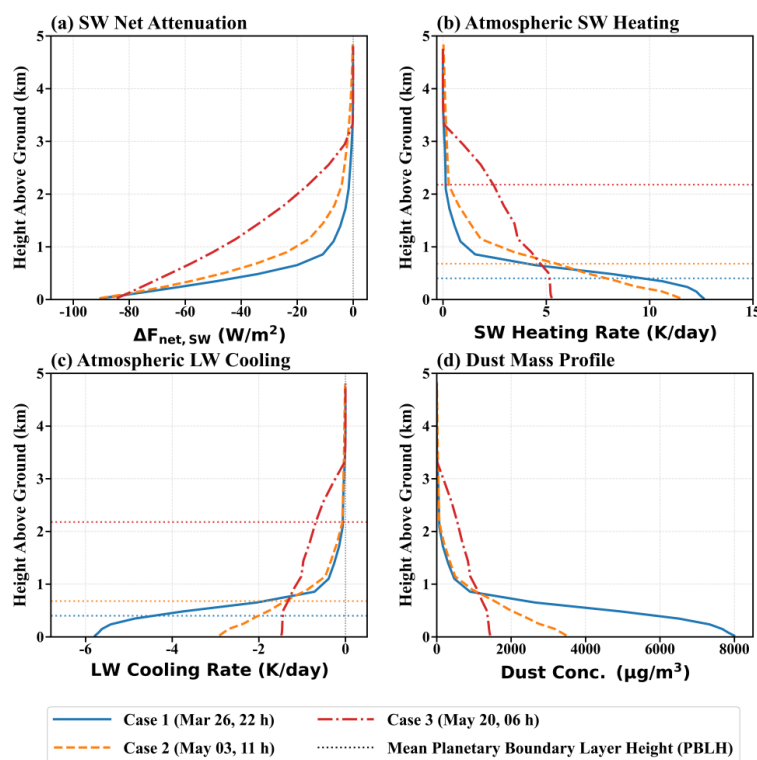


Fig 8 Vertical profiles of net shortwave radiation attenuation (a), atmospheric shortwave heating rate (b), and dust mass concentration (c) during dust periods.

Note: The horizontal dotted lines in panel b indicate the mean PBLH during the dust period for each event; the curves represent the vertical variation from 0 to 5 km.

Figure 9 shows a longitude–height cross-section along 39°N passing through the Tazhong station, with height expressed in kilometres above sea level (ASL) using



485 geopotential height. The figure presents the daily-mean dust concentration and
486 radiative heating characteristics for the three dust storms.

487 The daily-mean dust concentration and its vertical distribution (Fig. 9a), reveal
488 distinct transport and vertical-lifting characteristics among the three events. The 26
489 March event occurred in early spring, when dust was mainly confined to a shallow
490 layer extending from 76.0°E–90.0°E, with a peak concentration of 8238.4 $\mu\text{g}/\text{m}^3$ and
491 the top of the main dust-layer remaining below 3.35 km. The 20 May event exhibited
492 a greater vertical extent, with a maximum daily-mean dust height of 5.07 km, clearly
493 higher than those of the two earlier events.

494 The daily-mean radiative heating and cooling structure (Fig.9b,c) show that
495 shortwave absorption within the dust layer produces atmospheric heating, whereas
496 longwave radiation effects produce cooling. The maximum daily-mean shortwave
497 heating rates for the three events were 5.94, 10.99, and 17.38 K/day for 26 March, 3
498 May, and 20 May, respectively, while the extreme longwave cooling rates ranged from
499 -9.38 to -5.34 K/day. When the shortwave and longwave effects are combined (Fig.
500 9d), the net radiative heating rate is generally positive in the dust-affected region, with
501 local values ranging from 0.60 to 8.00 K/day. These results indicate that, even in the
502 24 h daily mean, shortwave absorption by dust exceeds the longwave radiative
503 cooling, resulting in net radiative heating of the dust layer. Together with the reduced
504 surface shortwave radiation, this process alters the radiative energy partitioning in the
505 near-surface atmosphere.

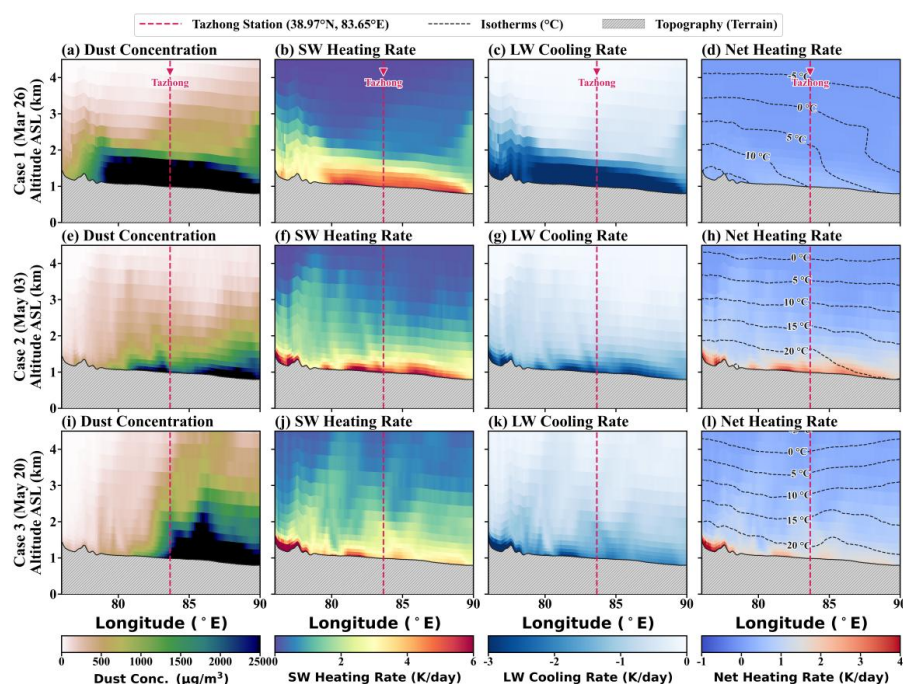


Figure 9 Longitude–height distribution along the 39°N cross-section of all-day mean dust mass concentration (a), shortwave heating rate (b), longwave cooling rate (c), and net radiative heating rate with isotherms (d) for the three dust days.

Note: The gray shaded area represents the actual basin topography, and the magenta vertical dashed line marks the Tazhong station at 83.65°E. The black dashed lines are atmospheric isotherms (°C). All variables are all-day averages from 00:00 to 23:00 BJT on the dust days.

3.3 Impact of dust radiative effects on PV irradiance and power generation

Using the radiation and meteorological variables simulated by WRF-Chem to drive the PV output model described in Sect. 2.5.5, we estimated the PV power loss attributable to dust radiative effects by comparing the simulated generation between the CTL and SENS experiments. When the CTL results were compared with the observed (Obs) daily generation for the three dust events, the correlation coefficient (R) between simulated and observed daily generation was 0.985 for the 26 March storm, with a root mean square error (RMSE) of 123.33 MWh and a mean bias (MB) of +24.08 MWh. The corresponding R values for the 3 May and 20 May events were



0.899 and 0.667, respectively. The R values for the equivalent utilization hours (H_{day}) across the three events were 0.989, 0.928, and 0.662, respectively, while those for the temperature correction factor (c_T) were 0.985, 0.915, and 0.920, respectively. Overall, the CTL experiment reproduced the PV generation variations of the three events reasonably well, providing a basis for further comparison with the SENS experiment.

Figure 10 shows the plane-of-array irradiance (POA), the simulated daily generation (E_{CTL}), and the absolute and relative changes between the CTL and SENS experiments during the six days periods preceding and following each dust event. After the strong 26 March storm, the daily cumulative POA dropped from the SENS background value of 20.44 MJ/m² to 10.01 MJ/m², a change of −10.43 MJ/m². The simulated daily generation dropped from 537.33 to 263.49 MWh, a decrease of 273.84 MWh (50.96%). From 27 to 29 March, under the continued influence of dust and residual airborne dust, daily generation remained 17.83%–26.81% below the background level. The 3 May storm reduced daily generation by 117.19 MWh (18.68%). The 20 May event had a shorter duration and lower simulated peak PM₁₀ concentration than the two earlier events. Its generation decreased by 11.82 MWh, corresponding to a 1.87% reduction.

On clear-sky or low-aerosol background days around the three events, the relative changes in daily generation were mainly in the range of −1.5% to +3.9%. This indicates that, under low aerosol loading, enhanced diffuse radiation and lower module temperature can partially offset reductions in PV output during certain periods. However, this compensation is clearly smaller than the direct radiation loss caused by strong dust storms.

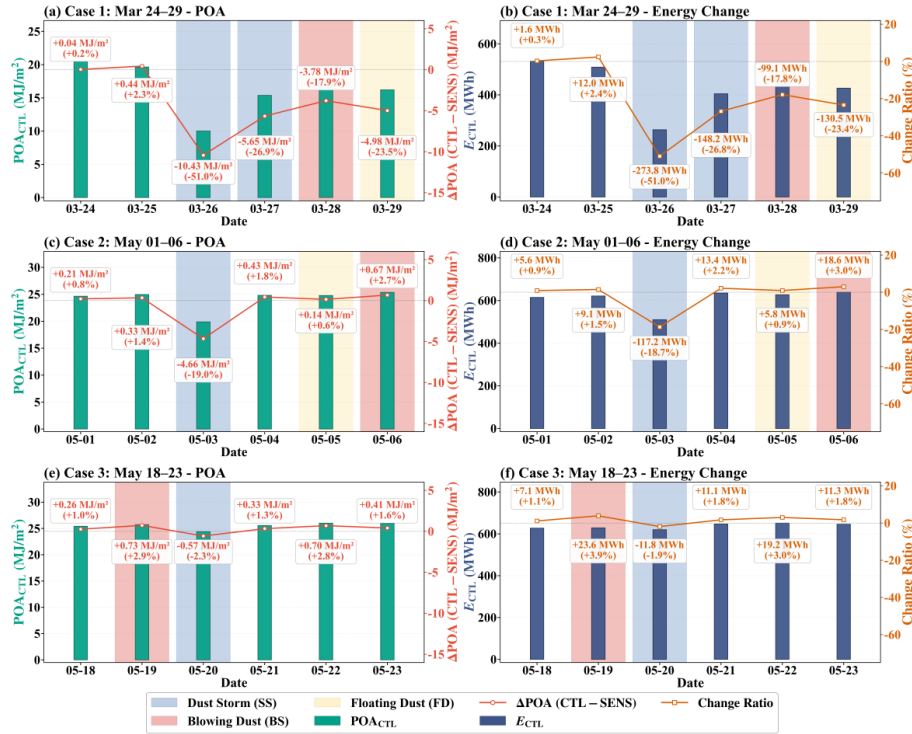


Figure 10 Daily comparison of POA irradiance and PV generation changes during the three dust events.

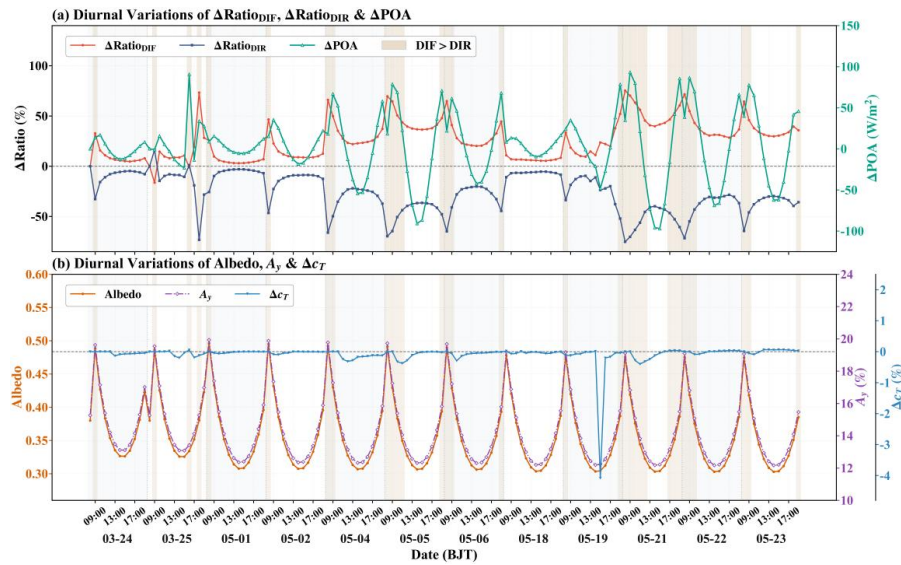
Figure 11 shows the hourly changes in the radiation components and module temperature for the 12 selected days on which daily generation increased slightly. The increase did not occur throughout the entire day but was concentrated mainly in the morning and evening, whereas decreases were observed around midday.

Regarding the radiation components (Fig.11a), low dust concentrations enhanced diffuse radiation. The change in the diffuse fraction ($\Delta\text{Ratio}_{\text{DIF}}$) ranged from -16.29% to $+75.19\%$, and the diffuse component even exceeded the direct component ($\text{DIF} > \text{DIR}$) during some periods. During the morning and evening, the desert surface albedo ranged from 0.328 to 0.496. The corresponding bifacial gain (A_f), was approximately 13.17% – 19.93% . The higher surface albedo, together with the enhanced diffuse radiation, increased the plane-of-array (POA) irradiance by 0.08 – 93.19 W/m^2 during some periods, ultimately resulting in daily generation increases of



560 1.57–23.64 MWh.

561 These generation gains occurred mainly under low dust concentrations or
 562 immediately before or after dust events and lasted only briefly. As dust concentration
 563 increased, direct-radiation losses intensified rapidly and soon exceeded the
 564 compensation provided by enhanced diffuse radiation and lower module temperature.
 565 Consequently, PV generation decreased over the dust events as a whole.



566
 567 **Figure 11** Continuous evolution of hourly radiation component fractions, POA increment, and module
 568 temperature changes on positive-gain sample days.

569 Figure 12 shows the empirical relationships between AOD_{550} , near-surface PM_{10} ,
 570 and POA irradiance loss, based on all valid daytime hourly samples from the three
 571 dust events. Figure 12a shows that the POA irradiance loss ratio increases nonlinearly
 572 with AOD_{550} . The fitted relationship is given by:

573
$$y = 100.0 \times (1 - e^{-0.16x})$$

574 The fitted relationship yielded a correlation coefficient of $R = 0.853$ ($P < 0.001$).
 575 When $AOD_{550} < 1.0$, the POA irradiance loss ratio is generally below 20%. When
 576 $AOD_{550} > 2.0$, the loss ratio increases markedly, reaching 50% – 60% during strong
 577 dust storms.

578 Figure 12b,c further show that ΔPOA follows significant power-law relationships



with both the column AOD₅₅₀ and the near-surface PM₁₀ concentration. The fitted equations are:

$$y = 74.1 \times x^{1.38}$$

$$y = 0.0092 \times x^{1.38}$$

Both relationships yielded $R = 0.889$ ($P < 0.001$). When near-surface PM₁₀ concentrations exceeds 1500 $\mu\text{g}/\text{m}^3$, POA irradiance attenuation (ΔPOA) exceeds 300 W/m^2 and can approach 500 W/m^2 . These results indicate that AOD₅₅₀ and near-surface PM₁₀ can both characterize the change in the irradiance received by PV arrays under dusty conditions, providing empirical relationships for estimating generation losses at desert PV plants where radiation measurements are unavailable.

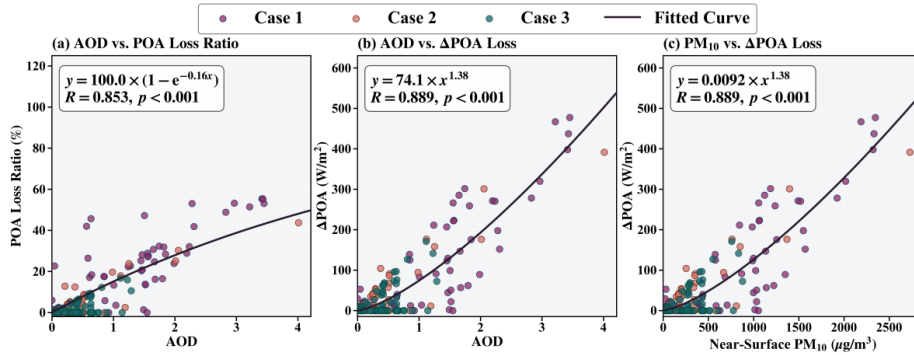


Figure 12 Empirical response relationships between dust parameters and PV POA radiation attenuation.

4 Discussion

4.1 Effects of dust event characteristics on radiation attenuation

The three spring dust storms exhibited clearly different radiation responses, indicating that dust loading and event duration jointly affect surface solar radiation attenuation. The 26 March event lasted about 22 h, with a peak PM₁₀ concentration of 19888.1 $\mu\text{g}/\text{m}^3$ and a peak AOD₅₅₀ of 4.505. The mean attenuation of total irradiance during the dust period was about 47.8%. In contrast, the 3 May and 20 May events lasted about 11 h and 6h, with corresponding attenuation values of 30.1% and 23.4%,



600 respectively. This difference indicates that when the dust-column loading remains
601 high and the event persists for a long time, a higher aerosol optical depth not only
602 strengthens the instantaneous radiation extinction but also prolongs the period of
603 strong surface radiation attenuation, thereby increasing the cumulative radiation loss
604 over the entire event.

605 In terms of the radiation components, dust does not simply reduce total surface
606 solar radiation; it also redistributes radiation between the direct and diffuse
607 components. As AOD increases, the direct radiation attenuates rapidly and the diffuse
608 fraction increases markedly (Li et al., 2025; Wild et al., 2012). The diffuse fraction K_d
609 averaged 0.992 during the 26 March event, indicating that surface solar radiation was
610 almost entirely diffuse under heavy dust conditions. Meanwhile, surface shortwave
611 radiative forcing was significantly negatively correlated with AOD₅₅₀ (Yu et al., 2006),
612 indicating dust optical loading is an important factor controlling surface shortwave
613 attenuation. This shift from a direct-dominated to a diffuse-dominated state is
614 consistent with the established understanding that aerosols enhance diffuse radiation.

615 It should be noted that, in the three events studied here, the dust intensity and
616 event duration varied together. Therefore, the results are better interpreted as
617 differences among events under the combined influence of these factors, rather than as
618 a clear separation of their individual contributions. In particular, the 26 March event
619 had the highest PM₁₀ concentration and AOD₅₅₀ as well as the longest duration. Its
620 larger cumulative radiation loss therefore reflects the combined effect of a higher dust
621 loading period of radiation attenuation. By contrast, the lower cumulative losses of the
622 two May events correspond to lower dust loading and shorter durations. These
623 difference suggests that, for assessing the impact of dust on solar energy resources,
624 instantaneous particle concentrations alone may be insufficient; the duration of dust
625 events should also be considered.



626 **4.2 Vertical redistribution of dust radiative energy between surface cooling and** 627 **atmospheric heating**

628 An important feature of the dust radiative effect is not simply a reduction in
 629 surface radiation but a redistribution of radiative energy between the surface and the
 630 dust layer. The differences between the CTL and SENS experiments indicate that,
 631 across the three events, the magnitude of the surface shortwave radiative forcing at
 632 Tazhong ranged from 84.46 to 90.52 W/m², while the atmospheric shortwave radiative
 633 forcing ranged from +86.56 to +102.99 W/m². Although the surface shortwave loss
 634 and the atmospheric shortwave radiative forcing are not strictly equivalent on a
 635 one-to-one basis, they are of comparable magnitude. This indicates that the absorption
 636 and redistribution of solar shortwave radiation by the dust layer are important
 637 contributors to the surface shortwave loss.

638 This energy redistribution also exhibits a clear vertical structure. The
 639 atmospheric shortwave heating rate peaks near the surface, reaching +12.61 and
 640 +11.49 K/day on 26 March and 3 May, respectively, whereas the radiative influence of
 641 the 20 May dust event extended above 3 km. This heating rate is consistent with the
 642 shortwave heating peak estimated by Huang et al. (2009) for strong dust events over
 643 the Taklimakan Desert, but substantially exceeds the annual-mean heating rate of 0.93
 644 K/day derived by Xu et al. (2023) from multi-year climatology. This contrast
 645 highlighting the intense radiative effect of extreme dust events on the local thermal
 646 structure. The vertical differences among the events indicate that the dust radiative
 647 effect depends not only on the total column AOD but also on the vertical distribution
 648 of dust (Ge et al., 2010). When high-concentration dust is confined near the surface,
 649 shortwave attenuation and heating are concentrated within the boundary layer. When
 650 the dust layer reaches higher altitudes, radiative heating also extends upward. This
 651 "surface cooling–lower-atmospheric heating" structure may further change the
 652 near-surface thermal conditions and boundary-layer development (Rémy et al., 2015),
 653 and is consistent with the temperature inversion observed near the dust-layer top of



654 the dust layer (Meng et al., 2026).

655 It should be emphasized that this study identifies the process mainly from the
656 perspective of radiative forcing and heating rates. Strong low-level dust heating may
657 enhance near-surface thermal stability and suppress some vertical mixing, but it does
658 not demonstrate that convection is completely suppressed. Dust radiative feedback not
659 only changes the solar energy resource reaching the surface but may also affect the
660 vertical evolution of the dust layer itself by modifying the atmospheric thermal
661 structure.

662 **4.3 PV generation attenuation caused by dust radiative effects**

663 The impact of dust on PV generation occurs mainly through changes in the
664 irradiance incident on the modules and its direct–diffuse composition, rather than
665 through a simple reduction in total solar irradiance. In all events, direct radiation was
666 rapidly attenuated during the intense dust stage, causing a marked decrease in POA
667 irradiance and consequently, PV generation. Simulated daily generation decreased by
668 50.96% during the intense dust storm on 26 March, a substantially greater reduction
669 than those observed in the two May events. This loss is comparable in magnitude to
670 the reduction in solar power estimated by Bergin et al. (2017) for severely
671 aerosol-polluted regions, highlighting the combined effects of high dust loading and
672 prolonged event duration on solar resource and power output.

673 In terms of radiation composition, dust enhances the scattering of solar radiation
674 in the atmosphere, increasing the diffuse fraction reaching the modules. This is
675 consistent with the recovery in PV output observed by Ravindra et al. (2017) under
676 light floating-dust conditions. Under low dust loading and during the transitional
677 stages of dust onset and dissipation, this enhanced scattering may partially
678 compensate the direct-radiation losses (Peters et al., 2019). At the same time, weaker
679 shortwave absorption may lower the module temperature, thereby partially offsetting
680 temperature-related power losses (Skoplaki & Palyvos, 2009). For bifacial glass–glass
681 modules, enhanced sky-diffuse and ground-reflected radiation may also contribute to



682 increased rear-side irradiance (Guerrero-Lemus et al., 2016; Janssen et al., 2015).
 683 Therefore, under low dust loading, PV generation does not necessarily decrease
 684 immediately or monotonically; short-term radiative compensation or even a slight
 685 increase in generation may occur.

686 However, this compensation occurs only under certain conditions. As AOD and
 687 PM₁₀ concentrations increase further, direct radiation losses rapidly outweigh the
 688 gains associated with enhanced diffuse radiation and rear-side irradiance, ultimately
 689 leading to a decrease in POA irradiance and PV generation. The impact of dust on PV
 690 systems therefore depends strongly on the prevailing radiation conditions. Under low
 691 dust loading, a compensation window may exist, whereas under high dust loading the
 692 impact shifts to an energy deficit dominated by direct-radiation losses. This also
 693 indicates that a simple classification of conditions as "dusty" or "non-dusty" may be
 694 insufficient to characterize the actual impact on PV systems.

695 **4.4 Short-term radiation compensation window under low dust loading and** 696 **transitional stages**

697 It is worth noting that the PV response was not uniform in direction or magnitude
 698 across all dust conditions. Under low dust loading and during dust onset and
 699 dissipation of dust events, POA irradiance and simulated generation increased slightly
 700 during some periods. Further analysis showed that these periods were characterized
 701 by a high contribution from diffuse radiation (Gu et al., 2020). In some samples, the
 702 bifacial gain coefficient A_y reached 13.17%–19.93%, corresponding to increases in
 703 POA irradiance of 0.08–93.19 W/m² and a daily generation of 1.57–23.64 MWh. This
 704 indicates that, under specific radiation conditions, the reduction in direct radiation
 705 associated with increasing dust loading does not translate directly into an equivalent
 706 net loss in PV output. Enhanced diffuse radiation, ground-reflected radiation, and
 707 lower module temperature may jointly provide partial compensation.

708 For bifacial glass–glass modules, this compensation has a physical basis. In
 709 addition to receiving front-side solar radiation, bifacial modules can utilize



710 ground-reflected and diffuse radiation incident on their rear sides. Their response
 711 therefore depends not only on total irradiance but also on the direct-to-diffuse ratio,
 712 surface albedo, and rear-side irradiance. In this study, higher surface albedo and the
 713 calculated bifacial gain during some morning and evening periods, together with
 714 changes in shortwave radiation composition, contributed to a small increase in PV
 715 output. It should be emphasized, however, that this compensation occurs only under
 716 low-to-moderate dust optical loading and specific solar elevation angles. It is
 717 short-lived, and as the dust loading increases, direct-radiation losses soon outweigh
 718 the gains associated with diffuse radiation and potential rear-side contributions.

719 Therefore, from a PV operational perspective, dust events should not be treated
 720 as a single load state; they can be divided into pre-onset, intensification, peak-dust,
 721 and dissipation stages. During low-loading and potential rear-side contributions from
 722 bifacial modules may provide partial compensation. During high-loading stages,
 723 generation loss caused by direct-radiation attenuation should be the primary concern.
 724 This understanding provides a useful perspective for developing PV operational
 725 assessment methods that account for the dust optical state and radiation composition.
 726 However, the magnitude of the actual gains still needs to be validated through
 727 longer-term field observations of PV modules and independent experiments under
 728 different installation configurations.

729 **5 Conclusions**

730 Using the WRF-Chem model, we performed paired simulations with and without
 731 dust radiative feedback for three dust storms over the Tazhong region in spring 2025
 732 (26 March, 3 May, and 20 May). Combined with surface observations and reanalysis
 733 data, these simulations were used to analyze the effects of the dust events on the
 734 radiation budget, atmospheric heating, and PV generation. The main conclusions are
 735 as follows.

736 (1) The model reproduced the three dust events and their radiative evolution.
 737 The correlation coefficient between simulated and observed PM_{10} was 0.86 for the 26



738 March event and lower for the 3 May and 20 May events. The correlation coefficients
 739 between the simulated AOD₅₅₀ and the MERRA-2 dust AOD were 0.781, 0.465, and
 740 0.538, respectively. Although the shortwave radiation was somewhat overestimated
 741 and the longwave radiation somewhat underestimated, the model captured the main
 742 radiative changes during the dust events.

743 (2) Dust radiative feedback markedly weakened the surface shortwave radiation,
 744 producing a surface radiative response dominated by shortwave cooling. Across the
 745 three events, the surface shortwave radiative forcing at Tazhong ranged from -90.52 to
 746 -84.46 W/m², while the surface longwave radiative forcing ranged from +33.09 to
 747 +39.72 W/m². The longwave warming was insufficient to offset the shortwave cooling.
 748 As dust loading increased, direct radiation was attenuated rapidly and the diffuse
 749 fraction increased, with K_d averaging 0.992 during the 26 March event, indicating a
 750 marked change in the composition of surface solar radiation under heavy dust loading.

751 (3) The dust radiative effect involved a vertical redistribution of radiative
 752 energy, with simultaneous surface cooling and atmospheric heating. The atmospheric
 753 shortwave radiative forcing at Tazhong ranged from +86.56 to +102.99 W/m²,
 754 comparable in magnitude to the concurrent surface shortwave radiative forcing. The
 755 maximum near-surface atmospheric shortwave heating rates reached +12.61 and
 756 +11.49 K/day on 26 March and 3 May, respectively, while the radiative influence of
 757 the 20 May event extended above 3 km. Dust not only weakens the solar radiation
 758 reaching the surface but also absorbed and redistributes part of the shortwave energy
 759 within the dust layer, altering the radiative energy partitioning between the surface
 760 and the atmosphere.

761 (4) The effects of dust radiative forcing extended to the PV incident irradiance
 762 and PV generation, with clear stage dependence. Simulated daily generation
 763 decreased by 50.96%, 18.68% and 1.87% during the 26 March, 3 May, and May event,
 764 respectively. During the strong-dust stage, direct-radiation losses dominated. Under
 765 low dust loading and during dust onset and dissipation of dust events, enhanced



diffuse radiation, lower module temperature, and potential contributions from rear-side irradiance in bifacial modules could provide partial compensation, resulting in small increases in POA irradiance and generation during some periods. However, these gains could not offset the radiative loss under heavy dust loading.

(5) PV irradiance loss was nonlinearly related to the dust aerosol loading. The POA loss ratio increased nonlinearly with AOD_{550} , while the absolute POA irradiance loss followed power-law relationships with both AOD_{550} and near-surface PM_{10} . Both relationships had correlation coefficient of $R = 0.889$ ($P < 0.001$). These results establish a quantitative relationship between dust aerosol loading and PV irradiance loss, providing a reference for assessing solar energy resources and PV generation under dusty conditions.

777

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798

799 **Conflict of interest**

800 The authors declare that they have no conflict of interest.

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802 **Data availability statement**

803 The data presented in this study are available on request from the corresponding
 804 author.

805

806 **References**

807 Bergin, M. H., Ghoroi, C., Dixit, D., Schauer, J. J., and Shindell, D. T.: Large reductions in solar energy
 808 production due to dust and particulate air pollution, *Environ. Sci. Technol. Lett.*, 4, 339–344,
 809 <https://doi.org/10.1021/acs.estlett.7b00197>, 2017.

810 Chen, Y., An, J., Qu, Y., and Wang, H.: Dust- versus cloud-radiation impacts on the diurnal temperature range for
 811 long-lasting dust weather over the Taklimakan Desert, *Atmos. Environ.*, 342, 120946,
 812 <https://doi.org/10.1016/j.atmosenv.2024.120946>, 2025.

813 Chen, J., Zhu, Y., and Hong, L.: Simulation study of an adjustable-tilt photovoltaic generation system based on
 814 bifacial modules, *Advances in New and Renewable Energy*, 8, 356–365, 2020.
 815 DOI:10.3969/j.issn.2095-560X.2020.05.003. [in Chinese]

816 Chen, Y., Chen, S., Zhou, J., Zhao, D., Bi, H., Zhang, Y., Alam, K., Yu, H., Yang, Y., and Chen, J.: A super dust
 817 storm enhanced by radiative feedback, *npj Clim. Atmos. Sci.*, 6, 90,
 818 <https://doi.org/10.1038/s41612-023-00418-y>, 2023.

819 Saidou Chaibou, A. A., Ma, X., and Sha, T.: Dust radiative forcing and its impact on surface energy budget over
 820 West Africa, *Sci. Rep.*, 10, 12236, <https://doi.org/10.1038/s41598-020-69223-4>, 2020.

821 Deline, C., MacAlpine, S., Marion, B., Toor, F., Asgharzadeh, A., and Stein, J. S.: Assessment of bifacial
 822 photovoltaic module power rating methodologies – inside and out, *IEEE J. Photovoltaics*, 7, 575–580,
 823 <https://doi.org/10.1109/JPHOTOV.2017.2650565>, 2017.

824 Skoplaki, E., and Palyvos, J. A.: On the temperature dependence of photovoltaic module electrical performance: a
 825 review of efficiency/power correlations, *Sol. Energy*, 83, 614–624,
 826 <https://doi.org/10.1016/j.solener.2008.10.008>, 2009.



- 827 Ge, J. M., Su, J., Ackerman, T. P., Fu, Q., Huang, J. P., and Shi, J. S.: Dust aerosol optical properties retrieval and
828 radiative forcing over northwestern China during the 2008 China–U.S. joint field experiment, *J. Geophys.*
829 *Res.-Atmos.*, 115, D00K12, <https://doi.org/10.1029/2009JD013263>, 2010.
- 830 Gu, W., Ma, T., Ahmed, S., Zhang, Y., and Peng, J.: A comprehensive review and outlook of bifacial photovoltaic
831 (bPV) technology, *Energy Convers. Manag.*, 223, 113283, <https://doi.org/10.1016/j.enconman.2020.113283>,
832 2020.
- 833 Guan, H., Schmid, B., Bucholtz, A., and Bergstrom, R.: Sensitivity of shortwave radiative flux density, forcing,
834 and heating rate to the aerosol vertical profile, *J. Geophys. Res.-Atmos.*, 115, D06209,
835 <https://doi.org/10.1029/2009JD012907>, 2010.
- 836 Guerrero-Lemus, R., Vega, R., Kim, T., Kimm, A., and Shephard, L. E.: Bifacial solar photovoltaics – a
837 technology review, *Renew. Sust. Energ. Rev.*, 60, 1533–1549, <https://doi.org/10.1016/j.rser.2016.03.041>,
838 2016.
- 839 Han, J. F., Zhao, W. W., Guo, Z. Y., Wu, H., and Ma, X. B.: Factors affecting the rear-side power generation of
840 double-glass bifacial modules, *Science and Technology of Enterprise*, 22, 238,
841 <https://doi.org/10.13751/j.cnki.kjyqy.2015.22.205>, 2015 (in Chinese).
- 842 Hogan, R. J. and Mason, S. L.: Modelling atmospheric radiative transfer: ecRad practical with answers, ECMWF,
843 2021, available at:
844 [https://events.ecmwf.int/event/473/contributions/5067/attachments/3352/5750/ecrad_practical_ANSWERS.p](https://events.ecmwf.int/event/473/contributions/5067/attachments/3352/5750/ecrad_practical_ANSWERS.pdf)
845 [df](https://events.ecmwf.int/event/473/contributions/5067/attachments/3352/5750/ecrad_practical_ANSWERS.pdf) (last access: 24 October 2026).
- 846 Song, H. and Xing, Q.: Projected spring dust emissions in China under future climate scenarios, *ESS Open*
847 *Archive* [preprint], <https://doi.org/10.22541/essoar.173655409.95111252/v1>, 2025.
- 848 Hu, Z., Huang, J., Zhao, C., Jin, Q., Ma, Y., and Yang, B.: Modeling dust sources, transport, and radiative effects
849 at different altitudes over the Tibetan Plateau, *Atmos. Chem. Phys.*, 20, 1507–1529,
850 <https://doi.org/10.5194/acp-20-1507-2020>, 2020.
- 851 Huang, J., Fu, Q., Su, J., Tang, Q., Minnis, P., Hu, Y., Yi, Y., and Zhao, Q.: Taklimakan dust aerosol radiative
852 heating derived from CALIPSO observations using the Fu-Liou radiation model with CERES constraints,
853 *Atmos. Chem. Phys.*, 9, 4011–4021, <https://doi.org/10.5194/acp-9-4011-2009>, 2009.
- 854 Janssen, G. J. M., van Aken, B. B., Carr, A. J., and Mewe, A. A.: Outdoor performance of bifacial modules by
855 measurements and modelling, *Energy Procedia*, 77, 364–373, <https://doi.org/10.1016/j.egypro.2015.07.051>,
856 2015.
- 857 Jin, L., Zhou, S., He, Q., and Abbas, A.: Characteristics of solar radiation at Xiaotang, in the northern marginal
858 zone of the Taklimakan Desert, *PeerJ*, 9, e12373, <https://doi.org/10.7717/peerj.12373>, 2021.
- 859 Kok, J. F., Storelvmo, T., Karydis, V. A., Adebisi, A. A., Mahowald, N. M., Evan, A. T., He, C., and Leung, D.
860 M.: Mineral dust aerosol impacts on global climate and climate change, *Nat. Rev. Earth Environ.*, 4, 71–86,
861 <https://doi.org/10.1038/s43017-022-00379-5>, 2023.



- 862 Li, H. and Wang, C.: Impact of dust radiation effect on simulations of temperature and wind – a case study in
863 Taklimakan Desert, *Atmos. Res.*, 273, 106163, <https://doi.org/10.1016/j.atmosres.2022.106163>, 2022.
- 864 Li, Y., Jiang, J., Geng, Y., et al.: Analysis of standard test methods for electrical parameters of bifacial
865 photovoltaic modules, *China Standardization*, 2020, 229–235,
866 <https://doi.org/10.3969/j.issn.1002-5944.2020.00.038> (in Chinese).
- 867 Liu, L., Huang, X., Ding, A., and Fu, C.: Dust-induced radiative feedbacks in north China: a dust storm episode
868 modeling study using WRF-Chem, *Atmos. Environ.*, 129, 43–54,
869 <https://doi.org/10.1016/j.atmosenv.2016.01.019>, 2016.
- 870 Meng, L., He, Q., Yi, Z., Zhao, T., Yang, F., Zhu, C., and Wang, T.: Vertical observational evidence of dust
871 aerosol radiative forcing on the atmospheric boundary layer over the Taklimakan Desert, China, *Atmos. Sci.*
872 *Lett.*, 27, e70014, <https://doi.org/10.1002/asl2.70014>, 2026.
- 873 Peters, I. M., Karthik, S., Liu, H., Buonassisi, T., and Nobre, A.: Urban haze and photovoltaics, *Energy Environ.*
874 *Sci.*, 11, 3043–3054, <https://doi.org/10.1039/C8EE01100A>, 2018.
- 875 Ravindra, B.: Performance of a crystalline silicon photovoltaic power plant during sandstorms, *arXiv [preprint]*,
876 *arXiv:1710.03790*, <https://doi.org/10.48550/arXiv.1710.03790>, 2017.
- 877 Rémy, S., Benedetti, A., Bozzo, A., Haiden, T., Jones, L., Razinger, M., Flemming, J., Engelen, R. J., Peuch, V. H.,
878 and Thepaut, J. N.: Feedbacks of dust and boundary layer meteorology during a dust storm in the eastern
879 Mediterranean, *Atmos. Chem. Phys.*, 15, 12909–12933, <https://doi.org/10.5194/acp-15-12909-2015>, 2015.
- 880 Sun, X., Khan, M. R., Deline, C., and Alam, M. A.: Optimization and performance of bifacial solar modules: a
881 global perspective, *Appl. Energy*, 212, 1601–1610, <https://doi.org/10.1016/j.apenergy.2017.12.041>, 2018.
- 882 Tian, L., Chen, L., Zhang, P., and Bi, L.: Estimating radiative forcing efficiency of dust aerosol based on direct
883 satellite observations: case studies over the Sahara and Taklimakan Desert, *Atmos. Chem. Phys.*, 21, 11669–
884 11687, <https://doi.org/10.5194/acp-21-11669-2021>, 2021.
- 885 Wang, F., Qi, M., Ren, S., Zhu, M., Xing, Q., Wang, M., Song, H., Wang, Q., and Liu, P.: Effects of spring dust
886 aerosols on direct radiative forcing in China from 2000 to 2020, *Remote Sens.*, 15, 4564,
887 <https://doi.org/10.3390/rs15184564>, 2023.
- 888 Wild, M.: Enlightening global dimming and brightening, *Bull. Am. Meteorol. Soc.*, 93, 27–37,
889 <https://doi.org/10.1175/BAMS-D-11-00074.1>, 2012.
- 890 Wulayin, Y., Li, H., Zhang, L., Mamtimin, A., Liu, J., Huo, W., and Liu, H.: Evaluating the prediction
891 performance of the WRF-CUACE model in Xinjiang, China, *Remote Sens.*, 16, 3747,
892 <https://doi.org/10.3390/rs16193747>, 2024.
- 893 Xu, X., Pan, S., Luo, T., Yang, Y., and Xiong, Z.: Characteristics of optical properties and heating rates of dust
894 aerosol over Taklimakan Desert and Tibetan Plateau in China based on CALIPSO and SBDART, *Remote*
895 *Sens.*, 15, 607, <https://doi.org/10.3390/rs15030607>, 2023.



- 896 Yu, H., Kaufman, Y. J., Chin, M., Feingold, G., Remer, L. A., Anderson, T. L., Balkanski, Y., Bellouin, N.,
897 Boucher, O., Christopher, S., DeCola, P., Kahn, R., Koch, D., Loeb, N., Reddy, M. S., Schulz, M., Takemura,
898 T., and Zhou, M.: A review of measurement-based assessments of the aerosol direct radiative effect and
899 forcing, *Atmos. Chem. Phys.*, 6, 613–666, <https://doi.org/10.5194/acp-6-613-2006>, 2006.
- 900 Zeng, X., Sun, W., Jia, M., Xue, Z., Zhou, C., and Sun, L.: Global high-resolution mapping of photovoltaic power
901 plants from 2019 to 2025 using unsupervised index-based multi-source data fusion method, *Int. J. Appl. Earth*
902 *Obs. Geoinf.*, 145, 105005, <https://doi.org/10.1016/j.jag.2025.105005>, 2025.