Decrease trend of East Asia dust during the 21st century in CMIP6

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Key Points:

- Dust emission in East Asia will decrease during the twenty-first century due to the reduction of surface winds under the warming climate
- The percentage of dust emission reduction depends on the magnitude of warming
- In the extreme warming scenario, dust optical depth over source regions in East Asia will decrease by 5.6% by the end of the 21st century

Abstract

A reduction of dust emission over the major dust source regions in East Asia in the twenty-first century is diagnosed in the climate change simulations of the Sixth Climate Model Intercomparison Project (CMIP6). Such change is attributable to the reduction of surface wind speeds in the dust source regions. To evaluate how the magnitude of warming affects dust emission, we examined two model scenarios, one high-forcing pathway and one medium-forcing pathway. We find dust optical depth over dust source regions would decrease by 5.6% by the end of the twenty-first century under the high-forcing pathway. Under the medium-forcing pathway, dust optical depth would decrease by less than 2%. These results provide a quantitative understanding of how global warming affects dust emission in the major dust source regions in East Asia.

Plain Language Summary

Over the past half-century, dust emission in the major dust source regions in East Asia exhibited a downward trend due to reduced surface winds. It has been pointed out that such a trend will continue in the twenty-first century under global warming. However, the magnitude of the reduction is unclear. Here we attempt to evaluate quantitatively how dust emission in East Asia will vary in the twenty-first century under two warming scenarios using climate models. We find dust optical depth, which is closely associated with dust emission, will decrease by 5.6% under the extreme warming scenario, while it will decrease by less than 2% in the medium warming scenario. Thus, we suggest that the variability of dust, which is not included in most climate models, needs to be taken into consideration for understanding the dust-climate feedback.

1 Introduction

Dust emission in East Asia is estimated to account for 11% of the global dust emission (Kok et al., 2021). Dust originated in East Asia can transport downwind by westerlies across the Pacific to North America (Hu et al., 2019; Voss et al., 2020), affecting air quality (Wang et al., 2010), radiative balance (Stanelle et al., 2014), and ocean biogeochemistry along the way (Jickells et al., 2005).

Dust emission in East Asia undergoes interannual variability and is known to be associated with a number of factors, such as surface wind speeds, precipitation, and surface temperatures in the source regions (Guan et al., 2017; Kurosaki & Mikami, 2003; Wu et al., 2021). It is also known that dust emission in East Asia is associated with atmospheric circulations (Zhu et al., 2008) and oceanic oscillations such as the Pacific decadal oscillation (Gong et al., 2006). Dust events frequency in East Asia has exhibited a downward trend since the 1950s (Tan et al., 2014; Wu et al., 2021; Zhao et al., 2004), and such trend is attributed to reduced wind speeds (Guan et al., 2017; Wu et al., 2021; Xu et al., 2020), enhanced precipitation (Wang, 2005), and increasing surface temperatures (Guan et al., 2017; Wu et al., 2021). Among these factors that affect dust emission, winds are found to play a dominant role (Gong et al., 2006; Guo et al., 2019).

Although it has been found that dust emission in the major dust source regions would decrease in East Asia under the warming climate during the twenty-first century (Liu et al., 2020; Zong et al., 2021), the magnitude of reduction remains unclear and warrants further investigation. In this work, we propose using surface wind speeds alone to estimate dust emission in East Asia during the twenty-first century using two scenarios of the Sixth Climate Model Intercomparison Project (CMIP6), namely, one high-forcing pathway and one medium-forcing pathway. Both scenarios show a statistically significant downward trend in dust emission over the major dust source regions in East Asia during the twenty-first century under a warming climate.

2 Data

Here we use the Deep Blue and Dark Target combined aerosol optical depth from the level 3 daily aerosol products from the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua platform (Platnick et al., 2017) to study dust optical depth (DOD) over the major dust source regions in China from 2003 through 2020. In order to eliminate other types of aerosols to obtain DOD, the following three criteria were applied based on previous works. First, the Angstrom exponent is less than 0.6 (Schepanski et al., 2007). Since dust is mostly coarse particles, this criterion excludes fine aerosols (Dubovik et al., 2002). Second, the single scattering albedo (SSA) is less than 0.95. This criterion effectively excludes sea salt in the coastal regions as sea salt has an SSA close to 1 (Ginoux et al., 2012). Third, the SSA at 412 nm is less than that at 670 nm as dust absorption increases from red to blue. Daily mean DOD from MODIS is used to construct monthly mean and long-term mean DOD. The spatial resolution of DOD is at 1° longitude by 1° latitude.

To understand the effect of surface winds on DOD, we use monthly mean wind speeds at 10 m above the surface to construct the relationship between surface winds and DOD. Monthly mean wind speeds at 10 m were taken from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) from 2003 through 2020 (Muñoz Sabater, 2019). We also use monthly mean precipitation from the Global Precipitation Climatology Project (GPCP) Version 2 (Adler et al., 2003) to construct the climatology of precipitation from 1979 through 2020 in the major dust source regions.

Monthly mean wind speeds at 10 m from two scenarios of CMIP6 were selected to estimate the future change of dust. The two scenarios used in this work are the shared socioeconomic pathway 2 with radiative forcing reaching a level of 4.5 Wm^{-2} in 2100 (ssp245), a medium-forcing pathway, and the shared socioeconomic pathway 5 with radiative forcing reaching a level of 8.5 Wm^{-2} in 2100 (ssp585), a high-forcing pathway. Only models with both scenarios were selected in this work, and all ensemble members of each model were included for estimating the future change of dust in East Asia. Table 1 summarizes the modeling centers, model names, and ensemble members for both scenarios used in this work.

Table 1. CMIP6 models used in this work. Shown are the modeling centers, model names, and ensemble members for both scenarios.

Institution	Model	ssp245	ssp585
Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology (CSRIO; Australia)	ACCESS-CM2	5	5
	ACCESS-ESM1-5	40	10
Alfred Wegener Institute (AWI; Germany)	AWI-CM-1-1-MR	1	1
Chinese Academy of Meteorological Sciences (CAMS; China)	CAMS-CSM1-0	2	2
Chinese Academy of Sciences (CAS; China)	CAS-ESM2-0	2	2
National Center for Atmospheric Research (NCAR; United States)	CESM2	3	3
	CESM2-WACCM	5	5
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC; Italy)	CMCC-CM2-SR5	1	1
	CMCC-CM2-ESM2	1	1
Centre National de Recherches Météorologique (CNRM; France)	CNRM-CM6-1	6	6
	CNRM-CM6-1-HR	1	1
	CNRM-ESM2-1	10	5
Canadian Centre for Climate Modeling and Analysis (CCCma; Canada)	CanESM5	50	50
European consortium (EC)	EC-Earth3	1	1
	EC-Earth3-CC	1	1
Chinese Academy of Sciences (CAS; China)	FGOALS-f3-L	1	1
First Institute of Oceanography, Ministry of Natural Resources (FIO; China)	FIO-ESM2.0	3	3
National Oceanic and Atmospheric Administration Geophysical Fluid Dynamic Laboratory (GFDL; United States)	GFDL-ESM4	1	1
National Aeronautics and Space Administration Goddard Institute for Space Studies (GISS; United States)	GISS-E2-1-G	30	11
Met Office Hadley Centre (MOHC; United Kingdom)	HadGEM3-GC31-LL	5	4
Indian Institute of Tropical Meteorology (IITM; India)	IITM-ESM	1	1
Institute for Numerical Mathematics (INM; Russia)	INM-CM4-8	1	1
	INM-CM5-0	1	1

Institut Pierre-Simon Laplace (IPSL; France)	IPSL-CM6A-LR	11	6
National Institute of Meteorological Science-Korea Meteorological Administration (NIMS-KMA; Korea)	KACE1-0-G	3	3
Korea Institute of Ocean Science and Technology (KIOST; Korea)	KIOST-ESM	1	1
Model for Interdisciplinary Research on Climate (MIROC; Japan)	MIROC-ES2L	30	11
	MIROC6	33	50
Max Planck Institute for Meteorology (MPI; Germany)	MPI-ESM1-2-HR	2	2
	MPI-ESM1-2-LR	30	10
Meteorological Research Institute (MRI; Japan)	MRI-ESM2-0	5	6
Nanjing University of Information Science and Technology (NUIST; China)	NESM3	2	2
Norwegian Climate Centre (NCC; Norway)	NorESM2-LM	13	1
	NorESM2-MM	1	1
National Center for Atmospheric Research (NCAR; Taiwan, China)	TaiESM1	1	1
Met Office Hadley Centre (MOHC; United Kingdom)	UKESM1.0-LL	6	5

3 Results

3.1 DOD and 10 m wind speeds

The two major dust source regions in East Asia include the Taklamakan Desert in northwestern China and the Gobi Desert in Northern China (Figure 1a). The long-term mean DOD from satellite from 2003 through 2020 over the major dust source regions is 0.15 (Figure 1a). The Taklamakan Desert is an extreme arid region with a mean annual precipitation of 100 mm, while the Gobi Desert is an arid region with a mean annual precipitation of 223 mm averaged from 1979 through 2020 using GPCP (Figure 1a). Although it has been observed that the annual precipitation over these major dust source regions has been increasing over the past half-century (Su et al., 2020) and the increase in precipitation can strengthen soil cohesion and enhance vegetation cover, thus reducing dust emission, previous studies found no correlation between vegetation and dust emission in northwestern China as vegetation there is sparse (Zhang et al., 2003; Zou & Zhai, 2004). In addition, the correlation between soil moisture and dust emission is much weaker compared with that between surface wind speeds and dust emission in this region (Guo et al., 2019; Wu et al., 2021).

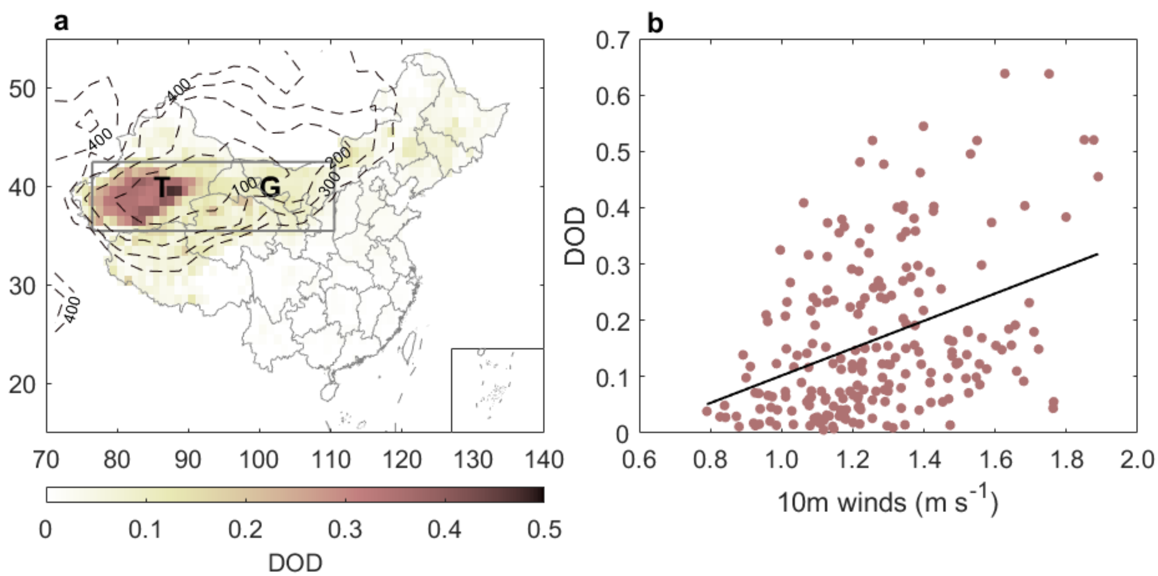

Figure 1. Long-term mean DOD and precipitation and the relationship between DOD and 10 m winds. (a) Long-term mean DOD at 1° by 1° over China from 2003 through 2020 using MODIS daily DOD. The contour lines are the mean annual precipitation in mm using monthly mean precipitation from GPCP from 1979 through 2020. The gray box indicates the major dust source regions (74.5° to 110.5°E, 35.5° to 42.5°N). T and G indicate locations of the Taklamakan Desert and the Gobi Desert, respectively. (b) Scatterplot of monthly mean DOD as a function of monthly mean 10 m winds averaged over the major dust source regions from 2003 through 2020. Monthly mean 10 m winds are from ERA5. The black line is the least-squares regression line described by the equation y = 0.24x – 0.14.

The relationship between dust emission and surface wind speeds is well-established (Fécan et al., 1999). The monthly mean DOD averaged over the major dust source regions exhibits a statistically significant correlation with the monthly mean 10 m wind speeds averaged over the same region from 2003 through 2020 (Figure 1b). The correlation between 10 m wind speeds from ERA5 and DOD from MODIS is 0.4 ($p < 0.01$), indicating that 10 m wind speeds can be used to approximate DOD at the monthly scale, which is closely associated with dust emission in the source regions. Such correlation between satellite-retrieved DOD and wind speeds from other reanalyses, such as the Modern-Era Retrospective analysis for Research and Application, Version 2, is also robust. Since surface winds from ERA5 offer the best agreement among reanalyses when compared with in situ observations (Ramon et al., 2019), in this work, the relationship between DOD and 10 m wind speeds from ERA5 is used to estimate DOD over the major dust source regions in East Asia during the twenty-first century.

3.2 DOD during the twenty-first century

Figure 2 shows the estimates of DOD over the major dust source regions in East Asia during the twenty-first century using 10 m winds from two scenarios of CMIP6. As winds from models vary significantly due to the model's internal variability, wind speeds from each model are scaled so that the mean wind speeds from each model are equal to those from ERA5 for the period of 2015 through 2020. In the ssp585 scenario, the multimodel mean time series shows a statistically significant downward trend of -0.008±0.0003 in DOD per 100 years (Figure 2a), representing roughly a 5.6±0.2% reduction of the long-term mean DOD obtained from MODIS for the period from 2003 through 2020.

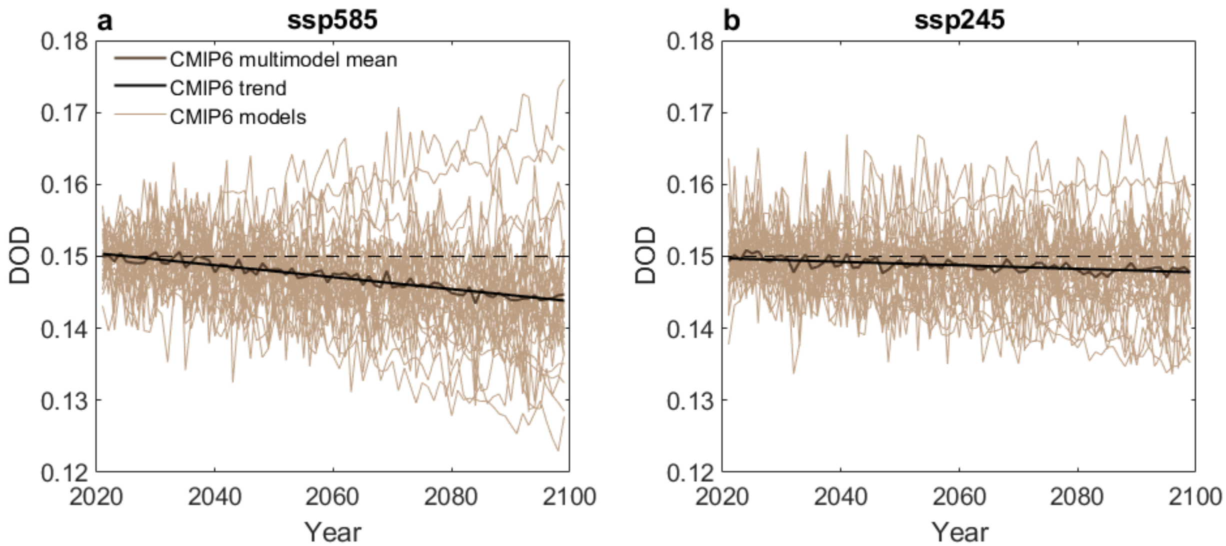

Figure 2. Time series of DOD over the major dust source regions during the twenty-first century. (a) The CMIP6 ensemble mean time series, the multimodel mean time series and its linear trend estimated using monthly mean 10 m winds from ssp585 of CMIP6. (b) The same as (a) using monthly 10 m winds from ssp245.

Among the 36 models considered here, 30 models exhibit statistically significant downward trends in DOD, while only four models exhibit statistically significant upward trends in DOD (Figure 3a). The same analysis was repeated using the ssp245 scenario, in which the multimodel mean time series shows a statistically significant downward trend of -0.0024±0.0003 in DOD per 100 years, 30% of that for the ssp585 scenario (Figure 2b). 16 of the 36 models exhibit statistically significant downward trends in DOD, while four models exhibit statistically significant upward trends in DOD (Figure 3b).

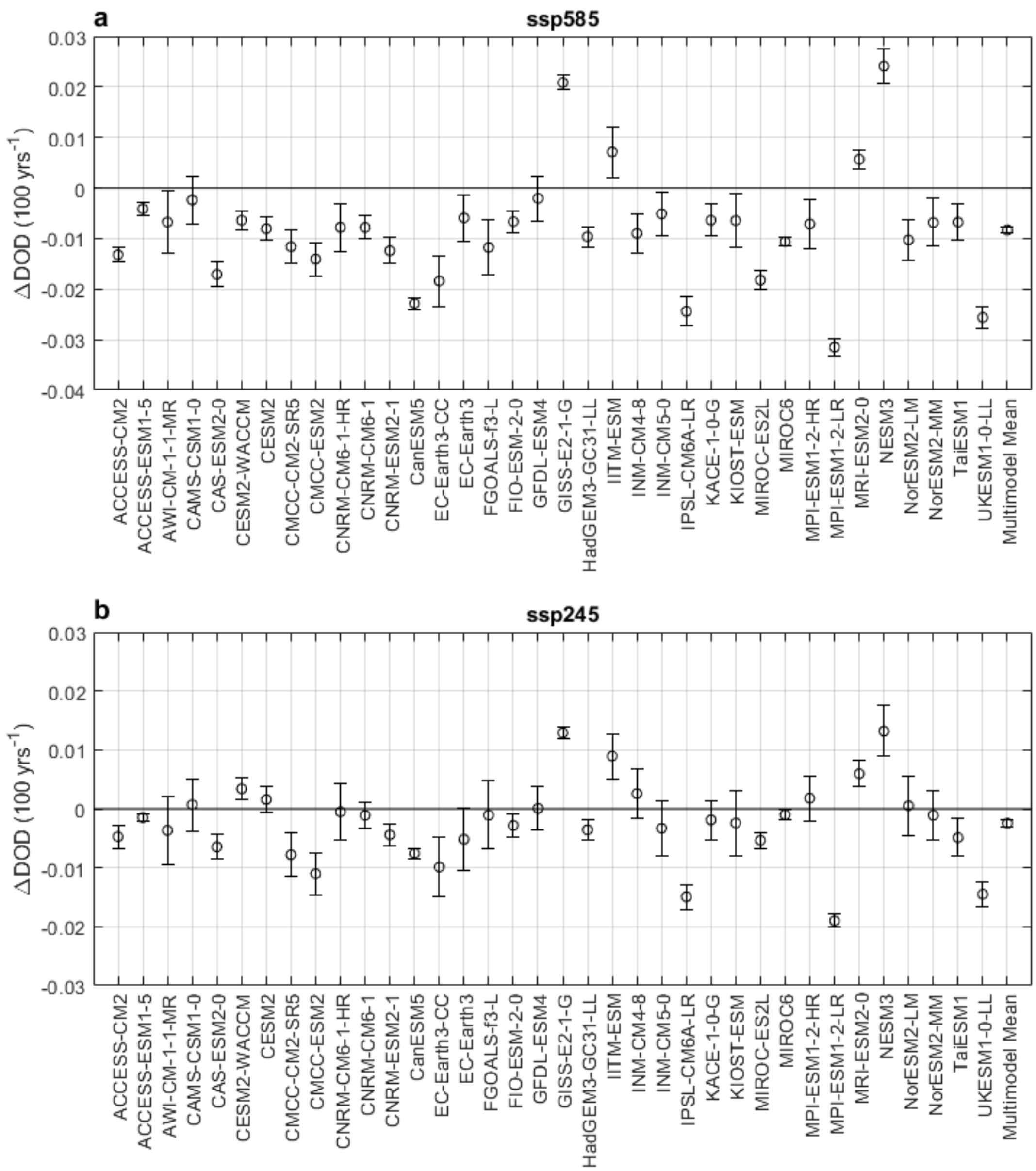

Figure 3. CMIP6 ssp585 and ssp245 twenty-first century trends in DOD. (a) The linear trend and 95% confidence intervals of the ensemble mean and the multimodel mean trend for ssp585. (b) The same as (a) but for ssp245.

4 Discussion

This decline in DOD indicates that dust emission in the major dust source regions in East Asia will decrease during the twenty-first century, which would likely contribute to the improvement of air quality in the dust source regions and downwind regions, especially in the springtime, when dust events are frequent. Under the warming climate, not only dust emission in East Asia will decline, but in other major dust source regions, such as the Saharan Desert, the largest desert in the world, dust emission will also decline due to reduced surface wind speeds (Evan et al., 2016). In addition, decreasing dust has been observed in the Middle East over the past decade as a result of enhanced soil moisture and precipitation and reduced surface wind speeds (Xia et al., 2022).

So far, the radiative effect dust has on climate is uncertain. It is known that dust reflects shortwave radiation, but how dust interacts with longwave radiation is less clear. As large particles can absorb longwave radiation more effectively, the radiative effect of dust depends on the size of the particle (Mahowald et al., 2014). On the global scale, the direct radiative effect of dust is estimated to be between -0.48 and +0.2 Wm^{-2} (Kok et al., 2017). But on the regional scale, the direct radiative effect of dust can be one order of magnitude larger. For example, during a two-week observation in Zhangye, located between the Taklamakan and Gobi Deserts, the direct longwave radiative effect of dust was estimated to vary between 2.3 and 20 Wm^{-2}, compensating for over one-half of the shortwave cooling effect at the surface (Hansell et al., 2012). Given the radiative effect of dust, the decrease in dust emission in the twenty-first century will inevitably affect the energy balance of the surface and the atmosphere, particularly in the source regions.

Currently, the interannual variability of dust is not included in most climate models. In addition, the indirect effects of dust on climate are poorly understood. Thus, efforts should be given to better represent dust variability in models to understand and predict the dust-climate feedback in the future.

5 Conclusions

This work estimated the trend of East Asia dust during the twenty-first century under two warming scenarios. We did so by examining DOD, derived from surface winds in CMIP6 models, over the major dust source regions. Under the high-forcing pathway, that is, radiative forcing reaching a level of 8.5 Wm^{-2} in 2100, DOD in East Asia is estimated to reduce by 5.6% compared with the mean DOD from 2003 through 2020 over the dust source regions. Under the medium-forcing pathway, that is, radiative forcing reaching a level of 4.5 Wm^{-2} in 2100, DOD in East Asia is estimated to reduce by less than 2%. It is worth noting that such estimations did not take into consideration the complex dust-climate feedback that is not well understood, nor did they include other factors that may affect dust emission, such as land use change. Nevertheless, our results provide a quantitative understanding of East Asia dust emission in the twenty-first century and indicate that the degree dust emission responds to climate change varies with the magnitude of warming.

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Conflict of Interest

The authors declared no conflict of interest relevant to this study.

Open Research

MODIS Aqua level 3 daily aerosol products are ordered from https://dx.doi.org/10.5067/MODIS/MYD08_D3.061. ERA5 monthly mean 10 m winds are available at https://doi.org/10.24381/cds.68d2bb30. GPCP data are available at https://psl.noaa.gov/data/gridded/data.gpcp.html. CMIP6 data are available through the Earth System Grid Federation at https://pcmdi.llnl.gov/CMIP6/. The CMIP6 models in this work are listed in Table 1.

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