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# Spatio-Temporal Trends of Dust Storms Drivers and Their Role in the Decline of Dust Activity over North Africa

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## Abstract

This study investigates the spatiotemporal trends of key environmental drivers of dust emission over North Africa especially precipitation, surface wind speed, low vegetation leaf area index (LAI), and the Saharan Heat Low (SHL). Using reanalysis data spanning the past four decades (1984-2023), we analyze the spatial trends and assess their statistical significance. The aim is to evaluate how long-term changes in these local meteorological drivers may have contributed to the observed decline in dust activity over North Africa. Results reveal a widespread increase in precipitation and LAI, particularly across the Sahel region (10˚N-20˚N), suggesting enhanced surface wetness and vegetation cover that act to suppress dust mobilization. Simultaneously, a significant negative trend in 10 m wind speed was observed across both the Sahel and parts of Sahara, limiting the surface wind stress required for dust uplift. In contrast, the SHL exhibited a notable intensification and westward expansion, especially over the southern Sahara. Although SHL strengthening is typically associated with increased dust activity, our findings point to a more nuanced role, wherein its recent expansion coincides with broader dust-suppressing environmental trends. These co-evolving changes provide a compelling mechanistic explanation for the observed decline in North African dust activity over recent decades and enhance our understanding and climate models capabilities related to dust activity over North Africa.

## Keywords

Dust Storms, North Africa, Meteorological Drivers, Saharan Heat Low, Dust Decline, Climate Variability

## 1. Introduction

North Africa, particularly the Sahara and Sahel regions, is the world's largest source of mineral dust, contributing over half of the global dust emissions annually (Ginoux et al., 2012; Evan et al., 2016). Dust storms originating from this region play a critical role in modulating the Earth's climate system by influencing radiation budgets, cloud microphysics, and biogeochemical cycles, notably through nutrient transport to the Atlantic Ocean and Amazon Basin (Shao et al., 2011; Yu et al., 2015). Though, recent decades have witnessed a notable decline in dust activity over North Africa (Ridley et al., 2014; Evan et al., 2016). Using horizontal visibility Shao et al. (2013) showed a significant decrease in North African dust activity. Some studies like Cowie et al. (2013) tried to understand the mechanism behind that decline in dust activity. Despite many efforts, the causes of this decline remain only partially understood and are the subject of continued scientific debate.

Previous studies have identified several environmental and meteorological drivers that govern dust emission and transport in this region. These include soil moisture, vegetation cover, surface wind speed, and regional circulation patterns, particularly the dynamics of the Saharan Heat Low (SHL). The drivers interact at seasonal and interannual scales to modulate the availability of dust sources and the efficiency of dust mobilization (Goudie & Middleton, 2006; Knippertz & Todd, 2012).

Precipitation, particularly during the West African Monsoon (WAM) season, is a key regulator of dust activity through its effect on soil moisture and surface crust formation. Wetter conditions suppress dust emissions by increasing soil cohesion, while dry spells following wet periods can promote emissions through crust breakage (Prospero & Lamb, 2003; Pu & Ginoux, 2018). Vegetation, quantified through indices such as the Leaf Area Index (LAI), acts as a physical barrier that reduces dust availability by shielding the soil surface. Vegetation trends across the Sahel have been linked to changes in precipitation patterns and anthropogenic land use (Fensholt et al., 2012; Pierre et al., 2012).

In their studies, Fiedler et al. (2013) showed the fundamental role of surface wind speed in controlling dust uplift. Especially, a threshold wind speed required for dust uplift, remains the immediate driver of emission events. Variability in near-surface winds, including those associated with low-level jets and convective downdrafts, has been shown to strongly influence dust frequency and intensity across the region (Heinold et al., 2013). Using Satellite remote sensing, Guehaz et al. (2024) investigated the March 2022 dust storm over the Algerian Sahara and found that local factors and atmospheric circulation play a significant role in the dust storm initiation.

Among these drivers, the Saharan Heat Low (SHL) plays a central role in the summer dust climatology of North Africa. The SHL is a seasonal, thermally-induced low-pressure system that develops over the western-central Sahara during boreal summer (Lavaysse et al., 2009). Its intensity and location are closely coupled with the West African Monsoon (WAM) system. A stronger SHL enhances the meridional pressure gradient between the Sahara and the equatorial Atlantic, promoting the northward penetration of the WAM (Peyrillé & Lafore, 2007; Lavaysse et al., 2010). This interaction governs the location and strength of the African Easterly Jet (AEJ) and the monsoon trough, which in turn modulate low-level winds, moisture convergence, and the formation of convective systems such as Mesoscale Convective Systems (MCSs) that can generate dust through haboob events (Bercos-Hickey et al., 2020).

Changes in the SHL's structure whether through surface warming, enhanced radiative heating, or land-atmosphere feedbacks, can therefore lead to significant shifts in dust storm dynamics (Evan et al., 2016; Kim et al., 2017; Schepanski et al., 2017). For instance, an intensified SHL has been associated with stronger Harmattan winds and increased dust emissions from key source regions such as the Bodélé Depression (Todd et al., 2007). Conversely, some studies suggest that SHL-driven shifts in the monsoon system could also suppress dust activity by increasing rainfall and vegetation cover across the Sahel (Pu & Ginoux, 2018; Zhao et al., 2021).

Despite the recognized importance of these drivers, few studies have systematically assessed their spatiotemporal trends and how they may collectively explain the observed decline in dust storm activity. Addressing this knowledge gap is essential for improving our understanding of dust-climate interactions and for projecting future dust variability under climate change.

In this study, we investigate the long-term (four decades,1984 - 2023) trends in key dust-related environmental and dynamical drivers over North Africa. We focus on four principal variables: precipitation (soil moisture proxy)**,** leaf area index (vegetation proxy)**,** 10-meter wind speed (surface wind proxy), and SHL intensity (regional circulation proxy)**.** By examining their seasonal and spatial trends using robust statistical methods, we aim to determine whether changes in these drivers can help explain the declining dust activity observed across the Sahara and Sahel.

## 2. Data and Methods

### 2.1. Study Area

The study focuses on the Sahara and Sahel regions (20˚W, 10˚N) and (34˚E, 38˚N). The Sahel's semiarid climate, marked by a steep north-south rainfall gradient (~100 - 600 mm/yr) (Nicholson, 2013), makes it highly sensitive to SHL driven monsoon shifts and dust emissions. The western Sahara (15˚W-10˚E) hosts the SHL's core, where summer surface temperatures exceed 40˚C (Lavaysse et al., 2009), fueling thermal lows that modulate both Sahelian rainfall and trans-Atlantic dust transport (Evan & Mukhopadhyay, 2010; Evan et al., 2016). Key dust sources (e.g., Bodélé Depression, Mali) align with MERRA-2's highest column mass density values (Pu & Ginoux, 2018), while the Sahel's rainfall variability is captured by CHIRPS' high-resolution observations (Funk et al., 2015). This domain encompasses the full SHL-rainfall-dust coupling chain, from emission zones to monsoon receptor regions.

### 2.2. Datasets

In the present study, we use 40 years (1984-2023) of high-quality, gridded datasets to analyze the Saharan Heat Low's influence on Sahel rainfall and dust loading during the WAM. The datasets were selected for their reliability, spatial coverage, and relevance to the study aims.

The ERA5 reanalysis (ECMWF) provides key atmospheric and surface variables at 0.25˚ × 0.25˚ (longitude × latitude) resolution (Hersbach et al., 2020). We use 925, and 700 hPa geopotential to characterize SHL intensity, 10m winds to assess dust emission potential, and 2m Temperature to evaluate land surface conditions. Monthly rainfall data come from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS v3.0) dataset at 0.05˚ × 0.05˚ (longitude × latitude) resolution (Funk et al., 2015). This high-resolution (0.05˚/~5 km) product combines satellite infrared observations with *in situ* rain gauge data from over 1,200 stations across Africa, generating reliable, long-term (1981-present) rainfall estimates particularly suitable for studying monsoon variability in the Sahel region. By incorporating the Tropical Rainfall Measuring Mission (TRMM) 3B42 precipitation fields and gauge-based calibrations, CHIRPS improves detection of light rainfall events (>0.1 mm/day) that are critical for dust suppression in the Sahel region. The dataset's spatial continuity and demonstrated accuracy in West Africa (Dembélé et al., 2020) address key limitations of sparse ground observations while capturing fine-scale gradients across the Saharan-Sahelian transition zone.

Dust loading is analyzed using the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) at 0.5˚ × 0.625˚ (longitude × latitude) resolution (Gelaro et al., 2017). We focus on dust column mass density (kg/m$^2$), which effectively captures dust emission and transport patterns across North Africa. For the homogeneity of our analysis, all the datasets were regridded to 0.5˚ × 0.5˚ (longitude × latitude).

### 2.3. Methods

We computed SHL after Lavaysse et al. (2009) based on the low level atmospheric thickness (LLAT) between 925 and 700 hPa geopotential at 06:00. The LLAT expressed in meter is defined by the following equation:

$$LLAT = \frac{R}{g}\int_{p2}^{p1} Td\left(\ln\left(p\right)\right)$$

where R is the gas constant for air, g is the gravitational acceleration, T is the temperature, and p is the pressure. p2 and p1 correspond to 925 and 700 hPa (Lavaysse et al., 2009). As in Lavaysse et al. (2009), we chose to work on daily basis. The SHL (dimensionless) is defined where the LLAT exceeds a given threshold. In this study, the threshold corresponds to the 90% of the daily cumulative probability distribution function of the LLAT. Then the monthly SHL is obtained by aggregating the daily computed SHL into monthly.

To evaluate whether there exists a monotonically increasing or decreasing trend of the variable under analysis, we employed Mann-Kendall test (MK). This test is a robust method for detecting monotonic trends in time series that is insensitive to outliers and non-normal data distributions (Mann, 1945). For each gridded monthly time series (SHL intensity from ERA5, precipitation from CHIRPS, and dust loading from MERRA-2), we computed the MK statistic ($\tau$) and associated p-value to determine the significance of trends at the 95% confidence level ($p < 0.05$). A positive $\tau$ indicates an increasing trend, while a negative $\tau$ denotes a decreasing trend. The magnitude of trends was quantified using Sen's slope estimator, which provides the median rate of change over time. This approach is particularly suited for hydroclimatic variables, as it avoids assumptions about linearity and handles missing data effectively (Sen, 1968; Von Storch & Navarra, 1995). We use percentage trends to normalize the trends relative to the long-term mean of each variable, which allows for a more intuitive interpretation of changes. This approach has been commonly used in climate and aerosol trend studies (e.g., Ridley et al., 2014; Evan et al., 2016), especially when the aim is to quantify relative change. To account for serial autocorrelation, which can inflate trend significance, we pre-whitened local meteorological drivers (e.g., wind speed, 2m temperature, SHL, Precipitation anomalies, …) using Auto-Regressive Integrated Moving Average (ARIMA(1, 0, 0)) modeling, following established methods for autocorrelated climate data (Wilks, 2011; Cowie et al., 2013; Yu et al., 2015).

## 3. Climatology of Dust Mass Column Density and Dust Mass Fluxes

To understand dust emission climatology over North Africa, we computed the dust mass columns density and dust mass fluxes from reanalysis data.

**Figure 1** presents the monthly climatology of dust column mass density (shaded colors) and dust mass fluxes (arrows) over North Africa particularly the Sahara and Sahel regions. The spatial distribution of dust and its transport pathways show pronounced seasonal variation, driven by dynamic meteorological and climatic forcings. During the boreal winter months (December - February), the highest dust concentrations are observed over the central Sahara, particularly the Bodélé known as one of the most active dust sources globally (Prospero et al., 2002). Dust is transported predominantly south-westward toward the Guinea Coast and the tropical North Atlantic under the influence of Harmattan winds. These results align with the findings of (Yu et al., 2015), who noted peak Atlantic dust loading in winter and spring.

As the seasons progress into the pre-monsoon months (March-May), the dust plume expands both latitudinally and longitudinally. Dust emission intensifies across the central and western Sahara, with increased transport toward the Sahel and Atlantic Ocean. The enhanced fluxes in April and May coincide with strong surface winds associated with the SHL intensification and the breakdown of the

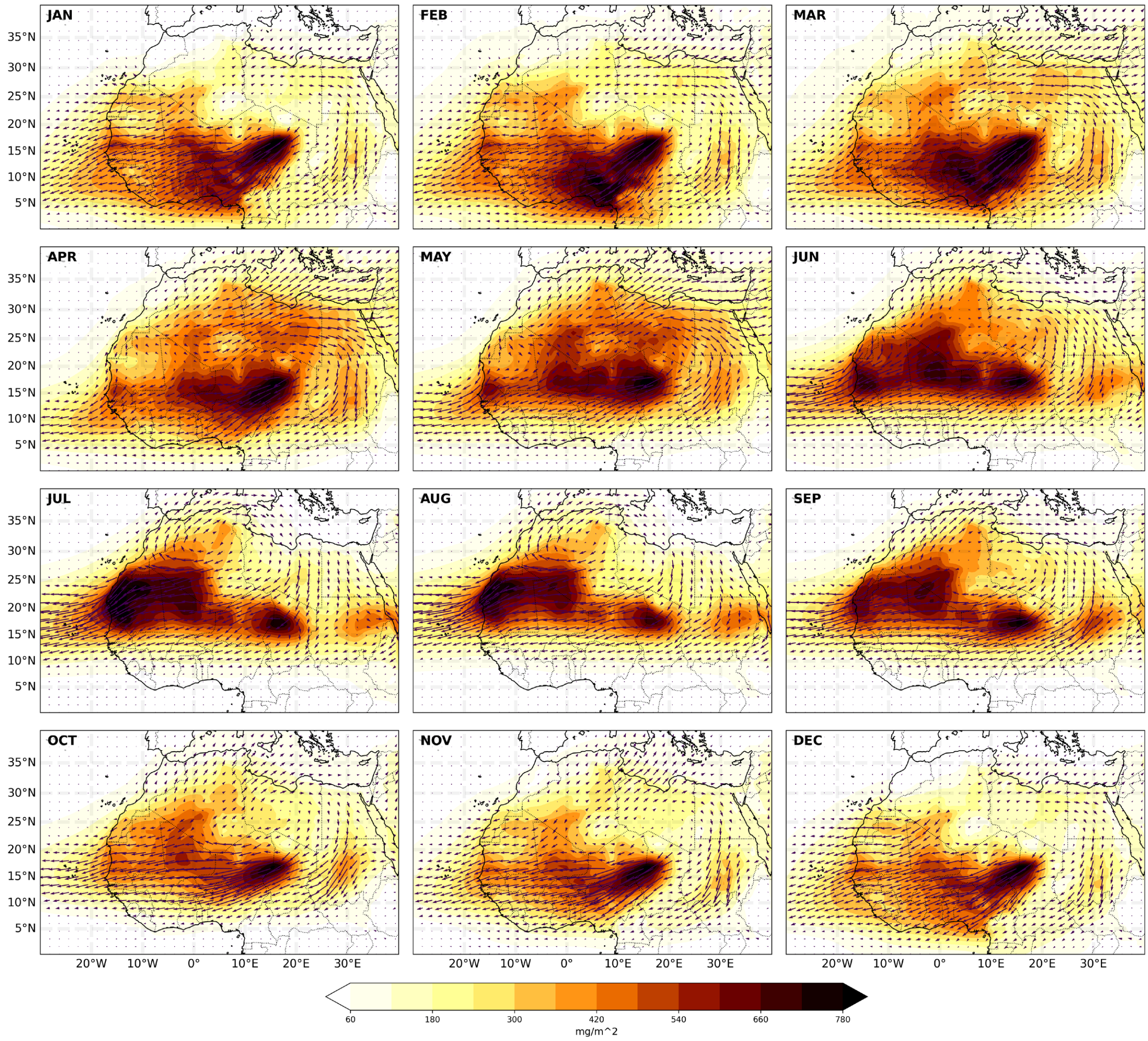

**Figure 1.** Climatology of dust column mass density (color). The dust mass fluxes (vectors) indicate the pathways of dust transport.

Harmattan flow, particularly in the western Sahel leading to the northward extension of the dust plume as indicated by the dust mass fluxes. This agrees with findings by (Marsham et al., 2013), who emphasized the pre-monsoonal SHL strengthening as a key driver of widespread dust mobilization.

In summer (June - August), the dust plume shifts further northward in response to the northward migration of the Intertropical Convergence Zone (ITCZ) and the strengthening of the West African Monsoon. Dust emission from the central and western Sahara remains strong, but the overall southward flux is reduced as low-level monsoonal westerlies oppose the northeasterly dust-carrying winds. Nevertheless, substantial westward fluxes continue, driven by the strong SHL-induced pressure gradients. The dust plume extends westward, reaching the subtropical Atlantic, consistent with studies showing that Saharan summer dust contributes substantially to mid-Atlantic aerosol loading (Ridley et al., 2014). June shows the peak in dust mass density over the western Sahara, consistent with climatological onset of SHL found by (Lavaysse et al., 2009) and surface wind speeds during this period.

In the post-monsoon months (September - November), dust activity gradually decreases, and the flux pattern begins to resemble the wintertime configuration. The dust plume contracts equatorward, and the prevailing easterly winds reestablish westward transport, particularly from the central Sahara. November and December again show intensification of dust emission and a more confined dust plume along the Sahelian corridor.

Overall, the seasonal cycle of dust emission and transport highlights the dominant role of the meteorological factors such as SHL, low-level winds, and monsoon dynamics in shaping the dust climatology over North Africa. Moreover, the dust mass flux vectors show persistent westward transport across all seasons, reflecting the role of low-level easterly winds (Fiedler et al., 2013), especially the African Easterly Jet (AEJ) in summer (Bercos-Hickey et al., 2020) and the Harmattan in winter (Schepanski et al., 2017).

## 4. Drivers and Dust Column Mass Density Correlations

To show the relationship between key meteorological drivers and the dust load, we presented in **Figure 2** both linear regression and Pearson correlation coefficient over the Central Sahel (10-15˚N, 5-15˚E) and Western Sahara (17-25˚N, 10˚W-5˚E). The analysis focuses on sub-regional domains to avoid dilution effects that can arise when averaging over the full Sahara or Sahel belt. The relationships are derived from pre-whitened seasonal data to account for autocorrelation.

Over the Central Sahel, dust load shows a strong positive correlation with surface wind speed ($R^2 = 0.40$, $p < 0.001$), consistent with the established role of enhanced low-level winds in promoting dust emission by exceeding threshold friction velocities (Marticorena & Bergametti, 1995; Tegen & Schepanski, 2009; Fiedler et al., 2013). Conversely, dust load correlates negatively with precipitation ($R^2 = 0.56$, $p < 0.001$) and leaf area index (LAI) for low vegetation ($R^2 = 0.74$, $p < 0.001$), indicating the suppressive effect of antecedent rainfall and vegetation growth on dust mobilization consistent with previous findings such as Evan et al. (2016) and Kim et al. (2017). Rainfall enhances surface moisture and fosters vegetation cover, which in turn stabilizes soil and reduces the frequency and intensity of dust emission events.

In the Western Sahara, a strong and significant positive relationship is found between SHL intensity and dust column mass density ($R^2 = 0.88$, $p < 0.001$). This finding aligns with previous studies showing that an intensified Saharan Heat Low (SHL) strengthens low-level cyclonic circulation and enhances the pressure gradient between the SHL core and surrounding regions, thereby amplifying wind-driven dust uplift (Lavaysse et al., 2009). The strong fit suggests that SHL variability is a dominant driver of dust emission dynamics in this region during the boreal summer.

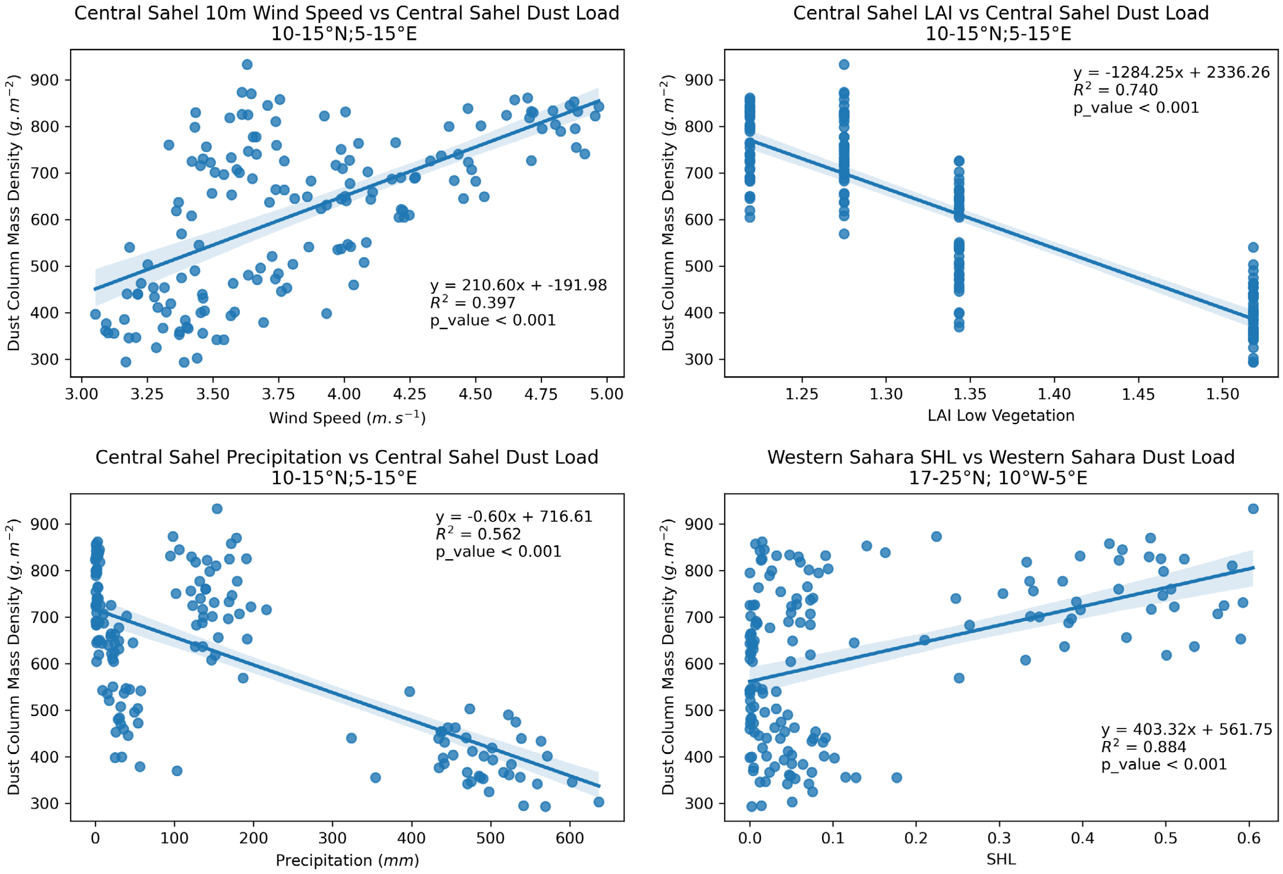

**Figure 2.** Correlation between dust column density and the drivers. The p-value and coefficient of determination are obtained from prewhitened data.

Overall, the results highlight the regionally distinct but physically consistent relationships between dust load and its key environmental drivers. They also demonstrate the advantage of sub-regional and seasonal analyses in capturing meaningful correlations that might be obscured when considering large, heterogeneous domains.

## 5. Surface Wind Spatial Trends

In this section, we present the spatial trends of 10 m wind speed, a key factor in dust emission process.

Figure 3 presents the spatial distribution of the percentage trends in 10 m wind speed across the Sahel and Sahara regions. Positive trends are indicated in red hues, while negative trends are shown in blue. The black dots denote regions where the trends are statistically significant at the 95% confidence level.

A prominent pattern emerges across the Saharan region. There is a widespread increase in wind speed trends, particularly over central and western parts of Algeria, northern Mali, and north-western Niger. The Bodélé Depression in northeastern Chad also exhibits a notable positive trend, aligning with its role as a dominant dust source.

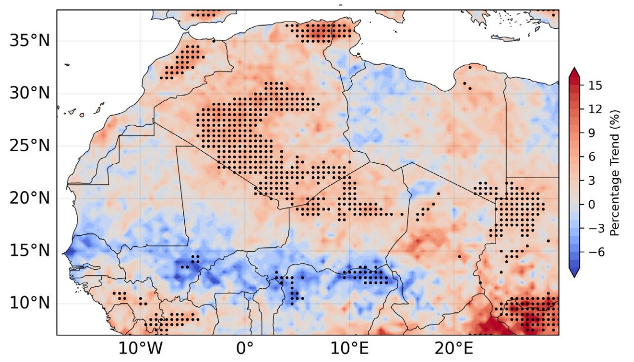

**Figure 3.** Spatial trends of 10 m wind speed. Black dots represent the 95th significance (p-value < 0.05).

In contrast, over Sahelian region, a strong decreasing trend in 10 m wind speed is evident expanding between 13˚N and 16˚N latitude across much of the western Sahel, especially in Senegal, southern Mali, Burkina Faso and between 10˚N and 15˚N latitude across central Sahel especially in northern parts of Benin and Nigeria. Meanwhile, the trends are significant only over northern Nigeria, the decreasing suggests a weakening of near-surface wind activity along the Sahel belt. These contrasting trends underscore the latitudinal climatic gradient between the hyper-arid Sahara and the more vegetated, monsoon-influenced Sahel.

The observed wind speed increase in the Sahara may indicate enhanced pressure gradients or thermal contrast, potentially influenced by warming and associated intensification of the Saharan Heat Low (SHL) system. Conversely, the declining wind speeds in the Sahel are likely associated with increased vegetation cover and precipitation both of which dampen surface wind through increased roughness and boundary layer stabilization (e.g., Heinold et al., 2013; Evan et al., 2016).

These findings align with previous studies that reported:

- A substantial weakening of Sahelian winds due to land surface changes and greening (e.g., Pausata et al., 2016),
- And Saharan intensification of dust-driving winds (Li et al., 2020) linked to larger-scale circulation changes, including the Arctic Oscillation (AO) and Atlantic variability.

From a dust emission perspective, the increasing wind speed trends over key Saharan source regions such as the Bodélé Depression and Algeria may sustain or enhance dust mobilization, depending on surface conditions. Meanwhile, the decreasing trends in the Sahel suggest reduced dust lifting capacity, consistent with observed declines in dust events frequency across the region (Cowie et al., 2013). This spatial differentiation in wind speed trends offers a mechanistic insight into the observed regional dust trends. In particular, the Sahelian dust decline may be largely driven by weaker winds and increased vegetation, while Saharan dust emissions remain more resilient, modulated by both stronger winds and persistent aridity.

## 6. Leaf Area Index Trends and Implication for Dust Storms Activity

To understand the negative trends of surface wind speed, we investigate the vegetation cover over Sahel and Sahara region. We display the spatial distribution of the percentage trends (**Figure 4**) of low vegetation Leaf Area Index (LAI) across North Africa. The green shades represent increasing LAI (greening), while red indicates a decreasing trend. Although the trends shown are not statistically significant, spatial patterns still offer useful insights when interpreted alongside other variables.

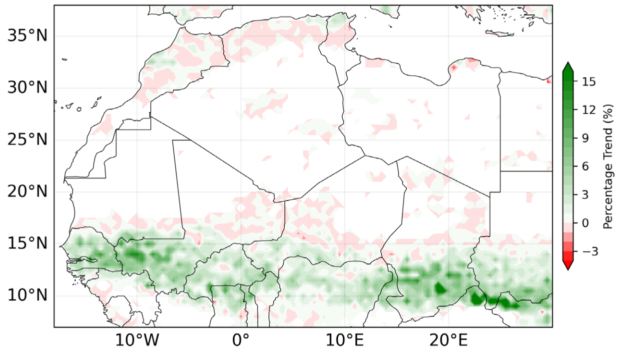

**Figure 4.** Spatial trends of low vegetation leaf area index (the trends are not significant).

Positive LAI trends are observed predominantly across the southern Sahel zone, particularly between latitudes 10˚N and 15˚N, encompassing countries such as Senegal, Mali, Burkina Faso, Niger, and northern Nigeria. This region has experienced episodic greening in recent decades, likely supported by enhanced rainfall and land surface responses to warming conditions. In contrast, most of the Saharan belt shows weak or neutral trends, reflecting its naturally sparse vegetation cover and limited hydrological support.

These findings align with previous studies reporting Sahelian greening in response to increased precipitation and land management practices (e.g., Herrmann et al., 2005; Dardel et al., 2014). Although the observed trends here do not reach statistical significance, the spatial consistency suggests a potentially relevant role of vegetation in modulating dust emission, particularly in the Sahel.

Increased LAI in the Sahel likely contributes to reduced dust storm activity through several mechanisms:

(i) Enhanced ground cover reduces the availability of loose soil particles;

(ii) Improved soil moisture retention binds surface particles; and

(iii) Vegetation roughness elements disrupt wind flow and suppress dust uplift.

Given the strong negative trends previously observed in the distribution of wind trends, the spatially coherent greening trends may reflect one of the local surface factors suppressing dust emissions in recent decades. In contrast, over the Sahara, where the LAI trends are largely neutral, other drivers like wind speed and

SHL dynamics likely exert a stronger control on dust variability.

These results reinforce the idea that vegetation changes, though not dominant in all regions, play a meaningful role in the dust-climate system, particularly in transitional zones like the Sahel as highlighted the studies of Cowie et al. (2013).

## 7. Precipitation Trends and Implication for Dust Storms Activity

The sections 5 and 6 presented the near surface wind and leaf area index trends and their implication in dust storms activity over North Africa. This section explores the trends of precipitations, a key factor controlling soil moisture dust activity over North Africa. The black dots indicate the 95th significance level. **Figure 5** shows the percentage change in precipitation across North Africa, with statistically significant trends indicated by black dots. The trends show a latitudinal contrast, with strong and widespread increases in precipitation between 10˚N and 20˚N, encompassing much of the Sahel region, while changes in the Sahara to the north remain weak and largely insignificant.

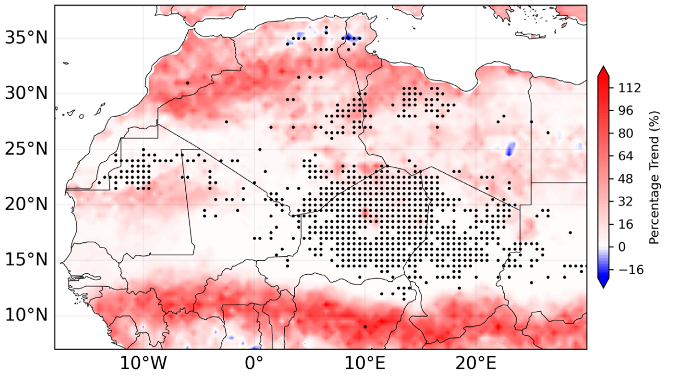

**Figure 5.** Spatial trends of precipitation. Black dots represent the 95th significance (p-value < 0.05).

The Sahelian zone, from Senegal and Mali in the west to Niger, Chad and Sudan in the east, exhibits robust and statistically significant positive precipitation trends, with increases exceeding 15% in many areas. This finding is consistent with numerous studies reporting a recovery in Sahel rainfall since the mid-1980s following the prolonged droughts of the 1970s and early 1980s (Nicholson, 2013; Sanogo et al., 2015). The increase is commonly attributed to both natural decadal variability and external climate forcing, including Atlantic Multidecadal Oscillation (AMO)-driven SST anomalies and anthropogenic warming (Giannini et al., 2003; Biasutti, 2013).

The enhanced rainfall over the Sahel has important implications for regional dust storm dynamics. First, greater precipitation increases soil moisture, which inhibits the entrainment of dust particles. Second, increased rainfall supports vegetation regrowth, stabilizing the soil surface and reducing dust source activation. This is corroborated by the observed positive trends in low vegetation Leaf Area

Index (LAI) over the same latitudinal band (**Figure 3**), even though these trends are not statistically significant likely due to interannual variability and short-term greening responses.

Furthermore, this rainfall increase is co-located with negative trends in 10 m wind speed (**Figure 3**), which reduces the mechanical force available to mobilize dust. This combination of wetting, greening, and weakening winds aligns with the decreasing dust storm frequency observed in the Sahel, suggesting a multi-faceted suppression mechanism involving both dynamic and land-surface feedbacks.

In contrast, the Sahara (above 20˚N) exhibits much weaker or spatially inconsistent precipitation trends. This is expected given its hyper-arid climatology, where even substantial percentage changes often translate into small absolute differences. Dust trends in the Sahara are therefore likely more influenced by atmospheric circulation features, such as the Saharan Heat Low (SHL) and low-level jets, than by local precipitation.

Overall, the precipitation trends support the emerging consensus that Sahelian dust emissions are declining due to a combination of climatic and ecological recovery processes, consistent with findings by Cowie et al. (2013), and Evan et al. (2014). The spatial coherence between increased rainfall, reduced wind speeds, enhanced vegetation, and declining dust frequency further strengthens the causal attribution to climate-driven land–atmosphere interactions.

## 8. Saharan Heat Low Intensification and Dust Activity

This section explores the role of SHL in shaping dust storms over North Africa and complete the trends of primary drivers of dust events.

**Figure 6** illustrates the percentage trend in the Saharan Heat Low (SHL) intensity, represented here by its thermal core strength. The results reveal a pronounced and statistically significant intensification of the SHL between 10˚N and 25˚N latitude across the eastern Sahel and Sahara over Sudan, Chad and southern parts of Libya with trends exceeding 30%. Confined non-significant trends exceeding 80% are observed between 15˚N and 22˚N from the western Mali through Niger to Bodélé Depression where the trends are significant per grid cells. These results are consistent with earlier findings by Lavaysse et al. (2009) and Wang et al. (2017), who documented long-term strengthening and expansion of the SHL in association with increased land surface warming and changes in large-scale atmospheric circulation.

The spatial extent of the SHL intensification overlaps with the zone of increasing rainfall and vegetation greening (**Figure 4** and **Figure 3** respectively), particularly between 10˚N and 20˚N. While the SHL is traditionally associated with dust mobilization due to the formation of strong low-level winds and pressure gradients, the observed co-location with precipitation and vegetation increases suggests a more nuanced role in recent decades. In fact, a stronger SHL can enhance moisture convergence and monsoon progression into the Sahel, reinforcing rainfall patterns (Biasutti, 2013; Lavaysse et al., 2016). This feedback may help explain the synergy between enhanced SHL activity and vegetation-driven surface stabilization, despite the SHL's potential to enhance surface winds.

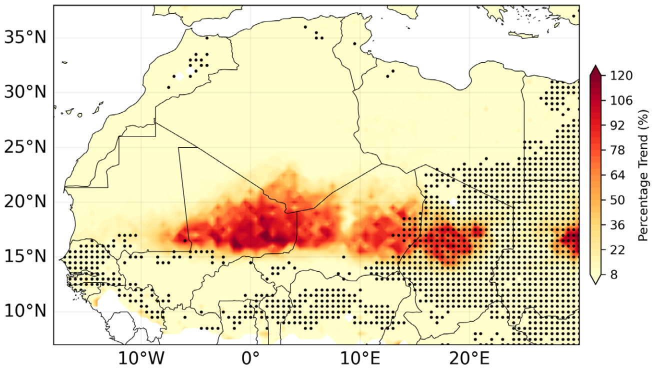

**Figure 6.** Spatial trends of SHL. Black dots represent the 95th significance (p-value < 0.05).

Moreover, when considered alongside the observed negative trends in surface wind speeds (**Figure 2**), these results indicate that mechanical dust lifting is being increasingly constrained. As highlighted by Goudie (2014) and Knippertz & Todd (2012), a strengthened SHL can also stabilize the lower troposphere, reducing vertical mixing and thereby inhibiting dust uplift. A plausible explanation is that while the SHL thermally intensifies, the concurrent increase in soil moisture, vegetation cover, and reduced near-surface wind energy weakens the net dust emission response. This suggests that SHL-driven dynamics alone are insufficient to sustain high dust activity in the presence of surface wetting and greening feedbacks.

The results underscore the complexity of dust-climate interactions in the region. Rather than acting in isolation, the SHL, wind speeds, precipitation, and vegetation trends are interlinked components of a coupled land–atmosphere system undergoing significant climate-driven transformation. These findings are in line with recent observational and modeling studies that emphasize the decline in Sahelian dust emission due to multi-driver interactions, despite persistent dynamical drivers (Cowie et al., 2013; Evan et al., 2016).

## 9. Conclusion

This study investigated the seasonal evolution of dust mass column density, proxy of dust emission over North Africa and its relationship with key meteorological drivers. Using reanalysis data, we found significant trends in meteorological drivers related to dust events occurrence across both the Sahel and Sahara regions. The trends in surface wind speed revealed a widespread decline, particularly across the Sahel band (10˚-15˚N), a region that also experienced notable increases in vegetation cover (LAI) and precipitation. These trends suggest enhanced surface roughness and soil moisture, both of which are unfavorable for dust emission.

In the Sahel, a significant intensification of the Saharan Heat Low (SHL) was observed. While SHL is traditionally associated with dust uplift through thermal low formation and wind enhancement, its recent intensification has coincided with decreasing surface winds, suggesting a possible suppression of dust due to altered circulation patterns. This interpretation aligns with recent studies that have highlighted the complex and regionally dependent role of SHL in dust mobilization.

Together, these findings provide strong evidence that the observed decline in North African dust activity is closely tied to a combination of decreasing surface winds, increasing vegetation and rainfall, and changes in regional thermal structures such as the SHL. The results underscore the importance of evaluating dust trends in the context of multi-variable environmental change and provide a mechanistic basis for explaining the long-term reductions in dust emission observed in recent decades. These findings enhance our understanding on the dynamic of meteorological drivers related to dust activity and climate models capabilities to predict North African dust dynamic.

## Data Availability Statement

The data used in this study are publicly available, the pressure level fields (925 hPa and 700 hPa geopotential; https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=download), the single level fields (10 m wind speed, and Leaf Area Index; https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download), CHIRP V3 precipitation data (https://data.chc.ucsb.edu/products/CHIRPS/v3.0/monthly/global/netcdf/), the MERRA 2 data (https://gmao.gsfc.nasa.gov/reanalysis/merra-2/data_access/).

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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## Appendix

The analysis was conducted using Python programming language with specialized packages for handling geospatial data (e.g., NetCDF, Xarray), time-series analysis (e.g., pandas) and statistical testing (e.g., scipy). Visualization of the result was performed using tools such as Matplotlib and Cartopy for mapping and plotting.