

IMPACT OF CLIMATE VARIABILITY
ON ATMOSPHERIC DRIVERS OF
MAJOR DUST STORMS OVER NORTH
AFRICA

By

KOLOTIOLOMA, YEO
(MCS/20/7725)

JULY, 2025

IMPACT OF CLIMATE VARIABILITY ON ATMOSPHERIC DRIVERS OF MAJOR DUST STORMS OVER NORTH AFRICA

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B.Sc. (Physics)

M.Sc. (Atmospheric Physics)

(MCS/20/7725)

A Thesis of the Doctoral Research Programme of the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) in the Department of Meteorology and Climate Science submitted to the School of Postgraduate Studies in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Meteorology and Climate Science of the Federal University of Technology, Akure, Ondo State, Nigeria.

JULY, 2025

DECLARATION

I hereby declare that this Thesis was written by me and is a correct record of my own research work. It has not been presented in any previous application for any degree of this or any University. All citations and sources of information are clearly acknowledged by means of references.

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CERTIFICATION

We certify that this Dissertation ENTITLED “Impact of Climate Variability on Atmospheric Drivers of Major Dust Storms over North Africa” is the outcome of the research carried out by Kolotioloma, YEO under the WASCAL DRP-WACS in the Department of Meteorology and Climate Science of the Federal University of Technology, Akure, Nigeria.

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ABSTRACT

Dust storms over North Africa represent a critical component of the regional and global climate system, influencing radiation balance, precipitation processes, ecosystem functioning, and human health. Despite their importance, recent studies suggest a multidecadal decline in dust activity across the region, though the driving mechanisms remain debated. This study investigates the spatiotemporal trends in North African dust storm frequency over the past four decades and explores the meteorological and climate drivers underlying these changes using a combination of observational datasets, reanalysis products, and statistical and machine learning methods. Seasonal and annual dust frequency trends derived from surface visibility records reveal a pronounced decrease in dust activity, particularly across the Sahel and central Sahara. Using Theil-Sen trend estimation and Mann-Kendall significance testing, we detect statistically significant declines in surface wind speeds and increases in vegetation cover (leaf area index) and precipitation, especially between 10°N and 15°N. Concurrently, the Saharan Heat Low (SHL) shows signs of intensification and expansion, suggesting possible suppression of dust uplift due to modifications in regional circulation and thermodynamic stability. Correlation analyses further highlight strong seasonal associations between dust storm frequency and drivers such as 10-m wind speed, precipitation, SHL strength, and climate indices (Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO)). A Self-Organizing Map (SOM) classification of sea level pressure and 925 hPa wind patterns during dust storm days reveals dominant atmospheric configurations associated with dust generation, with a clear seasonality and regional preference in SOM node activation. Additionally, Long Short-Term Memory (LSTM) models using climatic and environmental predictors demonstrate skill in reconstructing the historical evolution of dust storms, reinforcing the predictability of dust activity based on climate variability. Overall, the

results support the hypothesis that recent declines in North African dust storm activity are linked to a combination of decreased surface wind stress, increased vegetation and rainfall, and changes in the SHL and large-scale climate drivers influence. These findings provide an updated understanding of dust-climate interactions and underscore the importance of land-atmosphere coupling and climate teleconnections in shaping dust variability.

DEDICATION

This Thesis is dedicated to my Late Father YEO Tana, my Late Mother TUO Sanata and my Late Aunt TUO Fanta.

May Allah accept you in his Paradise Al Firdaus.

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Say, "Nothing will ever befall us except what Allah has destined for us. He is our Protector". So in Allah let the believers put their trust."
Quran 9:51

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LIST OF ACRONYMS

Acronym.	Meaning
AEJ:	African Easterly Jet
AERONET:	Aerosol Robotic Network
AEW:	African Easterly Waves
AMO:	Atlantic Multidecadal Oscillation
AO:	Arctic Oscillation
AOD:	Aerosol Optical Depth
AOT:	Atmospheric Optical Thickness
ARIMA:	Auto Regressive Integrated Moving Average
BADC:	British Atmospheric Data Center
CALIPSO:	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CNN:	Cloud Condensation Nuclei
CPC:	Climate Prediction Center
ECMWF:	European Center for Medium-Range Weather Forecast
ENSO:	El Nino-Southern Oscillation
GGWI:	Great Green Wall Initiative
HNLC:	High-Nutrient, Low-Chlorophyll
IOC:	Indian Ocean Dipole
ITCZ:	Intertropical Convergence Zone
ITD:	Intertropical Discontinuity
ITF:	Intertropical Front
Km ² :	square kilometer

LAI:	Leaf Area Index
LLAT:	Low-Level Atmospheric Thickness
LLJ:	Low-Level Jet
MCSs:	Mesoscale Convective Systems
MEI:	Multivariate ENSO Index
METAR:	Meteorological Aviation Routine Weather Report
MIDAS:	Met Office Integrated Data archive Center
MODIS:	Moderate Resolution Imaging Spectroradiometer
Mt:	Million ton
MT:	Monsoon Trough
NA:	North Africa
NAO:	North Atlantic Oscillation
NOAA:	National Oceanic and Atmospheric Administration
NOI:	Northern Oscillation Index
NO _x :	Nitrogen oxides
PBL:	Planetary Boundary Layer
SEVIRI:	Spinning Enhanced Visible and Infrared Imager
SHL:	Saharan Heat Low
SO ₂ :	Sulfur Dioxide
SOI:	Southern Oscillation Index
SST:	Sea Surface Temperature
SYNOP:	Surface Synoptic Observations
Tg:	Tera-gram

Tmax:	Maximum Temperature
Tmin:	Minimum Temperature
TOA:	Top of the Atmosphere
TOMS & OMI:	Total Ozone Mapping Spectrometer and Ozone Monitoring Instrument
UK:	United Kingdom
UNDESA:	United Nations Department of Economic and Social affairs
UTC:	Universal Time Coordinate
VIIRS:	Visible Infrared Imaging Radiometer Suite
WA:	West Africa
WAHL:	West African Heat Low
WAM:	West African Monsoon

CHAPTER ONE

INTRODUCTION

1.1 Background

Dust storms are meteorological phenomena characterized by the intense wind-driven mobilization of fine-grained particles. They are a prominent feature of the North African (NA) landscape. During dust storms occurrence, important amount of dust is lifted into the atmosphere. The lifted dust is spreading from the source regions to the southwestern part of West Africa (WA) where it can be mobilized for days and regions around. The spatial distribution and frequency of dust storms vary with the seasons of the year (Shao *et al.*, 2011). Large-scale monsoon-type flows associated with an acceleration towards continental heat low; mobile synoptic-scale systems such as anticyclones, cyclones and their cold fronts, typically in late winter and spring; gust fronts generated by outflow from moist convective storms, most common in during the beginning of the summer rainy season; intense dry convection in the daytime PBL particularly during summer are the generic meteorological phenomena leading to dust storms (Knippertz, 2014). The monsoon flow influences precipitation patterns, surface wind dynamics, and soil moisture levels, all of which are crucial in determining the intensity and frequency of dust storms (Bou Karam *et al.*, 2008; 2009). At this stage, the notice is that, the occurrence and intensity of dust storms are intricately linked to a complex interplay of factors, including wind speed, atmospheric stability, surface moisture, and the soil type. These factors are themselves sensitive to variations in climate. Thus, climate variability, driven by phenomena such as El Nino Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), and changes in sea surface temperature, can significantly influence atmospheric circulation patterns, precipitation regimes, and vegetation

cover. This suggests that the AMO, in particular, may play a primary role in driving decadal-scale dust variability (Shao *et al.*, 2013). It is still a key challenge to weather forecasting models to correctly predict dust storms occurrence, the amount of dust lifted into the atmosphere as well as its transport, concentration and radiative effects (Tulet *et al.*, 2008). Satellites and numerical models have been a good alternative to globally improved our understanding of dust storms, and dust impacts particularly over NA, the Earth largest dust sources region with relatively sparse distribution of weather stations. Satellites data are therefore limited in dust sources identification as satellites observe transported dust, as well as, entrained dust (Shao *et al.*, 2011).

Different studies have investigated the atmospheric dynamics (Schepanski *et al.*, 2009), the meteorological causes (Knippertz, 2014; Francis *et al.*, 2020), the formation and transport of dust storms (Knippertz *et al.*, 2009; Shao *et al.*, 2010) over NA.

The author highlighted the dust storms profound influence on regional and global climate systems, impacting atmospheric circulation, radiation budget, and precipitation patterns. Analyzing, the march 2006 major dust storm Slingo *et al.* (2006) showed a reduced of Outgoing Long Radiation (OLR) by 30W.m^2 compared with the nearby regions and a drop of surface emission by 100W.m^2 corresponding to a surface cooling of 13°C . For the same event, Tulet *et al.* (2008) suggested a modification in the atmospheric stability by as much as 9.5K in term of potential temperature when the dust layer is located over the boundary layer. In another case Asutosh *et al.* (2022) showed that the June 2020 dust storm induced an atmospheric radiative forcing 200% more than the climatology resulting in an elevated warming followed by a drop in relative humidity. The study of N'Datchoh *et al.* (2018) showed that dust in the atmosphere can substantially reduce the clouds formation over West African region leading to a decline in precipitations.

Beyond their climatic significance, dust storms pose substantial challenges to human health, agriculture, and ecosystems across NA. During dry season (December-April) where dust storms activity is prominent, the Harmattan flow transports large amount of dust particles generated by dust storms from dust sources both in Sahara and Sahel regions, across the Sahel, the Guinea Coast and the Atlantic Ocean, causing reduced visibility and severe air quality issues (Querol *et al.*, 2019). This period also corresponds to the peak of meningitis disease cases in the sub-Saharan Africa (García-Pando *et al.*, 2014). The study conducted by Agier *et al.* (2013) revealed a consistent time-lag relationship between dust and meningitis seasonality in Niger, supporting the role of dust in driving meningitis outbreaks. A similar study conducted by Yarber *et al.* (2023) in Senegal, showed that Desert dust significantly influences meningitis seasonality in Senegal. Though, the wet season is characterized by the Monsoon flow that influences the seasonal migration of the Intertropical Convergence Zone (ITCZ), affecting rainfall patterns, surface winds, atmospheric stability as well as the activation of dust sources (Sultan & Janicot, 2000; Bou Karam *et al.*, 2008, 2010; Janicot *et al.*, 1998, 2009; Knippertz *et al.*, 2009). Additionally, the vulnerability of NA to climate change effects, exacerbated the vulnerability of extreme events such as extreme precipitations, and extreme dust storms occurrence. The climatic shifts, in turn, can modulate the frequency, intensity, and spatial distribution of dust storms.

Despite the above investigations, our understanding on how climate variability impacts dust storms drivers in the atmosphere over NA where numerical models still challenging to predict the climate due to its variability remains unclear. However, a comprehensive understanding impact of climate variability on dust storms drivers, requires a holistic approach that integrates the influence of multiple climate factors on the full spectrum of atmospheric drivers.

1.2 Problem statement

There has been a substantial increase in interest in dust storms and dust studies within the scientific community over the past decades. Latest studies have mainly focused on the role of dust in the Earth system (Shao *et al.*, 2011; Knippertz & Stuut, 2014). Even though, the factors contributing to dust storm occurrences may vary throughout the year, surface conditions such as surface wind and sea level pressure remain crucial determinants in triggering dust storms. Several previous studies have shown the determinant role of strong surface wind speeds associated with mesoscale processes in generating dust storms over NA (Bou Karam *et al.*, 2010; Fiedler *et al.*, 2013; Cowie *et al.*, 2014; Francis *et al.*, 2020; Asutosh *et al.*, 2022). Klose *et al.* (2010) used mean sea level and 10m wind to identify the synoptic patterns associated with dust accumulation events over the Sahel. Though, the extensive spatial and temporal distribution of dust loaded in the atmosphere by dust storms directly impacts climate variability through interactions with clouds, the Ocean and the land surface (Evan *et al.*, 2011; Shao *et al.*, 2011). Climate variability will undoubtedly impact the drivers of dust storms, influencing both their frequency and intensity. While previous research has explored the individual aspects of dust storm dynamics, a comprehensive understanding of the interplay between climate variability and the atmospheric drivers of these events remains elusive. This study will investigate the impact of climate variability on dust drivers of dust storms over NA using Man Kendal static tools, Self-Organizing Maps (SOM) and Long Short-Term Memory (LSTM). Furthermore, it investigates the potential link between dust frequency, dust drivers and large-scale climate patterns.

1.3 Research justification

Based on climate scenarios above 1.5 degrees Celsius (IPCC, 2018), NA is the most vulnerable region to climate change impacts. Moreover, the region is widely regarded as the Earth's largest source of dust (Propero *et al.*, 2002; Washington *et al.*, 2003).

Dust storms pose significant challenges to human health, agriculture, and regional economics in NA. Their hazardous nature has brought them to the attention of the United Nations General Assembly, which has adopted resolutions entitled “Combating sand and dust storms” in 2015 and proclaimed the 12th July as the “International Day of Combating Sand and Dust Storms” under the resolution ([A/RES/77/294](#)).

Understanding the factors that influence the occurrence and intensity of dust storms is crucial for developing effective mitigation and adaptation strategies. (Shao *et al.*, 2013) investigated dust trends and highlighted a decreasing in dust concentration over NA. The explanation for the decrease lies within the complex interplay between climate variability and the drivers of dust storms.

The findings of this study will provide valuable insights for policymakers and stakeholders in developing effective strategies to mitigate the impact of dust storms, such as implementing early warning systems, air quality management, and promoting sustainable land use practices. For the scientific community, the study will contribute to climate modeling, climate change assessment, and scientific advancement.

1.4 Aim and objectives

The aim of this research is to investigate the impact of climate variability on atmospheric dust drivers of major dust storms over North Africa. This aim can be broken into the three following specific objectives as following:

- (i) Evaluate the characteristics of dust storms, and dust drivers from 1984 to 2023;

- (ii) Identify the dominant synoptic-scale patterns during dust storms using SOMs;
- (iii) Simulate climate variables related to dust drivers in near future using LSTM.

CHAPTER TWO

LITERATURE REVIEW

This chapter summarizes recent research studies on dust storms and their characteristics as well as their impacts through observation stations, satellites, reanalysis and modeling studies during the seasons of the year, highlighting dust storms activity over Sahara and the Sahel. A state of climate characteristics over North Africa as well the WAM and the SHL key climatic features of the area is given in the section below, which are specific features of the region during the year.

2.1 North African Monsoon System

The North African monsoon is a dynamical climate system characterized by a seasonal reversal of winds and associated in precipitation patterns across North Africa. This system plays a crucial role in modulating dust storms activity, influencing both the generation and the transport of the mineral dust. This section focuses on the specific features of North African Monsoon and their direct implications for dust storms in the region.

2.1.1 Seasonal Evolution of the Inter-Tropical Discontinuity (ITD) and the Inter-Tropical Convergence Zone (ITCZ).

Numerous studies showed that the monsoon system is driven by the seasonal migration of the ITCZ, which influences precipitation patterns, surface winds, and atmospheric circulation patterns across NA (Bou Karam *et al.*, 2008; Nicholson, 2013, 2018). The interaction of these elements creates conditions conducive to the mobilization and transport of dust, making the studies of the monsoon critical for understanding dust storms dynamics. Therefore, the seasonal migration of the

ITCZ and the ITD remain a fundamental aspect of the NA monsoon. The ITCZ referring to Monsoon Trough (MT) over land, to mark the zone of vigorous tropical disturbances, occurs where the trade winds from both hemispheres converge, leading to convective rainfall (Lafore et al., 2017; Nicholson, 2018). During the boreal summer, it shifts northward, bringing monsoonal rainfall to the Sahel, while retreating southward in winter, results in drier conditions (Sultan & Janicot, 2000, 2003; Sultan *et al.*, 2003; Nicholson, 2013; Lafore *et al.*, 2017). The ITD often referred as Inter-Tropical Front (ITF) , which represents the boundary between dry Saharan air and moist monsoonal air at the surface, follows a similar seasonal pattern and plays a critical role in regional dust emissions (Lélé & Lamb, 2010; Lafore *et al.*, 2017).

2.1.2 Monsoon Circulation and Wind patterns: Drivers of Dust mobilization.

Harmattan, SHL, and WAM are the three major element of the atmospheric circulation over NA (Schepanski *et al.*, 2017). Monsoon circulation significantly influences wind patterns, which act as primary drivers of dust mobilization. Washington *et al.* (2003) showed that the strong Harmattan winds, dominant during the dry season, facilitate extensive dust uplift, particularly from major dust source regions such as Bodélé Depression. Additionally, monsoon surges and mesoscale convective systems (MCS) generate gust fronts and downdrafts that enhance dust lifting (Flamant *et al.*, 2009). Strong meridional soil moisture gradients form a mid-latitude easterly jet known as African Easterly Jet (AEJ) (Cook, 1999). This jet plays a key role in transporting dust westward across the Atlantic, while interaction with mid-latitudes westerlies can contribute to long range transport (Knippertz & Todd, 2012).

2.1.3 Temperature gradients and Atmospheric Stability: Influencing dust Transport.

The intense heating over the Sahara during summer creates a highly unstable atmosphere, which promotes vertical mixing of dust to higher latitudes. This heating leads to high surface temperature and low surface pressure characterized by a low-level cyclonic circulation and mid-level anti-cyclonic circulation about the center of low pressure surface (Lavaysse *et al.*, 2009). This phenomenon is known as Saharan Heat Low (SHL). Intense surface heating strengthens the SHL, enhancing convective mixing and increasing dust suspension in the atmosphere (Wang *et al.*, 2017). Additionally, the temperature contrast between the SHL and surrounding regions influences pressure gradients, shaping regional wind systems that control dust transport pathways (Todd & Cavazos-Guerra, 2016).

2.1.4 Interaction with Large-scale climate Drivers: Complexities of Dust Storm Prediction.

The occurrence and intensity of dust storms in NA are not only governed by the seasonal dynamics of the monsoon but also influenced by large-scale climate drivers. These drivers modulate atmospheric circulation patterns, wind regimes, and precipitation, thereby altering the conditions for dust emission and transport.

El Nino-Southern Oscillation (ENSO): Numerous studies have showed that the ENSO cycle significantly affects the North African climate by shifting atmospheric circulation patterns and modulating the strength of the WAM. During ENSO years, anomalous warming in the tropical Pacific is linked to a weaker monsoon, reducing precipitation over the Sahel, and enhancing surface dryness, all which contribute to increase dust emissions (Prospero & Lamb, 2003). This occurs due to changes in the Walker circulation, which suppress convection over West Africa and reduce moisture transport from the Gulf of Guinea.

Conversely, La Nina conditions often result in stronger monsoonal activity, increased vegetation cover, and reduced dust emissions (Nicholson & Kim, 1997; Nicholson, 2013). Additionally, ENSO driven changes in the strength and position of the AEJ and the Tropical Easterly Jet (TEJ) further impact dust transport pathways (Vashisht *et al.*, 2021). Studies by Doherty *et al.* (2012) and DeFlorio *et al.* (2016) highlight how ENSO related teleconnections influence Saharan dust variability, with ENSO years showing increased dust transport across the Atlantic due to strengthened westerly winds.

Recent research has also explored the combined effects of ENSO and the Indian Ocean Dipole (IOD) on North African dust activity, demonstrating that interactions between these climate modes can amplify or mitigate dust storm occurrences (Evan *et al.*, 2016; Endris *et al.*, 2019).

Atlantic Multidecadal Oscillation (AMO): The AMO, a multi-decadal variability in North Atlantic Sea surface temperatures, influences the strength and position of the monsoon system. Positive AMO phases are associated with increased rainfall over the Sahel, leading to reduced dust emissions due to enhanced soil moisture and vegetation growth. In contrast, negative AMO phases contribute to drought conditions, intensifying dust storms over NA (Wang *et al.*, 2012; Martin & Thorncroft, 2014). In the same vein, studies have shown that positive AMO phases can enhance the northward shift of the ITCZ, increasing precipitation over the Sahel, while negative phases push the ITCZ southward, reducing rainfall and increasing dust storm frequency (Zhang & Delworth, 2006; Martin & Thorncroft, 2014). The AMO's influence extends beyond precipitation changes, affecting the intensity of the SHL and modifying the position of the AEJ, both of which have implications for dust transport pathways. Studies also linked AMO variability to fluctuation in dust loading over the tropical Atlantic, showing how changes in Sea Surface Temperature (SST) can regulate dust emission on decadal timescales (Martin & Thorncroft, 2014). Shao *et al.* (2013)

have detected a significant negative correlation between Saharan dust and the AMO and suggested that under current climate, the global dust trend is determined by the climate system governing the North Atlantic and North African regimes. Additionally, the AMO interacts with other climate modes, such as ENSO and the North Atlantic Oscillation (NAO), to create complex feedbacks affecting dust emission and transport (Prospero & Lamb, 2003).

North Atlantic Oscillation (NAO): The NAO, which modulates the pressure gradient between the Azores High and the Icelandic Low, also impacts dust storm activity. During positive NAO phases, enhanced trade winds strengthen the transport of Saharan dust westward toward the Atlantic Ocean (Moulin *et al.*, 1997; Ginoux *et al.*, 2004). Positive NAO are also associated with increased storm activity over the North Atlantic, which can contribute to stronger surface winds over the Sahara, enhancing dust uplift and transport (Hurrell & Deser, 2010; Evan *et al.*, 2016). Furthermore, the increased subsidence over North Africa during positive NAO phases suppresses precipitation, leading to drier soil conditions that favor dust mobilization (Moulin *et al.*, 1997).

Negative NAO phases, on the other hand, are associated with weaker winds and reduced dust mobilization (Ginoux *et al.*, 2004). Additionally, during negative NAO phases, shifts in the storm tracks and weakened subtropical ridges contribute to changes in transport pathways of dust, often leading to more localized deposition over NA rather than long-range transport across the Atlantic (Wang *et al.*, 2017). These variations in NAO phases contribute to interannual and decadal fluctuations in Saharan dust emissions and their impacts on regional and global climate.

Madden Julian Oscillation (MJO): the MJO is a key driver of intra-seasonal variability, characterized by eastward moving atmospheric disturbances that affect convection and wind patterns on a 30-30 day cycle (Matthews, 2004). Studies suggest that active MJO phases enhance convective activity over WA, influencing monsoon strength and associated dust transport

mechanisms. Conversely, suppressed MJO phases, reduced convective activity leads to drier conditions and stronger Harmattan winds, which increase dust storm occurrences over the region (Alaka & Maloney, 2012). The influence of the MJO on African dust activity highlights the importance of sub-seasonal variability in dust storm prediction and early warning systems.

2.1.5 Topography of North Africa.

The topography of NA is diverse, featuring vast deserts, mountain ranges, and low-lying depression. These geographical features play a crucial role in shaping wind patterns and dust emissions.

The Sahara Desert: previous studies showed that the Sahara is the world's largest hot desert, covering approximately 9.2 million square kilometers. It consists of mix of sand seas (ergs), rocky plateaus (hamadas), and gravel plains (regs). The extensive ergs, such as the Grand Occidental and the Grand Erg Oriental in Algeria, act as significant dust sources, particularly under the influence of strong surface winds (Ginoux *et al.*, 2012).

The Bodélé Depression: Located to the northeast of lake Chad, the Bodélé Depression is the lowest point in the Sahara and is considered the most intense dust source globally (Washington *et al.*, 2003; Koren *et al.*, 2006). This basin was once part of the ancient Mega-Chad lake system, leaving behind fine-grained sediments that are easily mobilized by the region's strong, channelized winds (Todd *et al.*, 2007). The surrounding Tibesti, Ennedi and Ouaddai Mountains further accelerate wind speeds, enhancing dust uplift (Washington *et al.*, 2009).

Mountain Ranges and their Role in Dust Activity:

-The Tibesti and Hoggar Mountains: These volcanic mountain ranges in Chad, Niger, and Algeria serve as major topographic features influencing regional wind patterns (Schepanski *et al.*, 2009).

They disrupt the prevailing trade winds, leading to localized wind jets that contribute to dust entrainment and transport ;

-The Atlas Mountains: Stretching across Morocco, Algeria, and Tunisia, the Atlas Mountains act as a climatic divide, separating the humid Mediterranean zone from the arid Sahara. These mountains block northerly moist air masses, contributing to the hyper-arid conditions of the Sahara (Gkikas *et al.*, 2015) ;

-The Red Sea Hills and Libyan Plateau: These elevated regions in eastern North Africa influence dust transport pathways, particularly during monsoonal shifts and Mediterranean cyclones (Karami *et al.*, 2024).

2.1.6 Soil Types and Dust Emission potential.

The types of soils found in NA are a major factor in determining the intensity and frequency of dust storms. The region is characterized by arid and semi-arid soil types, many of which contain fine-grained, unconsolidated sediments that are highly susceptible to wind erosion. This subsection states the main types of soils in NA region.

Sandy soils: Sandy soils dominate large portions of the Sahara Desert, particularly in areas with extensive dune systems such as the Grand Erg Oriental and the Grand Erg Occidental in Algeria (Driessen *et al.*, 2001). These soils have high sand content, low organic matter, and weak soil structure, making them prone to wind erosion, especially during strong Harmattan winds (Rajot *et al.*, 2003).

Gravelly and rocky soil: these types of soils are found in desert pavements and hamada regions, such as the Hamada du Draa in Morocco. These soils have little vegetation cover and are composed of a mixture of gravel, sand, and finer silt particles. While they are more resistant to erosion than

sandy soils, disturbances such as vehicle movement or droughts can increase dust emissions (Goudie, 2014).

Alluvial soils: Alluvial soils are found in river valleys and dry lake beds, such as the Bodélé Depression in Chad and the Chotts of Tunisia and Algeria. These soils originate from past water deposition and contain fine silts and clays, which make them highly susceptible to wind uplift when dry (Koren *et al.*, 2006).

Gypsisols and Calcisols (Gypsum and Calcium Rich soils): These soils are found in arid regions with high evaporation rates, such as parts of Libya, Egypt, and Sudan (Driessen *et al.*, 2001). Gypsisols contain significant amounts of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), while Calcisols have high calcium carbonate content. These soils are relatively resistant to erosion but can contribute to dust emissions when their fine fractions are exposed due to land degradation (Driessen *et al.*, 2001; Goudie & Middleton, 2006).

Clay-Rich-Soils: Also known as vertisols, clay-rich-soils are characterized by high clay content and are found in semi-arid regions of sudano-sahelian zone, and some depressions in the Sahara (Driessen *et al.*, 2001; Pierre *et al.*, 2019). These soils form deep cracks during dry seasons, and when disturbed by wind or human activities, they can generate large dust plumes (Marticorena *et al.*, 2017).

Anthropogenic and Disturbed Soils: Human activities have significantly altered the natural landscape in parts of the Sahel and NA, exacerbating dust emissions and contributing to regional dust storms. Soil degradation due to overgrazing, deforestation, and unsustainable agricultural practices has led to increased surface vulnerability and wind erosion (Prospero *et al.*, 2002; Ginoux *et al.*, 2012; Knippertz & Todd, 2012). Overgrazing, particularly in arid and semi-arid regions, removes protective vegetation cover, exposing loose soil particles to the effects of strong winds

(Wang & Jenkins, 2003). In many parts of the Sahel, excessive livestock grazing has resulted in land degradation, reducing soil stability and increasing the frequency of dust outbreaks (Middleton, 2018; Slayi *et al.*, 2024). Similarly, deforestation, often driven by fuelwood collection and land conversion for agriculture, reduces the ability of soils to retain moisture and resist wind erosion (Wang & Jenkins, 2003; IPCC, 2022). The loss of vegetation cover and disturbance of topsoil lead to increased wind erosion, contributing to regional dust storms (Prospero *et al.*, 2002; Shao, 2008).

Agricultural expansion and intensive land use have further intensified soil disturbance. For instance, inappropriate tillage techniques, monocropping, and irrigation mismanagement disrupt soil structure, leading to desertification and increased dust emissions (Tegen *et al.*, 2002). The conversion of grasslands into croplands in marginal areas has also exposed fragile soils to the elements, increasing their susceptibility to erosion (AbdelRahman, 2023). Additionally, urbanization and infrastructures development in NA have contributed to dust emissions. In urban areas, construction activities, road networks, and industrial zones generate large amounts of loose particulate matter, which can be lifted into the atmosphere by strong winds. Therefore, dust resuspension from degraded lands near urban centers has been linked to deteriorating air quality, posing health risks to local populations (Middleton, 2018). The impact of anthropogenic activities on dust emissions highlights the need for sustainable land management practices, including reforestation, rotational grazing, and conservation agriculture, to mitigate soil degradation and reduce atmospheric dust loads (Herrmann & Hutchinson, 2005).

2.2 Dust Sources, and Identification in North Africa

Dust storms play a significant role in the Earth's climate system, impacting air quality, visibility, human health, and ecosystems (Shao *et al.*, 2011). NA particularly, the Sahara Desert, is the largest global source of mineral dust, contributing to atmospheric dust transport across the Atlantic Ocean and beyond (Middleton & Goudie, 2001; Prospero *et al.*, 2002). Numerous studies have shown that understanding the sources and mechanisms of dust emissions in this region is critical for predicting dust storms occurrences and their environmental impacts. This section states the identification means of dust sources, and the major dust sources as well as their intra-seasonal activation and the anthropogenic activities impact on dust sources over NA.

2.2.1 Identification of Dust Sources over NA.

Identifying dust sources is essential for understanding their contribution to atmospheric dust loading and transport. Several techniques have been used to locate active dust emission zones in NA, including satellite remote sensing, ground-based measurements, and numerical modeling. In the same vein, numerous studies have been conducted to enhance the identification of these sources, contributing to a more comprehensive understanding of dust dynamics in the region. This section states the techniques and means used to investigate the potential dust source regions.

2.2.1.1 Ground-Based Measurements

Ground-based observations play a crucial role in validating and complementing satellite data by providing direct measurements of dust concentrations, optical properties, and chemical composition. These measurements enhance our understanding of dust emission processes and their atmospheric impacts.

Earlier, D’Almeida, (1986) used ground data from the African turbidity network to identify four major dust sources areas. From their analysis, source 1 extends from western Sahara to northern Mauritania. Source 2 is located in the triangle formed by the Hoggar, Adrar des Iforas, and Air mountains (in Algeria and Niger), northeast of Gao (Mali). Source 3 is situated north to northeast of Bilma (Niger) off the west side of Tibesti Massif, and source 4 is located in northern part of the Sudan and southern part of Egypt. Largest dust sources are source 1, 2, 3 with dust export annual production more than 200 Mt each; dust emission from source 4 is relatively weak (D’Almeida, 1986). Similar to African turbidity network, the Aerosol Robotic Network (AERONET) is a network of ground-based automatic radiometers providing Aerosol Optical Depth (AOD) measurements (Holben *et al.*, 1998). AERONET stations provide continuous, long-term Aerosol Optical Depth (AOD) measurements, which are essential for assessing dust aerosol properties, validating satellite retrievals, and improving model simulations (Dubovik *et al.*, 2002). These data sets help in determining seasonal and interannual variations in dust emissions. Numerous other studies used AERONET network to assess aerosols (Todd *et al.*, 2007; Tegen *et al.*, 2013; Heinold *et al.*, 2016; Oluleye & Folorunsho, 2019).

Ground-based lidar and ceilometers are also used to capture the vertical distribution of dust particles in the atmosphere. These instruments provide information on dust layer height, transport dynamics, and mixing processes, improving our ability to analyze the evolution of dust plumes over time (Tesche *et al.*, 2011; Shin *et al.*, 2018).

Dust traps and samplers are efficient method in collecting deposition dust samples. Physical collection of airborne dust particles using samplers allows for chemical and mineralogical analyses. These data help in identifying dust source regions based on the composition of collected samples and in assessing potential health and environmental impacts (Van Der Does *et al.*, 2021).

Sun photometers measure atmospheric optical properties such as AOD and the Ångström exponent, which are crucial for characterizing dust particle size and concentration. These measurements serve as a critical reference for validating satellite-derived aerosol products and assessing atmospheric visibility conditions (Martínez & Chaboureau, 2018).

The above state of the literature highlights the crucial role of ground-based observations in understanding dust emission and its impacts. However, due to the limited spatial coverage of observatories in regions like North Africa, satellite observations serve as a valuable complement to ground-based measurements.

2.2.1.2 Satellite Observations.

Satellite sensors provide valuable insights into dust emission hotspots, transport pathways, and temporal variability (Schepanski *et al.*, 2012). By using a combination of optical, infrared, and lidar-based remote sensing technologies, researchers can track dust sources, measure aerosol properties, and analyze transport dynamics in near real-time and over long-term periods.

Moderate Resolution Imaging Spectroradiometer (MODIS): MODIS, onboard NASA's Terra and Aqua satellites, provides continuous global coverage with high spatial and temporal resolution. It detects dust storms (e.g., Figure 2.1), identifies emission hotspots, and tracks long-range transport of dust particles.

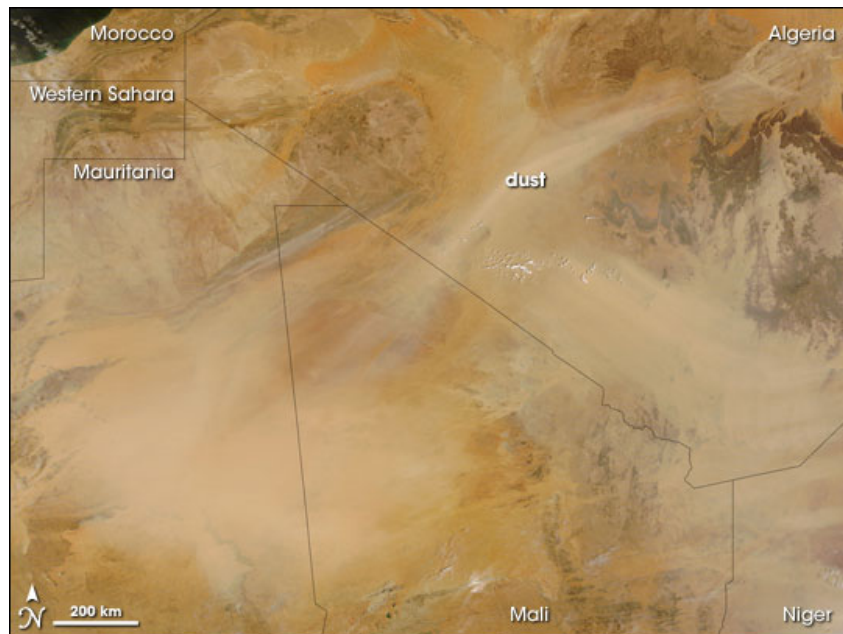


Figure 2.1: Sahara dust storm captured by MODIS Terra satellite on April 26, 2008

(<https://earthobservatory.nasa.gov/images/19845/saharan-dust-storm>, MODIS Rapid Response team. Caption by Michon Scott).

For instance, Francis *et al.* (2020) and Shao *et al.* (2010) used MODIS visible imagery to characterize major dust storms occurred in NA. MODIS data have been widely used for dust climatology studies, helping to map seasonal and interannual variations in dust activity (Ginoux *et al.*, 2012; Hamzeh *et al.*, 2021).

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO): CALIPSO employs lidar technology to measure the vertical distribution of dust plumes in the atmosphere. Unlike passive sensors, CALIPSO provides precise information on the altitude of dust layers, which is critical for understanding transport mechanisms and interactions with clouds and radiation (Yu, Chin, Bian, *et al.*, 2015; Hamzeh *et al.*, 2021; Asutosh *et al.*, 2022).

Spinning Enhanced Visible and Infrared Imager (SEVIRI): SEVIRI, onboard the Meteosat Second Generation satellites, continuously monitors dust movement over Africa and surrounding regions. Its high temporal resolution (15-minute intervals) allows for real-time tracking of dust outbreaks, making it a valuable tool for early warning systems and aviation hazard assessments (Schepanski *et al.*, 2007, 2009; Banks *et al.*, 2018, 2019).

Total Ozone Mapping Spectrometer and Ozone Monitoring Instrument (TOMS and OMI): These onboard instruments provide long-term aerosol index records, which are essential for studying historical trends in dust emissions and variability. The TOMS aerosol index has been crucial in identifying major dust sources and tracking dust transport across oceans, while OMI continues this legacy with improved spatial resolution (Middleton & Goudie, 2001; Prospero *et al.*, 2002).

Visible Infrared Imaging Radiometer Suite (VIIRS): VIIRS, onboard the Suomi-NPP satellite, offers enhanced capabilities for detecting and characterizing dust sources compared to MODIS. With its improved spatial resolution and multiple spectral bands, VIIRS enables better

discrimination of dust plumes from clouds and surface features, improving the accuracy of dust emission inventories (Hsu *et al.*, 2019).

Satellites cover a large zone compared to ground-based observations, therefore a problem with satellite data for dust source identification is that satellites observe transported, as well as, entrained dust (Shao *et al.*, 2011).

2.2.1.3 Modeling Approaches.

Numerical modeling plays a crucial role in simulating dust emissions, transport, and deposition processes. These models help simulate past dust events, predict future trends, and assess the impact of atmospheric dust on climate, air quality, and ecosystems. The models can be classified in three main groups: the numerical models, the reanalysis datasets and the global models.

Numerical Climate Models (e.g., WRF-Chem, HYSPLIT, CEMSYS and DREAM): These models simulate dust emissions, transport pathways, and interactions with meteorological conditions. Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem) provides high-resolution simulations of dust storms (Parajuli *et al.*, 2019), while Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) is widely used for back-trajectory analysis and forecasting dust dispersion. Computational Environmental Modelling System (CEMSYS) consists of an atmospheric model and schemes for land-surface processes, dust emission, transport and deposition, as well as a GIS database (Shao *et al.*, 2010). Dust REgional Atmospheric Model (DREAM) specializes in regional dust transport simulations (Kok *et al.*, 2014).

Reanalysis Datasets (e.g., MERRA-2, ERA5, NCEP/NCAR Reanalysis): These datasets provide historical and real-time meteorological information, allowing researchers to reconstruct dust events and analyze long-term trends. Modern-Era Retrospective analysis for Research and

Applications, Version 2 (MERRA-2) offers global dust data, while ECMWF Reanalysis 5th Generation (ERA5) provides detailed weather and climate data used for dust modeling (Gelaro *et al.*, 2017; Hersbach *et al.*, 2020).

Global Dust Models (e.g., GOCART, GEOS-Chem, CHIMERE, CAMS): These models estimate dust emission fluxes, transport dynamics, and deposition rates. Goddard Chemistry Aerosol Radiation and Transport (GOCART) and Goddard Earth Observing System - Chemistry (GEOS-Chem) are widely used for global and regional dust studies. CHIMERE and Copernicus Atmosphere Monitoring Service (CAMS) integrate observational data to improve dust forecasting accuracy (Ginoux *et al.*, 2004; Menut *et al.*, 2013).

2.2.1.4 Remote Sensing and GIS Application.

GIS-based tools and remote sensing techniques are essential for mapping and analyzing dust sources. These methods improve dust source identification, enhance monitoring capabilities, and provide valuable insights into dust transport patterns.

GIS-Based Source Mapping: Integrates satellite imagery, land-use data, and meteorological information to improve dust source identification (El-Askary *et al.*, 2003).

Back-Trajectory Analysis: Identifies the origin of dust plumes and assesses transport pathways using meteorological reanalysis datasets and trajectory models (Stuut *et al.*, 2009).

Machine Learning Applications: AI-based models utilize satellite data to predict dust source activation, offering improved accuracy and real-time forecasting (Biagio *et al.*, 2019).

Multispectral and Hyperspectral Imaging: These techniques provide high-resolution spectral data that distinguish dust sources from other land surface types (Mahowald *et al.*, 2014).

Synthetic Aperture Radar (SAR) Technology: the SARs are used to detect surface roughness changes and monitor dust emission dynamics (Leung *et al.*, 2023).

In this section, different techniques and modelling systems to detect dust emission as well as dust sources have been presented, therefore these techniques are not exhaustive.

2.2.2 Major Dust Sources in North Africa.

Several major dust sources areas in NA have been identified based on the techniques presented in the above section. These sources contribute significantly to the global dust cycle, affecting regional and intercontinental atmospheric composition, climate, and ecosystems. Figure 2.2 presents the major dust sources and transport routes of Saharan dust. This section presents the characteristics of some of these major dust sources in NA region.

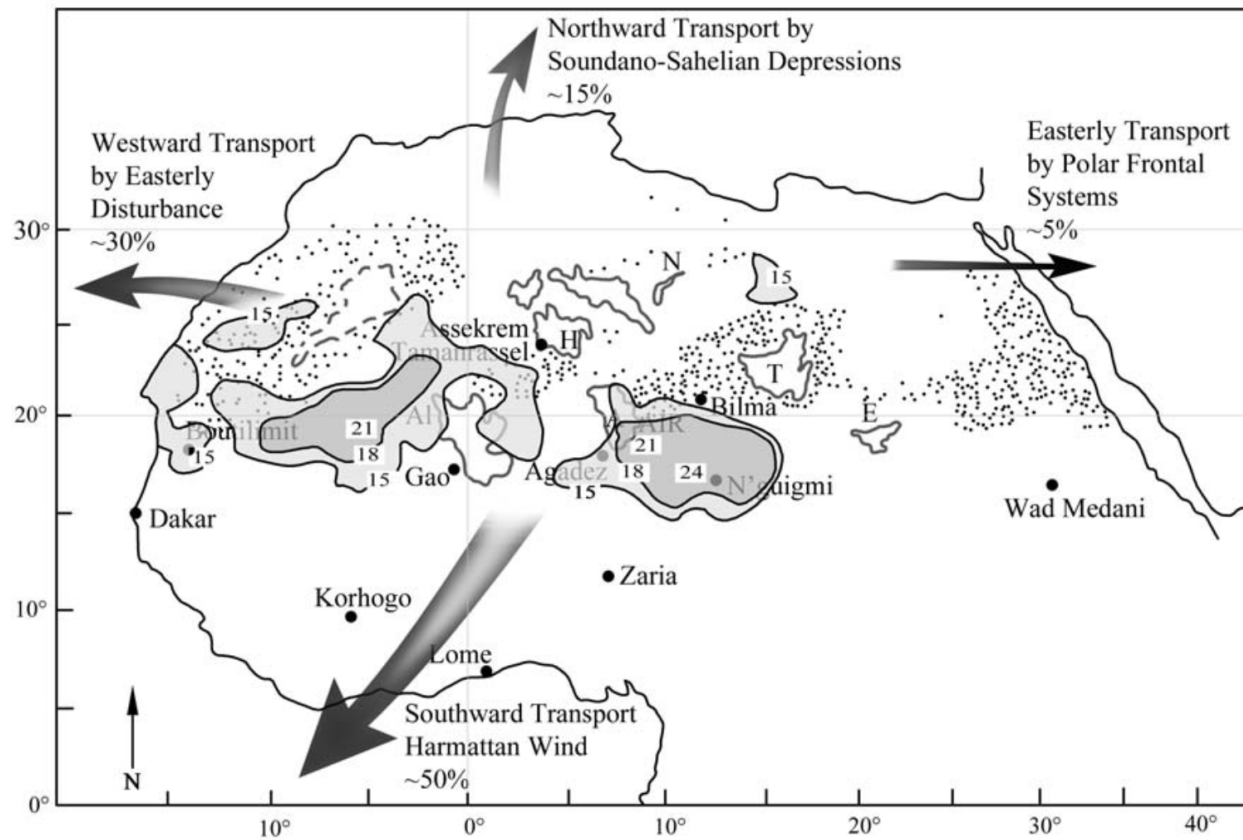


Figure 2.2: Major dust sources and transport routes of Saharan dust. Dotted areas indicate dust sources identified by D'Almeida, (1986), shaded areas indicate high TOMS absorbing aerosol index identified by Prospero *et al.* (2002) (adopted from Shao *et al.*, (2010)).

2.2.2.1 The Bodélé Depression

Located in Chad, the Bodélé Depression is considered the most intense dust source worldwide due to persistent, strong surface winds that mobilize fine, unconsolidated sediments from the ancient Mega-Chad lake basin (Washington *et al.*, 2003; Washington & Todd, 2005; Koren *et al.*, 2006). This region experiences frequent and intense dust emissions due to the channeling effect of the surrounding Tibesti and Ennedi Mountains, which accelerate the northeast trade winds, leading to high dust uplift rates (Todd *et al.*, 2007; Knippertz & Todd, 2012). The combination of topographic forcing, strong pressure gradients, and the presence of loose, silt-sized diatomite sediments creates ideal conditions for massive dust entrainment and transport (Bou Karam *et al.*, 2008; Ginoux *et al.*, 2012). The dust from the Bodélé Depression plays a crucial role in global biogeochemical cycles. Rich in iron oxides, it significantly contributes to oceanic and terrestrial ecosystems by fertilizing the Atlantic Ocean and the Amazon rainforest, enhancing primary productivity (Mahowald *et al.*, 2005, 2010; Yu, Chin, Yuan, *et al.*, 2015). Studies using satellite observations and modeling approaches have shown that the Bodélé Depression supplies nearly half of the mineral dust transported across the Atlantic (Engelstaedter *et al.*, 2006; Knippertz *et al.*, 2009; Schepanski *et al.*, 2009; Schulz *et al.*, 2012).

Meteorologically, the Bodélé Low-Level Jet (LLJ here and after) has been identified as a key mechanism driving dust uplift in the region. This nocturnal jet intensifies due to large-scale atmospheric circulations and strong diurnal heating contrasts, leading to enhanced surface wind speeds in the morning hours (Washington & Todd, 2005; Flamant *et al.*, 2009; Fiedler *et al.*, 2013). Observational campaigns such as the Bodélé Dust Experiment (BoDEX) have provided valuable insights into dust mobilization processes and the role of surface wind dynamics in governing dust emission rates (Tegen *et al.*, 2006; Todd *et al.*, 2007; Washington *et al.*, 2009). Furthermore, the

contribution of Bodélé dust to climate forcing has been extensively studied. Studies like Evan *et al.* (2016) and Schepanski (2018) showed that dust aerosols from Bodélé region influence radiation budgets, cloud microphysics, and regional weather patterns. The interplay between dust emission, atmospheric circulation, and precipitation patterns highlights the complex feedback mechanisms that link Saharan dust sources to global climate variability (Goudie & Middleton, 2006; Evan *et al.*, 2016).

2.2.2.2 The Western Sahara and Mauritania

The Western Sahara and Mauritania are recognized as some of the most significant dust-producing regions globally due to their vast expanses of hyper-arid landscapes, which include extensive sand dunes, ephemeral riverbeds, and dry lake basins rich in fine-grained sediments (Ginoux *et al.*, 2012; Middleton & Goudie, 2001). The geomorphology of these regions provides an ample supply of loose, erodible material that becomes highly susceptible to wind-driven mobilization. Studies have shown that the primary meteorological drivers of dust uplift in this region include the strong and persistent Harmattan winds, which originate from the northeast and dominate during the winter months, and mesoscale convective systems (MCSs), which frequently generate intense haboobs during the summer (Engelstaedter *et al.*, 2006; Knippertz & Todd, 2012). These haboobs, characterized by sudden, dense dust storms, can loft large quantities of mineral dust into the atmosphere, significantly affecting air quality and visibility over vast distances.

Observations from satellite remote sensing (e.g., MODIS, CALIPSO, and TOMS) and numerical model simulations have revealed that dust plumes originating from the Western Sahara and Mauritania are regularly transported across the Atlantic Ocean, reaching the Caribbean, South America, and even the southeastern United States (Yu *et al.*, 2015; Prospero *et al.*, 2020). These

transatlantic dust events play a crucial role in Earth's biogeochemical cycles by delivering essential nutrients, such as iron and phosphorus, to marine and terrestrial ecosystems, including the Amazon rainforest, where they contribute to soil fertilization and sustain primary productivity (Mahowald *et al.*, 2005; Maher *et al.*, 2010; Yu, *et al.*, 2015). Furthermore, dust emissions from this region have notable implication in the formation of the Sahel dust zone (Klose *et al.*, 2010; Shao *et al.*, 2010).

2.2.2.3 The Sahelian Belt

The Sahelian Belt, stretching from Senegal in the west to Sudan in the east, is a semi-arid transition zone between the Sahara Desert to the north and the savanna regions to the south. This region is a significant contributor to global dust emissions, with seasonal variability driven by climatic conditions, land use changes, and meteorological processes (Marticorena *et al.*, 2010; Evan *et al.*, 2016). The interactions between natural and anthropogenic factors makes the Sahel a complex and evolving dust source with far-reaching environmental and societal implications. Unlike the hyper-arid Sahara, where vast sand dunes and dry lake beds dominate the landscape, dust emissions in the Sahel arise primarily from land degradation, vegetation loss, and increased human activities, such as overgrazing, agricultural expansion, and deforestation (Cowie *et al.*, 2013; Middleton & Kang, 2017). The gradual reduction in vegetation cover reduces soil stability, making fine-grained sediments more susceptible to wind erosion, particularly during the dry season when surface moisture is minimal (Ginoux *et al.*, 2012). Meteorologically, dust uplift in the Sahel is frequently triggered by convective cold pools from MCSs and LLJs, which generate intense wind gusts capable of lifting large quantities of fine sediment into the atmosphere (Flamant *et al.*, 2007; Heinold *et al.*, 2013; Cowie *et al.*, 2015). MCSs, which are prevalent during the West African

monsoon season, produce powerful downdrafts that generate large dust plumes known as haboobs. These dust storms can reduce visibility to hazardous levels, disrupt transportation, and exacerbate respiratory diseases in densely populated urban centers across West Africa (Goudie, 2014; Aghababaeian *et al.*, 2021).

The Sahelian dust sources differ from those in the Sahara in terms of composition and transport dynamics. Studies conducted by Ryder *et al.* (2018) have shown that while Saharan dust tends to contain coarser particles that settle relatively quickly, Sahelian dust consists of finer, more clay-rich particles that remain suspended in the atmosphere for extended periods. These smaller particles contribute significantly to atmospheric aerosol loading, affecting regional and global climate by modulating cloud properties, altering radiation budgets, and influencing precipitation patterns (Adebiyi & Kok, 2020). Additionally, long-range transport of Sahelian dust has been observed over the Atlantic Ocean, reaching as far as the Caribbean and the Americas, where it impacts air quality and ecological processes (Prospero & Lamb, 2003).

2.2.2.4 The Libyan Desert and Great sand Sea

The Libyan Desert, one of the most arid regions on Earth, stretches across Libya, Egypt, and Sudan, and is characterized by extensive dune fields, dried-out riverbeds, and paleo-lake basins that serve as major dust sources (D’Almeida, 1986; Goudie, 2014). Within this hyper-arid environment, the Great Sand Sea, covering approximately 72,000 km², consists of megadunes and complex sand formations that frequently contribute to large-scale dust emissions (Bubenzer *et al.*, 2020). Dust emission in this region is driven by a combination of strong surface winds, low soil moisture, and high surface temperatures, which create favorable conditions for dust entrainment (Schepanski *et al.*, 2009). The prevailing northwesterly winds and thermal lows during summer

can trigger intense dust storms, while wintertime dust activity is often associated with synoptic-scale cyclonic systems moving across NA (Gkikas *et al.*, 2013).

Satellite observations and numerical models indicate that dust storms originating from the Libyan Desert and the Great Sand Sea can be transported over long distances, often reaching the Mediterranean Basin, Southern Europe, and even as far as the Middle East (Gkikas *et al.*, 2013; Varga *et al.*, 2014). These dust plumes influence regional air quality, solar radiation budget, and cloud microphysics, affecting weather patterns and atmospheric visibility in affected regions (Moulin *et al.*, 1998). Furthermore, the deposition of mineral dust from Libyan Desert into the Mediterranean and European ecosystems has implications for biogeochemical cycles, soil nutrient enrichment, and marine productivity (Guerzoni *et al.*, 1999).

Overall, the Libyan Desert and the Great Sand Sea remain integral to the broader North African dust system, contributing significantly to both regional and transcontinental dust transport dynamics.

2.2.2.5 The Tibesti and Hoggar Mountains ranges

The Tibesti and Hoggar mountain ranges, located in Chad, Niger, and Algeria, play a significant role in dust emission and transport across North Africa and beyond. These rugged terrains influence regional atmospheric circulation by shaping local wind patterns, which in turn contribute to dust mobilization (Schepanski *et al.*, 2007). Studies by Bou Karam *et al.* (2008) showed that the steep slopes of these mountain ranges generate downslope winds and katabatic flows, particularly during nocturnal cooling, which can intensify dust lifting in the surrounding arid regions.

One of the primary mechanisms linking these mountains to dust activity is their role in modifying low-level atmospheric circulation. Strong pressure gradients formed due to topographic

forcing enhance surface wind speeds, leading to the frequent occurrence of dust storms (Knippertz & Todd, 2012). Furthermore, the interaction between local convective systems and the SHL contributes to stronger dust uplift, particularly during the boreal summer when temperature contrasts between the elevated mountains and the surrounding desert amplify wind speeds (Lavaysse *et al.*, 2009; Allen & Washington, 2014). Beyond regional dust emissions, the Tibesti and Ahaggar Mountains are closely linked to large-scale atmospheric systems such as Saharan cyclones and Rossby wave activity, both of which influence dust transport pathways. Saharan cyclones, which frequently form near the northern fringes of the Sahara, are associated with intense dust storms that can extend into Europe and the Middle East (Klose *et al.*, 2010). Additionally, dust plumes from these mountain sources are often entrained into mid-latitude westerlies, facilitating long-range dust transport across the Mediterranean and Atlantic (Engelstaedter *et al.*, 2006).

Satellite observations and aerosol transport models have confirmed that dust emissions from the Tibesti and Hoggar regions contribute significantly to the global dust budget (Ginoux *et al.*, 2012). These emissions not only affect regional air quality but also play a role in climate modulation by altering radiative forcing and influencing cloud microphysics over North Africa and adjacent regions (Ridley *et al.*, 2014).

2.2.2.6 Other Dust Sources

In addition to the major Saharan dust-producing regions, several other significant sources contribute to dust emissions, playing a crucial role in regional and global dust transport dynamics. The Ténéré Desert (Niger): The Ténéré Desert in Niger is a prominent dust hotspot characterized by extensive sand seas and highly erodible surfaces. This region experiences frequent dust

outbreaks due to the presence of loose, fine-grained sediments and the influence of strong surface winds, particularly during the dry season (Washington & Todd, 2005). The region is also affected by the Harmattan wind, a dry and dusty trade wind that enhances dust mobilization and transport across West Africa and beyond (Middleton & Goudie, 2001). Satellite observations and aerosol transport models have identified the Ténéré Desert as one of the most active dust sources within the central Sahara, with plumes frequently reaching the Atlantic Ocean (Prospero *et al.*, 2002).

Chotts and Sebkhas (Tunisia, Algeria, Egypt): The Chotts and Sebkhas, found across Tunisia, Algeria, and Egypt, are vast dry salt flats that act as seasonal dust sources. These evaporite basins, which were once ancient lake systems, consist of fine sediments that become highly susceptible to wind erosion during dry periods (Bergametti *et al.*, 2007). Dust activity in these areas is largely modulated by seasonal hydrological variations. When surface moisture levels decrease, previously stabilized sediments become exposed and available for mobilization (Mahowald *et al.*, 2014). Additionally, episodic strong winds, such as those associated with baroclinic disturbances and regional depressions, can lead to intense dust storms originating from these areas, affecting air quality and visibility in NA and the Mediterranean Basin (Gkikas *et al.*, 2015).

These dust sources, along with the major Saharan and Sahelian dust-producing regions, highlight the complex interactions between geomorphology, climate, and atmospheric circulation in controlling dust emissions and transport.

2.2.3 Intra-seasonal Activation of Dust Sources

Dust emissions in North Africa are subject to significant intra-seasonal variability, with different sources becoming most active depending on seasonal meteorological conditions. This variability is driven by atmospheric circulation patterns, surface wind, precipitation regimes, and boundary

layer processes (Fiedler *et al.*, 2013; Schepanski *et al.*, 2017). This section deals with the seasonal activation of dust sources over NA.

2.2.3.1 Winter (December-February (DJF))

During boreal winter, dust emissions in North Africa are primarily influenced by the intensification of the Harmattan winds, which originate from the northeastern Sahara and transport dust across the Sahel (Prospero & Lamb, 2003; Klose *et al.*, 2010; Cowie *et al.*, 2014). The intensity of the Harmattan, the trade winds over NA, depends on the pressure gradient between the subtropics and the tropics, while its northeasterly flow is shaped by local topography and influenced by changes in pressure distribution (Schepanski *et al.*, 2017). Additionally, the strengthening of the Saharan High and cold air outbreaks from mid-latitudes enhance surface wind speeds, mobilizing dust from hyper-arid regions such as the Bodélé Depression and the Ténéré Desert (Washington & Todd, 2005; Engelstaedter *et al.*, 2006; Washington *et al.*, 2009). Studies using satellite observations and reanalysis data have shown that dust storms during winter period can travel long distances, impacting air quality as far as the Caribbean and North America (Yu, Chin, Bian, *et al.*, 2015).

2.2.3.2 Spring (March-May (MAM))

The pre-monsoon season marks a transition toward higher dust emissions, particularly in the Sahel and central Sahara, where convective mixing and strong LLJs enhance dust mobilization (Fiedler *et al.*, 2013; Heinold *et al.*, 2013). Klose *et al.*, (2010) have shown that the prominence of dust emission at this season creates a zone of suspension dust in the Sahel that they named “the Sahel Dust Zone”. The breakdown of the winter pressure system leads to increased surface winds, while convective storms initiate haboobs that contribute to localized dust outbreaks (Bou Karam *et al.*,

2010; Marsham, Hobby, *et al.*, 2013). Studies ground-based observations have highlighted that dust plumes during this season frequently originate from dried-out ephemeral lakes and alluvial deposits, particularly in regions such as the Chotts and Sebkhass of Tunisia and Algeria (Ginoux *et al.*, 2012). As surface temperatures increase, thermal turbulence plays a key role in mobilizing fine sediment, particularly in areas with sparse vegetation cover (Knippertz & Todd, 2012).

2.2.3.3 Summer (June-August (JJA))

The summer season represents the period of the northward shift of the ITD marking the peak of precipitations and moisture in the Sahel region and surroundings (Bou Karam *et al.*, 2008; Janicot *et al.*, 2009). Schepanski *et al.*, (2017) investigated summertime north African dust sources activation and showed that the activation of Saharan dust sources differs noticeably from that of Sahelian dust sources in terms of the time of day when dust emission starts. The last authors have shown that dust source activation, in the Sahara, mainly occurs in the morning, driven by the breakdown of the nocturnal LLJ, whereas in the Sahel, dust sources are primarily triggered in the afternoon, influenced by downdrafts from deep moist convection. This period coincides with the intensification of the SHL and the monsoon system (Lavaysse *et al.*, 2009; Evan *et al.*, 2016). The SHL deepens the planetary boundary layer, allowing for enhanced vertical mixing and increased dust transport (Wang *et al.*, 2017). In the central Sahara, where LLJs and monsoon surges lead to strong surface winds, dust emission is particularly intense (Fiedler *et al.*, 2013; Schepanski *et al.*, 2017). Although, the position of the ITCZ favors the formation of MCSs which are a dominant driver of dust emission, generating large-scale haboobs that propagate southward into the Sahel (Marsham *et al.*, 2013; Allen & Washington, 2014). Satellite-based analyses indicate that summertime dust storms contribute to some of the highest AOD values recorded over the Sahara

(Asutosh *et al.*, 2022). For instance, Francis *et al.* (2020) investigated the summertime major dust storm occurred in June 20th 2020 and have shown that the local AOD measured was 3.5 in excess. Moreover, long-range transport of Saharan dust toward Europe and the Atlantic is most frequent in summer due to the influence of the AEJ and tropical waves (Ridley *et al.*, 2014).

2.2.3.4 Autumn (September-November (SON))

The post-monsoon period sees a gradual decline in dust emissions as wind speeds decrease and surface conditions stabilize (Schepanski *et al.*, 2012). However, residual convective activity and weakening synoptic systems can still trigger sporadic dust outbreaks in the Sahel and along the margins of the Sahara (Allen *et al.*, 2013). As ephemeral water bodies from the monsoon season begin to dry out, previously inundated areas may become temporary dust sources, contributing to localized emissions (Mahowald *et al.*, 2003; Ginoux *et al.*, 2012). The gradual weakening of the SHL leads to reduced boundary layer mixing, limiting vertical dust transport compared to the summer months (Lavaysse *et al.*, 2009).

2.2.4 The Sahel Green Wall Initiative

In response to escalating land degradation and increasing dust emissions, the African Union launched the Great Green Wall Initiative (GGWI), a large-scale afforestation and land restoration project across the Sahel region (African Union, 2024). The initiative aims to combat desertification by restoring degraded lands, improving soil stability, and enhancing vegetation cover, thereby mitigating wind erosion and reducing atmospheric dust concentrations (UNCCD, 2020).

Research suggests that large-scale reforestation efforts in arid and semi-arid regions can significantly lower wind-driven soil erosion, subsequently reducing dust emissions (Fassinou *et*

al., 2024). Moreover, satellite-based studies indicate that increased vegetation cover can alter surface albedo, modify local climate conditions, and reduce the frequency of dust storms (Engelstaedter *et al.*, 2003).

Despite its potential benefits, the effectiveness of the GGWI remains a subject of debate. Several studies highlight challenges such as water scarcity, weak governance structures, and limited community engagement, which hinder large-scale implementation and long-term sustainability (Goffner *et al.*, 2019). Additionally, climate variability and land-use changes influence the success of reforestation efforts, making outcomes uncertain in different regions of the Sahel (Reij & Winterbottom, 2015).

While the GGWI represents a promising strategy for reducing dust emissions and enhancing ecosystem resilience, further research is needed to assess its long-term impact on dust source dynamics, regional climate, and socio-economic conditions in the Sahel.

2.2.5 Dust Sources Under Climate Change

Climate change is expected to have profound impacts on dust emissions across NA, influencing both the frequency and intensity of dust storms. Rising temperatures and shifting precipitation patterns are key factors that may alter dust activity by affecting soil moisture, vegetation cover, and wind dynamics (Mahowald *et al.*, 2005; Evan *et al.*, 2016). The expansion of arid and semi-arid regions due to increasing temperatures is likely to enhance dust emissions in some areas by creating drier and more erodible surfaces (Evan *et al.*, 2016). Additionally, intensification of atmospheric circulation patterns, such as the AEJ and SHL, may modify regional wind regimes, further impacting dust transport pathways (Lavaysse *et al.*, 2009; Fiedler *et al.*, 2014).

Some studies suggest that increased aridity and drought conditions could lead to greater dust emissions due to soil desiccation and loss of vegetation cover (Middleton & Kang, 2017). However, other research highlights potential counteracting effects, such as enhanced vegetation growth in certain regions due to increased atmospheric CO₂, which may stabilize soils and reduce dust emissions (Schepanski, *et al.*, 2009). Moreover, changes in precipitation patterns may lead to intermittent wetting of desert surfaces, temporarily suppressing dust activity in some locations while intensifying it in others through the formation of ephemeral lakes that later dry out and become dust sources (Mahowald *et al.*, 2003).

Despite these insights, significant uncertainties remain regarding how dust emissions will evolve under future climate scenarios. Climate models struggle to accurately simulate the complex interactions between land surface processes and atmospheric circulation, leading to diverging projections (Evan *et al.*, 2016). Regional variability also poses challenges, as some areas may experience increased dust emissions while others see declines due to competing influences of soil stability, vegetation changes, and human land use (Ginoux *et al.*, 2012).

2.3 Meteorological Drivers of Dust Storm

Dust storms are complex meteorological phenomena driven by a combination of atmospheric circulation patterns, surface conditions, and climatic variability. Knippertz, (2014) investigated the meteorological aspect of dust storms. The last author has shown that dust emission takes place when erodible soil is available, and near-surface wind speeds exceed the local emission threshold. Various meteorological phenomena drive dust emissions across Earth's source regions and can be categorized as follows: (1) large-scale monsoon-type flows accelerating toward continental heat lows, mainly in late spring and early summer; (2) mobile synoptic-scale systems, including

anticyclones, cyclones, and cold fronts, typically occurring in late winter and spring; (3) gust fronts produced by outflows from moist convective storms, most common at the onset of the summer rainy season; and (4) intense dry convection in the daytime boundary layer during summer, generating dust devils and dusty plumes (Knippertz, 2014). This section reviews the primary meteorological drivers of dust storms, including synoptic-scale weather systems, low-level jets, convective processes, and the influence of large-scale climatic patterns such as the WAM.

2.3.1 Synoptic-Scale systems and Dust Mobilization

Synoptic weather systems play a crucial role in dust storm initiation, particularly in arid and semi-arid regions where surface conditions favor dust entrainment. Schepanski *et al.*, (2017) describe the atmospheric circulation over North African dust source regions, primarily the Sahara and the Sahel, as being governed by three major regimes: (1) the Harmattan (trade winds), (2) the SHL, and (3) the WAM circulation. The last authors argued that the strength of these regimes influences Saharan dust outflow by shaping the spatio-temporal distribution of dust emission, transport pathways, and deposition fluxes. These factors are known as key drivers of dust storms over NA.

2.3.1.1 Saharan Heat Low (SHL)

The SHL is a heat-induced low-pressure system that develops due to intense solar warming of the desert surface (Schepanski *et al.*, 2017). Lavaysse *et al.*, (2009) investigated the seasonal evolution of the West African Heat Low (WAHL) and have shown that this WAHL is located over the Sahara in the early summer and referred to as the SHL with the center between Atlas Mountains and the Hoggar Massifs. They proposed a detection criterion based on the dilation of the low-level atmospheric thickness (LLAT) defined as the difference of the geopotential heights at 700 and 925

hPa. Studies like Wang *et al.*, (2017) have shown the implication of the SHL in the summertime dust emission. Previous studies like Prospero *et al.*, (2002) have shown that the WAHL area is the most active dust source on the Earth. Knippertz, (2008) through a case study, illustrated two important mechanisms responsible of the summertime dust emission in this region. According to the author, the first mechanism is a nocturnal flow acceleration associated with the heat trough (HT) circulation, mostly in northwesterly or northerly flow, while the second is a dense outflow from moist convection penetrating into the Sahara with the northward shifting. In addition, strong winds in the subtropics are generated through the mechanism of Atlas lee cyclo- genesis and a cold surge from the Mediterranean (Knippertz, 2008). Schepanski *et al.*, (2017) speculate that the SHL may affect the position of the AEJ, as the temperature gradient between the hot and dry Sahara and the cold moist Gulf of Guinea impacts the state of the AEJ. Moreover, the SHL plays a pivotal role in the WAM system in Spring and Summer (Lavaysse *et al.*, 2016).

2.3.1.2 North Easterly Harmattan winds

During the boreal winter (DJF), the Harmattan, which names the north easterly winds, is a dry, dusty, and cold wind that originates over the Sahara Desert and extends across the Sahel, West Africa, and the Gulf of Guinea. The trajectory of Harmattan winds varies due to local topography, and their intensity is modulated by variations in pressure distribution (Schepanski *et al.*, 2017). These winds play a major role in dust mobilization and transport, significantly affecting air quality, visibility, and regional climate dynamics (Knippertz & Todd, 2012; Evan *et al.*, 2016). Additionally, Harmattan winds enhance dust mobilization from major sources such as the Bodélé Depression in Chad, the largest single dust source globally, and other arid regions across the Sahara and Sahel (Washington & Todd, 2005; Todd *et al.*, 2007). Moreover, these winds

transport large amounts of Saharan dust across WA and into the Atlantic Ocean, significantly affecting air quality, visibility, and regional climate (Prospero & Lamb, 2003; Evan *et al.*, 2016; Oluleye, 2017).

Harmattan dust storms have significant environmental and climatic impacts. The fine mineral dust particles lifted by these winds reduce solar radiation, leading to surface cooling and modifying regional atmospheric circulation (Goudie & Middleton, 2001; Schepanski *et al.*, 2009; Solomon *et al.*, 2012). Dust outbreaks also contribute to air pollution, causing respiratory health issues and reducing visibility, sometimes disrupting air and land transportation (Longueville *et al.*, 2013; Goudie, 2014; Aghababaeian *et al.*, 2021; Yarber *et al.*, 2023). The intensity and frequency of Harmattan dust storms vary interannually, influenced by climate variability patterns such as the NAO and ENSO (Ridley *et al.*, 2014).

2.3.1.3 Cold Fronts and Baroclinic Systems

Extratropical weather systems, particularly mid-latitude troughs and associated cold fronts, play a significant role in dust emissions over NA, especially during winter and spring. These baroclinic disturbances create strong surface winds that enhance turbulent mixing and lift large amounts of dust from arid regions (Engelstaedter *et al.*, 2006). The passage of cold fronts generates gusty, shifting winds, which efficiently mobilize dust and contribute to long-range transport across the Mediterranean and into Europe (Varga *et al.*, 2014). Such events are particularly pronounced in the Saharan and Sahelian regions, where the interaction between synoptic-scale disturbances and local topographic features further enhances dust entrainment and advection (Fiedler *et al.*, 2013).

2.3.2 LLJs and winds Dynamics

LLJs play a crucial role in dust mobilization across the Sahara and Sahel, forming due to strong temperature gradients and nocturnal radiative cooling, which enhance near-surface wind speeds (Allen & Washington, 2014). The Saharan LLJ, a prominent nocturnal wind maximum, intensifies at night and mixes downward after sunrise, generating strong surface winds that contribute to dust emissions (Fiedler *et al.*, 2013). The last author has shown that the breakdown of the LLJ has been associated with morning dust outbreaks across NA. In addition to LLJs, convective systems significantly enhance dust emission, particularly during the monsoon season. Haboobs, intense dust storms triggered by thunderstorm outflows, are frequent in the Sahel and central Sahara, lifting dust that can be transported over vast distances, affecting air quality and visibility in downstream regions (Roberts & Knippertz, 2012).

2.3.3 WAM and Dust Emission

The WAM is a key driver of seasonal dust variability in the Sahel and Sahara, as it modulates surface winds, moisture availability, and atmospheric circulation patterns. It is characterized by the northward migration of moist southwesterly winds from the Gulf of Guinea, which interact with the dry Harmattan winds, influencing dust emissions throughout the year (Nicholson, 2013). During the pre-monsoon period (March–May), the monsoon circulation has not yet fully developed, leaving the Sahara and Sahel extremely dry with strong surface winds that mobilize dust (Knippertz & Todd, 2012). In this dryness, intense LLJs and baroclinic systems generate dust storms, which can be transported over long distances (Schepanski *et al.*, 2009). Additionally, synoptic-scale high-pressure systems over NA enhance dust mobilization, contributing to high aerosol loading across the Sahel and the Mediterranean (Bou Karam *et al.*, 2008).

The boreal summer marks the peak of the WAM with the northward shift of the ITD, increasing precipitations over the Sahel. Rainfall and vegetation growth enhance soil stability, leading to a decline in dust emissions (Pierre *et al.*, 2012). However, dust production does not cease entirely, as MCSs generate strong outflows, lifting dust into the atmosphere (Marsham *et al.*, 2013). In the post-monsoon and dry season (October–February), the monsoon retreats southward, leading to drier conditions and an increase in surface dust availability. Strengthened Harmattan winds, transport Saharan dust southward, significantly reducing visibility across WA (Yu, *et al.*, 2015; Evan *et al.*, 2016). This period marks the peak of long-range dust transport, with Saharan dust frequently reaching the tropical Atlantic, South America, and even the Caribbean (Prospero *et al.*, 2020).

2.3.4 Climate Variability and Long-Term Dust Trends

Climate variability plays a crucial role in modulating dust emissions through its influence on precipitation, vegetation cover, and large-scale atmospheric circulation. AMO is the primary climate drivers a long-term variability in North Atlantic sea surface temperatures (Knight *et al.*, 2005). During positive AMO phases, enhanced Sahel rainfall leads to increased vegetation cover, stabilizing soils and reducing dust emissions, whereas negative AMO phases are associated with drier conditions and elevated dust activity (Zhang & Delworth, 2006; Evan *et al.*, 2016). Similarly, the ENSO influences dust transport by altering precipitation patterns and subtropical westerly winds. Studies have shown that ENSO events typically suppress rainfall over the Sahel and NA, increasing dust emissions and enhancing trans-Atlantic dust transport, while La Niña phases have the opposite effect (Prospero & Lamb, 2003; Doherty *et al.*, 2012). Shao *et al.* (2013) found a significant negative correlation between Saharan dust frequency and AMO. The last authors

therefore suggested the global dust trend to be influenced by the climate systems that drive the Atlantic and North African regions. However, the global near-surface dust concentration has experienced a decrease at about 0.21-0.50 μgm^{-3} per year over four decades with a significant decrease for North African region dust (Shao *et al.*, 2013).

Anthropogenic climate change is also expected to impact dust emissions, though projections remain uncertain. Rising global temperatures and shifts in precipitation patterns could lead to increased aridity in some regions, potentially intensifying dust storms (Kok *et al.*, 2018; Pu & Ginoux, 2018). However, other studies suggest that changes in land use, vegetation cover, and human interventions, such as reforestation projects, may counterbalance these effects by stabilizing soils and reducing wind erosion (Mahowald *et al.*, 2010; Webb & Pierre, 2018). The complex interplay between climate variability, land surface conditions, and atmospheric circulation highlights the need for improved climate models to accurately predict future dust trends under different climate scenarios.

2.4 Dust cycle

Previous studies showed that the dust cycle is a dynamical process that plays a crucial role in the Earth system. It involves five main interconnected stage: emission, transport, transformation, deposition and stabilization (Shao *et al.*, 2011). Each stage involves specific mechanisms that govern the movement and influence of mineral dust in the environment. Figure 2.3 illustrates a synthesis summary of the different stages with the related meteorological mean causes. The following sub-sections present studies on the main stages, without addressing their causes.

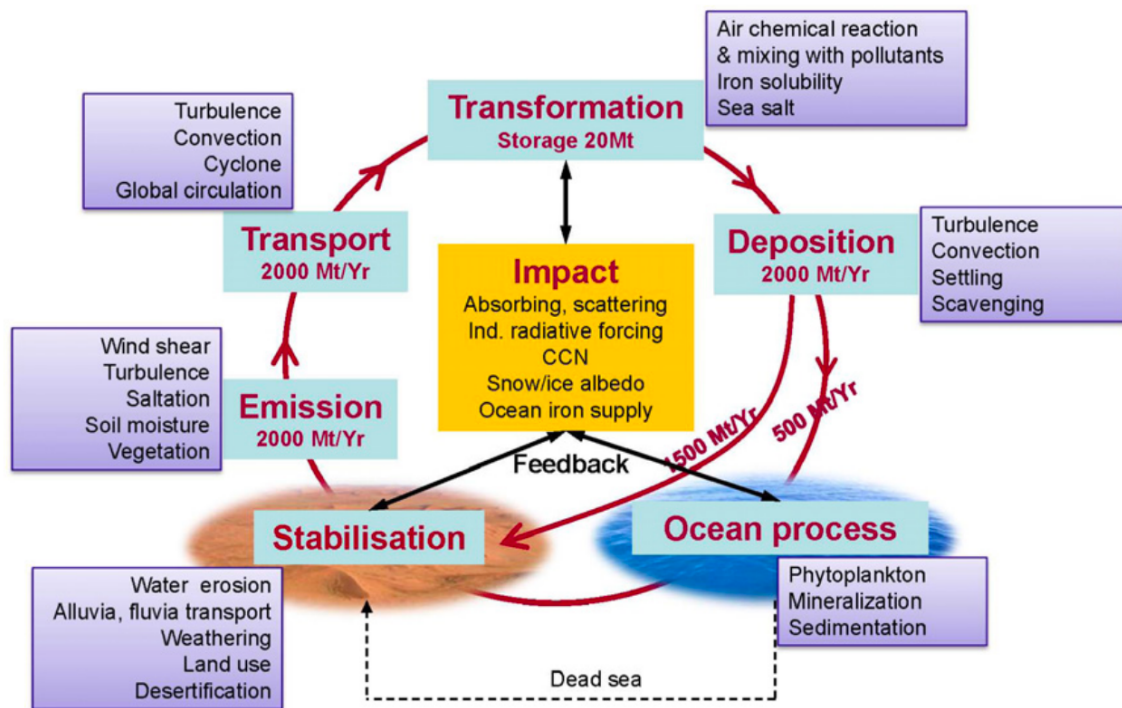


Figure 2.3: An illustration of the dust cycle in the Earth system and the main processes in which dust plays an important role (adopted from Shao et al., 2011)

2.4.1 Dust Emission

Dust emission represents the initial phase of the cycle, primarily occurring in arid and semi-arid regions like Sahel and Sahara regions, where loose sediments are exposed to wind action. Larger sand-size particles through saltation are lifted by wind into the air and move in short, hopping motion across the surface (Bou Karam *et al.*, 2008). These particles seldom travel far but are essential in initiating the dust emission process. During the saltation, collisions between airborne particles and the ground dislodge finer dust particles. These smaller particles, typically less than 10 μ m diameter known as PM10, become suspended in the atmosphere (Shao *et al.*, 2011; Kok *et al.*, 2012).

Natural factors such as wind speed, soil composition, vegetation cover, and surface moisture level significantly influence the efficiency of dust emission. Anthropogenic activities, including deforestation, overgrazing, and land-use changes, can exacerbate the process, particularly in regions like the Sahel and Sahara Desert (Mahowald *et al.*, 2014).

2.4.2 Dust Chemical Transformation

Once emitted, dust particles undergo physical and chemical transformation within the atmosphere. The stage significantly impacts the particles' properties and behavior during transport and deposition. According to Shao *et al.* (2011), dust particles react and mix with anthropogenic air pollutants, which intercept and reflect atmospheric radiation and create Cloud Condensation Nuclei (CCN). Smaller particles may collide and aggregate, forming large particles, which influences their settling velocity and transport distance (Shao, 2008).

Dust particles interact with atmospheric gases and pollutants, such as sulfur dioxide (SO₂) and nitrogen oxides (NO_x). These interactions can alter the particle composition, hygroscopicity, and

radiative properties (Formenti *et al.*, 2003). In the atmosphere, water vapor and other substances can form a coating on dust particles, changing their optical properties and their ability to act as (CNN) (Zhang *et al.*, 2024). Therefore, the transformation processes are influenced by environmental factors including humidity, temperature, and atmospheric chemical composition, making this a dynamical and complex stage in dust cycle (Aryal & Evans, 2023).

2.4.3 Dust Transport

Dust particles transport over vast distances is assured by atmospheric circulation patterns, influencing ecosystems, weather, and climate in downwind regions (Prospero, 1999; Schepanski *et al.*, 2009; Bou Karam *et al.*, 2010). For instance, during dry season (November to March), strong northeasterly Harmattan winds transport dust from the Sahara southward into the Sahel and the Gulf of Guinea significantly contributing to regional air quality deterioration and influencing seasonal weather patterns (Middleton & Goudie, 2001; Prospero & Lamb, 2003). Harr *et al.* (2024) showed that greatly intensified African Easterly Jet (AEJ) over West Africa plays a critical role in westward dust transport across the Atlantic Ocean during wet season (June to September). Beside the above drivers, trade winds further carry Sahara dust across the Atlantic, influencing regions as far as the Caribbean and the Amazon Basin (Evan *et al.*, 2016).

Therefore, the height and duration of dust suspension depend on particle size, with finer particles remaining aloft longer and travelling greater distances. This phenomenon influences radiative and the global dust budget (Mahowald *et al.*, 2010; Kok *et al.*, 2021).

2.4.4 Dust Deposition

The dust deposition represents the final stage of the atmospheric process of dust, where particles are removed from the atmosphere and settle on the Earth's surface. Marticorena *et al.* (2017) showed this process plays a crucial role in shaping regional and global ecosystems, with deposition occurring via two primary mechanisms: dry and wet deposition.

The dry deposition involves the gravitational settling of larger dust particles directly onto terrestrial and marine surfaces. This mechanism is particularly significant during arid seasons, such as the Harmattan period over West Africa, when dry conditions and strong winds prevail, limiting the role of precipitation in removing particles (Middleton & Goudie, 2001; Schepanski *et al.*, 2017; Kok *et al.*, 2021). Therefore studies like Mahowald *et al.* (2014) process is influenced by particle size, with larger particles depositing closer to their source regions due to their higher settling velocity.

The wet deposition, or humid deposition, occurs when precipitation scavenges dust particles from the atmosphere. This mechanism is more efficient at removing fine and ultrafine particles, especially during the rainy season in tropical and subtropical regions like the Sahel (Marticorena *et al.*, 2017). The last authors also showed that convective systems in these regions significantly enhance wet deposition, contributing to the seasonal variability in dust removal processes.

The ecological and climatic impacts of dust deposition are profound. Mineral dust acts as a major source of essential nutrients, such as iron and phosphorus, which are critical for sustaining both terrestrial and marine ecosystems. For example, Mahowald *et al.* (2010) showed in they study that Saharan dust deposition is a key contributor to soil fertility in the Amazon rainforest, where it reconstructs nutrients that are continuously depleted by heavy rainfall. This nutrient flux also supports primary productivity in marine environments, particularly in the nutrient-depleted regions

of the Atlantic Ocean, where iron from dust stimulates phytoplankton growth (Schulz *et al.*, 2012). Moreover, seasonal variations in deposition mechanisms have significant implications for regional ecosystems and the global carbon cycle. During the summer months (June to September), wet deposition dominates in areas affected by monsoonal rainfall, while dry deposition prevails in drier seasons like the Harmattan (Evan *et al.*, 2016; Marticorena *et al.*, 2017). This seasonal pattern affects the timing and extent of nutrient delivery to sensitive ecosystems, such as tropical forests and oceans, highlighting the interconnectedness between dust transport, deposition, and environmental processes.

Finally, the spatial variability in deposition mechanisms underscores the complexity of the dust cycle. Studies have shown that proximal regions, such as the Sahel and NA, experience high rates of dry deposition due to their proximity to dust sources, whereas distal regions, including the Amazon Basin and the Caribbean, are more influenced by wet deposition from trans-Atlantic dust plumes (Yu *et al.*, 2015).

2.4.5 Dust Stabilization

The stabilization of deposited dust represents the final phase of the dust cycle, where particles integrate into terrestrial and marine ecosystems. Once deposited, dust interacts with environmental processes that sustain ecosystem productivity and influence global biogeochemical cycles. Therefore the stabilization of dust deposits are much long-term processes which involves weathering and soil formation (Shao *et al.*, 2011). The stabilization phase plays a critical role in linking atmospheric transport, terrestrial nutrient cycling, and marine productivity.

2.4.5.1 Contribution to Terrestrial and Marine Ecosystems

For ecosystems, dust deposition serves as a critical source of nutrients that replenish nutrient-poor soils. For instance, Saharan dust provides phosphorus and other essential minerals to regions such as the Sahel and the Amazon Basin, compensating for nutrient losses caused by heavy rainfall or leaching processes (Prospero *et al.*, 2020). The Amazon rainforest, in particular, relies heavily on phosphorus-rich dust for maintaining its productivity despite nutrient limitations in its highly weathered soils (Yu *et al.*, 2015).

Marine ecosystems also benefit significantly from dust deposition, particularly in High-Nutrient, Low-Chlorophyll (HNLC) regions (Meng *et al.*, 2022). Iron-rich dust delivered to oceanic surfaces stimulates phytoplankton blooms, which are essential for supporting marine food webs and enhancing the ocean's biological pump (Tripathy & Jena, 2019). These blooms promote carbon sequestration by facilitating the downward transport of organic carbon into deep ocean layers, contributing to climate regulation (Maher *et al.*, 2010). In regions like the North Atlantic, seasonal Saharan dust pulses have been observed to align with peaks in marine primary productivity, illustrating the dust-ocean connection (Ridgwell & Watson, 2002).

2.4.5.2 Dynamic Stabilization and Environmental Implications

The stabilization of dust in ecosystems is not static but influenced by several dynamic factors, including vegetation cover, soil moisture, and land management practices. In terrestrial environments, deposited dust integrates into the soil matrix, improving its structure, moisture retention, and nutrient availability (Goudie & Middleton, 2001; Reynolds *et al.*, 2006). However, stabilized dust remains susceptible to reactivation under conditions of low vegetation cover, high

wind speeds, or anthropogenic disturbances such as agriculture and deforestation (Prospero *et al.*, 2002).

In coastal and marine systems, deposited dust can also undergo chemical transformation upon interaction with seawater, altering its bioavailability and ecosystem impacts (Mahowald *et al.*, 2014). For example, atmospheric processing of dust particles with pollutants such as sulfates and nitrates enhances their solubility, making nutrients like iron more accessible for marine biota (Ito & Shi, 2016). These processes highlight the intricate interplay between atmospheric chemistry, deposition patterns, and ecosystem responses.

Overall, the stabilization phase underscores the importance of dust as a connector between Earth's atmosphere, land, and ocean systems. Understanding these dynamics is essential for assessing the long-term impacts of dust deposition on ecosystem functioning, particularly in the context of climate change and increasing human influence on land-use patterns (Ginoux *et al.*, 2012).

2.5 Impacts of dust storms

Dust storms are a common phenomenon in NA, significantly impacting the region's climate, environment, human health, and economy. The Sahara Desert, the world's largest source of mineral dust, along with the Sahel contribute large amounts of airborne particles that travel across continents, influencing local and global systems. This section explores the impacts of dust storms in NA, focusing on climatic, health, environmental, and economic effects.

2.5.1 Climatic impact

Dust storms climatic impact has been investigated in numerous studies. The studies undoubtedly highlight the crucial role of dust storms in atmospheric processes by affecting solar radiation, cloud

microphysics, and precipitation pattern. According to Shao *et al.* (2011), mineral dust particles influence the Earth's radiation balance by absorbing and scattering solar radiation, leading to temperature variations. For instance, Cavazos *et al.* (2009) investigated the 6-11 March 2006 Saharan dust outbreak as a case study using a Regional Climate Model version 3 (RegCM3). Their study highlighted a profound impact on the surface solar radiation budget of $\sim -140 \text{ W m}^{-2}$ per atmospheric optical thickness (AOT) unit while the shortwave radiative at the top of the atmosphere (TOA) was about $\sim -10 \text{ W m}^{-2}$ per AOT unit leading to an anomaly of 2-m air temperature between -10 and 4K. In the same vein, study driven by Francis *et al.*, (2022) showed that dust loaded by 20th June 2020 major dust storm, induced a net warming of 1.1K over the Ocean surface and a net warming of 1.8 K on the air temperature with an increase of $+14 \text{ W m}^{-2}$ in the nighttime surface radiation flux. However, the deposition of dust in the Atlantic Ocean and other regions contributes to nutrient cycling, particularly through the fertilization of marine ecosystems (Prospero *et al.*, 2020). For example, Mahowald *et al.* (2010) highlighted the important for the Ocean biogeochemistry of the micronutrient carried by Desert dust. Additionally, dust storms can suppress rainfall by altering cloud microphysics, reducing regional precipitation (Evan *et al.*, 2016). Konare *et al.* (2008) have shown that dust shortwave radiation forcing effect leads to reduce precipitations over the Sahel with a cooling response over the Sahara.

In NA, the interaction between dust storms and the SHL influences monsoon dynamics and regional weather patterns (Lavaysse *et al.*, 2011). The presence of dust can intensify the SHL, modifying the temperature gradients that drive monsoonal circulations. This, in turn, affects the WAM system, leading to fluctuations in precipitation and storm activity across the Sahel and surrounding regions (N'Datchoh *et al.*, 2018). Furthermore, dust storms contribute to surface cooling during the day by blocking solar radiation while simultaneously trapping heat at night,

leading to temperature asymmetry (Nukapothula *et al.*, 2023). Dust aerosols also act as CCN, altering cloud properties and atmospheric stability. Depending on the size and composition of dust particles, they can either promote or inhibit cloud formation, affecting weather systems on local and regional scales (Kok *et al.*, 2018). Moreover, dust storms influence cyclogenesis in the Mediterranean and influence extratropical storm tracks, impacting weather patterns beyond NA (Soupiona *et al.*, 2020).

2.5.2 Health impact

Dust storms in NA have significant health implications, particularly concerning respiratory and cardiovascular conditions. The fine particulate matter PM_{2.5} and PM₁₀ present in dust can penetrate deep into the respiratory system, exacerbating ailments such as asthma and bronchitis. A systematic review by Aghababaeian *et al.*, (2021) highlighted that dust storms adversely affect cardiovascular and respiratory health, leading to increased hospital admissions and emergency visits. Beyond respiratory issues, dust storms are carriers of pathogens and heavy metals, contributing to the spread of infectious diseases. Griffin, (2007) emphasized that microorganisms, including bacteria and fungi, can be transported over long distances via dust storms, posing health risks upon inhalation. This transportation of bioaerosols has been linked to outbreaks of diseases such as meningococcal meningitis in sub-Saharan Africa. For instance, Agier *et al.* (2013) highlighted a seasonal relation between dust and meningitis in Africa. A scoping review by Lwin *et al.* (2023) found that small dust particles could penetrate the respiratory tract, causing damage to the cardiovascular, blood, and immune systems. The study also noted that dust storms could spread infectious diseases, further impacting vulnerable groups.

In urban areas with high pollution levels, the health impacts of dust storms can be more severe due to the combination of urban pollutants and dust particles. This synergy can lead to heightened respiratory and cardiovascular issues among city dwellers. Tobias *et al.* (2019) conducted a systematic review that underscored the effects of Saharan dust events on health, emphasizing the increased risk for urban populations.

2.5.3 Environmental impact

The environmental consequences of dust storms extend beyond atmospheric changes. Dust deposition affects soil fertility by transporting essential nutrients, such as iron and phosphorus, which can benefit distant ecosystems (Jickells *et al.*, 2005). However, excessive dust deposition can also degrade soil quality and reduce agricultural productivity (Ravi *et al.*, 2011). In coastal and marine environments, dust inputs influence ocean biogeochemistry, affecting primary production and marine biodiversity (Jickells *et al.*, 2005; Mahowald *et al.*, 2005, 2010). Additionally, dust storms contribute to desertification by removing topsoil and reducing land productivity, a growing concern in NA's arid and semi-arid regions (Middleton & Goudie, 2001).

2.5.4 Economic impact

The economic consequences of dust storms are substantial, particularly in agriculture, transportation, and infrastructure. Crop damage due to dust accumulation and soil erosion leads to significant reductions in agricultural yields, posing a serious threat to food security and rural livelihoods. Moreover, dust storms deposit fine particles on crop surfaces, reducing photosynthetic efficiency by blocking sunlight and clogging stomata, which hinders gas exchange and water uptake (Mahowald *et al.*, 2014). Additionally, dust deposition can alter soil chemistry by

introducing salts and heavy metals, leading to soil degradation and reduced fertility (Field *et al.*, 2010).

Soil erosion caused by strong winds during dust storms removes nutrient-rich topsoil, which is essential for crop growth. This loss of topsoil decreases soil moisture retention capacity, making it more difficult for plants to access water, particularly in arid and semi-arid regions where water availability is already limited (Ravi *et al.*, 2011). Over time, repeated dust storms can lead to land degradation, reducing arable land and forcing farmers to abandon previously productive fields (Webb & Pierre, 2018).

The economic consequences of dust-induced crop damage are severe, as lower yields translate into reduced income for farmers and higher food prices for consumers. In regions heavily reliant on agriculture, such as North Africa, frequent dust storms exacerbate food insecurity and increase dependency on food imports (Goudie, 2014). Furthermore, rural communities suffer from livelihood disruptions, as agricultural losses contribute to increased poverty and migration in search of better living conditions (UNCCD, 2017).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Domain

The study covers the domain of 0°N to 38°N and 30°W to 34°E (Figure 3.1), comprising a diverse range of geographical, climatic, and topographical features that play a crucial role in dust generation and transport. The domain includes North Africa, the Sahel, and portions of the Atlantic Ocean to the west and south. Key features include the Sahara Desert, extending over much of the northern part of the region, and the Sahel, a transitional zone bordering the Atlantic Ocean to the south. The region spans approximately 8.5 to 9 million km² and is home to over 250 to 270 million people (UNDESA, 2024), with populations concentrated in the Nile Valley, coastal areas, and major Sahelian cities.

The Saharan Desert is dominated by vast sand dunes, rocky plateaus, and depressions, while the Sahelian zone transitions into low-lying plains interspersed with river valleys and seasonal water bodies (OECD & Sahel and West Africa Club, 2014). One of the most significant dust-emitting areas is the Bodélé Depression in Chad, situated 155 meters below sea level, which acts as a major global dust hotspot (Washington *et al.*, 2009). The depression's unique topography, combined with strong, channelized surface winds, facilitates the uplift of fine-grained diatomaceous sediments, making it one of the most active dust sources (Washington *et al.*, 2003).

Figure 3.1 illustrates the topography of North Africa showing critical features influencing dust emission and transport such as: (1) the vast, low-lying Saharan sedimentary basins (e.g., Bodélé Depression, Chott el-Jérid) that provide fine-grained sediment sources (Engelstaedter *et al.*, 2003; Washington *et al.*, 2006); (2) the Atlas and Ahaggar Mountains that channel Harmattan winds, accelerating particle mobilization (Schwanghart & Schütt, 2008; Schepanski *et al.*, 2017); and (3)

an elevation gradients between desert interiors (<400 m) and coastal margins that promote drainage winds and haboob formation (Roberts & Knippertz, 2012; Marsham, Hobby, *et al.*, 2013). This terrain-dust interaction is particularly evident in seasonal patterns, where orographic steering of northeasterly winds enhances dust export from source regions toward the Sahel and Atlantic (Klose *et al.*, 2010; Prospero *et al.*, 2020).

As shown on Figure 3.1, the study domain encompasses highs which are notable topographical features including the Hoggar Mountains, 3003 m altitude (Algeria) and the Tibesti Mountains, 1500 m altitude (border of Chad-Libya). These mountain ranges influence local wind patterns by creating turbulence and accelerating downslope winds, which enhance dust lifting in nearby lowland areas (Allen & Washington, 2014). In contrast, the Senegal-Mauritania coastal region exhibits lower elevation, and while it contributes to dust transport, its proximity to the Atlantic allows for moisture influx that can suppress dust emissions at times (Yu *et al.*, 2015). The presence of ancient riverbeds and paleo-lake systems, such as Lake Mega-Chad's remnants, provides additional sources of dust, as these dry basins are rich in fine-grained, easily erodible sediments (Washington *et al.*, 2009).

Dust storm activity in the study domain results from complex interactions between large-scale climate drivers, atmospheric circulation, topography, soil properties, and land use patterns. The combination of intense surface winds, arid conditions, and loose, fine-grained sediments makes this region one of the most significant contributors to global dust transport (Evan *et al.*, 2016). Additionally, the study domain supports a range of economic activities, which vary across the different climatic zones. For instance, in the Sahelian and semi-arid zones, agriculture is a primary economic activity, but it is highly dependent on seasonal rainfall (Sissoko *et al.*, 2011).

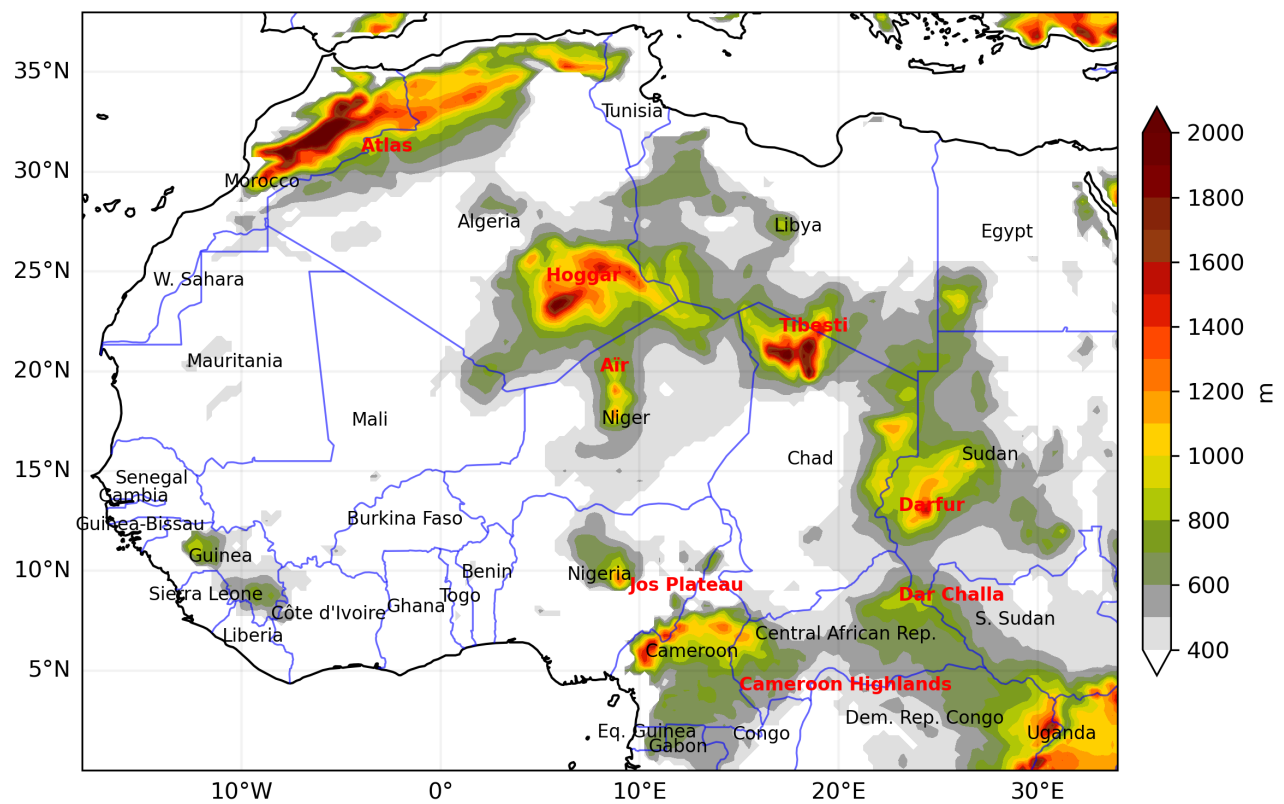


Figure 3.1: Topographical map of North Africa (Author's work).

Unsustainable land-use practices, coupled with climate variability, deforestation, and population growth, have intensified desertification processes, increasing dust storm frequency and severity (Middleton & Kang, 2017). Moreover, intensive land cultivation, slash-and-burn agriculture, and the expansion of farmlands into fragile ecosystems have accelerated soil degradation, reducing the land's ability to retain moisture and withstand wind erosion (Herrmann & Hutchinson, 2005). During the dry season, dust storms strip away nutrient-rich topsoil, decreasing agricultural productivity and exacerbating food insecurity in the dust source areas (Ward *et al.*, 2014; Eekhout & De Vente, 2022; Middleton, 2024). The Sahelian countries, particularly Mali, Niger, and Chad, experience recurrent droughts, further stressing agricultural output and making dust storms a significant hazard for farmers (Siva Kumar *et al.*, 2005).

Livestock herding is another dominant livelihood in the region, particularly among nomadic and semi-nomadic communities in the Sahel and Saharan fringes. The pastoralists depend on seasonal grazing lands, but overgrazing and water scarcity have significantly contributed to vegetation loss and land degradation (Dardel *et al.*, 2014). The removal of natural vegetation exposes fine-grained sediments, making them susceptible to wind erosion and enhancing dust storm activity (Eekhout & De Vente, 2022; Zhang *et al.*, 2024).

3.1.1 Climate Features

The climatic features within the study domain are primarily governed by aridity, strong seasonal variations, and large-scale atmospheric circulation patterns. The northern part of the domain, including the Sahara Desert, is characterized by an extremely arid climate, with annual rainfall ranging from 100 to 600 mm and large temperature variability between day and night, typically from 10°C at night to over 45°C during the day. (Lavaysse *et al.*, 2016; Armon *et al.*, 2024). The

central and southern parts of the domain, encompassing the Sahelian region including Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, Eritrea, and a part of southern Algeria, experience a semi-arid climate, with rainfall ranging from 100 to 600 mm annually, mostly concentrated during the WAM (Nicholson, 2013). Meanwhile, the spatial and temporal distribution of precipitation in the region is strongly influenced by the seasonal movement of the ITD, which separates the hot, dry Saharan air mass from the moist, cooler monsoonal flow from the south (Sultan & Janicot, 2003). The ITD undergoes a pronounced latitudinal shift throughout the year, migrating northward from March to August as solar heating intensifies over the Northern Hemisphere, and retreating southward from September to February as the thermal gradient reverses (Sultan *et al.*, 2003; Sultan & Janicot, 2000, 2003; Nicholson, 2018). The seasonal oscillation plays a critical role in dictating the onset, duration, and intensity of the WAM and, consequently, the dust emission processes within the domain. During the boreal winter and early spring, when the ITD (Figure 3.2 a, b) is at its southernmost position, the Harmattan winds dry, dust-laden northeasterly winds prevail across much of the Sahel and northern WA, facilitating widespread dust uplift and transport (Evan *et al.*, 2016; Schepanski *et al.*, 2017). In contrast, the northward shift of the ITD (Figure 3.2 c) during the summer months allows the monsoon flow to penetrate further inland, increasing humidity and precipitation over the Sahel while suppressing dust emissions in the monsoon-influenced regions (Evan *et al.*, 2016).

Another dominant climatic feature is the SHL influencing dust activity in the region, particularly during summer when it strengthens due to intense surface heating (Schepanski *et al.*, 2017). The SHL shapes the pressure gradient between the hot dry Sahara and the wet moist Gulf of Guinea during boreal summer (June-August), reinforcing the low-level westerly monsoon flow and impacting the intensity of the harmattan winds (Lavaysse *et al.*, 2009). Furthermore, synoptic-

scale weather systems, such as African AEJ, and AEWs, modulate dust emissions by generating convective storms and surface gusts that enhance dust mobilization, especially during the monsoon transition period (Schepanski *et al.*, 2009; Oluleye & Folorunsho, 2019; Bercos-Hickey *et al.*, 2020). The interaction of these atmospheric features, combined with interannual variations in rainfall and land surface conditions, controls the frequency, intensity, and spatial extent of dust events across the study domain.

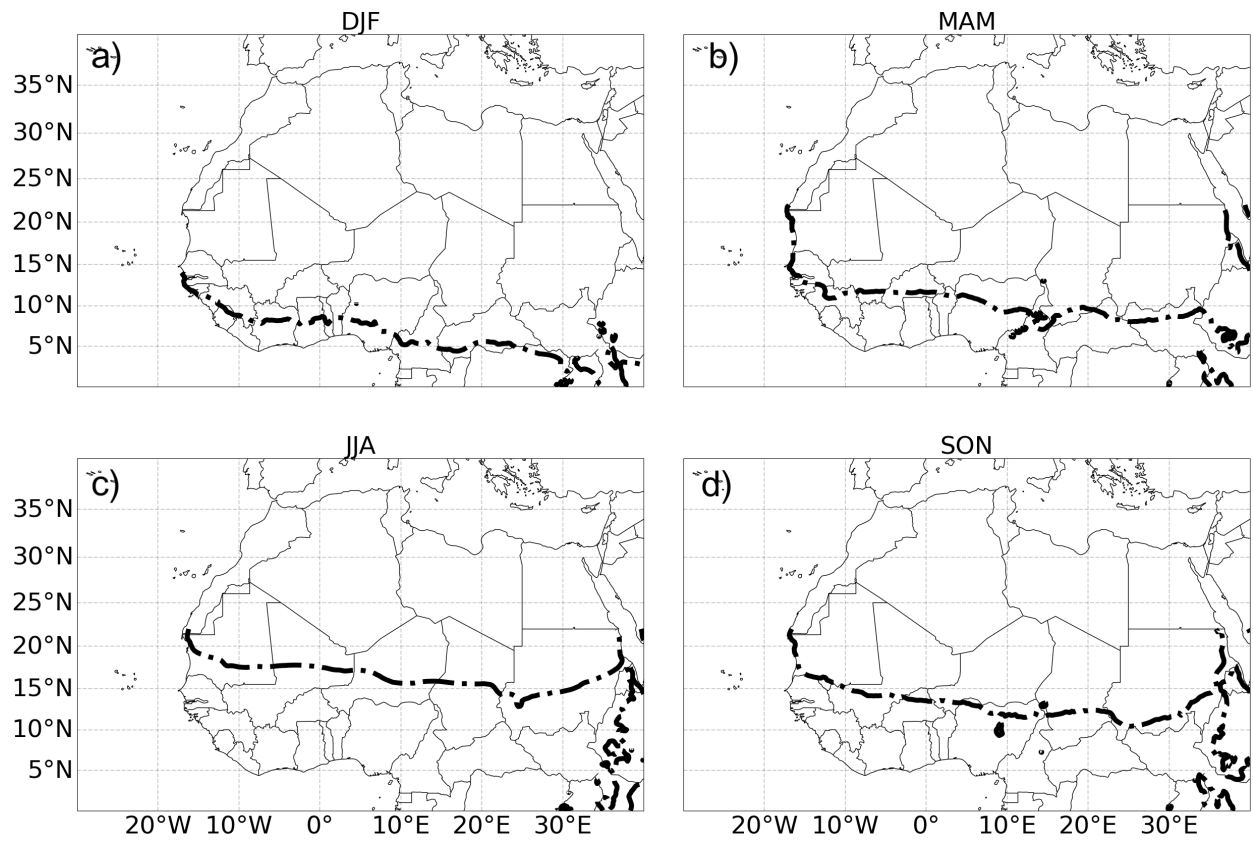


Figure 3.2: ITD (black dots) migration during the WAM (Author's work).

3.1.2 Soil Types

The domain exhibits diverse soil types, which significantly influence dust emissions and transport. Sandy soils dominate the central and northern Sahara, particularly in the Erg Chech and Grand Erg Occidental dune systems (Rajot *et al.*, 2003). These soils consist mostly of quartz particles, which are not as easily lifted as finer silts and clays but still contribute to localized dust storms when strong winds occur (Middleton & Kang, 2017; Bubenzer *et al.*, 2020; FAO, 2023). In contrast, loamy and clayey soils are prevalent in the Sahel, where alluvial deposits from past river systems provide a source of finer particles. For instance, the Bodélé Depression, contains diatomite-rich sediments, which are extremely fine and readily lifted into the atmosphere (Washington *et al.*, 2009). Similarly, dried wadi beds and seasonal floodplains serve as secondary dust sources, especially during dry periods when surface crusts break apart under wind stress. Soil degradation due to overgrazing, deforestation, and agricultural expansion has further contributed to increased dust emissions in many parts of the domain. As vegetation cover declines, surface soils become more vulnerable to wind erosion, exacerbating the frequency and intensity of dust storms (Ginoux *et al.*, 2012).

3.1.3 Land Use / Cover of the Study Domain

The land cover in the study domain is highly heterogeneous, ranging from hyper-arid desert landscapes in the north to semi-arid savannas and agricultural lands in the south. Saharan Desert is largely devoid of vegetation, with only isolated pockets of oases and ephemeral water bodies supporting plant life (Nicholson, 2000). In contrast, the Sahelian region exhibits seasonal vegetation dynamics, with grasslands and shrublands expanding during the wet season and retreating in the dry season (Pierre *et al.*, 2012).

Agricultural expansion in the Sahel, particularly in countries such as Mali, Niger, and Sudan, has altered land cover patterns, leading to increased soil disturbance and dust emissions (Sissoko *et al.*, 2011). In some areas, the overexploitation of marginal lands has resulted in desertification, further amplifying dust production. Therefore, protected areas and reforestation efforts, such as the Great Green Wall Initiative (GGWI), aim to mitigate land degradation and reduce dust emissions by restoring vegetation cover (Siva Kumar *et al.*, 2005; Fassinou *et al.*, 2024). Additionally, anthropogenic activities such as urbanization, mining, and livestock grazing have contributed to changes in land use (Nicholson, 2000; Ibrahim *et al.*, 2022). In some coastal regions, industrial developments and road networks have introduced new sources of dust pollution, influencing local air quality and atmospheric composition (Webb & Pierre, 2018).

The topographic controls on dust emission (Fig. 3.1) interact with the region's pronounced vegetation changes, as revealed by the 1984–2023 Leaf Area Index (LAI) change trends (Fig. 3.3). The Sahel shows widespread greening with LAI increase exceeding 45% ($p < 0.05$, blue dots), particularly in southern Mauritania, Niger, and Chad (10°N–15°N), likely due to increased rainfall and land use changes (Herrmann *et al.*, 2005). This greening has two competing dust modulation effects: (1) reduced local emission through soil stabilization by vegetation in the Sahel (Cowie *et al.*, 2013), and (2) potential transport pathway shifts as the strengthened West African Monsoon (associated with greening) alters wind regimes (Evan *et al.*, 2016). The 95th-percentile significant changes (blue dots) cluster along the Sahel's southern flank, suggesting a northward shift of the vegetation-controlled dust inhibition boundary, while hyper-arid zones maintain emission potential.

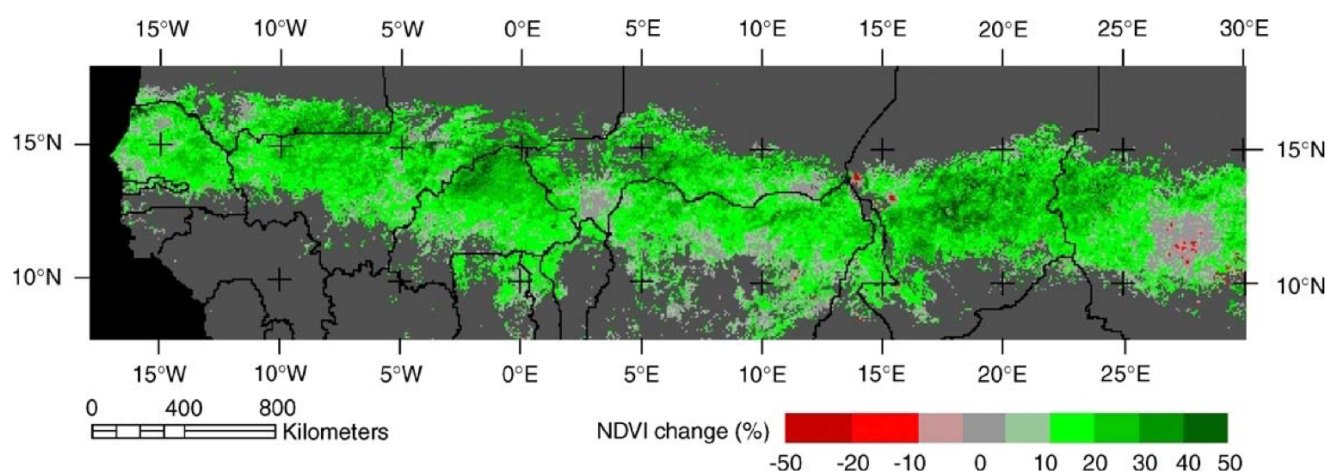


Figure 3.3: Overall trends in vegetation greenness based on the monthly AVHRR NDVI for the period 1982 to 2003 (adopted from Herrmann et al. 2005).

3.2 DATA

3.2.1 MIDAS Land Surface Stations Data

Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations data (UK Meteorological Office, 2024), available from British Atmospheric Data Center (BADC), are used in this study for 40 years from 1984 to 2023. Other data sets are available from the BADC, including the United Kingdom (UK) dataset that dates back to 1853 and a nonglobal dataset that dates back to 1900. The reliability of the data set used in this study has been discussed by Shao *et al.* (2013) and Xi (2021).

The MIDAS data sets consist of meteorological records such as visibility, temperature, wind speed, precipitation, ... reported at 6 or 3-hourly intervals in SYNOP (Surface Synoptic Observations) and METAR (Meteorological Aviation Routine Weather Report) codes. The records can be from either manned or automatic weather stations. Only stations from manned SYNOP stations are used in this study. In the data set, dust events are recorded using the present weather codes (*ww*) and classified according to the horizontal visibility. Figure 3.4 presents the SYNOP stations (Red and Blue dots) distribution over the study domain. Red dots represent the stations that records are used for the present study.

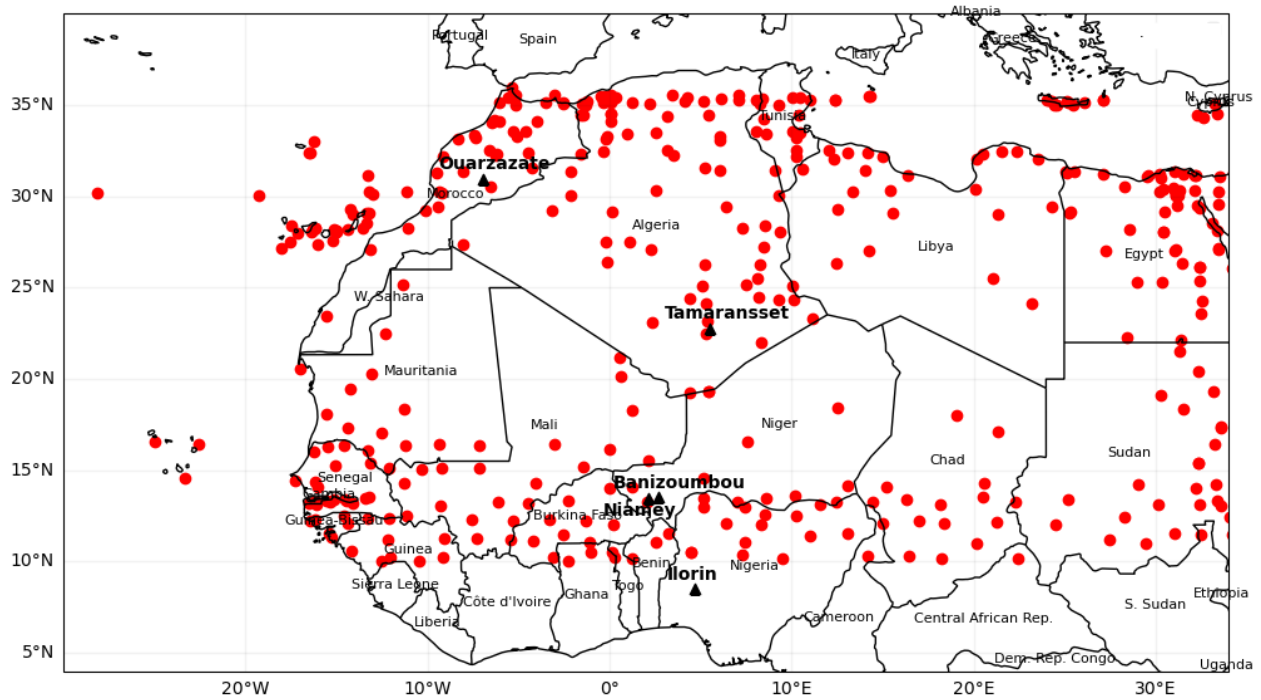


Figure 3.4: SYNOP stations coverage up to December 2023. Red points represent the stations records used in the study. Black triangles represent stations used for the validation (Author,s work).

3.2.1.1 Present Weather Codes.

The present weather codes from manned stations, abbreviated as *ww* by the World Meteorological Organization (WMO), are widely used in SYNOP and METAR reports to describe ongoing weather conditions (WMO, 1995). This coding system describes ongoing weather conditions such as precipitation, dust storms, fog, thunderstorms, and other meteorological phenomena based on visibility, precipitation type and intensity, and obstructions to vision. The codes range from 00 (clear sky) to 99 (severe weather events), with specific numbers dedicated to various meteorological occurrences. For the dust events, the codes describe the near surface dust conditions with varying intensity (i.e., slight, moderate, or heavy), proximity to the station (i.e., at the station, in the vicinity of the station, or distant from the station), and developing stage (i.e., decrease, no appreciate change, or increase) (Xi, 2021). Table 3.1 presents the present weather codes (*ww*) and their definition from the WMO code table 4677 (WMO, 1995). The dust event records in the present weather code (*ww*) are categorized based on visibility. For example, *ww* = 06 describes widespread dust in suspension caused by atmospheric dust transport events from non-local sources, not lifted at or near the station during observation, with visibility typically not exceeding 10 km. *ww* = 07, describes dust or sand lifted at or near the station during observation time, reducing visibility to between 1 and 10 km. Short-lived local events over hot, dry, and flat surfaces like dust devils or swirls and sand whirls observed at or near the station at the preceding hour or the time of the observation are described by the code *ww* = 08. The dust storms or sandstorms within sight at the time of observation, slight at or near the station during the preceding hour and slight or moderate dust storms or sandstorms decreasing, no changing or increasing are described by the codes *ww* = 09 or 30-32. These events, driven by strong winds, lift large amounts of dust particles, reducing visibility to between 200 and 1000 m (Shao et al., 2013). The codes *ww*

= 33-35 describe severe dust storms, events driven by very strong winds that lift large amount of dust particles reducing the visibility to less than 200 m. Thunderstorms combined with sand or dust storms are described by $ww = 98$.

This study only focused on dust storms and severe dust storms. For this purpose, dust events selected in this study are describes by $ww = 09, 30-32$ and 33-35 with the related visibility as described above. The selection criterion is further described in the methodology section.

Table 3.1: Dust weather types in the present weather reports from manned stations (ww) according to WMO code table 4677 (WMO, 1995).

ww	Dust code definition
05	Haze
06	Widespread dust in suspension in the air, not raised by wind at or near the station at the time of observation
07	Dust or sand raised by wind at or near the station at the time of observation, but not well-developed dust whirl(s) or sand whirl(s), and no dust storm or sandstorm seen; or, in the case of ships, blowing spray at the station
08	Well-developed dust or sand whirl(s) seen at or near the station during the preceding hour or at the time of observation, but no dust storm or sandstorm
09	Dust storm or sandstorm within sight at the time of observation, or at the station during the preceding hour
30	Slight or moderate dust storm or sandstorm - has decreased during the preceding hour
31	Slight or moderate dust storm or sandstorm - no appreciable change during the preceding hour
32	Slight or moderate dust storm or sandstorm - has begun or has increased during the preceding hour
33	Severe dust storm or sandstorm - has decreased during the preceding hour
34	Severe dust storm or sandstorm - no appreciable change during the preceding hour
35	Severe dust storm or sandstorm - has begun or has increased during the preceding hour
98	Thunderstorm combined with dust/sandstorm at time of observation

3.2.1.2 Visibility

Our daily lives rely heavily on the ability to gather and process information , whether from advanced technologies or natural human perception. Despite technological advancements, the eye-brain system remains the most essential imaging tool, constantly perceiving events and objects, where visibility significantly influences decision-making and management (Lee & Shang, 2016). Visibility plays a critical role in various aspects of life, particularly in transportation, aviation, and maritime navigation, where reduced visibility due to fog, dust, or precipitation can significantly impact safety and operational efficiency (Middleton, 2017). Traditionally, visibility has been defined as the greatest distance at which a black object of suitable dimensions, located on the ground, can be clearly seen and recognized against the horizon sky during daylight (Gultepe *et al.*, 2007). At night, visibility is assessed based on how well the object would be seen under artificial illumination simulating daylight conditions. One of the most widely accepted theoretical models for visibility measurement was proposed by Koschmieder (Mahowald et al., 2007; Lee & Shang, 2016; Xi, 2021). According to Koschmieder's law, visibility is determined by the extinction coefficient of the atmosphere, which quantifies the scattering and absorption of light by aerosols and gases. His formula defines meteorological visibility as the distance at which the contrast of an object with respect to the background reduces to a threshold value, usually 5%. Moreover, visibility reflects the total concentration of aerosols and particles between an observer and a distant object and can be expressed as a surface extinction value, representing the reduction of light due to aerosol scattering and absorption, as described by Koschmieder's formula (Godish, 2004; Mahowald *et al.*, 2007; Davis, 2021):

$$Extinction = 3.92/Visibility \quad (3.1),$$

where Visibility is expressed in km and Extinction of aerosol particles expressed in km^{-1} . Mahowald *et al.*, (2007) used Equation (3.1) to compare the visibility and AOD data in dust dominant zones. They highlighted the lack of statistical significance correlation between AOD and the visibility-derived variables for most of the surface meteorological stations. They then suggested this low correlation to be due to several factors such as strong boundary layer inversion, quality of the data, moisture impacts on the visibility through clouds and possible aerosol layers not seen by the visibility measurer but observed by the AERONET sensors.

Xi, (2021) based on Koschmieder equation included dust event frequency and the visibility harmonic mean to estimate the extinction coefficient contributed by dust aerosol as follow:

$$\beta = \frac{3.9}{V} * f \quad (3.2),$$

where V is the harmonic mean visibility (km) associated with dust events, f the dust event frequency (%) and β (km^{-1}) the extinction coefficient contributed by dust aerosol.

Under various definitions of visibility, WMO has adopted a standardized definition of visibility based on meteorological optical range. According to WMO, (2025), visibility, is the maximum distance at which a black object of appropriate size, located on the ground, can be clearly seen and identified against the horizon sky in daylight or could be visible if the ambient illumination were equivalent to normal daylight conditions. This definition ensures uniformity in meteorological observations and reporting worldwide. Visibility referred to in this study, is based on the definition of WMO, (2025). At global scale, Equation (3.1) and (3.2) are accurate in tracking dust events.

3.2.1.3 Quality Assessment of Synoptic Records

Quality assessment of synoptic records is essential to ensure the reliability and accuracy of meteorological observations, particularly for climate studies and weather forecasting. In this study,

The quality of visibility observations was assessed by deriving dust extinction using Equation (3.1) and validating it against independent aerosol measurements.

To validate the visibility-derived dust extinction estimates, comparisons were made them with Aerosol Optical Depth (AOD) at 1020 nm from co-located AERONET stations. AERONET provides high-quality, sun-photometer-derived AOD with uncertainties of ± 0.01 – 0.02 for cloud-screened Level 2.0 data (Holben *et al.*, 1998; Giles *et al.*, 2019). The selected AERONET site (Table 3.2.a, b) are located in major dust emission and transport regions across the Sahel, Sahara and Sudanian Savana (Prospero *et al.*, 2002; Cuesta *et al.*, 2009; Marticorena *et al.*, 2017). These sites offer long-term, high-quality aerosol records critical for validation efforts.

Table 3.2.a: AERONET site for the visibility data validation

AERONET Stations	Longitude	Latitude	Data Range
Banizoumbou (Niger)	02.66	13.54	1995-to 2023
Tamanrasset (Algeria)	05.50	22.79	2006-to 2023
Ouarzazate (Morocco)	-06.91	30.98	2012-2018
Ilorin (Nigeria)	04.67	08.48	1998-to 2023

Table 3.2.b: MIDAS sites to match AERONET sites

MIDAS Stations	Longitude	Latitude	Station ID
Niamey (Niger)	02.17	13.48	61052
Tamanrasset (Algeria)	05.50	22.79	60680
Ouarzazate (Morocco)	-06.91	30.98	60265
Ilorin (Nigeria)	04.67	08.48	65101

To ensure temporal consistency between the datasets, visibility-derived extinction and AERONET AOD were first aggregated into 3-hourly averages, retaining only periods with overlapping observations. To further reduce high-frequency variability while preserving seasonal signals, the matched data were subsequently averaged into monthly means.

Then correlation analyses were conducted between monthly extinction and AOD values using the Pearson correlation coefficient (r) to quantify their linear relationship. Recognizing that temporal autocorrelation can artificially inflate significance levels, a prewhitening procedure was applied based on an AutoRegressive Integrated Moving Average (ARIMA(1, 0, 0)) model where necessary (Wilks, 2011). Further details regarding the statistical robustness checks are provided in the Methods subsection. The resulting monthly aggregates formed the basis for assessing the reliability of visibility-derived dust extinction, with the correlation statistics summarized in the results section.

While ground-based observations provide localized, high-quality measurements of dust properties, reanalysis and satellite remote sensing offer complementary capabilities including global spatial coverage, temporal consistency, and multi-parameter detection that are essential for regional-scale analysis. To leverage these advantages, this study incorporates: (1) MERRA-2 dust mass concentration to constrain near-source emission intensity, and (2) OMI Aerosol Index for absorbing dust detection all of which have been extensively validated for dust monitoring across the study domain.

3.2.2 MERRA 2 Data

Surface dust mass concentration data were obtained from the Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2) produced via the Goddard Earth Observing

System-Data Assimilation System (GEOS-DAS, version 5.12.4) based on GEOS-5 climate model and Gridpoint Statistical Interpolation (GSI) analysis scheme (Gelaro *et al.*, 2017). The surface dust mass concentration variable represents the mass of mineral dust near the surface (kg m^{-3}) and is derived from an aerosol assimilation system that includes satellite retrievals of aerosol optical properties. For this study, monthly mean surface dust mass concentration fields were used to analyze dust loadings over the Sahara and Sahel regions. The data have a spatial resolution of $0.5^\circ \times 0.625^\circ$ (longitude x latitude) and cover the period from 1980 to 2023, providing a long-term perspective on surface dust variability relevant to dust emission, transport, and deposition processes.

3.2.3 OMI AI Data

Aerosol Index (AI) data from the Ozone Monitoring Instrument (OMI) aboard NASA's Aura satellite were used to characterize the distribution of dust aerosols over the Sahara and Sahel regions. The OMI AI product is particularly well suited for dust studies in these areas because it is highly sensitive to elevated, absorbing aerosols over bright surfaces such as deserts (Torres *et al.*, 2007). A key strength of the OMI-Aura product is the use of ultraviolet (UV) wavelength differences (354/388 nm) to detect absorbing aerosols, allowing for robust aerosol detection even over highly reflective desert surfaces. Unlike traditional optical depth measurements which measures the total columnar aerosol loading primarily through scattering, AI is less affected by surface reflectance providing additional information on aerosol type and vertical distribution, making it an effective tool for detecting mineral dust over the intensely reflective Sahara. For this study, the Level 3 daily gridded UV Aerosol Index product was used, averaged into monthly means at a $1^\circ \times 1^\circ$ (longitude x latitude) spatial resolution. High-quality retrievals were selected to

minimize the influence of clouds and sensor anomalies. The OMI AI data provided critical complementary information for assessing the spatial and temporal variability of dust activity, particularly during major dust outbreak seasons across North Africa.

3.2.4 Chirps Version 3 Data

Precipitation data were obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) Version 3 dataset (Funk *et al.*, 2015). This high-resolution ($0.05^\circ/\sim 5$ 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 suited for arid and semi-arid regions. 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. For this study, monthly total precipitation was used to analyze relationships between rainfall variability and dust activity. The dataset's spatial continuity and demonstrated accuracy in WA (Dembélé *et al.*, 2020) address key limitations of sparse ground observations while capturing fine-scale gradients across the Saharan-Sahelian transition zone.

3.2.5 ECMWF ERA 5 Reanalysis Data

The fifth generation European Center for Medium-Range Weather Forecast (ECMWF) Reanalysis (ERA5; Hersbach *et al.*, 2020) were used to characterize atmospheric dynamics and land-surface conditions relevant to dust storms processes. The dataset provides high-resolution $0.25^\circ \times 0.25^\circ$ (longitude x latitude) hourly estimates, from which daily averages of key variables: geopotential height at 700 hPa and 925 hPa were extracted to analyze SHL; 10 m wind speed components (u/v)

to assess dust emission potential; 2 m temperature for evaluating convective mixing; and land surface parameters including leaf area index (LAI) to quantify vegetation cover constraints on dust mobilization for the study period. ERA5's strength lies in its coupled atmosphere-land data assimilation system, which maintains physical consistency between variables particularly critical for representing the wind-soil moisture feedbacks that govern dust emission thresholds in the Sahel. Three-hourly ERA5 data (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 UTC) were specifically extracted to maintain temporal alignment with the synoptic observation times of present weather codes and visibility measurements. While ERA5 may underestimate fine-scale convective winds, its comprehensive physical framework and temporal resolution (hourly outputs averaged to daily) provide a robust basis for analyzing dust-climate interactions at regional scales (Suo *et al.*, 2024).

3.2.6 Large-Scale Climate Indices

Large-scale climate indices used in this study were downloaded from the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA). These indices include the Multivariate ENSO Index (MEI); the North Atlantic Oscillation (NAO); the Arctic Oscillation (AO); the Southern Oscillation Index (SOI); the Northern Oscillation Index (NOI), and the Atlantic Multidecadal Oscillation (AMO) index. The selection covers primary teleconnections known to influence Sahelian-Saharan climate variability through alterations in trade wind intensity (ENSO/AMO), mid-latitude storm tracks (NAO/AO), and monsoon dynamics (SOI), as demonstrated in previous dust-climate studies (Rodríguez *et al.*, 2015; Evan *et al.*, 2016). Each of these indices represents key modes of natural climate variability that can influence atmospheric circulation patterns, precipitation regimes, and dust activity across the Sahara and Sahel regions.

Monthly values were used to assess potential links between large-scale climate variability and dust-related processes. The CPC products are widely recognized as authoritative, with the ENSO and NAO indices demonstrating over 85% agreement with independent reanalysis datasets (Trenberth *et al.*, 2015).

3.3 Methods

3.3.1 Methods for Achieving Objective 1.

3.3.1.1 Dust Storms Selection Criterion.

As presented in Section 3.2.1, only station records represented by red points (Figure 3.4) that meet the selection criterion are used in the present study. The selection criterion is based both on present weather codes (Table 3.1) and horizontal visibility. For simplicity, dust event records in the present weather codes (ww) are categorized according to the visibility, like in Shao *et al.* (2013), into the following categories: (1) “dust storm” ($ww = 09$ or 30-35, high intensity dust event reducing visibility to less than 1000 m); (2) “dust event” ($ww = 05, 06, 07, 08$ or 98, moderate intensity dust event associated to visibility higher than 1000 m). Table 3.1 presents the weather codes and their definitions for the above categories. For the purpose of this study, thunderstorms combined with dust / sandstorms ($ww = 98$) are intentionally classified as moderate dust event even though they can reduce visibility to less than 1000 m.

Only category (1) dust storm ($ww = 09$ or 30-35, strong wind lifts large quantities of dust particles, reducing visibility to less than 1000 m) records are used for the analysis in this study. The spatial distribution of MIDAS records used in this study for northern Africa is presented in Figure 3.4. Red points represent station records used to assess dust storm occurrences meanwhile blue points represent stations not used (to show the regional coverage of records station). To account for

delayed hydrological and vegetation feedbacks on dust storm activity, distinct lag structures were applied to local dust drivers in the Sahel and the Sahara. For the Sahel, a 6-month precipitation anomaly lag was used to reflect soil memory effects, as demonstrated by Zender & Kwon, (2005), who showed this timescale captures the delay between rainfall deficits and dust emission peaks through soil moisture depletion. While 12-month LAI reflects the region's characteristic seasonal vegetation legacy (Klingmüller *et al.*, 2016). The Sahara region required shorter precipitation (3-month) and LAI (6-month) lags due to its hyper-arid conditions, where faster soil drying and ephemeral vegetation responses dominate (Cowie *et al.*, 2013).

3.3.1.2 Long-Term Trends Analysis.

To assess long-term trends in dust storm occurrences, two complementary non-parametric methods were employed: the Mann-Kendall (MK) test for statistical significance and the Theil-Sen estimator for trend magnitude estimation. This dual approach provides robust trend analysis capabilities resistant to non-normal distributions, outliers, and missing data points common in environmental time series (Wilks, 2011; Helsel *et al.*, 2020).

3.3.1.3 Mann-Kendall trend test.

The Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) is a non-parametric test that assesses the presence of a monotonic trend (increasing or decreasing) in a time series without requiring the data to follow a specific distribution. The test operates under the null hypothesis (H_0) that there is no trend, against the alternative hypothesis (H_1) of a monotonic increasing or decreasing trend. The MK test statistic (S) is calculated as follow:

$$S_k = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n-1} \text{sgn}(X_j - X_i) \quad (3.3)$$

where X_j and X_i are sequential data values of length n in years such that k is greater than i and

where sgn is a function defined as:

$$sgn(X_j - X_i) = \begin{cases} 1 & \text{if } (X_j - X_k) > 0 \\ 0 & \text{if } (X_j - X_k) = 0 \\ -1 & \text{if } (X_j - X_k) < 0 \end{cases} \quad (3.4)$$

The MK statistic's variance is determined using the following formulas under the null hypotheses of no trend and independence of the series:

$$Var(S_k) = \frac{N(N-1)(2N+5) - \sum_{p=1}^g t_p(t_p-1)(2t_p+5)}{18} \quad (3.5)$$

where g represents the number of tied group and where t_p refers to the number of data values in the p th group. The standard normal test statistic is computed using the statistic S_k which assumes a normal distribution for samples with $n \geq 10$ and sample sizes greater than 10 as follow:

$$Z_s = \begin{cases} \frac{S_k-1}{\sqrt{Var(S_k)}}, & \text{for } S_k > 0 \\ 0, & \text{for } S_k = 0 \\ \frac{S_k+1}{\sqrt{Var(S_k)}}, & \text{for } S_k < 0 \end{cases} \quad (3.6)$$

The associated density probability function for a normal distribution with a mean of 0 and a standard deviation of 1 is computed by following equation:

$$f(Z_s) = \frac{1}{\sqrt{2\pi}} e^{-\frac{Z_s^2}{2}} \quad (3.7)$$

If $|Z_s| > 1.96$ the trend is significant at the 95% confidence level. Thus, a positive Z_s value indicates an increasing trend, while a negative value suggests a decreasing trend.

3.3.1.4 Prewhitening Using ARIMA Models.

In time series analysis, the presence of autocorrelation, especially at lag-1, violates the assumption of independence required by the Mann–Kendall (MK) test. Autocorrelated residuals can inflate the variance of the test statistic, increasing the likelihood of detecting spurious trends (Von Storch & Navarra, 1995; Yue., 2002). To address this issue, prewhitening was applied using Auto-Regressive Integrated Moving Average (ARIMA) models.

The ARIMA model denoted, as $ARIMA(p, d, q)$, combines three components:

- Autoregression (AR) of order p ,
- Autoregression (I) of order d for differencing non-stationary data,
- Moving Average (MA) of order q ,

The general form for ARIMA model for a univariate time series $\{x_t\}$ is:

$$\phi(B)1 - B^d x_t = \theta(B)\varepsilon_t \quad (3.8)$$

where:

- B is the backshift operator such that: $Bx_t = x_{t-1}$ (3.9)
- $\phi(B) = 1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p$ Equation (3.10)

is the Autoregressive (AR) polynomial;

- $\theta(B) = 1 + \theta_1 B + \theta_2 B^2 + \dots + \theta_q B^q$ (3.10)

is the Moving Average polynomial ;

- ε_t is a white noise error term with zero mean and constant variance.

3.3.1.5 Theil-Sen Estimator for trend magnitude.

To quantify the magnitude of the trend detected by the MK test, the Theil–Sen (TS) estimator was used (Helsel *et al.*, 2020; Sen, 1968) which computes the median of all pairwise slopes between data points as follow:

$$\beta = \text{median} \left(\frac{x_j - x_i}{j - i} \right), \forall i < j \quad (3.11)$$

This estimator is notably robust against the influence of outliers and non-constant variance in the residuals, and remains effective in the presence of gaps in the time series. Its resistance to noise and strong statistical properties makes it a preferred alternative to traditional linear regression for detecting trends in environmental datasets (Von Storch & Navarra, 1995). The TS slope β represents the rate of change per year (or per season) in the studied variable (e.g., dust storm frequency). To express the trend as a percentage change relative to the mean, we computed:

$$\text{Trend} = \left(\frac{\beta}{\bar{x}} \right) \times 100 \quad (3.12)$$

3.3.1.6 Uncertainty and Significance Mapping.

To assess the uncertainty around TS trend estimates, non-parametric bootstrap resampling (n = 1000 iterations) was employed to generate 95% confidence intervals. If the interval did not contain zero, the trend was considered statistically significant.

For gridded or regional trend analyses, we performed the MK test and TS estimation at each grid cell or spatial unit. Significant trends ($p < 0.05$) were highlighted using overlaid markers (e.g., black dots on trend maps), aiding interpretation of spatial patterns.

3.3.1.7 LMG and Random Forest Approaches.

To assess the relative importance of meteorological and climate drivers in modulating dust storm frequency across the Sahel and Sahara regions, we applied two complementary methods: the LMG decomposition method from linear regression and the Random Forest algorithm from ensemble learning. These methods allowed cross-validation of results and offered insight into both additive and interaction effects of predictors.

3.3.1.7.a Drivers Importance Analysis using LMG

The LMG method, named after Lindeman, Merenda, and Gold., (1980) was first used, to quantify the relative importance of each predictor in a multiple linear regression framework. The LMG decomposes the coefficient of determination from a linear regression model into non-negative shares attributed to each predictor variable. This is achieved by computing the average increase in associated with adding each variable across all possible orderings of regressors:

$$LMG(X_j) = \frac{1}{p!} \sum_{\pi \in P} [R^2(S_j^\pi \cup \{X_j\}) - R^2(S_j^\pi)] \quad (3.13)$$

where:

- P is the set of all permutations of p predictors;
- S_j^π is the set of predictors preceding X_j in ordering π ;
- $R^2(S)$ is the model coefficient of determination with predictor S .

The LMG method, implemented using the approach of (Grömping, 2006, 2007, 2009), accounts for shared variance among predictors and yields an order-invariant and interpretable ranking of relative importance. Bootstrapping ($n = 1000$) was used to estimate 95% confidence intervals around each importance value, helping assess the statistical robustness of the ranking.

This analysis was applied separately for the Sahel and Sahara regions, using annual dust storm frequency as the response variable, and both meteorological variables (surface wind speed, sea level pressure, temperature anomalies, precipitation anomalies, SHL intensity, and leaf area index) and climate indices (Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), Multivariate El Niño Index (MEI), etc.) as predictors.

3.3.1.7.b Drivers Importance Analysis using Random Forest

To complement the linear assumptions of LMG and capture nonlinear dependencies and interactions among predictors, we applied Random Forest regression (Breiman, 2001). Random Forest (RF) is a robust ensemble machine learning method used for both classification and regression tasks. It operates by aggregating the outputs of multiple decision trees, each trained on a random subset of the data, thus improving predictive accuracy and reducing overfitting. In the context of this study, RF regression was applied to evaluate the relative importance of meteorological and climate drivers in explaining dust storm frequencies across the Sahel and Sahara regions. The model performance was evaluated using the out-of-bag (OOB) R^2 , calculated from the prediction error on samples not used during tree training:

$$R_{OOB}^2 = 1 - \frac{\sum (y_i - \hat{y}_i^{OOB})^2}{\sum (y_i - \bar{y})^2} \quad (3.14)$$

where $\hat{y}_i$ is the predicted value, y_i is the observed frequency, and $\bar{y}$ is the sample mean.

Variable importance was assessed using the Mean Decrease in Accuracy (MDA) metric, which estimates the increase in prediction error when a predictor is randomly permuted, breaking its association with the response:

$$MDA(X_j) = \frac{1}{T} \sum_{t=1}^T (MSE_{permuted,j}^{(t)} - MSE_{original}^{(t)}) \quad (3.15)$$

where:

- T is the number of trees;
- $MSE_{permuted,j}^{(t)}$ is the prediction error after permuting X_j in tree t ;
- $MSE_{original}^{(t)}$ is the original error.

To enhance interpretability, the importance scores were further multiplied by the sign of the Pearson correlation between each predictor and the dust storm frequency:

$$SignedImportance(X_j) = MDA(X_j) \cdot \text{sgn}(\text{cor}(X_j, \text{Freq})) \quad (3.16)$$

These signed importance values were normalized to lie within $[-1, 1]$ to facilitate the visual comparison between the Sahara and the Sahel regions.

The resulting rankings were used to validate and cross-check results from the LMG relative importance method, providing robustness to the findings. By combining LMG (additive linear contribution) and RF (nonlinear, interaction-inclusive) rankings, we ensured methodological robustness. Agreement in the top-ranked drivers between the two methods was taken as evidence of consistent influence, whereas divergence was interpreted as arising from nonlinear or interactive effects captured only by the RF model. This dual-method framework provides both explanatory power and generalization capacity, strengthening confidence in the interpretation of key drivers.

3.3.2 Methods for Achieving Objective 2

To identify and characterize the dominant synoptic-scale atmospheric circulation patterns associated with dust storm activity over the Sahara and Sahel, we employed the Self-Organizing Map (SOM) algorithm (Kohonen, 2001, 2013). SOMs are an unsupervised neural network-based clustering technique that projects high-dimensional data onto a lower-dimensional (typically 2D) map, preserving the topological structure of the input data.

3.3.2.1 Input Data and Preprocessing.

The SOM analysis was applied to two key meteorological fields: Sea Level Pressure (SLP) and zonal and meridional winds at 925 hPa.

These variables were chosen due to their relevance in modulating surface wind patterns, pressure gradients, and near-surface convergence zones, which are critical in dust storm initiation and transport. Figure 3.5 shows an illustration of an input vector X compared across the SOM model.

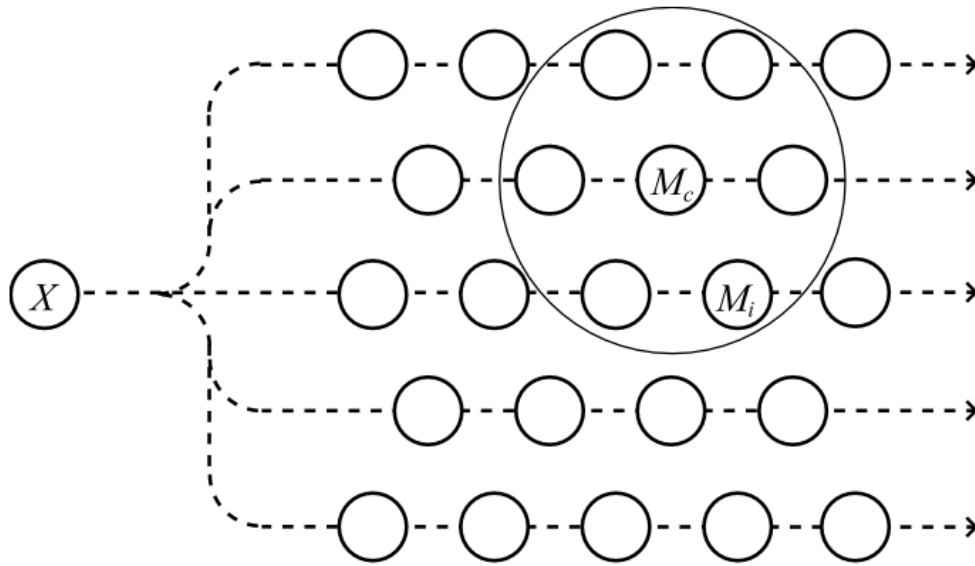


Figure 3.5: Illustration of self-organizing map. An input vector X is compared across all model nodes M_i in the SOM grid. The best-matching unit (BMU), denoted M_c , is the model closest to X . Neighboring nodes (within the larger circle) are also updated due to their proximity to M_c , indicating a better match with X compared to more distant nodes (adopted from Kohonen, (2013)).

The analysis was conducted for all grid points within the domain spanning North Africa, and for dates when dust storms were observed. To ensure comparability and remove biases due to variable magnitudes, each input field was standardized by subtracting the climatological mean and dividing by the standard deviation at each grid point:

$$X_i^{std} = \frac{X_i - \mu_i}{\sigma_i} \quad (3.17)$$

where:

- X_i is the raw field value at the grid i ,
- μ_i and σ_i are the mean and standard deviation of that grid point across all dust storm days.

3.3.2.2 SOM algorithm and Training.

The SOM consists of 2D grip (map) of nodes or neurons, each associated with a weight vector $W_j \in \mathbb{R}^n$, where j indexes the map node. As presented on figure 3.6, the SOM training follows an iterative competitive training process.

i) Initialization

Weights are initialized using linear initialization via Principal Component Analysis (PCA) or randomly. For this study, the SOM was initialized randomly.

ii) Best Match Unit (BMU) selection

For each input vector $X(t)$, the SOM identifies the Best Match Unit j^* as:

$$j^* = \arg \min_j \|X(t) - W_j\| \quad (3.18)$$

where $\| \cdot \|$ is the Euclidean distance.

iii) Weight Update

The weights of the BMU and it neighboring nodes are updated using:

$$W_j(t + 1) = W_j(t) + \alpha(t) \cdot h_{j,j^*}(t) \cdot (X(t) - W_j(t)) \quad (3.19)$$

where:

- $\alpha(t)$ is the learning rate (decays over time)
- $h_{j,j^*}(t)$ is the neighborhood kernel function, usually Gaussian:

$$h_{j,j^*}(t) = \exp\left(-\frac{\|r_j - r_{j^*}\|^2}{2\sigma^2(t)}\right) \quad (3.20)$$

With r_j the coordinates of node j on the map grid, and $\sigma(t)$ the width of neighborhood function (also decays over time).

The process is repeated for all training samples over multiple iterations until convergence.

iv) SOM Map Configuration and Node Selection

A set of 3×4 , 5×4 , 6×4 , 5×5 , 6×4 , 5×7 , and 6×6 SOM grids was use. The 6×6 SOM, yielding 36 nodes configuration was retained as it balances:

- Adequate pattern differentiation (synoptic diversity) ;
- Sufficient sample size per node for robust interpretation.

SOM training was implemented with the standard batch training algorithm. Each input vector corresponded to a day with a dust storm event over the Sahara or Sahel region.

v) Post Training Analysis

Once trained, each SOM node represents a typical atmospheric pattern associated with dust storms occurrence. We identified which SOMs nodes were associated with high vs. low dust storms frequencies, providing insight into the circulation regimes most conducive to dust generation.

Seasonal frequency distributions of SOMs patterns were also computed to investigate seasonal modulation of dominant dust-driving regimes.

3.3.2.3 SOMs in Climate Science

Self-Organizing Maps (SOMs) have been widely used in climate science to classify and interpret complex atmospheric circulation patterns and variability. Their ability to reduce the dimensionality of large spatiotemporal datasets while preserving the topological structure of input fields makes them particularly well-suited for exploring modes of climate variability. For example, Hewitson & Crane, (2002) employed SOMs to analyze synoptic-scale weather patterns over South Africa, while Cassano *et al.* (2011) applied SOMs to understand synoptic patterns control on temperature in Alaska. Reusch *et al.* (2005) used SOMs to investigate relationships between North Atlantic circulation and sea level pressure. In dust climatology, SOMs have also been used to classify meteorological conditions linked to dust outbreaks, as in the work by Notaro *et al.* (2013), who examined synoptic controls of dust events in the Middle East. These studies demonstrate SOMs' versatility in detecting dominant atmospheric regimes, evaluating teleconnections, and exploring climate-dust interactions.

3.3.3 Methods for Achieving Objective 3

3.3.3.1 Long Short-Term Memory (LSTM) Neural Network Modeling

Long Short-Term Memory (LSTM) networks (Hochreiter & Schmidhuber, 1997) were employed in this study to model the temporal dynamics between climate drivers, meteorological variables, and dust storm frequency. LSTM is a type of recurrent neural network explicitly designed to capture long-term dependencies in sequential data by mitigating the vanishing and exploding gradient issues that often affect standard RNNs, especially when relevant signals are separated by long time lags (Van Houdt *et al.*, 2020).

In climate science, non-linear and lagged relationships between climate drivers, meteorological variables, and environmental responses such as dust storm frequency are increasingly modeled using advanced methods. The architecture of these models allows them to retain information over extended time steps, making them well-suited for modeling time series influenced by complex climate-memory processes. Recent applications of LSTM networks in this domain include forecasting temperature and precipitation anomalies (Ma *et al.*, 2021), predicting drought conditions (Vo *et al.*, 2023), modeling air quality and pollutant concentrations (Zhao *et al.*, 2019), and assessing hydrological extremes such as floods and streamflow (Fang *et al.*, 2021; Li *et al.*, 2024). These studies highlight the strength of LSTM models in capturing both short- and long-range temporal dependencies, making them particularly suitable for analyzing the lagged influence of large-scale climate modes (e.g., ENSO, NAO, AMO) on regional meteorological processes and associated environmental outcomes.

3.3.3.2 Theoretical Background of LSTM

An LSTM unit is composed of memory cell regulated by gates (Figure 3.6). Below, figure 3.7 presents a network composed of N processing blocks and M inputs.

Block Input: in this step, the block input component is updated by combining the current input $x^{(t)}$ with the output of that LSTM $y^{(t-1)}$ unit in the last iteration. This can be done as depicted below:

$$z^{(t)} = g(W_z x^{(t)} + R_z y^{(t-1)} + b_z) \quad (3.21)$$

where W_z and R_z are the weights associated with $x^{(t)}$ and $y^{(t-1)}$, respectively, while b_z is the bias weight vector.

Input gate: in this step, the input gate is updated by incorporating the current input $x^{(t)}$, the previous output $y^{(t-1)}$ of that LSTM and the previous cell state $c^{(t-1)}$ in the iteration. This procedure is shown in the following equation:

$$i^{(t)} = \sigma(W_i x^{(t)} + R_i y^{(t-1)} + p_i \odot c^{(t-1)} + b_i) \quad (3.22)$$

where $\odot$ denotes point-wise multiplication of two vectors, W_i , R_i and p_i are the weights associated with $x^{(t)}$, $y^{(t-1)}$, and $c^{(t-1)}$ respectively, while b_i represents for the bias vector associated with this component.

In the preceding steps, the LSTM layer identifies the information to retain within the cell state $c^{(t)}$, including the candidate values $z^{(t)}$ proposed for inclusion and the input gate activations $i^{(t)}$ that regulate their contribution.

Forget gate: in this step, the LSTM unit determines which information should be discarded from the previous cell state $c^{(t-1)}$.

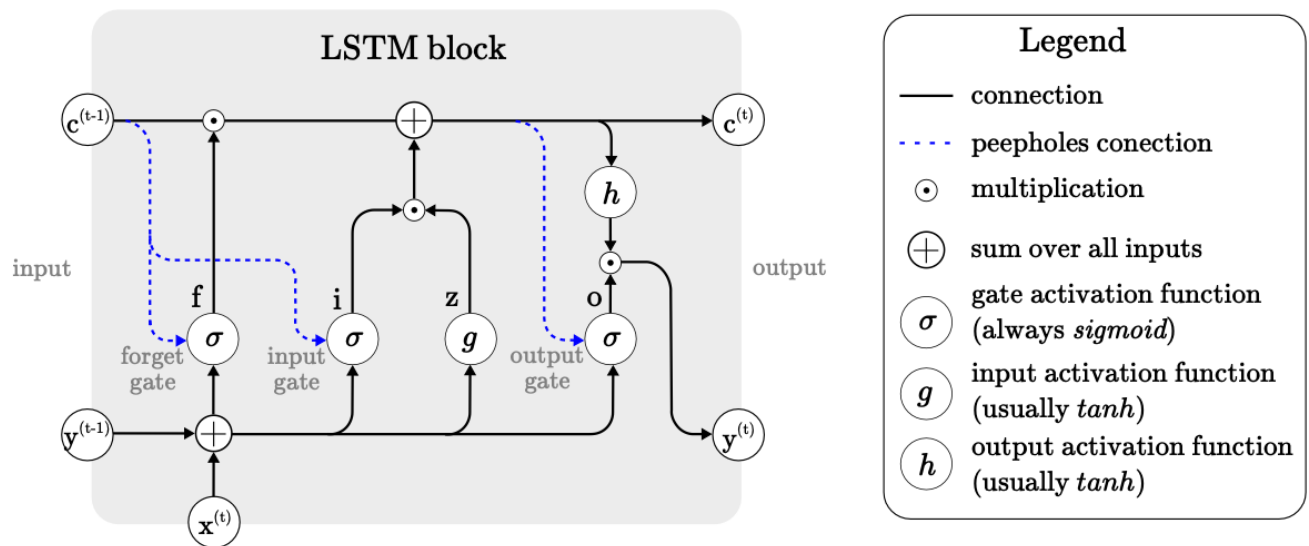


Figure 3.7 : Architecture of a LSTM bloc (adopted from Van Houdt et al. (2020))

To achieve this, the forget gate activations $f^{(t)}$ are computed based on the current input $x^{(t)}$, the previous hidden state $y^{(t-1)}$ the prior cell state $c^{(t-1)}$, the peephole connections, and the bias term b_f associated with the forget gate. This can be done as follow:

$$f^{(t)} = \sigma(W_f x^{(t)} + R_f y^{(t-1)} + p_f \odot c^{(t-1)} + b_f) \quad (3.23)$$

where W_f , R_f , and p_f are the weights associated with $x^{(t)}$, $y^{(t-1)}$, and $c^{(t-1)}$ respectively, while b_f represents the bias weight vector.

Cell: In this step, the updated cell state is computed by combining the candidate cell input $z^{(t)}$, the Input gate activation $i^{(t)}$, and the forget gate activation $f^{(t)}$, along with the previous cell state $c^{(t-1)}$. This can be done as depicted below:

$$c^{(t)} = z^{(t)} \odot i^{(t)} + c^{(t-1)} \odot f^{(t)} \quad (3.24)$$

Output gate: This step computes the output gate, which combines the current input $x^{(t)}$, the previous output $y^{(t-1)}$ of that LSTM and the previous cell state $c^{(t-1)}$ in the iteration. This is expressed by the following equation:

$$o^{(t)} = \sigma(W_o x^{(t)} + R_o y^{(t-1)} + p_o \odot c^{(t)} + b_o) \quad (3.25)$$

where W_o , R_o , and p_o are the weights associated with $x^{(t)}$, $y^{(t-1)}$, and $c^{(t-1)}$ respectively, while b_o represents the bias weight vector.

Block output: Finally, we compute the block output which combines, the current cell value $c^{(t)}$ with the current output gate as follow:

$$y^{(t)} = g(c^{(t)}) \odot o^{(t)} \quad (3.26)$$

In the steps described above, σ , g , and h denote point-wise non-linear activation functions. The logistic sigmoid $\sigma(x) = \frac{1}{1+e^{1-x}}$ is used as a gate activation function, while the hyperbolic tangent $g(x) = h(x) = \tanh(x)$ is often used as block input and output activation function.

These steps were adapted from Houdt *et al.* (2020).

3.3.3.3 Training and Evaluation

Before training the LSTM model, all input time series were standardized to ensure zero mean and unit variance, which helps stabilize and accelerate the learning process. The dataset was then divided into training and testing subsets, typically using a chronological split to preserve the temporal dependencies inherent in the climate data. To account for lagged effects of climate drivers on dust storm activity, appropriate lag features were engineered and included as additional inputs. The LSTM model was trained to predict dust storm frequency using sequences of meteorological variables and climate indices as input features. A sliding window approach was used to generate input-output pairs, where each input sequence spans a fixed time window (e.g., 12 months) and the target corresponds to the subsequent dust storm frequency. The model was optimized using the Adam optimizer, with mean squared error (MSE) as the loss function. Training performance was monitored via validation loss, and early stopping was employed to prevent overfitting. Model performance was evaluated on the test set using standard metrics such as Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2), providing a robust assessment of the model's predictive skill in capturing complex and delayed relationships between climate signals and dust activity.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Validation of Visibility Data

To evaluate the reliability of visibility data, we compute the dust extinction derived from visibility records. We compared them against AERONET Aerosol Optical Depth (AOD) observations at 1020 nm, a wavelength sensitive to coarse-mode particles such as mineral dust. Figure 4.1 presents the scatterplot of the monthly mean dust extinction and AOD values across selected AERONET stations (Banizoumbou, Ouarzazate, Tamanrasset and Ilorin). Niamey MIDAS station [station ID = 61090] was compared against the AERONET closest station (Banizoumbou). As outlined in the methodology section, both datasets were initially aggregated to 3-hourly resolution and subsequently averaged into monthly means for correlation. The regression lines shown are based on ordinary least squares fitting, while the coefficients of determination (R^2) are computed from the Pearson correlation applied to pre-whitened data to account for potential serial autocorrelation. The validation results show high correspondence at the Saharan stations (Figure 4.1.a, 4.1.b) of Ouarzazate ($R^2 = 0.85$) and Tamanrasset ($R^2 = 0.74$), indicating strong agreement between the visibility-derived metric and ground-based AOD in regions dominated by mineral dust. At the Sahelian sites (Figure 4.1.c) of Banizoumbou and Niamey and the southern site of Ilorin (Figure 4.1.d), the correlations are weaker ($R^2 = 0.45$ and $R^2 = 0.26$, respectively), likely due to increased atmospheric moisture, vegetation influence, or the presence of mixed aerosols types (e.g., biomass burning (Menut *et al.*, 2018), urban pollution) which can reduce visibility but are not purely associated with mineral dust. All correlations are statistically significant ($p\text{-value} < 0.001$), supporting the robustness of the visibility-derived dust extinction, particularly in arid environments. These results are consistent with prior validation efforts of visibility-based dust

proxies in data-sparse regions (e.g. Evan & Mukhopadhyay, (2010); Camino *et al.*, (2015)), justifying their use in the subsequent climatological analysis of dust storm activity over North Africa.

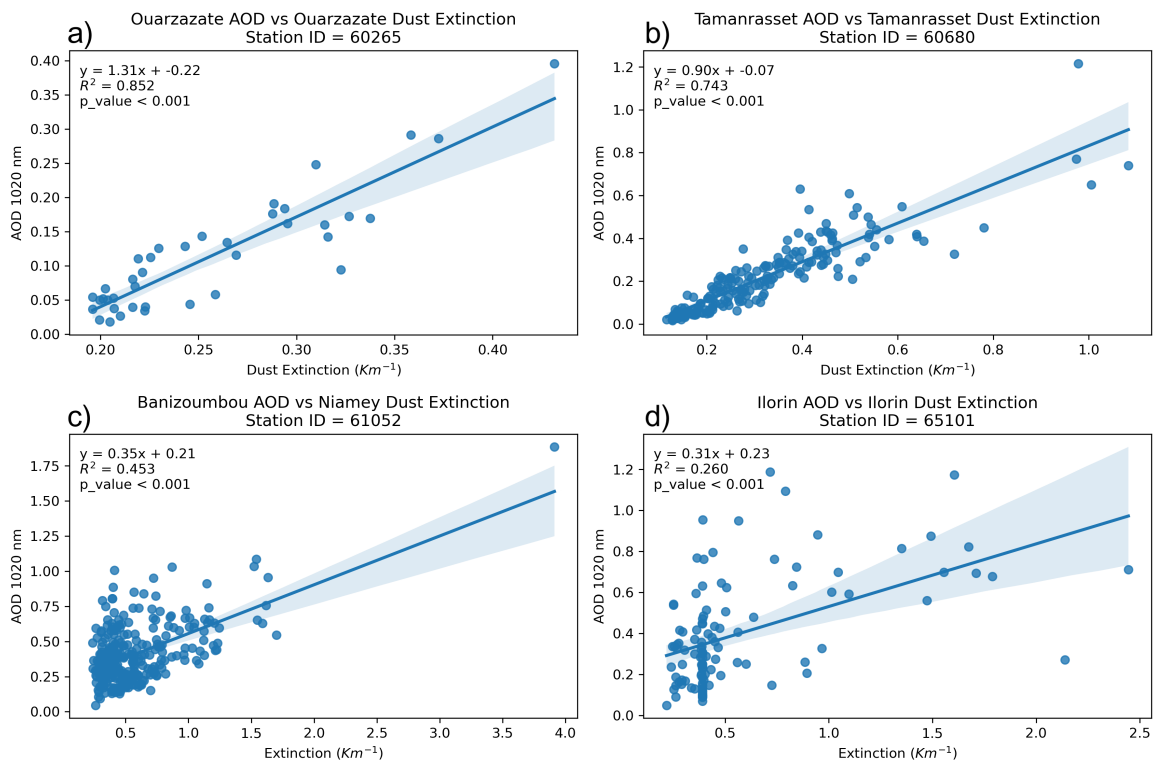


Figure 4.1: Dust extinction derived from visibility against AERONET 1020nm AOD for Banizoumbou, Niger; Tamanrasset, Algeria; Ouarzazate, Morocco and Ilorin, Nigeria.

4.2 Climatology of Dust Storm Occurrences

The analysis of dust storm frequency as presented in Figure 4.2 across North Africa reveals distinct spatiotemporal patterns that align closely with known atmospheric and surface drivers. The data show peak dust storms activity occurring in boreal spring (March-May), particularly across the western and central Sahel, where stations report overall frequencies exceeding 10%. This seasonal maximum correlates strongly with: the southernmost position of the Inter-Tropical Discontinuity (ITD), which enhances dry northeasterly Harmattan winds; pre-monsoon soil desiccation in key source regions such as the Bodélé Depression; and frequent cold pool outflows from mesoscale convective systems (Flamant et al., 2009; Knippertz & Todd, 2012).

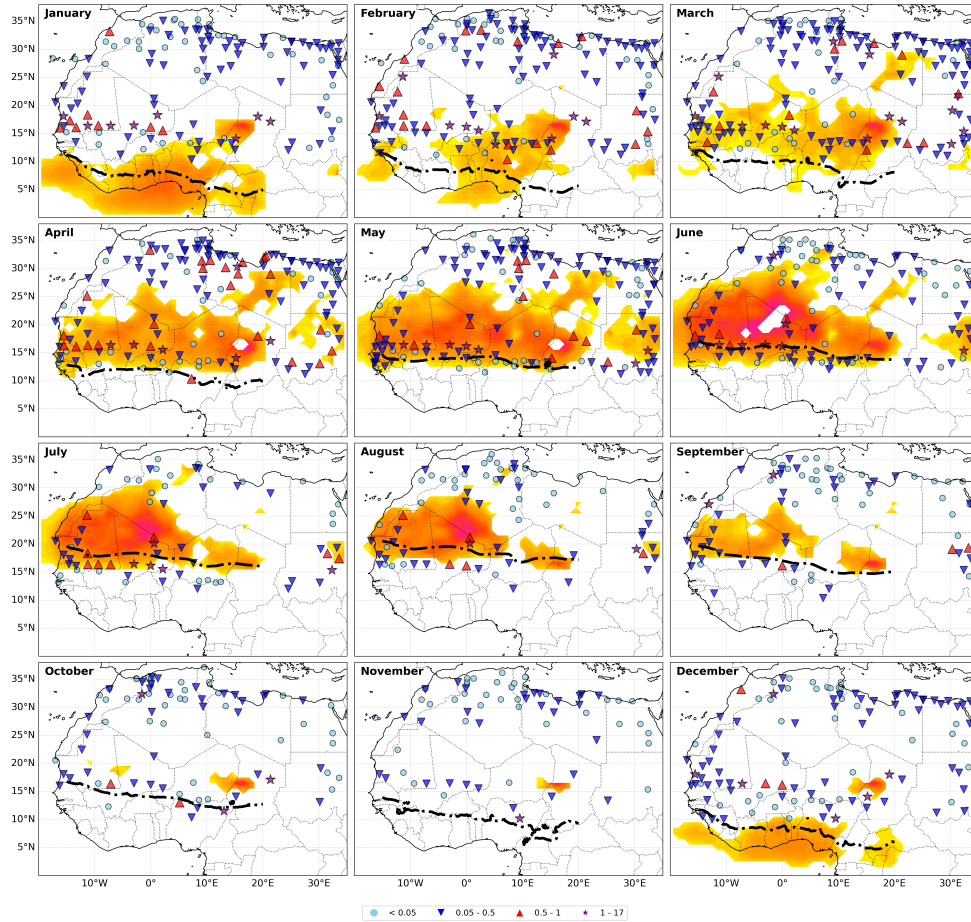


Figure 4.2: Relative frequency of dust storms over the period 1984-2023 from individual months.

The ITD mean position (black dashed lines) is derived according to Lafore et al., (2017). Yellow and orange areas indicate regions of monthly composite average OMI AI from 2005-2023 exceeding 1.8 and 3.5.

Satellite observations confirm these patterns, with OMI Aerosol Index (yellow and orange, Figure 4.2) values > 3.5 consistently co-located with areas of highest surface-reported dust storm frequency in pre-monsoon (spring) and monsoon (summer) seasons over Sahel. However, regions with high aerosol index values as seen in dry season (December-February) do not always indicate local dust sources, as the aerosol index primarily reflects transported dust rather than emission (e.g., Torres *et al.* (2007); Shao *et al.* (2010)) .

As the season progresses into summer (June-July), we observe a northward migration of dust activity captured by the satellite. This progress aligned with the ITD's latitudinal displacement, with intensified emissions in the central Sahara in early summer possibly due to the strengthening the SHL and associated wind patterns (Karam *et al.*, 2008). Notably, a spatial decoupling emerges between surface observations and column-integrated satellite measurements during this period, suggesting increased contributions from elevated dust layers transported via nocturnal low-level jets (Schepanski et al., 2009; Fiedler *et al.*, 2013). The late summer decline in Sahelian dust storms activity coincides with monsoon advancement and boundary layer stabilization, though residual hotspots persist in topographically favored regions where local wind systems dominate (Cuesta *et al.*, 2009).

This robust agreement between surface-based climatology, satellite aerosol measurements, and atmospheric dynamics not only validates the visibility-derived dust estimates but also highlights the primary controls on regional dust variability: seasonal positioning of the ITD and associated wind regimes, surface conditions modulated by the monsoon cycle, and mesoscale meteorological processes that can override large-scale patterns. The consistency of these relationships across multiple decades suggests their fundamental role in shaping North Africa's dust emission climatology.

4.2.1 Dust Mass Column Density and Dust Mass Fluxes: Monthly climatology

This approach provides complementary information to the OMI-derived aerosol index data, enabling a more complete characterization of dust emission climatology over North Africa.

Figure 4.3 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 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 (Marshall *et al.*, 2013), who emphasized the pre-monsoonal SHL strengthening as a key driver of widespread dust mobilization.

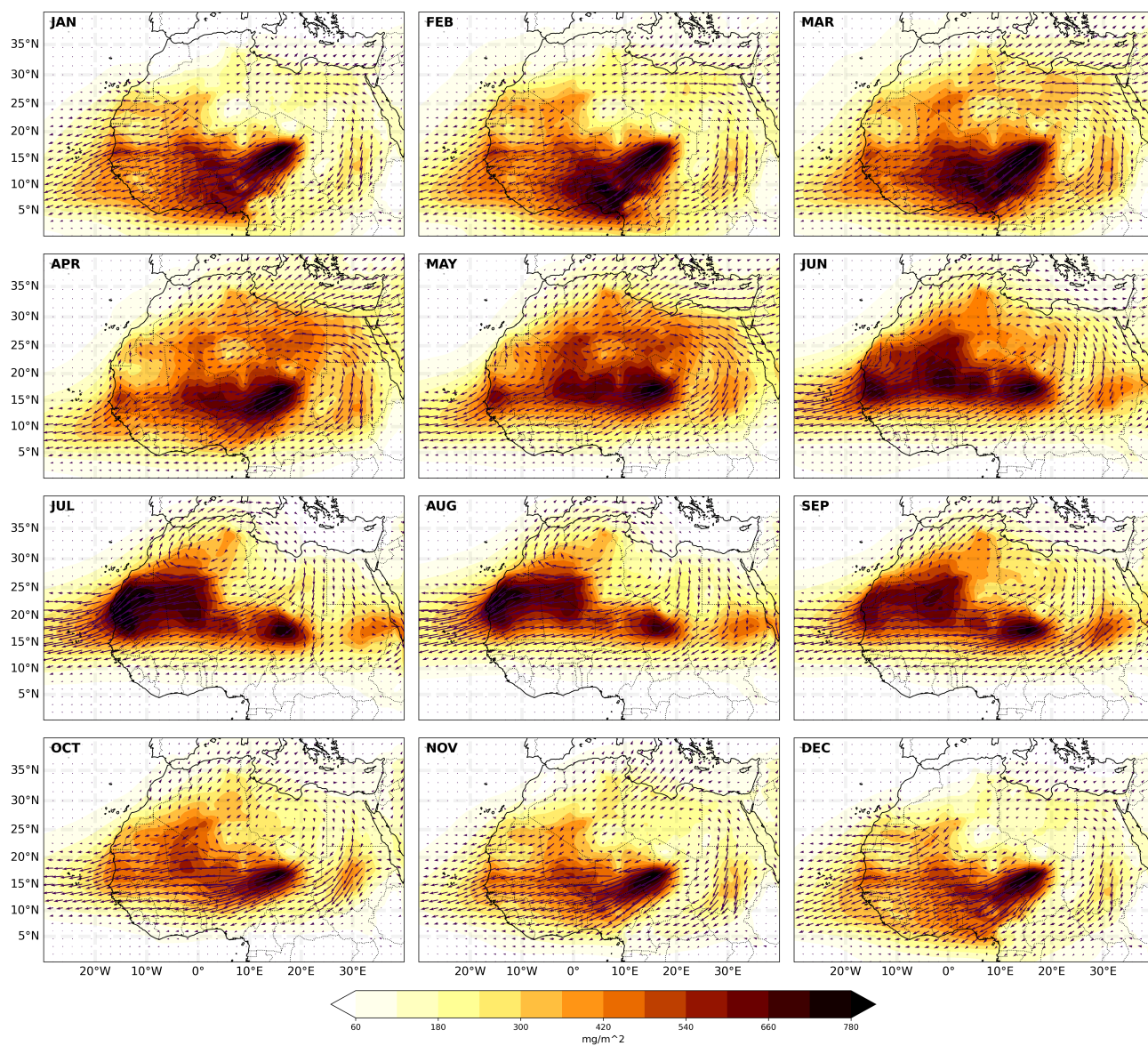


Figure 4.3: Climatology of dust mass density. The arrows represent dust mass fluxes.

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 WAM. 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 shifts 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 NA. This seasonal cycle aligns well with the dust storms frequency and OMI-derived dust aerosol index climatology, showing similar patterns in DJF, MAM and JJA seasons. 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).

4.2.2 Sahara and Sahel Dust Storm Trends

Following the selection criterion for dust storm events described in the methodology section, 8,114 dust storm records for the Sahara and 4,172 for the Sahel were validated over the study period. The time series of dust storm events in these regions are shown on Figure 4.4 and 4.5 respectively, spanning the period 1984-2023. The 5-year (blue dashed line) and 10-year (red dashed line) running means were plotted to illustrate shorter-term and long-term variability in dust storm frequency.

The data have been pre-whitened to remove the effects of serial correlation prior to trend analysis. Both panels (Figure 4.4 and 4.5) reveal a clear long-term decline in dust storm activity, supported by non-parametric trend tests. Over the Sahara (Figure 4.4), the Mann-Kendall (MK, here and after) test yields a negative tau coefficient ($\tau = -0.008$, $p = 0.006$), indicating a statistically significant decreasing trend. The Theil-Sen (TS, here and after) slope estimator further quantifies this trend at -0.110 events per year, that means a decline of 1.1 dust storm per decade. Similarly, for the Sahel (Figure 4.5), the decreasing trend is more pronounced (MK, $\tau = -0.15$ and $p < 0.001$) and a corresponding TS slope of -0.106 events per year, meaning a decline of 1 dust storm per decade like in the Sahara region. These findings align with earlier studies reporting a multi-decadal decline in dust activity across North Africa (e.g., Shao *et al.* (2013)).

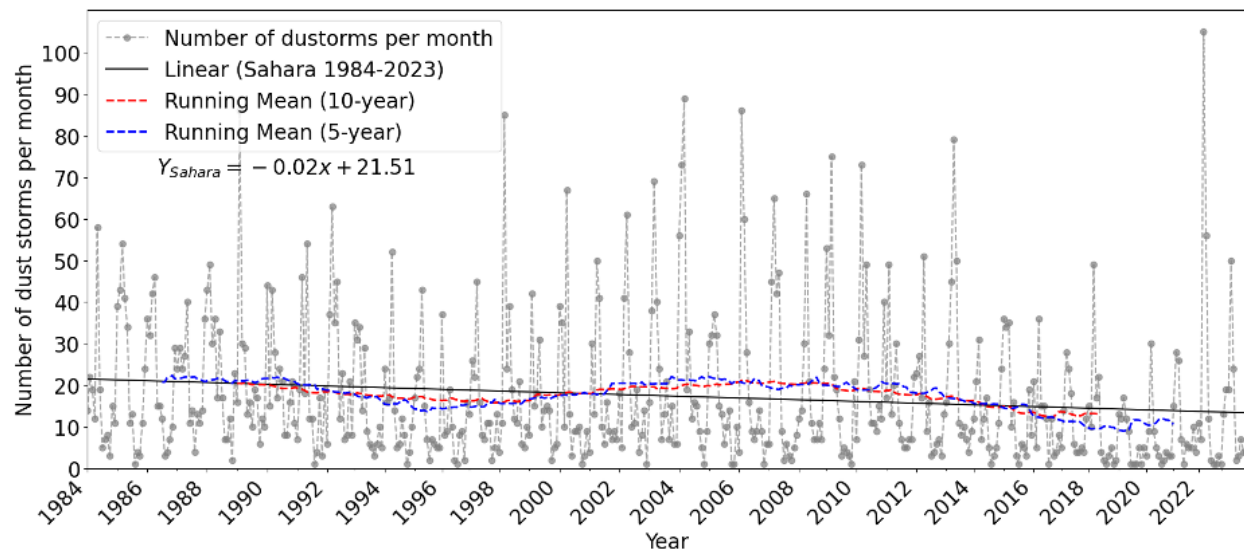


Figure 4.4: Time series of monthly dust storm activity in the Sahara from 1984 to 2023. The linear trend (black line), 5-years moving average (blue dotted line) and 10-years moving average (red dotted line) are also shown.

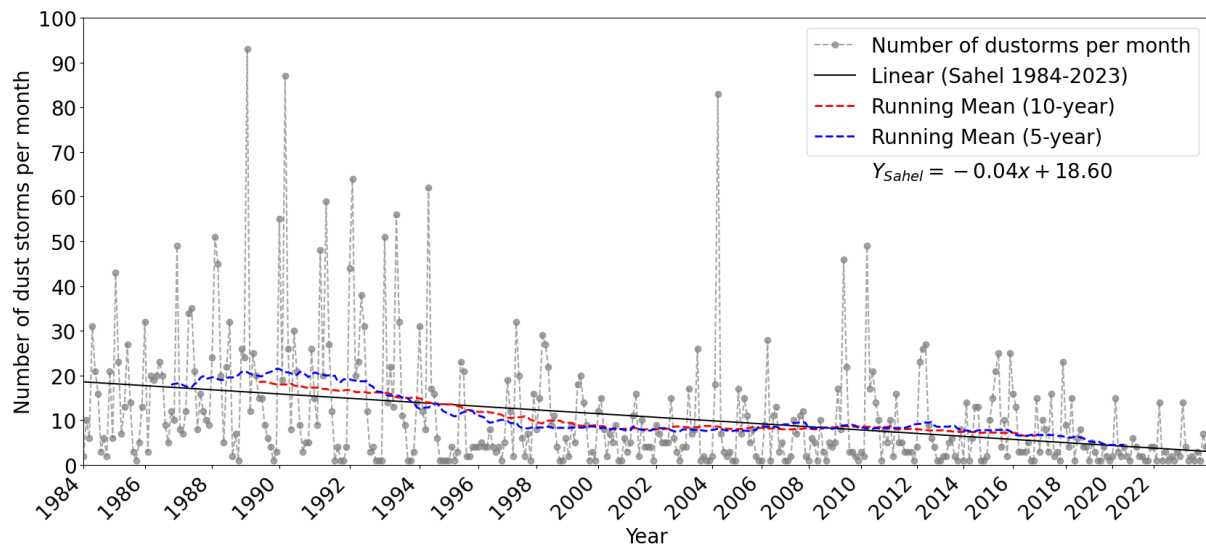


Figure 4.5: Time series of monthly dust storm activity in the Sahel from 1984 to 2023. The linear trend (black line), 5-years moving average (blue dotted line) and 10-years moving average (red dotted line) are also shown.

While these declines are temporally consistent with documented vegetation recovery (Dardel *et al.*, 2014; Fassinou *et al.*, 2024; Herrmann *et al.*, 2005) and declining surface wind speeds in reanalysis datasets, the running means reveal a decadal-scale variability, a consistent pattern with known phases like the Atlantic Multidecadal Oscillation (AMO) that modulate SHL intensity (Evan *et al.*, 2016).

Both regions exhibit periods of elevated dust storm activity in the late 1980s and early 1990s, followed by a gradual decline toward the early 2000s. A secondary peak is observed in the mid-2000s, particularly over the Sahara, after which a sustained downward trend continues through the 2010s. These fluctuations suggest the potential influence of periodic drivers such as regional-scale circulation anomalies, monsoon strength, and surface wind variability on dust storm activity. Notably, the smoother 10-year moving averages underscore the sustained decrease in dust storms over both regions, while the 5-year series captures interannual shifts that may reflect episodic dust-conducive conditions or modulation by large-scale climate modes.

Over the Sahara region, the dust storm events (Y_{Sahara}) has a linear trend with

$$Y_{Sahara} = -0.02x + 21.51 \quad (4.1),$$

and,

$$Y_{Sahel} = -0.04x + 18.60 \quad (4.2),$$

for the Sahel region where x represents the month from the beginning of the study period.

4.2.3 Seasonal Trend of Dust Storms and Climatic Implication

In the Sahel and Sahara regions, dust emission are related to climatic conditions that exhibit strong seasonal progression, with distinct meteorological drivers dominating different periods of the year (Brooks & Legrand, 2000; Bou Karam *et al.*, 2008, 2009). For instance, the Harmattan winds

prevail during boreal winter (DJF), monsoonal flows and its associated Saharan Heat Low characterize summer (JJA), while spring (MAM) and autumn (SON) represent transitional phases with competing atmospheric influences. To better understand the observed decline in dust storm activity across both the Sahel and Sahara, we conducted a comprehensive seasonal trend analysis spanning 1984 to 2023.

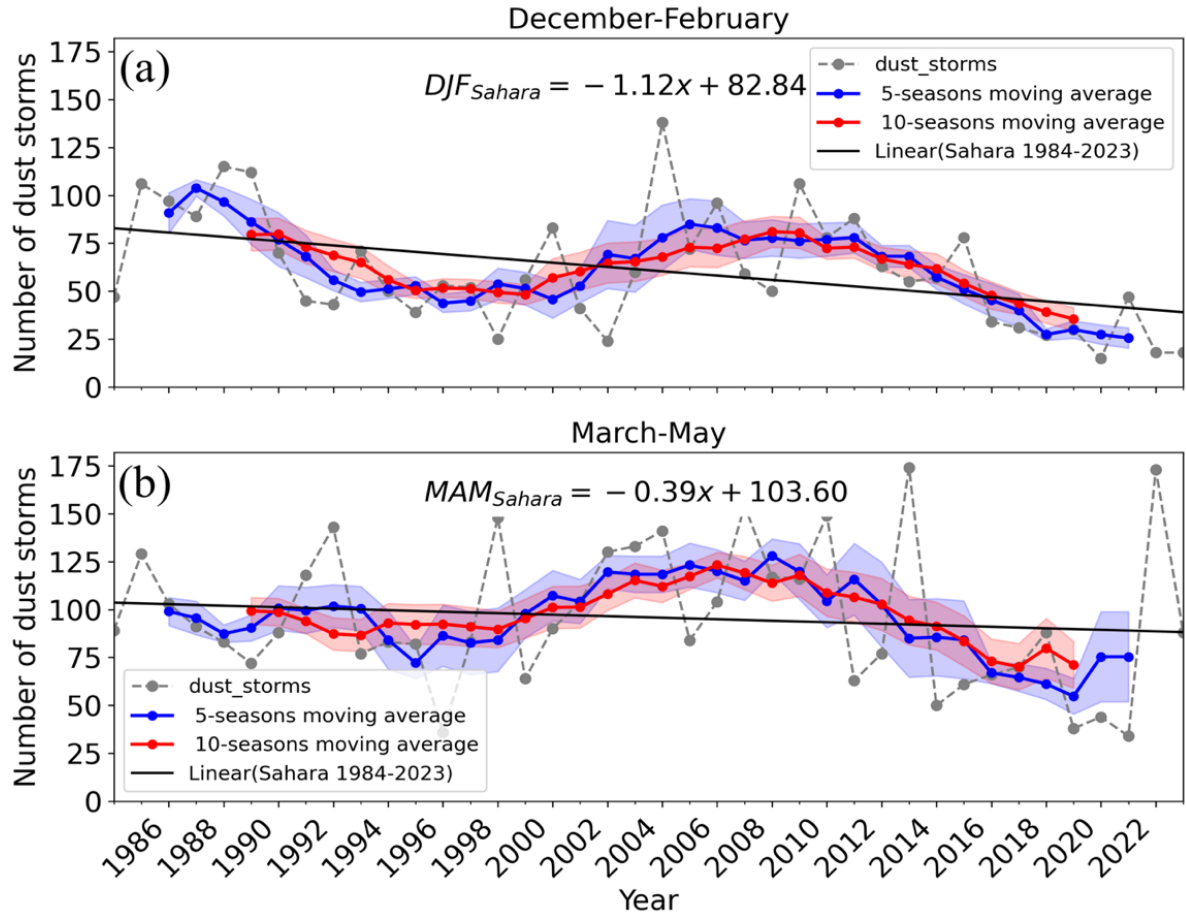


Figure 4.6: seasonal time series of dust storm activity. The 5-season moving average (blue line) and the 10-season moving average (red line) are plotted for DJF season (a) and MAM season (b) for Sahara region.

The analysis reveal significant long-term decline in dust storm activity across North Africa, with distinct seasonal and regional patterns (Table 4.1, Figure 4.6 - 4.9). The TS estimator and MK test demonstrated that:

- A Sahara-dominated winter declines in dust storm occurrences: DJF season shows a significant decline of -0.19 storms/year ($\tau = -0.24$, $p = 0.03$; Figure 4.a) and SON season - 0.19 storms/year ($\tau = -0.29$, $p < 0.01$; Figure 4.5) meaning a decadal decline of almost 2 dust storms in Sahara region. These reductions align with observed weakening of the Harmattan winds (Fontaine *et al.*, 2013; Hersbach *et al.*, 2020) and contraction of the Saharan High (Shekhar & Boos, 2017). The 5 and 10-year moving average exhibit multi-year variations with a consistent decreasing amplitude and longer periods of oscillation. This pattern suggests that dust storms have become less frequent in winter with the longer oscillation periods reflecting the more stable and prolonged influence of winter climatic factors.

The MAM and JJA seasons (Figure 4.6.b, 4.7.a) showed a non-significant decline, suggestion that dust storms activities over Sahara during these seasons are influenced by many concurrent factors. Therefore, the similarity with the DJF and JJA patterns remain with short periods of shifting in comparison with the previous seasons.

- A Sahel spring (MAM) and summertime (JJA) pronounced reduction in dust storm occurrences: MAM season (Figure 7.b) reveals the sharpest decline with -1.07 storms/year ($\tau = -0.27$, $p = 0.01$; Fig. 7.b) and expands to the JJA season (Figure 8.b) with a slight decline of -0.38 storms/year ($\tau = -0.25$, $p < 0.05$; Fig. 8.a). The MAM decline is the most important compared to all seasons in both regions. The Sahel trends coincide with both vegetation recovery (Dardel *et al.*, 2014) and declining frequency of convective downdrafts

from mesoscale systems (Marsham *et al.*, 2013). The 5 and 10-year moving averages show a modulated variability as in Sahara region suggesting that the both regions are under the similar climatic controls.

Conversely, the non-significant decline of dust storms activity during DJF and SON seasons (Figure 7.a and 8.b respectively) with similar patterns to other seasons, suggests that dust storm activity is controlled by similar factors as in other seasons.

Table 4.1. Seasonal Man-Kendall test and Theil Sens (TS) slope for the Sahara and Sahel regions.

	Sahara				Sahel			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
τ	-0.24	-0.11	-0.18	-0.29	-0.12	-0.27	-0.25	-0.10
TS	-0.19*	-0.23	-0.21	-0.19*	-0.34	-1.07*	-0.38*	-0.06
Trend	D	N	N	D	N	D	D	N

*D for decreasing trend and N for no trend, * for pvalue <0.005, TS for Theil-Sens slope*

Overall, the non-significant trends in a region whereas trends are significant in the other region at the same seasons, may indicate that the factors under dust storms variability are subject to seasons variability and are stronger in some regions at a given season than in the other region.

It can be hypothesized that the meteorological drivers through climate drivers are key factors of the dust storms occurrence in Sahara and Sahel regions. Summertime dust storm frequency in Sahara shows weaker decline (-0.23 storms/year) compared to Sahel (-0.38 storms/year), reflecting competing influences between monsoon rainfall (dust suppression) and Saharan Heat Low intensification (dust enhancement; Lavaysse *et al.* (2009)).

These seasonally divergent trends, particularly the sharp decline in MAM season for Sahel and DJF season for Sahara motivate a focused investigation of the underlying meteorological and large-scale controls.

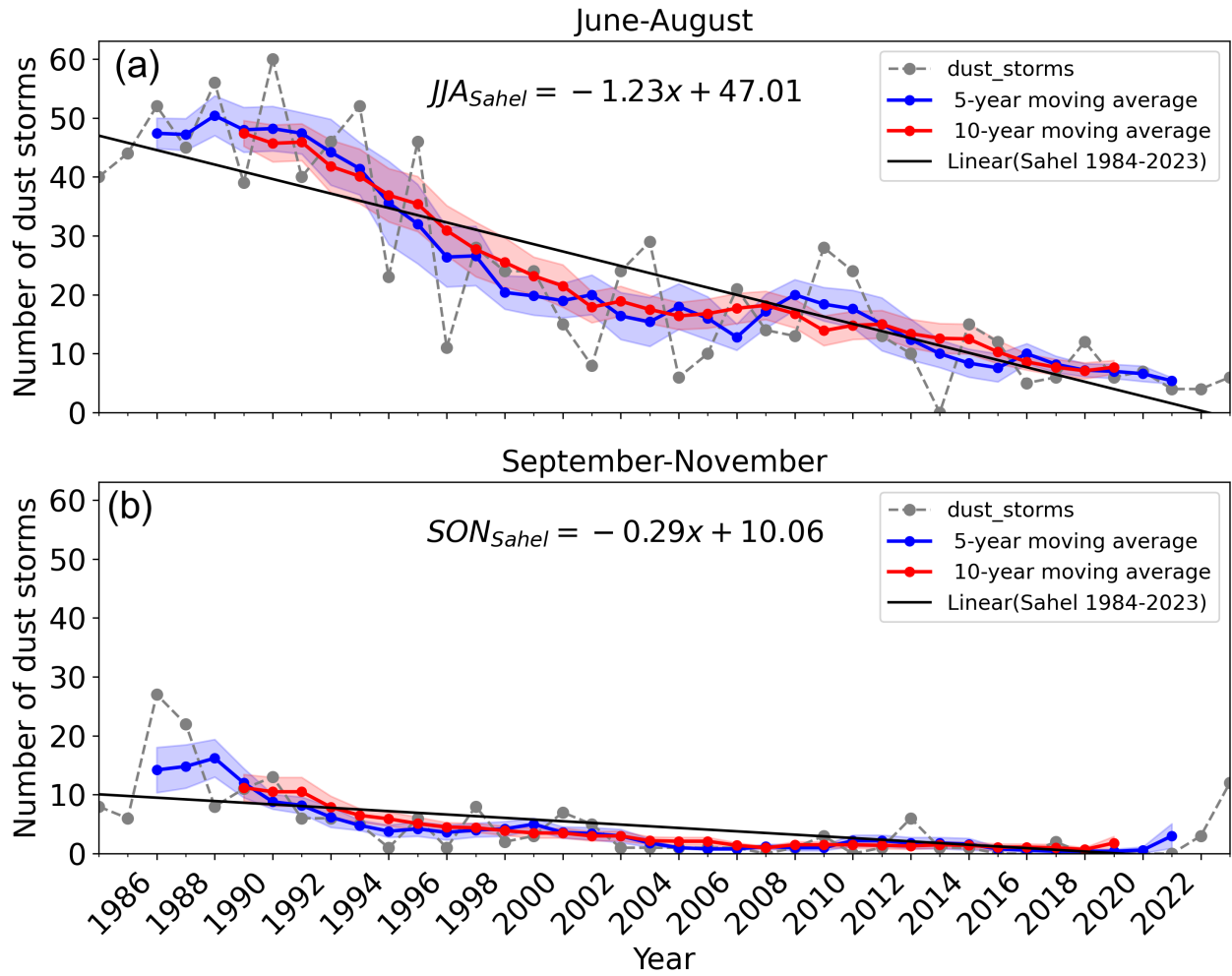


Figure 4.7: seasonal time series of dust storm activity. The 5-season moving average (blue line) and the 10-season moving average (red line) are plotted for JJA season (a) and SON season (b) for Sahara region.

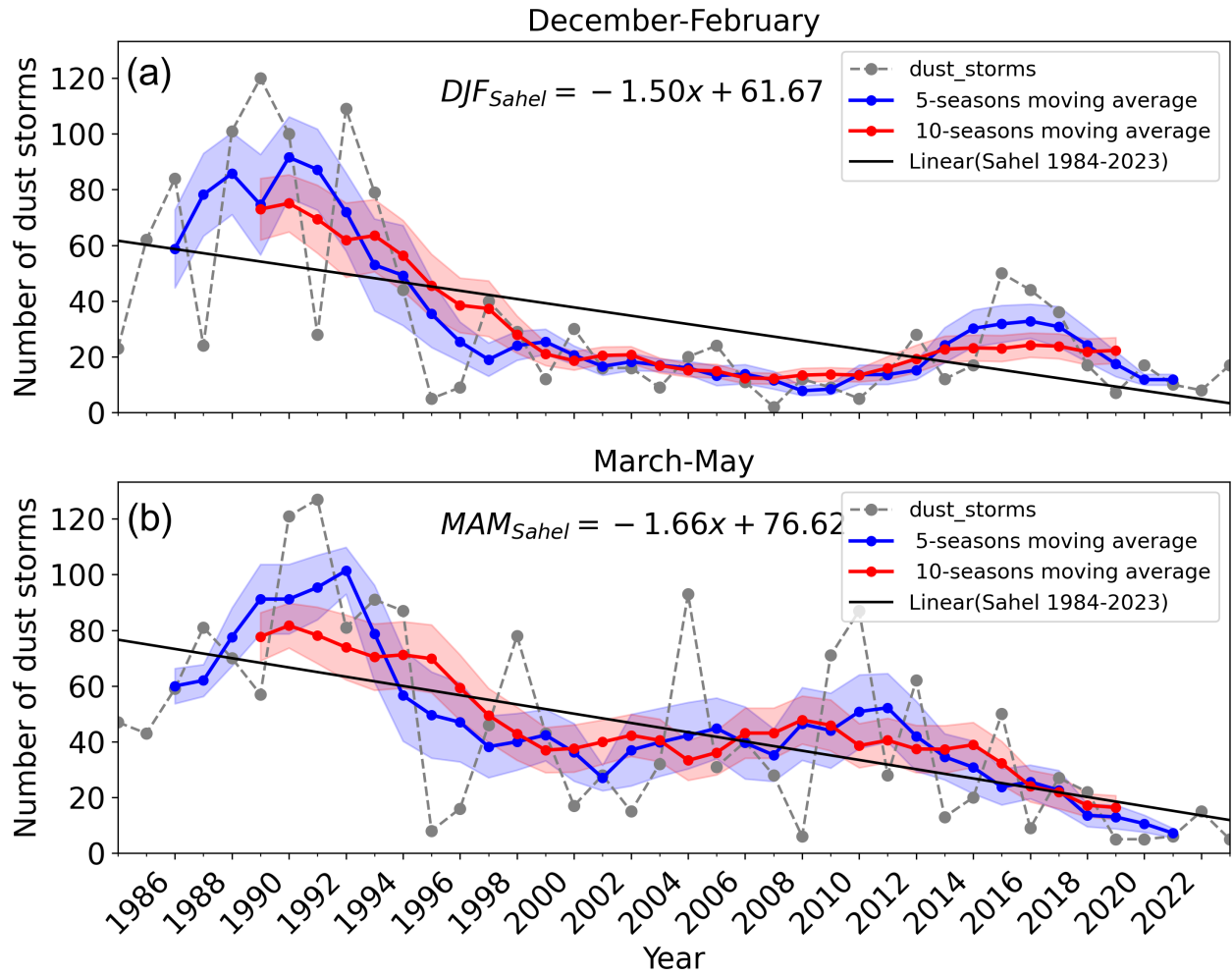


Figure 4.8: seasonal time series of dust storm activity. The 5-season moving average (blue line) and the 10-season moving average (red line) are plotted for DJF season (a) and MAM season (b) for Sahel region.

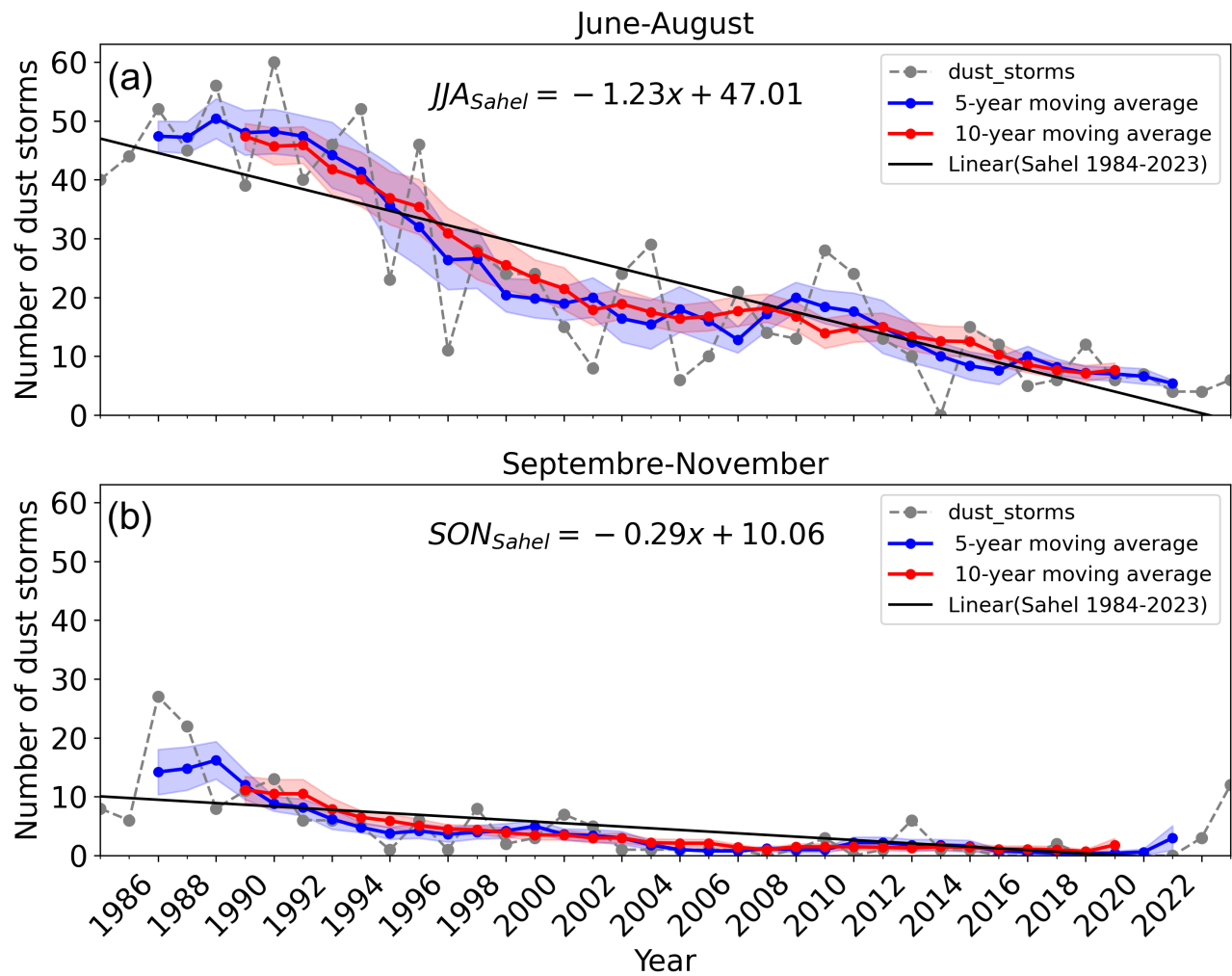


Figure 4.9: seasonal time series of dust storm activity. The 5-season moving average (blue line) and the 10-season moving average (red line) are plotted for JJA season (a) and SON season (b) for Sahel region.

4.2.4 Correlation between Drivers and Dust Storms

The results in section 4.2.3 reveal significant decrease in dust storms occurrence during MAM/JJA and SON/DJF in the Sahel and the Sahara regions respectively. This section assesses whether the trends align with shifts in meteorological and climate drivers.

To disentangle the role of local environmental conditions and climate drivers in dust storm variability, we first examine the relationship between dust storm frequency and key meteorological variables and secondly the climate drivers as cited in the methodology section. By quantifying these correlations, we aim to identify the most relevant atmospheric precursors of dust storm activity across different regions and seasons, providing insight into the physical mechanisms behind dust mobilization.

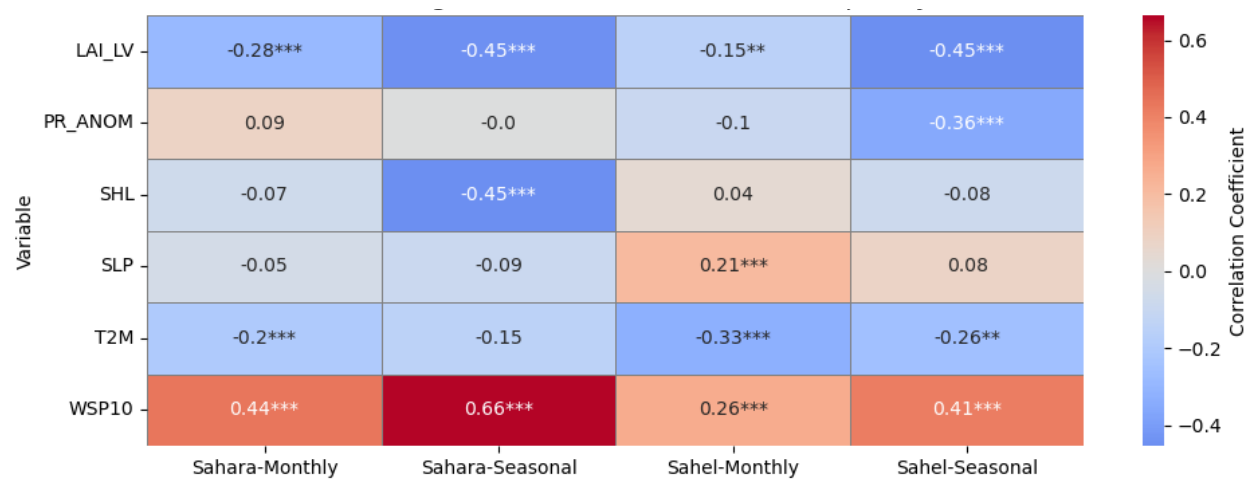


Figure 4.10: Correlations between dust storms frequency and meteorological drivers for Sahel region. *, ** and *** beside the correlation values indicated the 0.05, 0.01 and 0.001 significance levels respectively.

The meteorological variables data have undergone pre-whitened analysis to prevent autocorrelation. We compute the correlations between dust storms frequency and meteorological drivers, and between dust storms frequency and climate drivers relevant for the climate variability of North Africa. The results presented in Figure 4.10 and Figure 4.11 offer clear evidence of the dominant roles played by both regional meteorological conditions and large-scale climate modes in shaping dust storm frequencies across the Sahara and Sahel. Among the meteorological variables (Figure 4.10), 10 m Wind speed (WSP10) emerges as the most strongly and consistently correlated factor, particularly over the Sahara where seasonal correlations reach 0.66 ($p < 0.001$). This finding reaffirms the fundamental role of surface winds in initiating dust emission, as dust entrainment is highly sensitive to near-surface wind thresholds in arid regions (Bergametti *et al.*, 2007; Shao *et al.*, 2010; Knippertz, 2014). Conversely, the Leaf Area Index (LAI) low vegetation displays significant negative correlations with dust frequency, particularly in the Sahel (seasonal $r = -0.45$, $p < 0.001$). This supports the "greening Sahel" hypothesis, where increased vegetation stabilizes soils and suppresses dust emissions (Dardel *et al.*, 2014) and reflects the dual impact of soil moisture and vegetation cover in modulating dust availability (Evan *et al.*, 2016). Precipitation anomalies (PR_ANOM), however, exhibit weaker and more regionally variable relationships. While the Sahel shows a moderate negative correlation at seasonal scales ($r = -0.36$, $p < 0.001$), reflecting the lagged impact of rainfall on soil moisture and vegetation (Cowie *et al.*, 2013), the Sahara displays no significant link, underscoring the dominance of wind-driven processes in hyper-arid regions (Evan *et al.*, 2016). The Saharan Heat Low (SHL) correlates strongly with dust storms frequency in the Sahara at seasonal scales ($r = -0.45$, $p < 0.001$), suggesting its role in modulating atmospheric stability and wind patterns (Lavaysse *et al.*, 2009) that contributes to suppress dust emission conditions. Like the SHL, surface temperature (T2M) shows negative

correlations (e.g., Sahel monthly $r = -0.33$, $p < 0.001$), which may reflect dust's radiative cooling effects or covariation with other drivers. To account for land surface feedbacks, precipitation anomalies and LAI_LV were lagged by 6 and 12 months, respectively, which improved their correlations. The sea level pressure shows a significant monthly positive weak correlation with Sahel dust storms frequency suggesting the role of sea level pressure in dust storms occurrence over this region.



Figure 4.11: Correlations between dust storms frequency and climate drivers for Sahara region. *, ** and *** beside the correlation values indicated the 0.05, 0.01 and 0.001 significance levels respectively.

At large-scale, the AMO stands out as the most influential large-scale mode (Figure 4.11), with particularly yearly timescale strong negative correlations in the Sahel ($r = -0.70$, $p < 0.001$). This supports the AMO's recognized role in modulating Sahel rainfall via Atlantic SST gradients, which indirectly suppress dust activity through enhanced vegetation (Zhang & Delworth, 2006; Martin & Thorncroft, 2014). The result is also consistent with the finding of Shao *et al.* (2013) and Evan and Mukhopadhyay, (2010). They found evidence linking AMO warm phases to increased Sahel rainfall and reduced dust availability. Shao *et al.* (2013) used dust concentration derived from observations visibility and found a significant negative correlation between dust and AMO. Although the NAO and MEI indices exhibit moderate positive non-significant correlations both in the Sahel and the Sahara at seasonal and yearly time scale. Their impacts are more temporally and spatially constrained, reflecting their intermittent modulation of subtropical atmospheric circulation and the West African monsoon (Nicholson & Kim, 1997; Prospero & Lamb, 2003). Other indices, including the AO, SOI, and NOI, show limited standalone influence, suggesting that their impact may emerge only under specific synoptic regimes.

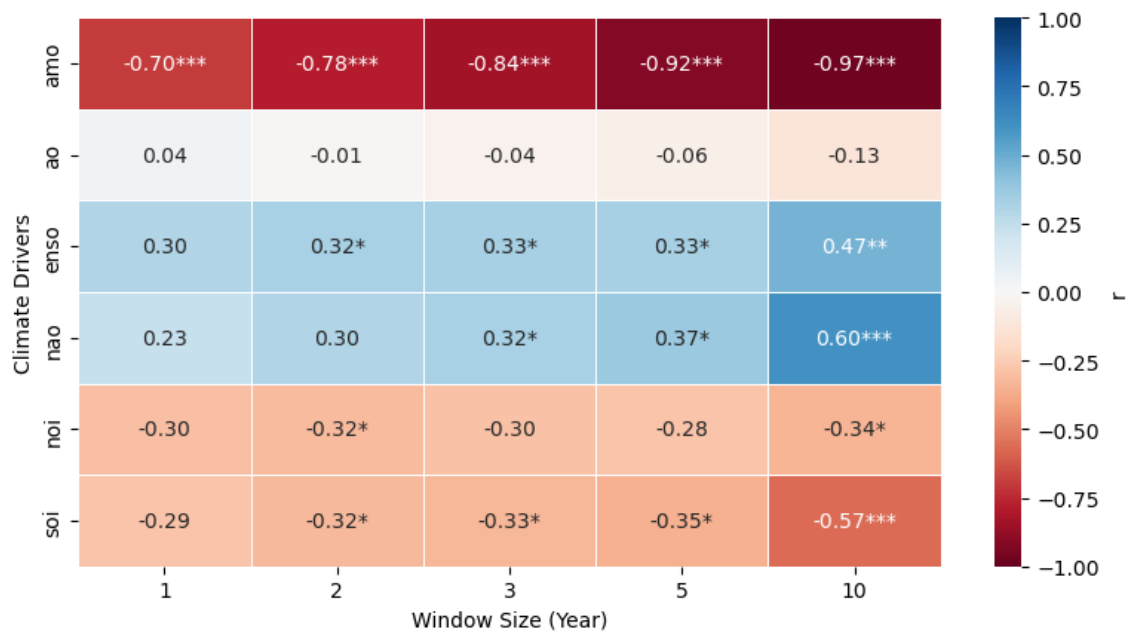


Figure 4. 12: Yearly moving average correlations between dust storms frequency and climate drivers for Sahel. *, ** and *** beside the correlation values indicated the 0.05, 0.01 and 0.001 significance levels respectively.

Moreover, yearly moving average were computed correlations to understand the short- and long-term relationship between the climate drivers and dust storms frequency. The analysis reveals distinct dust-climate coupling mechanisms between the Sahel and Sahara, supported by established climate dynamics. In the Sahel, the AMO's strong and significant negative correlation ($r = -0.97$, Figure 4.12) with dust storms at decadal scales aligns with documented AMO-phase impacts on West African monsoon rainfall (Zhang & Delworth, 2006) and subsequent vegetation feedbacks (Evan et al. 2016). This finding confirms the suggestion of Shao *et al.*, (2013) that AMO is a primary driver of dust variability for the decadal-scale. The weaker but significant ENSO and NAO positive correlations (0.47 and 0.60 respectively) are consistent with Prospero & Lamb's, (2003) findings of El Niño-induced Sahelian drying and Moulin *et al.*'s (1997) observations of NAO-modulated Harmattan winds.

These findings reinforce the well-documented climatic vulnerability of the Sahel, which is highly sensitive to changes in rainfall and land surface condition, an assertion echoed by the Intergovernmental Panel on Climate Change (IPCC, 2022), which identifies the Sahel as one of the world's most climate-sensitive and vulnerable regions.

In contrast, Sahara dust system shows different responses to the climate drivers compared to Sahel, consistent with Evan *et al.* (2016) attribution of Saharan dust variability primarily related to local meteorology like the SHL dynamics. The strengthening correlations at large windows in the Sahel (Figure 4.12) reflect the vegetation-mediated "memory effect" described by Cowie *et al.* (2013), where antecedent rainfall deficits propagate through ecosystem responses over multi-year timescales. These regional differences highlight a fundamental dichotomy in North African dust systems: the Sahel operates as a climate-sensitive ecotone where dust trends integrate ocean-atmosphere interactions (Chylek *et al.*, 2014), while the Sahara responds predominantly to

immediate aerodynamic forcing (Kok *et al.*, 2021). While the AMO still plays a significant role (-0.78 at the 10-year window, Figure 4.13), correlations with ENSO, NAO, and AO are generally modest or statistically insignificant. Its dominance across both regions, though with stronger Sahelian expression, reinforces its utility as a predictor in dust projection models, particularly given its well-characterized 70 year periodicity (Goldenberg *et al.*, 2001). This reflects the Sahara's hyper-arid baseline, where dust mobilization is less affected by year-to-year hydrological fluctuations and more influenced by persistent atmospheric circulation patterns and long-term SST anomalies. These results are in agreement with previous work by Ginoux *et al.* (2012), which found limited AO and NAO influence over Saharan dust sources. Thus, while the Sahara responds primarily to multidecadal ocean-atmosphere coupling, the Sahel remains far more sensitive to short- and long-term climate variability, particularly through its influence on vegetation and soil moisture, factors that are projected to become increasingly critical under future climate change scenarios as highlighted by the IPCC (2022).

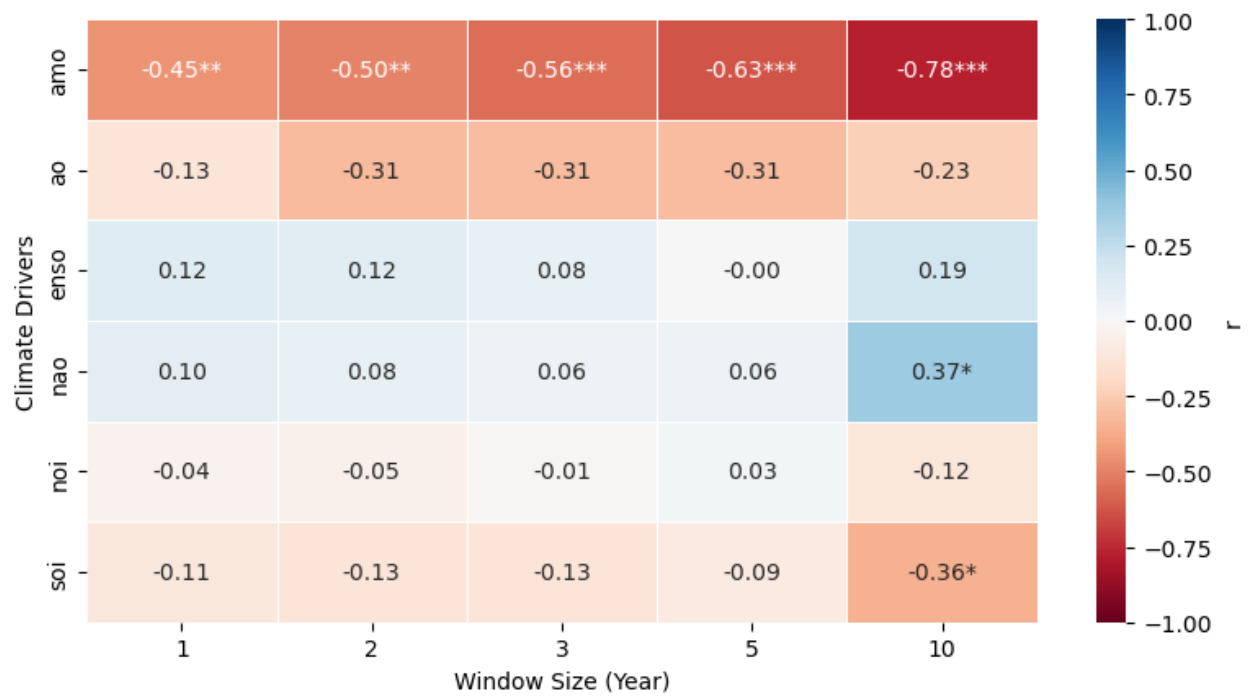


Figure 4.13: Yearly moving average correlations between dust storms frequency and climate drivers for Sahara. *, ** and *** beside the correlation values indicated the 0.05, 0.01 and 0.001 significance levels respectively.

4.2.5 Relative Importance of Drivers

We use Lindeman-Meranda Gold (LMG) and Random Forest (RF) models to assess the relative importance and the rank of meteorological and climate drivers to dust storms variability. The usage of the two models is to compare as the uncertainties in decomposing the mode R^2 (Grömping, 2006; Xi, 2021) which may lead errors in the causal relationship between the drivers and dust storm frequency. The results of the two models are presented in Table 4.2.

The models' results showed a strong agreement in the rank of drivers relatively to their importance to dust storms variability in Sahara and Sahel regions. AMO and Temp_anom (2m Temperature anomalies) are the top ranked drivers by the models highlighting the key influence of AMO on Atlantic region climate and particularly dust storms variability (Knight *et al.*, 2005; Zhang & Delworth, 2006; Chylek *et al.*, 2014). Thus, Saharan Heat Low (SHL) is ranked as the second factor relatively to its suppression role of dust storms activity over Sahara. This finding is consistent with the studies of Schepanski *et al.* (2017) that showed the complex interaction between Harmattan flow, the Saharan Heat Low and the West African Monsoon. Over Sahel, the models showed a negative importance for AMO and ranking it as the top factor influencing the dust variability. This finding is consistent with the role of AMO as primarily factor controlling Sahel rainfall (Littmann, 1991; Martin & Thorncroft, 2014).

Table 4.2: Rank of local and climate drivers relatively to their contribution to dust storms frequency at yearly time scale.

	LMG rank		Random Forests rank	
	Sahel	Sahara	Sahel	Sahara
WSP10	6	4	6	5
SHL	4	2	5	2
SLP	11	8	12	12
Temp_anom	2	1	4	1
Precip	5	12	3	8
LAI_lv	3	7	2	4
NAO	10	10	8	10
AMO	1	3	1	3
MEI	7	9	11	11
NOI	9	5	10	6
SOI	8	11	7	9
AO	12	6	9	7

Table 4.3: Rank of local drivers relatively to their contribution to dust storms frequency at seasonal time scale.

	LMG rank		Random Forest rank	
	Sahel	Sahara	Sahel	Sahara
WSP10	5	3	5	2
SHL	4	2	3	3
SLP	6	4	6	5
Temp_anom	1	1	1	4
Precip	2	6	4	4
LAI_lv	3	5	2	1

The same technique was applied at seasonal scale (Table 4.3). Among local drivers, LMG model ranks temperature, precipitation and leaf area index as the top three relative contributors with temperature ahead in Sahel region, meanwhile Random Forest ranks the temperature as top contributor, but ranks leaf area index and SHL as the other contributors in the top three. These findings highlight the key role of temperature and vegetation cover in controlling dust activity in Sahel region at the regional scale. Therefore, the top rank of leaf area index both by LMG and RF models may suggest a consistent greening of the southern flank of the Sahara like the Sahel greening (Dardel *et al.*, 2014). For the climate drivers (Table 4.4), LMG ranks AMO at the top importance followed by NOI for the Sahel, AO for the Sahara. The models highlight AO as an important contributor of Sahara dust storms activity. Therefore, there is a large divergent on the rank of AO in Sahel and Sahara at the seasonal time scale by the LMG model. While is ranked as the second driver influencing dust storms activity over Sahara, it ranked as the sixth over Sahel. This highlights the seasonal variability of climate drivers' roles in shaping dust storms activity.

Table 4.4: Rank of climate drivers relatively to their contribution to dust storms frequency at seasonal time scale.

	LMG rank		Random Forest rank	
	Sahel	Sahara	Sahel	Sahara
NAO	3	3	6	4
AMO	1	1	1	2
MEI	4	5	4	5
NOI	2	4	2	1
SOI	5	6	5	6
AO	6	2	3	3

Random Forests therefore ranks AMO at the top importance for Sahel region and second for Sahara region. NOI is ranked at the top importance influencing dust storms activity followed by AMO. The importance of NOI as highlighted by both models suggest the influence of Pacific Ocean on dust storms activity. Overall, the ranks of drivers at seasonal and yearly scale relatively to their contributions in dust storms activity align well with the findings of sections.

4.2.6 Spatial Trends of Meteorological Drivers

This section presents the spatial trends of meteorological drivers such as: wind speed, SHL, leaf area index, and precipitation. Their selection is related to their strong correlation with dust storms frequency.

4.2.6.1 Surface Wind Spatial Trends

In Figure 4.14, the spatial distribution of the percentage trends in 10 m wind speed across the Sahel and Sahara regions was presented. 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.

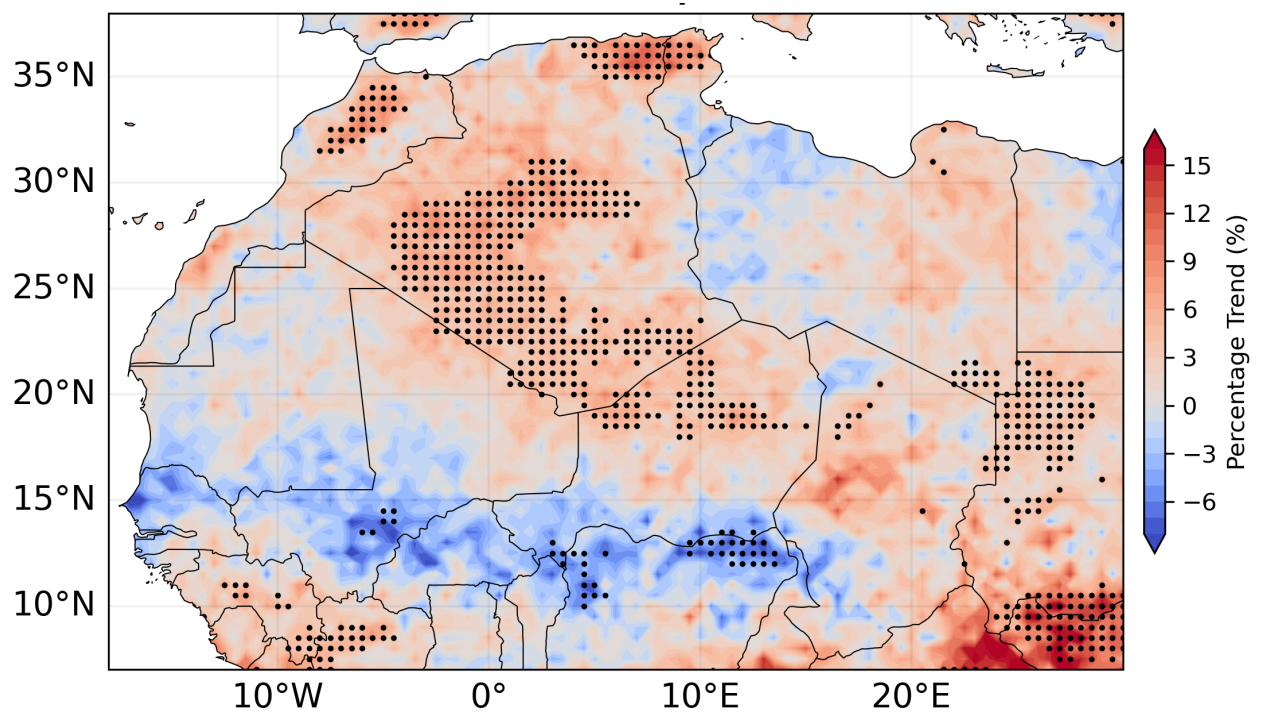


Figure 4.14: Spatial trends of 10 m wind speed. Black dots represent the 95th significance (p-value < 0.05)

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.

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 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 are in agreement 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 storm frequency across the region. 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.

4.2.6.2 Leaf Area Index Trends and Implication for Dust Storms activity

Figure 4.15 displays the spatial distribution of the percentage trends 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.

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 are in agreement 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.

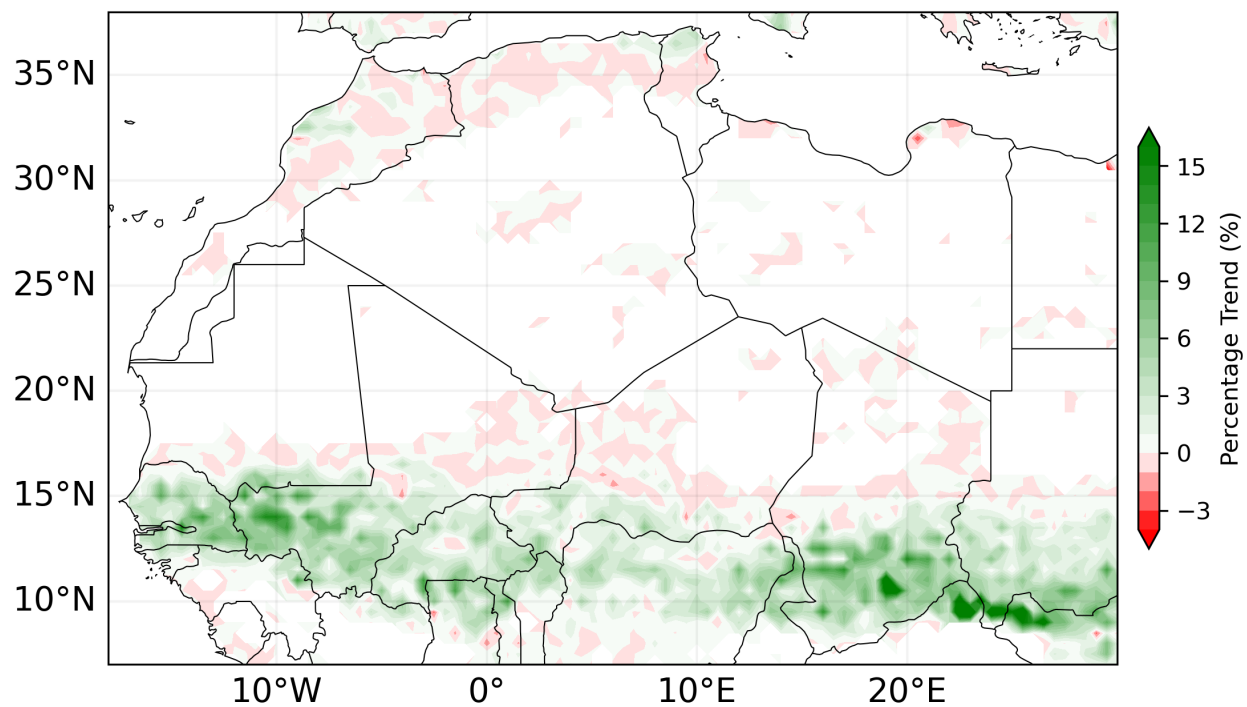


Figure 4.15: Spatial trends of low vegetation leaf area index. Black dots represent the 95th singnificance (p-value < 0.05).

Given the strong negative correlation previously observed between LAI and dust storm frequency over the Sahel, 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).

4.2.6.3 Precipitation Trends and Implication for Dust Storms Activity

The sections 4.2.5.1 and 4.2.5.2 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 dust storms activity over North Africa. The black dots indicate the 95th significance level. Figure 4.16 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.

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 4.15), even though these trends are not statistically significant likely due to interannual variability and short-term greening responses.

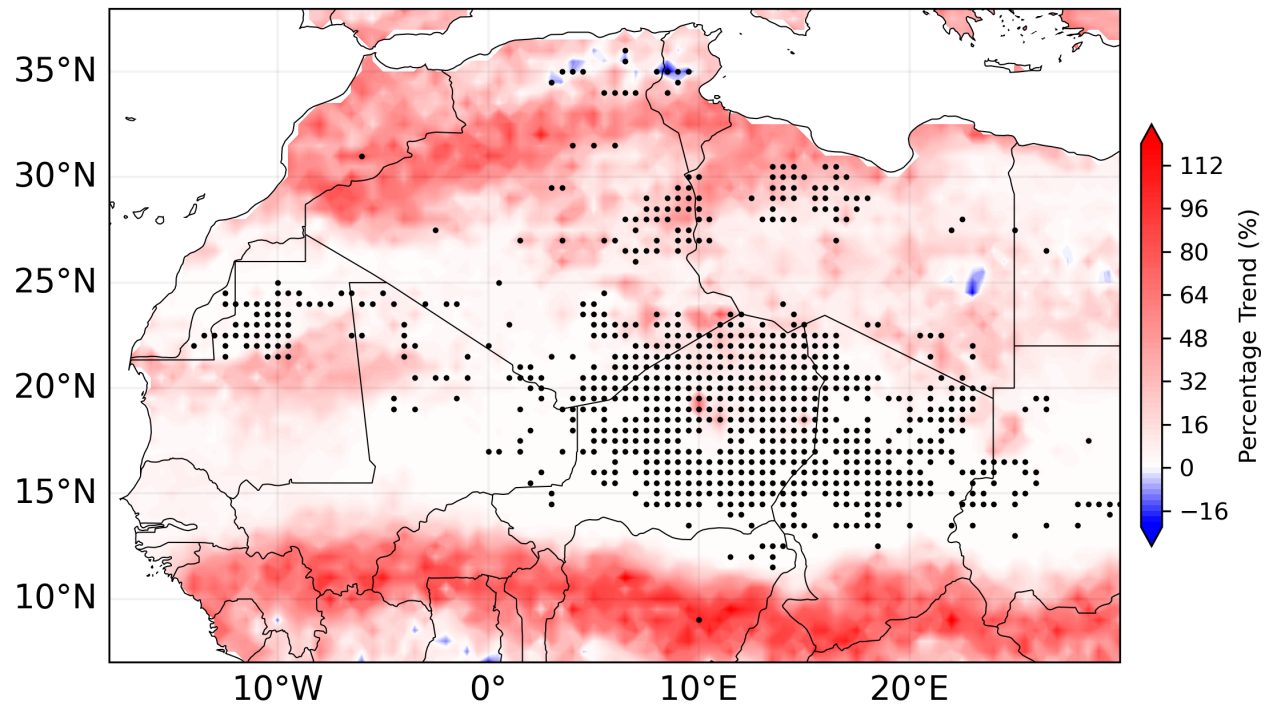


Figure 4.16: Spatial trends of precipitation. Black dots represent the 95th significance (p-value < 0.05).

Furthermore, this rainfall increase is co-located with negative trends in 10 m wind speed (Figure 4.14), 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 was expected given its hyper-arid climatology, where even substantial percentage changes often translate into small absolute differences. Dust trends in the Sahara are likely more influenced by atmospheric circulation features, such as the SHL and LLJs, 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.

4.2.6.4 Saharan Heat Low Intensification and Dust Storms activity

This section explores the role of SHL in shaping dust storms over North Africa.

Figure 4.17 illustrates the percentage trend in SHL, 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 (Figures 4.16 and 4.15 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.

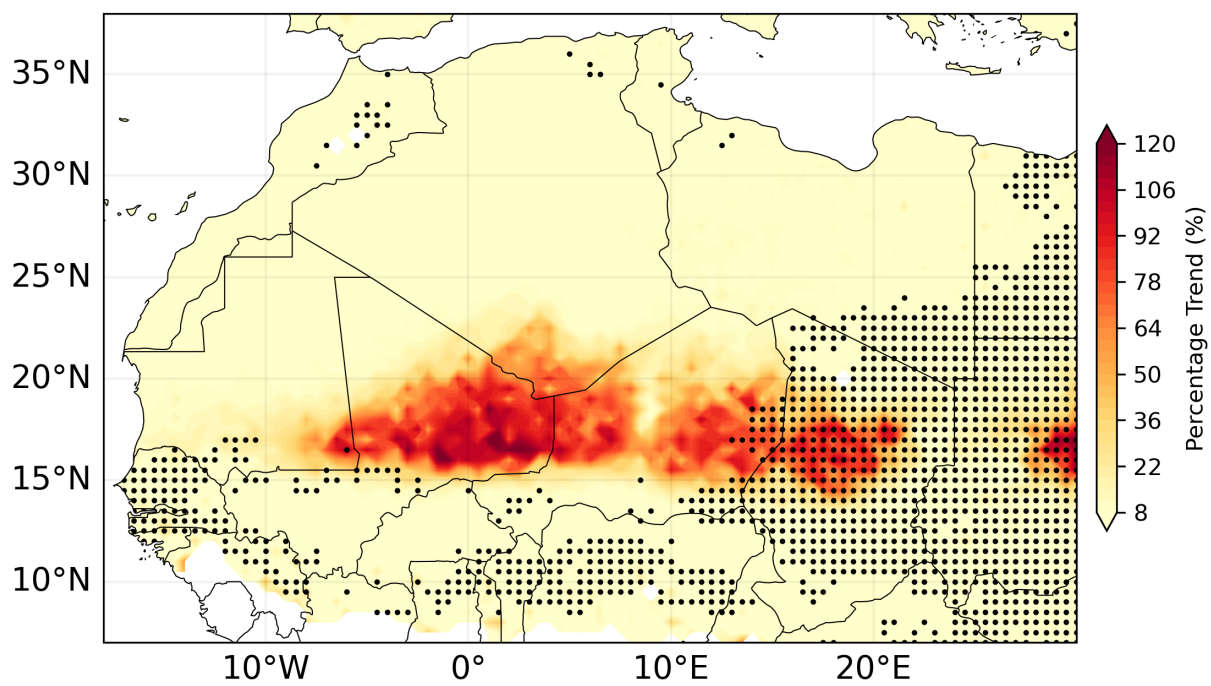


Figure 4.17: Spatial trends of SHL. Black dots represent the 95th significance ($p\text{-value} < 0.05$)

Moreover, when considered alongside the observed negative trends in surface wind speeds (Figure 4.14), 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).

4.3 Influence of Climate Drivers on Meteorological Drivers

Understanding how large-scale climate modes modulate meteorological conditions that favor dust storm activity is essential for diagnosing past dust trends and anticipating future variability. This section explores seasonal-scale lagged Pearson correlations between major climate indices such as AMO, NAO, MEI, AO, NOI, and SOI and key meteorological drivers of dust emission, such as 10-meter wind speed (WSP10), 2-meter temperature anomalies, precipitation anomalies, leaf area index (LAI), Saharan Heat Low (SHL), and sea-level pressure anomalies (SLP). Results are

presented separately for the Sahel and Sahara, with particular attention to statistically significant associations and comparison with earlier findings.

4.3.1 Seasonal-scale teleconnection between meteorological drivers and climate drivers for Sahel region.

In Figure 4.18, the lagged Pearson correlation between meteorological and climate drivers over the Sahel region was presented. The Atlantic Multidecadal Oscillation (AMO) emerges as a dominant driver:

- The positive correlation with temperature anomalies ($r = 0.54$, lag 0, Figure 4.18.b) suggesting that surface temperature over Sahel region is modulated by sea surface temperature (SST). This aligns with prior findings that link AMO warming phases to increased Sahelian surface temperatures (Giannini *et al.*, 2003; R. Zhang & Delworth, 2006).
- The positive lagged correlation with SHL ($r = 0.38$, lag -1 , Figure 4.18.e) suggests that AMO-driven warming strengthens the thermal low, consistent with the mechanism proposed by Peyrillé *et al.* (2007) and Lavaysse *et al.* (2009).
- A delayed positive relationship with WSP10 ($r = 0.27$, lag 2, Figure 4.18.a) hints at potential dynamical feedbacks between SHL expansion and low-level wind fields, a phenomenon consistent with the ventilation mechanism discussed in Knippertz & Todd, (2012)

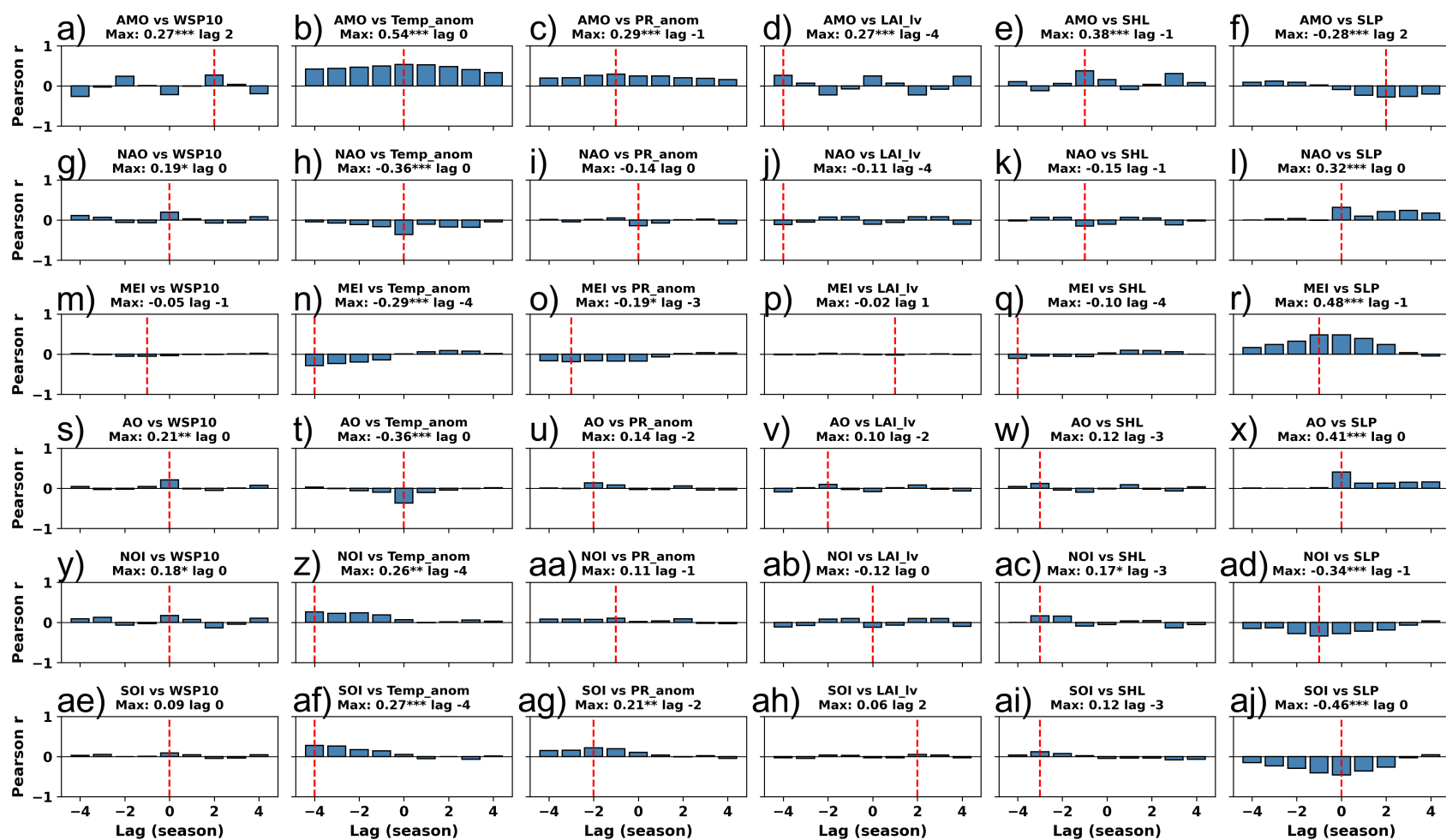


Figure 4.18: Seasonal cross-correlations between meteorological drivers and climate drivers for Sahel region. *, ** and *** beside the correlation values indicate the 0.05, 0.01 and 0.001 significance levels respectively.

For the North Atlantic Oscillation (NAO), it exhibits more modest yet non-negligible effects:

- Its negative influence on temperature ($r = -0.36$, lag 0, Figure 4.18.h) suggesting that NAO contributes to warm Sahel region. This result agrees with prior findings showing enhanced Sahelian warming during negative NAO phases (Gaetani *et al.*, 2011),
- the weak but significant positive effect on wind speed ($r = 0.19$, lag 0, Figure 4.18.g) is consistent with earlier studies that linked NAO phases to changes in the strength of the Harmattan flow (Rowell, 2003), although the influence appears secondary.

The Multivariate ENSO Index (MEI) shows a delayed cooling influence on temperature ($r = -0.29$, lag -4, figure 4.18.n) and weakly suppresses precipitation, consistent with previous work showing ENSO-induced subsidence and drying in West Africa (Janicot *et al.*, 2001). However, its effect on SHL intensity and wind appears negligible, suggesting a limited direct impact on dust mobilization at seasonal time scale.

The Arctic Oscillation (AO) and Southern Oscillation Index (SOI) also demonstrate moderate but seasonally constrained associations with temperature and SLP, in accordance with findings by Moulin *et al.*, (1997) who highlighted that these indices only partially account for dust season variability in the Sahel.

4.3.2 Seasonal-scale teleconnection between meteorological and climate drivers for Sahara region.

The same analysis was conducted for Sahara region. Figure 4.19 presents the cross-correlation.

Over the Sahara, the climate-dust linkages are both stronger and more direct:

- The AMO is again dominant, exerting a strong warming effect ($r = 0.67$, lag -1 , Figure 4.19.b) and a simultaneous strengthening of the SHL ($r = 0.32$, lag 0, Figure 4.19.e). This aligns well with the findings of Evan et al., (2016), who demonstrated that the AMO contributes significantly to Saharan warming and SHL expansion,
- A positive correlation with wind speed at lag 2 ($r = 0.30$) further supports the notion that AMO-induced thermal contrast intensifies northeasterly low-level winds key for dust uplift.

The NAO shows stronger correlations here than in the Sahel:

- Its positive correlation with SLP ($r = 0.52$, lag 0, Figure 4.19.l) and negative correlation with temperature ($r = -0.38$, lag 0, Figure 4.19.h) indicating that NAO phases modulate the strength of the Saharan High and indirectly affect the SHL,
- A concurrent negative relationship with precipitation ($r = -0.28$, lag 0, Figure 4.19.i) may influence surface dryness and vegetation, consistent with the hypothesis by Prospero & Lamb, (2003) on the link between NAO and Saharan dust sources.

The influence of MEI is modest but observable, with cooling effects ($r = -0.41$, lag -3 , Figure 4.19.n) and slight suppression of SHL and rainfall, in agreement with teleconnection pathways previously documented by Nicholson & Kim, (1997).

The AO again correlates strongly with SLP ($r = 0.66$, lag 0, Figure 4.19 x) and precipitation ($r = -0.38$, lag 0, Figure 4.19 u), reflecting its influence on midlatitude pressure patterns that may extend into northern Africa.

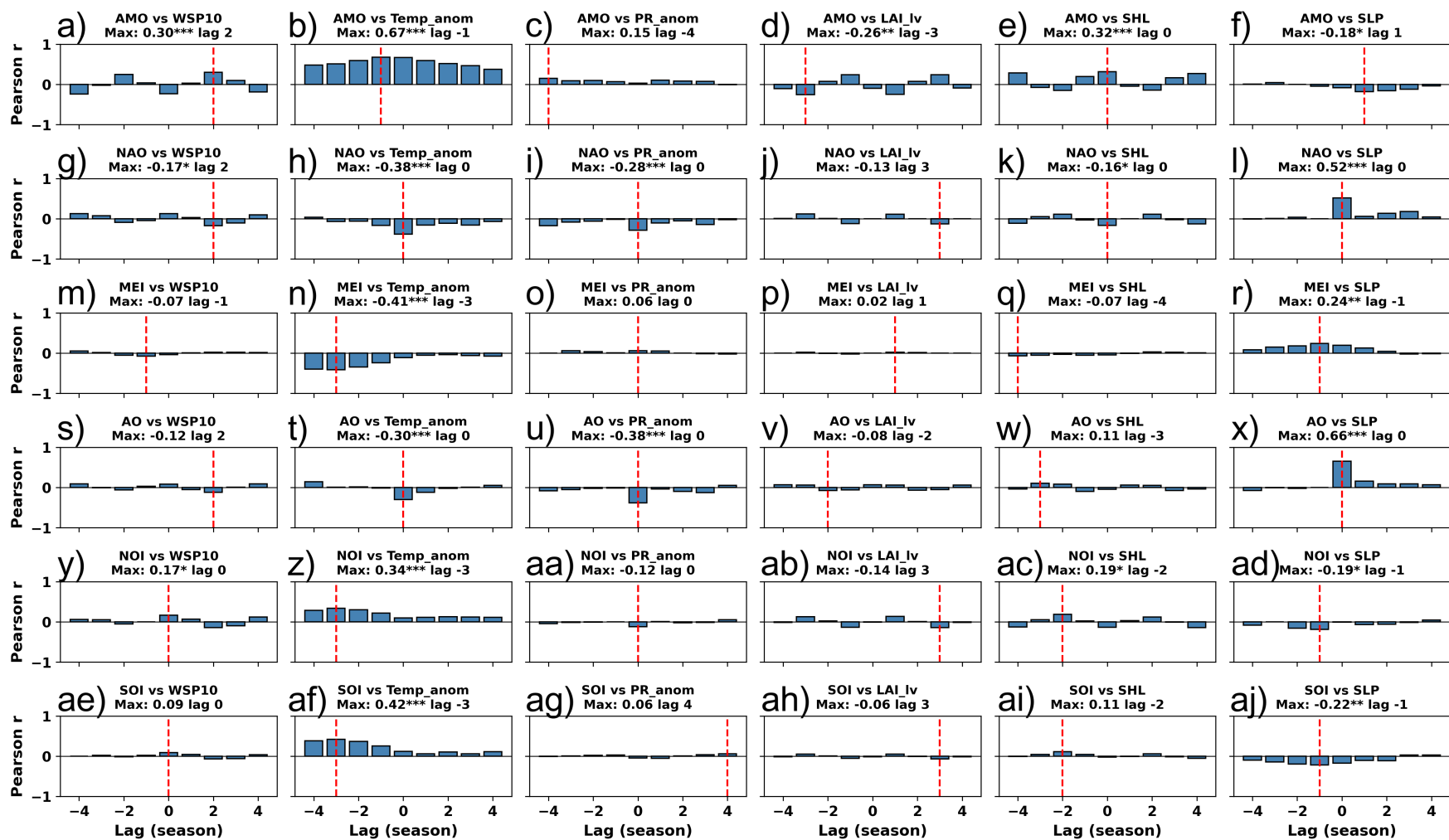


Figure 4.19: Same as Figure 4.18 but for Sahara region

The NOI and SOI show weak to moderate lagged correlations with temperature and SLP, but as in the Sahel, their direct influence on dust storm occurrence wind and SHL dynamics appears limited. This is consistent with prior regional studies (e.g., Chin *et al.*, 2014), which suggest that Pacific variability such as ENSO exerts only indirect influence on Saharan dust variability, compared to more regionally proximal drivers.

4.3.3 Yearly-scale teleconnection between meteorological drivers and climate drivers for Sahel region.

The same analysis was conducted at yearly time scale for Sahel region. Figure 4.20 presents the correlation between meteorological and climate drivers.

In the Sahel, AMO exhibits the most pronounced and statistically significant correlations as at the seasonal scale:

- temperature anomalies ($r = 0.77$, lag 0, Figure 4.20.b),
- SHL ($r = 0.71$, lag 0, Figure 4.20.e),
- precipitation ($r = 0.50$, lag 0, Figure 4.20.c)

These findings highlight the AMO's central role in modulating interannual warming, monsoon precipitation, and SHL strengthening in the Sahel. This supports existing literature suggesting that AMO-induced warming enhances the land-ocean thermal gradient and drives SHL and monsoon activity in the region (Giannini *et al.*, 2003; Zhang & Delworth, 2006).

The NAO, MEI and AO indices showed moderate positive correlations with sea level pressure and winds:

- NAO vs. SLP ($r = 0.39$, lag 0, Figure 4.20.l),
- AO vs. WSP10 ($r = 0.48$, lag 0, Figure 4.20.s),
- MEI vs. SLP ($r = 0.66$, lag 0, Figure 4.20.r).

These results suggest that the role of NAO, MEI and AO indices in controlling the sea level pressure and surface wind over Sahel is more perceptible at yearly time scale than at seasonal scale.

ENSO-related indices (MEI and SOI) showed a negative correlation with temperature and precipitation at lags of 1–2 years, indicative of delayed remote impacts:

- MEI vs. temperature anomalies ($r = -0.42$, lag 2, Figure 4.20.n),
- SOI vs. temperature anomalies ($r = 0.40$, lag 2, Figure 4.20.).

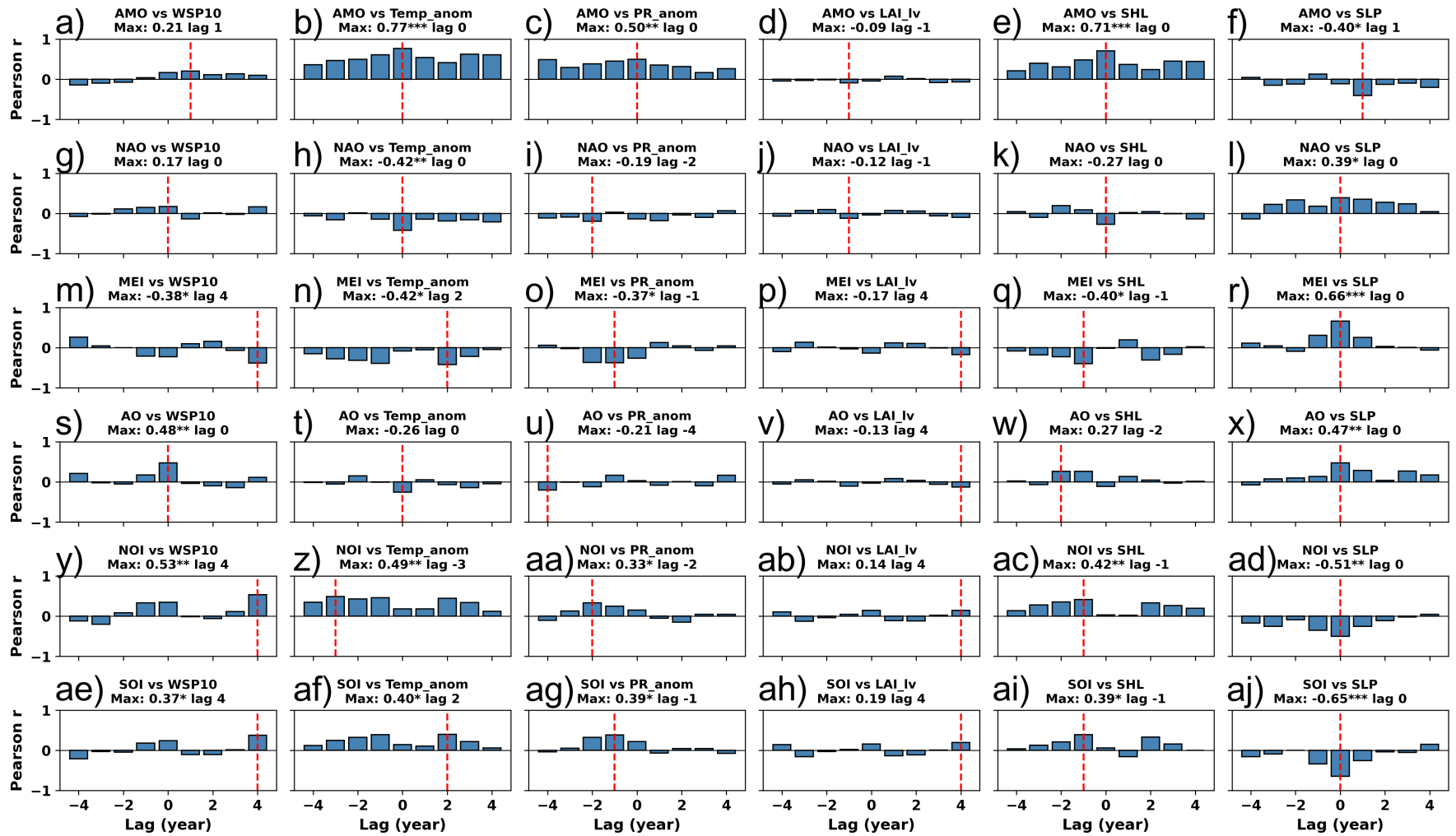


Figure 4.20: Yearly time scale cross-correlations between meteorological drivers and climate drivers over Sahel region. *, ** and *** beside the correlation values indicate the 0.05, 0.01 and 0.001 significance levels respectively.

These results imply that ENSO affects Sahelian climate through slower ocean-atmosphere teleconnection pathways, influencing the West African monsoon system. These results are consistent with the findings by Janicot *et al.* (2001) and Nicholson, (2013).

NOI and SOI showed a strong negative correlation with sea level pressure (Figure 4.20 ad and Figure 4.20 ai respectively) suggesting these indices are related to low pressure systems over Sahel region characterized by rising air mass that favor cloud formation and rainfall (Janicot et al., 1996).

4.3.4 Yearly-scale teleconnection between meteorological and climate drivers for Sahara region.

In the Sahara, the AMO again dominated, with the strongest correlations observed:

- AMO vs. temperature anomalies ($r = 0.84$, lag 0, Figure 4.21.b),
- AMO vs. SHL intensity ($r = 0.77$, lag 0, Figure 4.21.e)

These relationships emphasize the AMO's control over the SHL and surface wind fields, reinforcing the hypothesis that multidecadal Atlantic warming amplifies Saharan dust mobilization through SHL strengthening (Giannini *et al.*, 2003; Zhang & Delworth, 2006).

ENSO signals (MEI and SOI) displayed shorter-lag effects in the Sahara:

- MEI vs. temperature anomalies ($r = -0.48$, lag -1 , Figure 4.20.n),
- SOI vs. SHL intensity ($r = 0.49$, lag -1 , Figure 4.20.ai),

NAO, AO, and NOI also revealed moderate influence on surface pressure and temperature:

- NAO vs. SLP ($r = 0.51$, lag 0, Figure 4.20.l)

- AO vs. SLP ($r = 0.69$, lag 0, Figure 4.20.x)
- NOI vs. temperature anomalies ($r = 0.51$, lag -1 , Figure 4.20.z)

These results are consistent with previous studies showing that high-latitude atmospheric variability modulates Saharan pressure systems and thermal structures (Chin *et al.*, 2014).

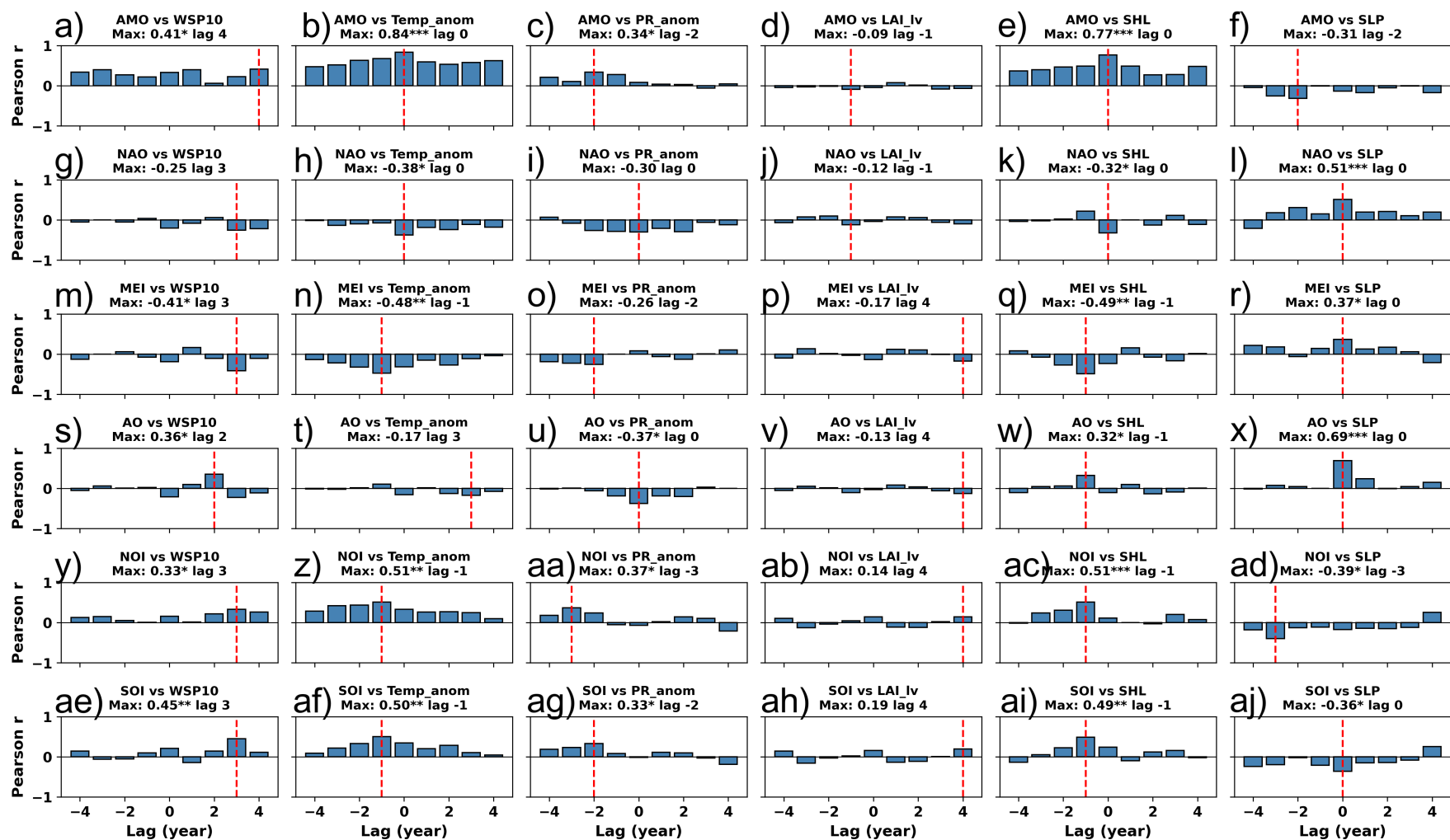


Figure 21: same as Figure 4.20 but for Sahara region.

Over all, the interannual-scale analysis underscores the dominant role of the AMO in shaping meteorological drivers of dust over both the Sahel and Sahara, particularly via thermal anomalies, SHL, and surface wind. ENSO and North Atlantic teleconnections modulate these effects at varying lags. These findings support the interpretation that recent North African dust trends are driven in part by large-scale, low-frequency climate variability, reinforcing conclusions drawn from seasonal and decadal trend analyses.

4.4 Self Organizing Map (SOM) analysis of dust storm patterns

To identify dominant dust storm configurations over the Sahara and Sahel, a Self-Organizing Map (SOM) analysis was conducted using daily dust storm occurrences. The SOM classified observed dust activity occurrence synoptic patterns into a 6×6 node grid, with each node representing a characteristic spatial synoptic pattern of dust storm occurrence. This unsupervised classification helps to isolate recurring modes of dust distribution and infer their relative frequency and intensity.

Key metrics were derived: nodes activation frequency, denoting the percentage of dust storm days assigned to each node (Figure, 4.22), synoptic patterns, showing the atmospheric circulation leading to storms occurrence (Figure, 4.23), seasonality of patterns and their occurrence frequencies (Figure, 4.24), dust storms count per node, quantifying the average number of dust storms associated with each pattern (Figure 4.25), and frequency of non-transition per node, showing the percentage of change of the pattern at a given node.

4.4.1 SOM nodes activation frequencies.

In Figure 4.22, nodes [6,5] and [6,6] exhibited the highest activation frequencies (4.8% and 5.3%, respectively), suggesting they represent the most recurrent spatial modes of dust storm occurrence.

These nodes likely capture robust synoptic-scale conditions favorable for widespread dust mobilization, such as intensified Saharan Heat Low (SHL) events or strong Harmattan surges. Other frequently activated nodes include [1,1] and [1,3], hinting at additional common dust storm structures likely tied to West African or subtropical dynamics.

In contrast, central nodes such as [4,2] and [3,2] showed the lowest activation frequencies (1.7–1.8%), indicating infrequent occurrence of the spatial dust configurations they represent. These may correspond to weaker or less spatially extensive events.

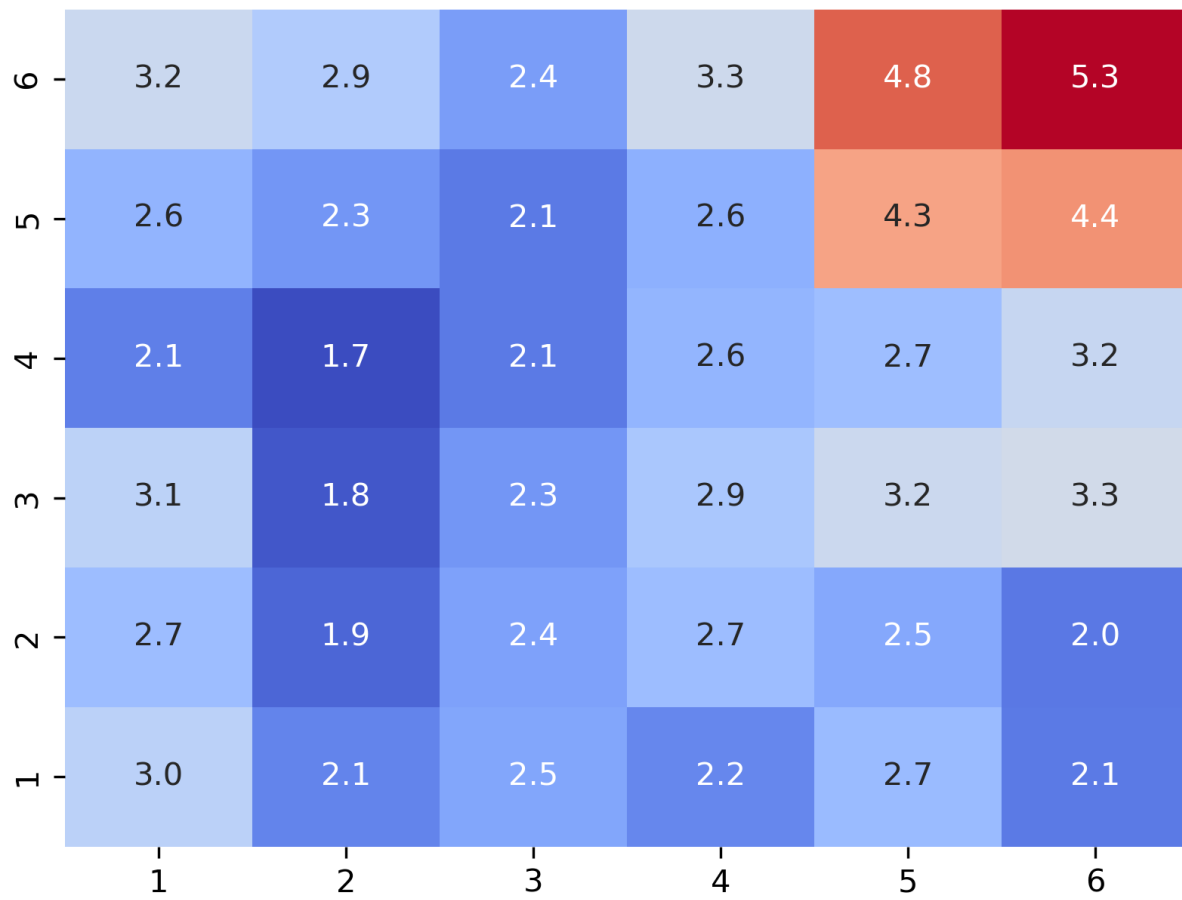


Figure 4.22: SOM Nodes activation frequencies

4.4.2 SOM Synoptic patterns and seasonality.

To elucidate the meteorological drivers behind each SOM node, composites of sea level pressure (SLP) and 925 hPa wind vectors were generated for all dust storm days associated with each node (Figure 4.23). This provides a physical basis to understand the dynamics underlying the SOM-classified dust patterns.

The most frequently activated and dust-days nodes particularly nodes [6,5], [6,6], [5,5], and [5, 6] display distinct and coherent atmospheric signatures (Figure 4.23).

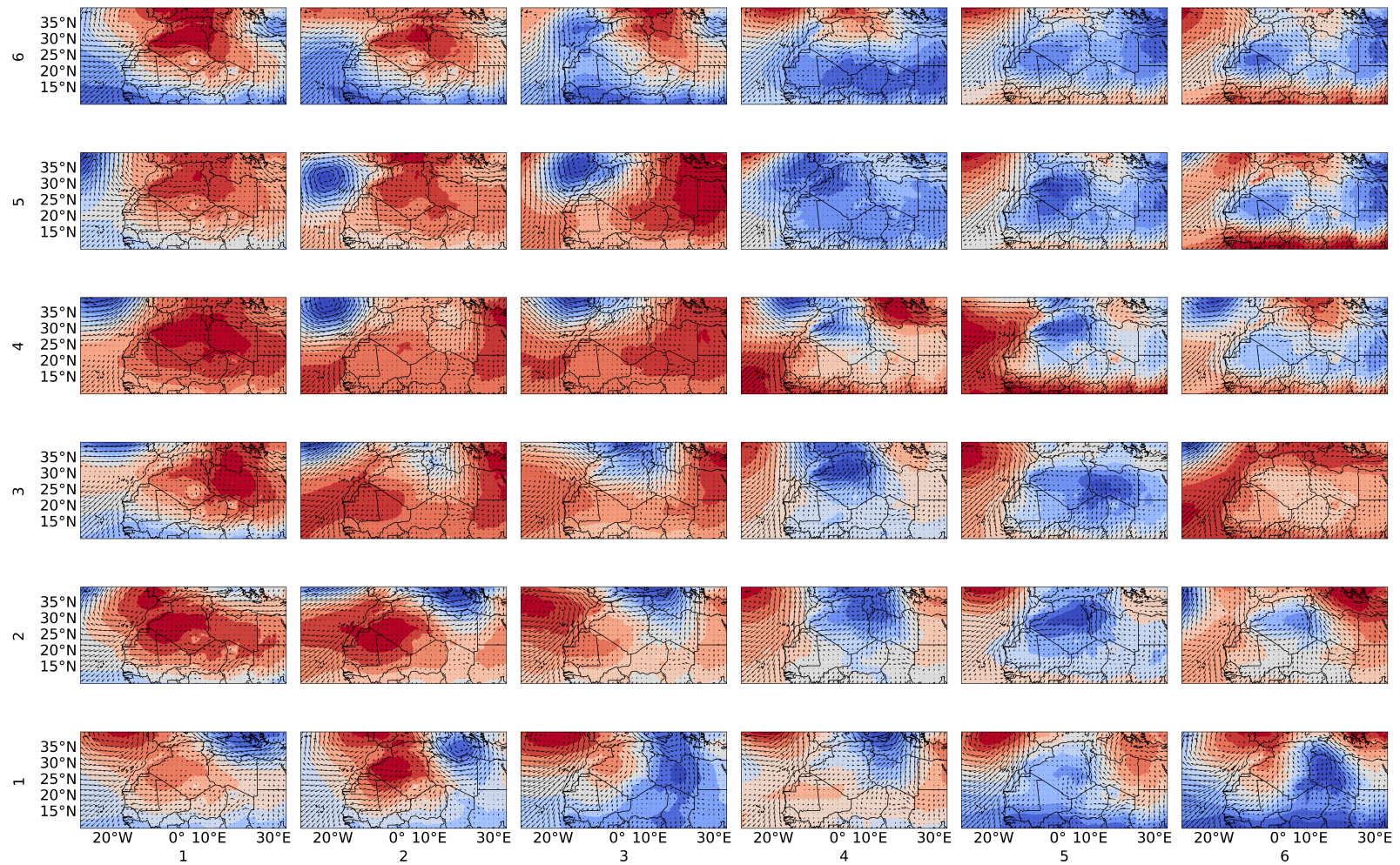


Figure 4.23: Synoptic patterns leading to dust storms occurrence over North Africa. Blue and red colors indicate low- and high-pressure systems respectively.

The nodes exhibit pronounced low-pressure anomalies over the western Sahara, accompanied by strong northeasterly to easterly flow across the central Sahara. The seasonality nodes reveal that these patterns are dominant in summer (Figure 4.24). The node [4, 6] also displays, a pronounced low-pressure anomaly over the central Sahel. The seasonality nodes show that this pattern is more recurrent in springtime. These synoptic patterns are consistent with intensifications of the Saharan Heat Low (SHL), a key summertime feature promoting dust uplift through enhanced baroclinicity and surface convergence (Lavaysse *et al.*, 2009). The robust wind fields point to long-range transport conditions potentially driving dust from Algeria, Mali, and Mauritania toward the Sahel, Atlantic or Mediterranean region.

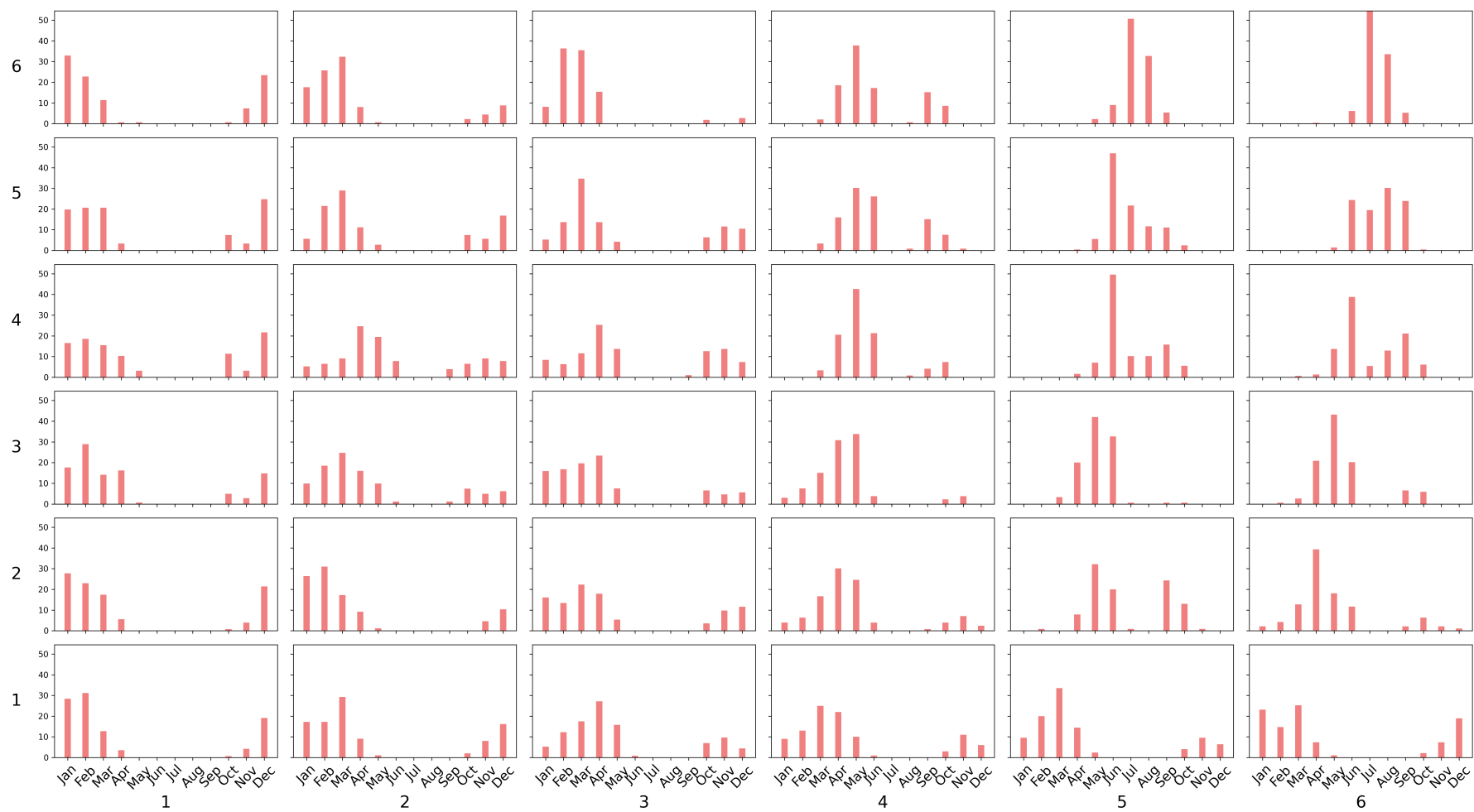


Figure 4.24: Seasonality of patterns and their occurrence frequency.

Node [6,1], another high-activity node, shows a pressure trough extending southward into the Sahel with accompanying southwesterly anomalies indicative of convective outflow conditions or post-monsoonal squall line dynamics. This implies a Sahelian source linked to cold-pool gust fronts, often associated with nocturnal convective systems.

Other notable configurations include:

- Node [6,1], which despite lower frequency has a high dust storm days, is characterized by a deep low over the central Sahara and strong northwesterly wind anomalies possibly tied to frontal incursions or mid-latitude wave interactions driving episodic, high-intensity dust outbreaks.
- In contrast, central nodes (e.g., [4,2], [3,2]) show weak or disorganized wind and pressure patterns, aligning with their low activation and storm counts. These may represent isolated synoptic situations or transitional phases without dominant dust-driving mechanisms.

The spatial continuity across node rows and columns also suggests a gradient of dust-driving regimes, from Saharan synoptic forcing in southern rows to Sahelian and subtropical influences in northern rows. This reflects the known zonal heterogeneity of North African dust climatology.

Together, the SOM node composites reinforce the interpretation of dust storm dynamics as arising from distinct meteorological drivers including SHL enhancement, low-level jets, squall lines, and synoptic disturbances and showcase the utility of SOM in organizing complex dust-weather interactions.

4.4.3 Seasonal characteristic of SOM nodes and link to dust climatology.

To explore the temporal dynamics of the SOM-classified patterns, we examined monthly frequency histograms for each node (Figure 4.24). These patterns exhibit clear seasonal organization, offering insight into the climatological regimes governing dust storm activity across North Africa.

Several key seasonal patterns emerge:

- Spring to Early Summer (MAM–JJA onset)
Nodes such as [6,6], [6,5], and [5,5] dominate during April to June. These patterns correspond with the intensification of the SHL as reported by Lavaysse *et al.* (2009), marked by a deepening thermal low and a tightening of the pressure gradient between the Sahara and the midlatitudes. Associated wind fields (Figure 4.23) show strong low-level northeasterlies and northerlies, ideal for dust uplift across the western and central Sahara. These patterns are consistent with the studies of Klose *et al.*, (2010) who found similar patterns in early spring responsible of the Sahel dust zone existence. The timing aligns with climatological studies identifying spring as the peak season for dust storm frequency in the Sahara, driven by dry convection, surface heating, and enhanced baroclinic activity along the SHL's flanks;
- Mid to Late Summer (JJA), nodes such as [1,1], [2,2], and [3,2] show maxima in July–August. These are linked to the northward displacement of the Intertropical Convergence Zone (ITCZ) and the full development of the West African Monsoon (WAM) system. During this period, convective outflows and African easterly waves (AEWs) contribute to dust emission in the Sahel region. The circulation patterns associated with these nodes

often feature strong easterlies at 925 hPa, sometimes with embedded cyclonic curvature suggestive of AEWs or convective outflows. These characteristics are consistent with Sahelian dust production tied to mesoscale convective systems, as highlighted in previous climatological analyses;

- Transitional Seasons (March, September–October) nodes like [3,3], [4,4], and [2,3] peak during seasons. These months are typically associated with increased synoptic variability, including the passage of cold surges from the north and baroclinic disturbances that trigger strong surface winds across northern Algeria and Libya. The spatial pressure anomalies in these nodes often reflect midlatitude incursions or residual SHL influence, indicating mixed forcing;
- Winter (DJF) only a few nodes (e.g., [5,1], [4,1]) show non-negligible activity in winter, consistent with the seasonal minimum of dust activity across North Africa. Dust storms in winter are generally less frequent and are typically linked to Mediterranean cyclones or strong westerly intrusions that momentarily reactivate Saharan source regions.

Taken together, these results confirm that the SOM framework successfully captures the seasonal evolution of dust-generating atmospheric drivers in North Africa. Each SOM node represents a distinct combination of surface pressure anomalies and near-surface wind patterns, whose seasonal preferences align with the known seasonal cycle of dust emission. The SOM thus provides a physically interpretable classification of dust storm regimes, mapping directly onto the seasonal dynamics of the SHL, ITCZ, AEJ, and synoptic-scale activity.

4.4.4 SOM dust storms related nodes.

While activation frequency highlights commonality, the frequency of dust storms per node (Figure 4.25) indicates the dust storm magnitude or intensity tied to each pattern. Here, node [1,6] clearly stands out, registering the highest storm load (4.8% storms), despite a more moderate activation frequency. This suggests node [6,1] captures high-intensity, less frequent dust events possibly linked to episodic Saharan Low developments or frontal intrusions.

Notably, node [1,1] also ranks high in both metrics (4.2% storms and 3.0% activation), marking it as a consistently dust-laden pattern. In contrast, node [4,2] not only activated infrequently but also carried the lowest dust burden (1.4% storms), underscoring its limited relevance to overall dust variability.

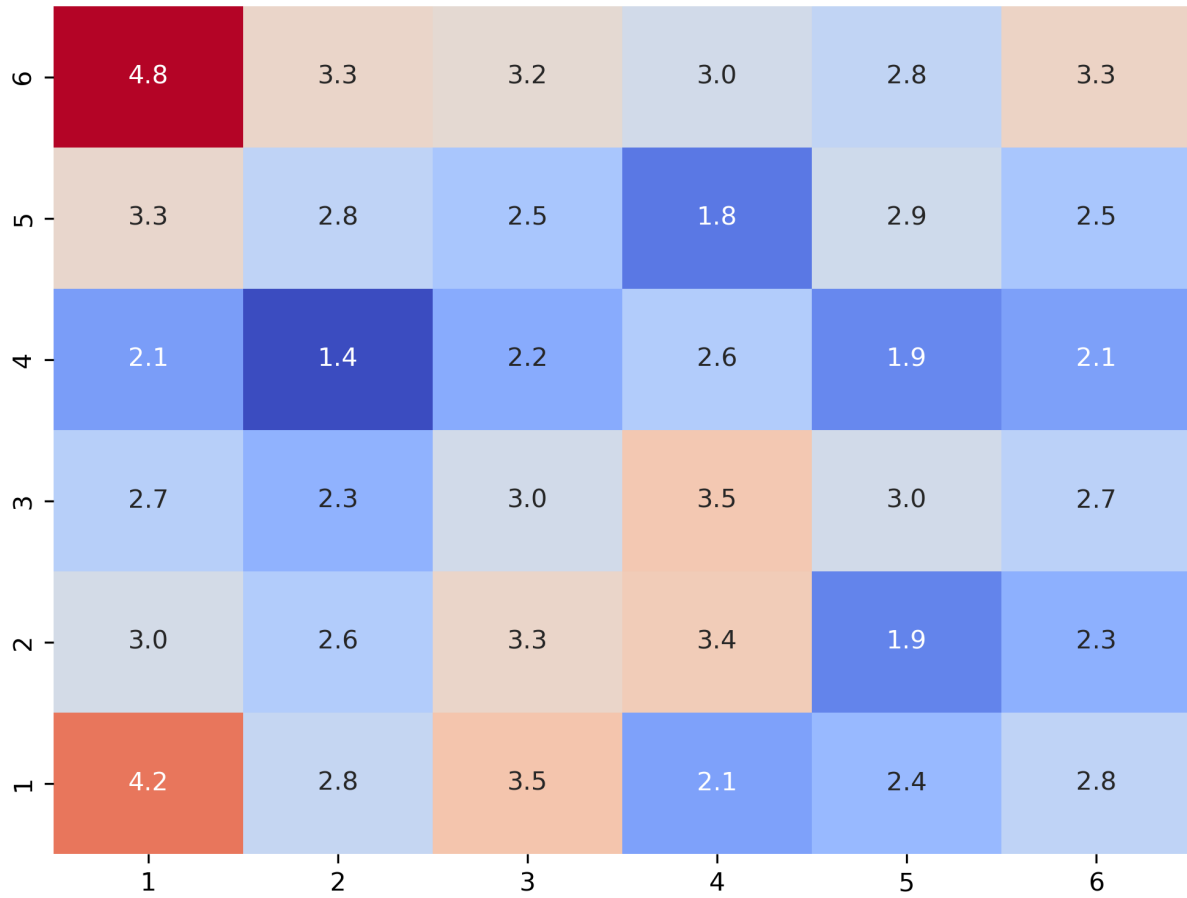


Figure 4.25: Dust storms frequency per node of the SOM.

4.4.5 SOM non-transition patterns.

The non-transition frequencies of dust storms related patterns (Figure 4.26) were computed. The results reveal that nodes [5, 6], [6, 6], and [5, 5] are the most persistent with 48% suggesting that the monsoon flow is persistent over Sahel driven by SHL. These findings corroborate the studies of Saley & Salack, (2023) and Schewe & Levermann, (2022) highlighting increase in Sahel rainfall. Node [1, 5] occurring in wintertime (DJF, Figure 4.24) also shows a persistent Harmattan flow supporting the role of Harmattan flow in winter dust uplift (Schepanski *et al.*, 2017). The lowest non-transition frequency is shown by nodes [2, 3] and [3, 3] with the frequencies of 13.6 and 13.1 respectively. Its highlight the variability of the associated patterns.

Overall, the Figure 4.26 presents the temporal state of each pattern associated to dust storms occurrence.

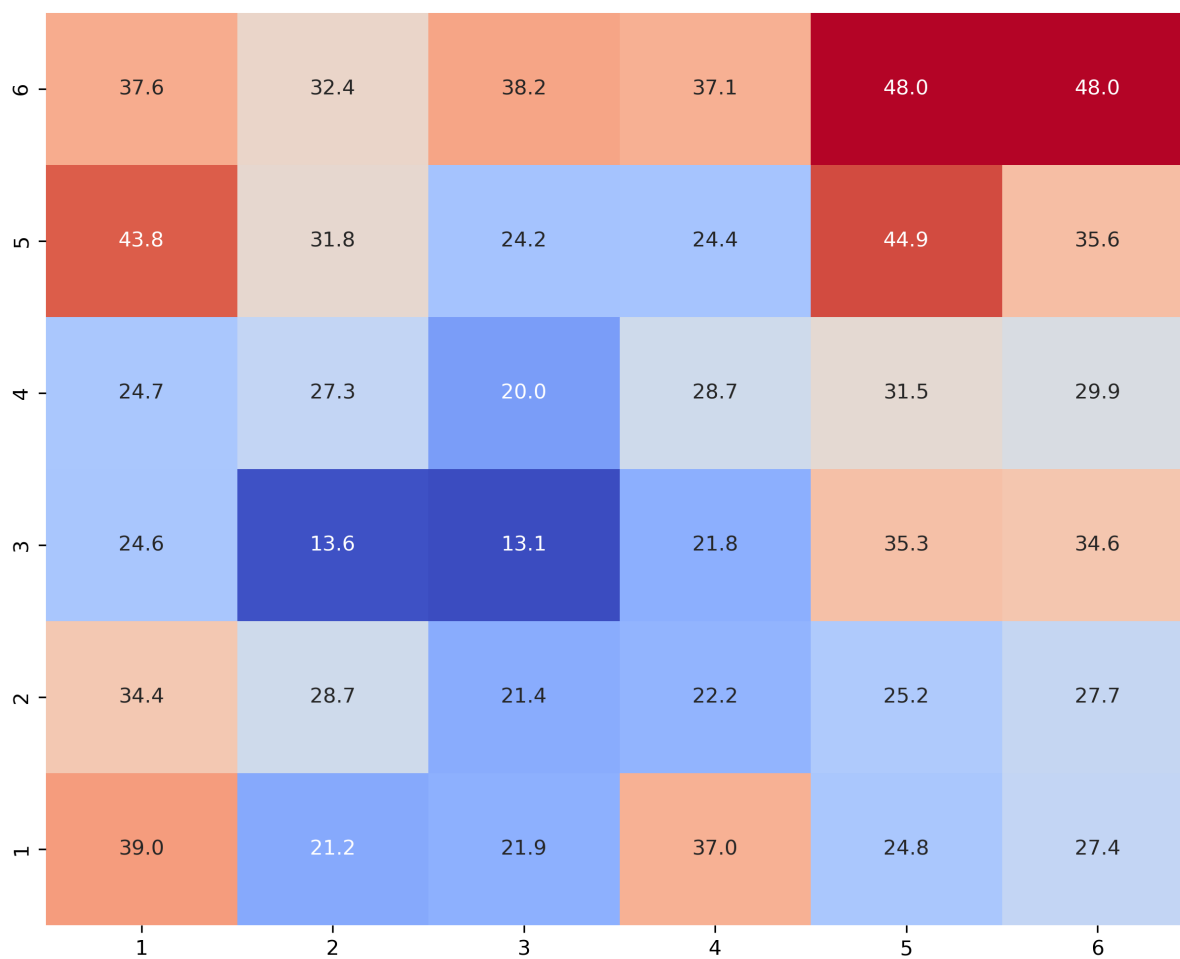


Figure 4.26: Frequency of non-transition of dust storms days synoptic patterns.

4.5 Long Short Term (LSTM) historical prediction of dust storms.

This section presents the outcomes of the Long Short-Term Memory (LSTM) model applied to predict historical dust storm frequency across North Africa. The LSTM model was trained using fixed random seeds for full reproducibility. We evaluated model skill using RMSE, MAE, and Pearson correlation, averaging results over 10 runs to account for training variability. The predictors are the key meteorological and climate variables previously identified as relevant dust storm drivers, including surface wind speed, precipitation, low vegetation leaf area index, and the SHL. A sample line graph of proposed scenario between predicted and observed dust storm frequency is presented in Figure 4.27.

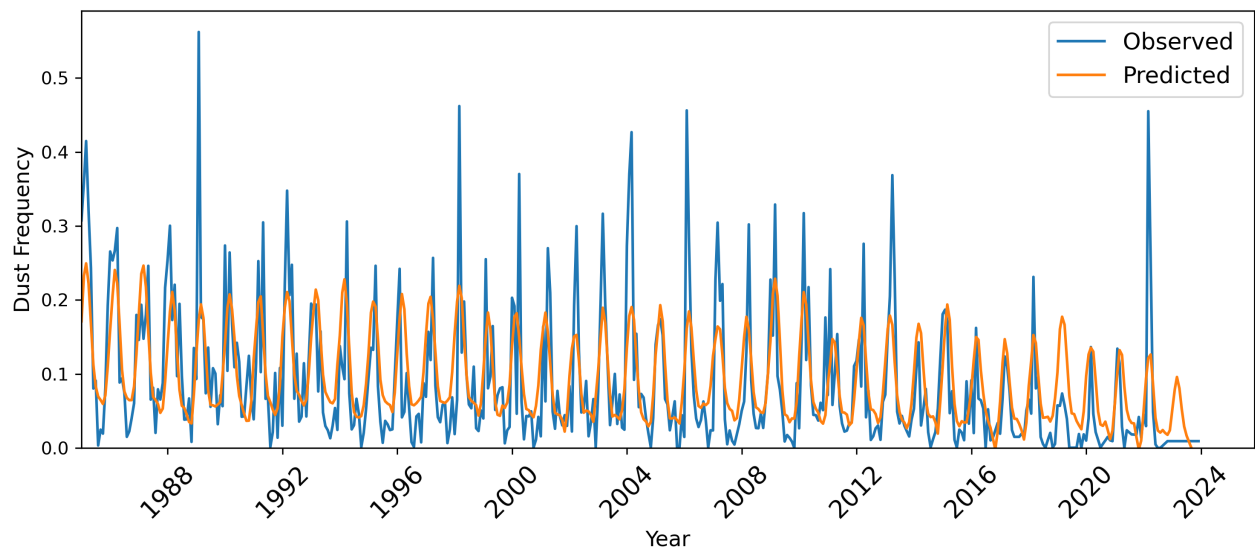


Figure 4.27: Line graph of proposed scenario between predicted and observed dust storm frequency over the study period..

4.5.1 Scenarios for the best learning for predicting dust storm frequency.

The predictive skill of the model is first evaluated using standard performance metrics, followed by a comparison of the LSTM predictions with observed dust storm frequency. The LSTM's capability to capture nonlinear temporal dependencies and long-term memory effects was evaluated to enable the model to reconstruct dust storm variability over time and assess its sensitivity to climate drivers.

The temporal patterns agreement between modeled and observed dust activity are then analyzed to validate the model's effectiveness. Figure 4.27 presents a line graph of proposed scenario between predicted and observed dust storm frequency. Finally, the contribution of individual predictors to dust storm variability is explored, providing further insights into the dominant processes driving dust emissions in different subregions (Sahara and Sahel). In Tables 4.5 presents the different scenarios and their statistical assessment over the Sahel and the Sahara regions respectively.

Table 4.5: input scenarios for the best learning for predicting dust storm frequency over Sahara.

Number	Scenarios	Performances			
		r	R ²	RMSE	MAE
1	WSP10-SHL-SLP	0.70	0.49	0.06	0.05
2	WSP10-SHL-SLP	0.67	0.45	0.07	0.05
3	WSP10-SHL-SLP-AMO	0.67	0.45	0.07	0.05
4	SHL-SLP-T2M	0.65	0.42	0.07	0.05
5	SHL-SLP-NAO-	0.67	0.45	0.07	0.05

The results show that scenario number 1 is the best to predict dust storm frequency over Sahel region. These results are similar to those by Hamidi & Roshani (2023) who used a similar approach and found that temperature (Tmin, and Tmax), precipitation and vegetation was the best scenario to predict dust AOD change in Iraq's dust activity.

These results support the robustness of the LSTM approach in modeling the complex, multiscale nature of dust-climate interactions.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study investigates the spatiotemporal variability, trends, and driving mechanisms of dust storm activity over North Africa, with a regional focus on the Sahel and Sahara. By integrating horizontal visibility observations, present weather codes, satellite and reanalysis datasets (OMI AI, CHIRPS precipitation, ERA5 wind, temperature, and leaf area index), and employing robust statistical methods including Theil-Sen trend estimation, Mann-Kendall significance testing with pre-whitening, and correlation analyses, the study provides a multi-scale perspective on the dynamics of dust storm occurrence and its evolution under changing climatic conditions.

The findings highlight a significant and widespread decline in dust storm frequency across both the Sahel and Sahara, particularly during key dust-active seasons (MAM, -1.07 storm/year; and JJA, -0.38 storm/year in the Sahel; SON and DJF -0.19 storm/year in the Sahara). These declines are found to align with statistically significant downward trends in surface wind speed and upward trends in vegetation cover (leaf area index) and precipitation, especially across the 10°N–20°N band, suggesting a suppression of dust emission due to increased surface moisture, biomass, and reduced erosive winds.

The Saharan Heat Low (SHL) shows a complex but regionally differentiated trend, with intensification in some areas. While traditionally associated with dust uplift, SHL intensification in this study appears to coincide with broader atmospheric changes that may also support dust suppression especially when linked to enhanced convective activity and precipitation. The positive

trends in leaf area index in the latitudinal band between 10°N and 15°N is associated to dust storms suppression in this zone.

On the large-scale, the climate drivers such as the Atlantic Multidecadal Oscillation (AMO) emerged as the dominant large-scale mode influencing dust variability across both regions and timescales. Positive AMO phases were associated with enhanced Sahelian rainfall and vegetation growth, thereby reducing dust emissions. In contrast, the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) exhibited weaker or seasonally varying relationships, modulating regional wind patterns and SHL strength in more indirect ways.

Self-Organizing Maps (SOM) identified dominant atmospheric circulation patterns associated with dust storm days, showing regionally consistent pressure and wind anomalies during high-dust events. These patterns also exhibit seasonal preference, aligning well with known climatology of dust seasonality in both regions. The dominant pattern, monsoon flow coupled with SHL, reinforces the hypothesis of Sahel and Sahara humidification during the last decades.

Furthermore, a predictive modeling effort using Long Short-Term Memory (LSTM) deep learning demonstrated the potential of using meteorological and climate variables to forecast dust storm frequency historically. Although prediction accuracy requires improvement, particularly in reducing bias and enhancing temporal resolution, this work represents a step forward in operational dust risk assessment.

Overall, this study contributes to the growing evidence indicating a sustained decline in North African dust activity in recent decades, likely driven by a synergy of enhanced vegetation, increased rainfall, weakening surface winds, and shifts in large-scale circulation patterns. These

findings are broadly consistent with previous research, while offering new insights through high-resolution spatial analyses and machine learning-based forecasting.

5.2 Limitations of the study

The most challenge in studying dust storms over North Africa is the in-situ data due to the sparsity of observatories in dust key sources. Despite the results of this study are consistent with previous findings, there may be errors in recording horizontal visibility and the associated present weather codes. The author inability to address all these uncertainties may affect the magnitude of trends in this study.

5.3 Recommendations

The findings of this study provide valuable insights into the impact of climate variability on the dust storms drivers and provide valuable information for decision-making and planning to prevent populations from dust related diseases and socio-economic impacts.

Future research can deepen our understanding of dust dynamics over North Africa and to enhance dust monitoring, prediction, and climate impact assessments:

1. Enhanced dust monitoring networks: Ground-based visibility observations remain spatially sparse and often inconsistent across the region. Expanding and harmonizing observational networks, particularly in under-sampled areas of the central Sahara, would improve trend detection and model calibration,
2. Improved representation of Land Surface Processes: Since vegetation and soil moisture changes are central to dust emission variability, future studies should incorporate dynamic

vegetation models and land use datasets that capture both seasonal and long-term land surface transformations. High-resolution land cover datasets and fractional vegetation cover metrics could yield more precise estimates of dust source activation and suppression,

3. **Coupled Climate-Dust Modeling:** Earth system models (ESMs) and regional climate models (RCMs) often treat dust as a passive tracer. Future modeling frameworks should better represent the feedbacks between dust, radiation, clouds, precipitation, and the SHL system. Coupling dust emission schemes with atmospheric circulation models will enhance our ability to simulate observed trends and anticipate future changes under different climate scenarios,
4. **Climate-Dust-Society Interactions:** Given the human and ecological relevance of dust storms, interdisciplinary studies that link atmospheric science with socioeconomic and health impact assessments are urgently needed. Quantifying the co-benefits of land restoration programs, afforestation, or changes in agricultural practices on dust suppression would help policymakers align environmental and public health strategies.

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