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Study of the PM_{10} levels in Ouargla city: health impact implication

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

يَرْفَعُ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ
وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ

Dedication



In the Name of God, the Most Gracious, the Most Merciful All praise is due to God, by whose grace good deeds are completed, and who has illuminated the path of knowledge and wisdom, granting me the strength and determination to reach this milestone in my academic journey.

While observing dust particles and climatic variations in the vast expanse of the desert, I realized with certainty that there are constants in my life that remain unaffected by the passage of time or the shifting winds—constants that are the essence of my existence, my safe harbor, and the source of my strength. To those whom God Almighty commanded : “And say, ‘My Lord, have mercy upon them as they brought me up [when I was] small’” (Quran 17 :24). To my dear parents, Nasser and Hakima; you were the atmosphere that shielded me from the frost of challenges, and the soil that nurtured the roots of my ambition, allowing it to grow into a branch that touches the sky. You are the source of love, giving, and sacrifice, who instilled in me the values of diligence and patience, and who remained my support and my prayers at every step of my life. I dedicate the fruit of this effort to you, apologizing that all the words of gratitude in my lexicon seem insufficient before the depth of your boundless giving. I ask God to reward you with the best of rewards and to bless your lives and health. To my dear siblings, the core of my life and the source of my joy—Marwa, Abderrahmane, Abdallah, and Asmaa—and to the soul of my beloved brother who resides in my memory and heart, Mohamed Tahar (may God have mercy upon him and grant him the highest place in Paradise); thank you for being my greatest support during times of fatigue and my companions in laughter during moments of success. Thank you for filling my life with warmth and love ; with you, my joy is complete, and by your presence, my days are adorned. To my extended family, who surrounded me with love and encouragement, and shared my moments of hope and fatigue ; you were my greatest support throughout this journey. To my journey’s companions, Aziza and Nour; you were more than just colleagues in my studies—you were my partners on this path, the sisters I never had. Thank you for sharing the burden of research and the details of long, sleepless nights, and for being my refuge when distances felt daunting and my unwavering motivation. Through your sincerity, support, and beautiful impact, this scientific journey became more beautiful and attainable. You have my deepest gratitude for every moment of loyalty and truth we shared. To every hand that reached out to help me, and every heart that believed in my success before I did—I dedicate this work to you all. It is the culmination of my thoughts, the product of my sleepless nights, and a promise that I shall always remain a seeker of truth, devoted to science, and faithful to everyone who planted in me a seed that has blossomed today into success.

Finally, to all my colleagues and friends, thank you sincerely for your kindness and support.

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Abstract

Desert-origin atmospheric particles with an aerodynamic diameter of less than 10 μm (PM_{10}) are among the most significant natural pollutants affecting air quality in arid and semi-arid regions, particularly in North Africa and areas frequently impacted by sand and dust storms. The study of these particles is of particular importance due to their ability to be transported over long distances and their potential impacts on public health, ecosystems, and local and regional climate. This work aims to provide a comprehensive review of suspended desert PM_{10} particles by examining their physical characteristics, natural sources, emission mechanisms, and atmospheric transport processes. The study also investigates the meteorological and climatic factors controlling the variability of PM_{10} concentrations, including wind speed and direction, atmospheric stability, and surface characteristics, as well as their role in the generation and transport of desert dust. In addition, special attention is given to the major environmental and health impacts associated with exposure to elevated PM_{10} concentrations, particularly respiratory and cardiovascular diseases, reduced visibility, and air quality deterioration. Furthermore, the review presents various techniques used for measuring and monitoring particulate matter, including ground-based monitoring stations, remote sensing observations, and atmospheric reanalysis products widely employed in environmental and climate studies. Previous studies have demonstrated that desert regions constitute a major source of atmospheric dust and that the temporal and spatial variations of PM_{10} concentrations are closely linked to prevailing climatic conditions and the intensity of dust events. The findings of this review emphasize the importance of continuous monitoring of desert particles and a better understanding of their temporal and spatial dynamics in order to improve air quality assessment and mitigate their adverse effects on human health and the environment. Moreover, they provide valuable support for future research related to climate change and extreme atmospheric phenomena.

PM_{10}

Keywords : PM_{10} , Desert Dust, Air Quality, Atmospheric Aerosols, Dust Storms, Environmental Impacts, Health Effects, Climate Variability

Résumé

Les particules atmosphériques d'origine désertique dont le diamètre aérodynamique est inférieur à $10\text{ }\mu\text{m}$ (PM_{10}) figurent parmi les principaux polluants naturels affectant la qualité de l'air dans les régions arides et semi-arides, en particulier en Afrique du Nord et dans les zones fréquemment exposées aux tempêtes de sable et de poussière. L'étude de ces particules revêt une importance particulière en raison de leur capacité à être transportées sur de longues distances ainsi que de leurs effets potentiels sur la santé publique, les écosystèmes et le climat à l'échelle locale et régionale. Ce travail vise à présenter une revue complète des particules désertiques en suspension PM_{10} à travers l'examen de leurs caractéristiques physiques, de leurs sources naturelles ainsi que des mécanismes d'émission et de transport atmosphérique. L'étude analyse également les facteurs météorologiques et climatiques contrôlant la variabilité des concentrations de PM_{10} , tels que la vitesse et la direction du vent, la stabilité atmosphérique et les caractéristiques de la surface, ainsi que leur rôle dans la mise en suspension et le transport des poussières désertiques. En outre, une attention particulière est accordée aux principaux impacts environnementaux et sanitaires liés à l'exposition à des concentrations élevées de ces particules, notamment les maladies respiratoires et cardiovasculaires, la réduction de la visibilité et la dégradation de la qualité de l'air. Par ailleurs, cette revue présente les différentes techniques de mesure et de surveillance des particules en suspension, notamment les stations de mesure au sol, les observations par télédétection et les produits de réanalyse atmosphérique largement utilisés dans les études climatiques et environnementales. Les études antérieures ont montré que les régions désertiques constituent une source majeure de poussières atmosphériques et que les variations temporelles et spatiales des concentrations de PM_{10} sont étroitement liées aux conditions climatiques dominantes et à l'intensité des phénomènes poussiéreux. Les résultats de cette revue soulignent l'importance de poursuivre la surveillance des particules désertiques et d'améliorer la compréhension de leur dynamique temporelle et spatiale afin de mieux évaluer la qualité de l'air et de réduire leurs effets négatifs sur la santé humaine et l'environnement. Ils contribuent également au développement des recherches futures relatives au changement climatique et aux phénomènes atmosphériques extrêmes.

Mots-clés : PM_{10} , poussières désertiques, qualité de l'air, aérosols atmosphériques, tempêtes de poussière, impacts environnementaux, effets sanitaires, variabilité climatique.. .

الملخص

تعد الجسيمات العالقة ذات القطر الديناميكي الهوائي الأقل من 10 ميكرومتر (PM_{10}) من أهم ملوثات الهواء في المناطق الصحراوية، نظراً لارتباطها المباشر بالعواصف الغبارية وبقدرتها على الانتقال لمسافات طويلة والتأثير في صحة الإنسان والبيئة. وتهدف هذه الدراسة إلى تحليل التباين الزمني لتركيزات الجسيمات الصحراوية PM_{10} في مدينة ورقلة خلال الفترة الممتدة من 2015 إلى 2024، مع تقييم آثارها الصحية المحتملة وإبراز العوامل المناخية المؤثرة في تغيراتها. اعتمدت الدراسة على بيانات إعادة التحليل الجوي الصادرة عن خدمة مراقبة الغلاف الجوي الأوروبية (CAMS)، حيث تم استخراج ومعالجة السلاسل الزمنية لتركيزات PM_{10} وتحليلها على المقاييس السنوية والفصلية والشهرية، بهدف تحديد الاتجاهات العامة والفترات الأكثر تعرضاً لارتفاع مستويات الغبار الجوي. كما تم ربط التغيرات المسجلة بالخصائص المناخية السائدة في المنطقة الصحراوية، خاصة نشاط الرياح، وارتفاع درجات الحرارة، وتكرار العواصف الرملية والغبارية. أظهرت النتائج وجود تذبذب واضح في تركيزات PM_{10} خلال فترة الدراسة، مع تسجيل قيم مرتفعة خلال فصلي الربيع والصيف نتيجة زيادة نشاط الرياح وتواتر الظواهر الغبارية، في حين لوحظ انخفاض نسبي خلال الفصول الأخرى. كما بينت النتائج أن البيئة الصحراوية لمدينة ورقلة تمثل عاملاً رئيسياً في ارتفاع مستويات هذه الجسيمات، مما يؤثر بشكل مباشر في جودة الهواء ويزيد من مخاطر التعرض لأمراض الجهاز التنفسي والقلب والأوعية الدموية، خاصة لدى الفئات الحساسة من السكان. وتؤكد هذه الدراسة أهمية المراقبة المستمرة للجسيمات العالقة PM_{10} وفهم ديناميكيتها الزمنية من أجل تحسين تقييم جودة الهواء ودعم استراتيجيات الحد من آثار التلوث الجوي، بما يساهم في حماية الصحة العامة وتعزيز التنمية المستدامة في المناطق الصحراوية.

الكلمات المفتاحية: PM_{10} ، الجسيمات الصحراوية، التباين الزمني، جودة الهواء، ورقلة، CAMS،

العواصف الغبارية، الآثار الصحية.

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Abbreviations

PM₁₀ :	Particulate Matter (particles with a diameter of 10 micrometers or less)
AERONET :	AErosol RObotic NETwork
MODIS :	Moderate Resolution Imaging Spectroradiometer
CALIPSO :	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
TOMS :	Total Ozone Mapping Spectrometer
BAM :	Beta Attenuation Monitor
AOD :	Aerosol Optical Depth

Part I

General Introduction

General Introduction

A clean environment is a fundamental requirement for human comfort, health, well-being, and climate stability. However, both developed and developing countries continue to face significant air pollution challenges with serious environmental and health impacts [Aghababaeian et al., 2021]. Particulate matter (PM) is not a single pollutant but a complex mixture of solid particles and liquid droplets such as dust, dirt, soot, and smoke, composed of both organic and inorganic substances suspended in the air. Based on particle size, PM is generally classified into coarse, fine, and ultrafine particles. Among them, PM₁₀ refers to particles with an aerodynamic diameter of 10 μm or less and has been extensively studied in recent decades due to its significant health relevance Elkama [2021]. Particulate matter originates from both natural and anthropogenic sources. Natural sources include wind-blown dust, sea salt, volcanic eruptions, forest fires, and soil erosion, whereas human activities contribute significantly through fuel combustion, industrial emissions, vehicle exhaust, and biomass burning. In urban environments, road dust resuspension represents a major contributor to PM₁₀ concentrations, particularly in areas with heavy traffic and disturbed surfaces. Moreover, the chemical composition of PM often includes toxic compounds such as metals and polycyclic aromatic hydrocarbons (PAHs), which vary depending on emission sources and environmental conditions. Meteorological factors such as temperature, humidity, and wind speed play a crucial role in controlling PM concentrations and dispersion patterns, leading to significant temporal and spatial variability in air pollution levels Zeb et al. [2024]. PM₁₀ is widely recognized as a major risk factor for adverse health effects, particularly respiratory and cardiovascular diseases. Exposure to these particles has been strongly associated with increased hospital admissions, respiratory complications, and cardiovascular mortality, with children being among the most vulnerable groups Stafoggia et al. [2016], Dominguez-Rodriguez et al. [2020]. In desert regions, PM₁₀ concen-

trations are strongly influenced by natural dust emissions. These particles consist of fine solid materials with diameters of $10\text{ }\mu\text{m}$ or less that remain suspended in the atmosphere for varying periods. They are mainly generated by wind-blown dust, especially during sandstorms, leading to elevated concentrations in the air Organization [2013]. The Sahara Desert is by far the most important dust source globally, contributing approximately 50-70% Todd [2012], Prospero et al. [2002]. The Bodélé Depression in Chad has been identified as a single most prolific source, where the interaction of low-level jets with dry lakebed sediments generates massive dust plumes Washington et al. [2006], Todd et al. [2008]. Their danger lies in their ability to penetrate deep into the respiratory system, causing diseases such as asthma, bronchitis, and other respiratory disorders, as confirmed by the World Health Organisation Organization [2013, 2021]. Epidemiological studies have demonstrated that a $10\text{ }\mu\text{g}/\text{m}^3$ increase in PM_{10} during dust events is associated with increases in natural mortality ranging from 0.55% to 0.65% Stafoggia et al. [2016]. Furthermore, desert dust particles can act as carriers of biological material including bacteria, fungi, and viruses, and may transport anthropogenic pollutants over long distances, thereby exacerbating their toxicity Querol et al. [2019], Lwin et al. [2023]. Therefore, studying desert PM_{10} is essential to better understand its environmental and health impacts, particularly in regions where dust storms are frequent and intense.

Problem Statement

The main challenge of this study is to understand the temporal variation of PM_{10} concentrations, which are influenced by the interaction between anthropogenic emissions, natural Saharan dust, and meteorological conditions. According to the World Health Organization, ambient air pollution, including desert dust, accounts for approximately 4.2 million premature deaths annually worldwide, with low- and middle-income countries bearing the highest burden Organization [2021]. Despite this alarming statistic, monitoring networks in dust-affected regions remain severely underdeveloped Gualtieri et al. [2024]. Accordingly, this research addresses the following questions:

- How do PM_{10} concentrations vary over time, and what are the peak periods?
 - What is the role of meteorological parameters and Saharan dust events in driving these variations?
 - To what extent are these fluctuations associated with adverse health outcomes?
- Research Objectives**

-
- **Analytical Objective:** To monitor and analyze the temporal variation patterns of PM₁₀ concentrations at multiple time scales (daily, monthly, seasonal, and annual).
 - **Source Apportionment:** To distinguish between natural (Saharan dust) and anthropogenic sources using the revised methodology proposed by Barnaba et al. [2017].
 - **Meteorological Analysis:** To investigate the influence of temperature, humidity, and wind speed on PM dispersion.
 - **Health Risk Assessment:** To evaluate the relationship between PM₁₀ exposure and respiratory and cardiovascular effects based on existing epidemiological evidence.
 - **Policy Support:** To provide scientific data that supports air quality management and early warning systems.

Methodological Approach

The data entry is based on the reanalysis of CAMS (Copernicus Atmosphere Monitoring Service) global atmospheric composition forecasts for a 10-year period (2015–2024). CAMS provides surface PM₁₀ concentrations calculated from 13 individual aerosol components including three size bins for desert dust Inness et al. [2019], Rémy et al. [2022]. The reanalysis products combine chemical transport models with satellite-based observations using advanced data assimilation techniques Inness et al. [2019]. The results will be validated using satellite MODIS (Moderate Resolution Imaging Spectroradiometer) Deep Blue Aerosol Optical Depth (AOD) retrievals, which have been specifically developed for aerosol monitoring over bright desert surfaces Hsu et al. [2004], Platnick et al. [2015].

Thesis Structure

This thesis is organized into six chapters:

1. General introduction to PM₁₀ particulate matter – Presents the background, problem statement, and objectives of the study.
2. Literature review: Desert particulate matter – Reviews existing knowledge on desert dust sources, emission mechanisms, temporal variability, long-range transport, physical and chemical properties, and health effects.
3. Physical context, theoretical relationships and measurement methods Describes the physical context of desert source regions, governing physical relationships of desert particles,

and measurement/detection methods including reanalysis and satellite observations.

4. Temporal variability of desert particles – Presents the data and methodology for PM₁₀ study, physical relationships for estimating PM₁₀, and data sources for temporal assessment.
5. Analysis of the results – Presents and discusses the findings on temporal variation patterns, source contributions, and health implications.
6. Conclusion – Summarizes the main findings, discusses limitations, and provides recommendations for future research and policy.

*Literature review: Desert
particulate matter PM_{10}*

1.1 Introduction

Particulate Matter (PM) is one of the most important components of atmospheric aerosols. It originates from a wide range of natural and anthropogenic sources and is characterised by complex formation mechanisms involving both direct emissions and secondary formation within the atmosphere. Particles may be emitted directly as **primary particulate matter (Primary PM)**, or they may form later in the atmosphere through chemical reactions involving precursor gases such as sulphur dioxide (SO₂), nitrogen oxides (NO_x), ammonia (NH₃), and non-methane volatile organic compounds (NMVOCs).

These reactions lead to the formation of secondary particulate matter (Secondary PM), which is generally finer in size and has a longer atmospheric residence time, particularly within the PM_{2.5} fraction [1].

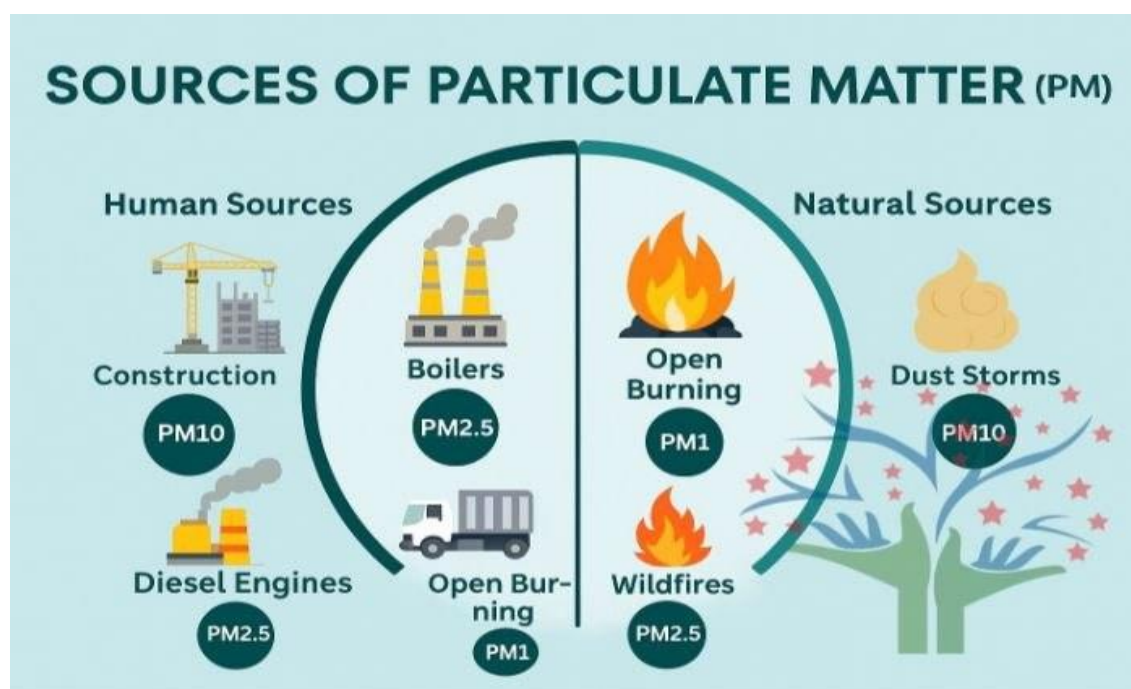


Figure 1.1 – Natural and non-natural sources of PM₁₀ particles[1].

In terms of sources, both primary and secondary emissions originate from natural and anthropogenic activities. Natural sources are associated with geophysical processes such as soil erosion, wind action, and weathering, whereas anthropogenic sources include fossil fuel combustion in transport (diesel and petrol), the burning of solid fuels in industry and households, as well as industrial activities such as mining and the production of cement and ceramics, in addition to road surface abrasion caused by traffic. Agricultural activities also represent a major

source of ammonia emissions, which contribute significantly to secondary particle formation in the atmosphere. [1]

In desert environments, the Sahara is regarded as the world's most significant source of mineral dust emissions, covering an area exceeding 9 million square kilometres and acting as a major contributor to dust storms at both regional and global scales. Dust uplift occurs throughout the year but intensifies during the dry season due to enhanced surface heating, which generates convective instability and strong winds capable of mobilising fine particles. Atmospheric circulation systems such as the Saharan thermal low and the Azores High play a key role in controlling wind dynamics and facilitating the transport of dust-laden air masses towards the Atlantic Ocean, Europe, and the Americas.

Dust transport over long distances occurs through several atmospheric pathways, the most important of which is the Saharan Air Layer (SAL). This is a warm, dry, and dust-rich air mass that extends over the North Atlantic and acts as a major transport corridor for particles over thousands of kilometres. In addition, the African easterly jet and tropical waves contribute to the redistribution of dust across Africa, the Mediterranean, and Europe. Local topography and atmospheric disturbances such as thunderstorms and sudden dust storms (haboobs) further enhance local dust emissions and mobilisation. From a chemical perspective, Saharan dust particles are primarily composed of silicate, carbonate, oxide, and sulphate minerals derived from the weathering of sedimentary and metamorphic rocks. The dominant minerals include quartz, feldspar, and clay minerals, reflecting the geological diversity of source regions. These particles may also contain organic matter, trace elements, and heavy metals such as lead, zinc, and cadmium, originating either from natural sources or from anthropogenic contamination acquired during atmospheric transport. The chemical and physical properties of dust particles evolve during atmospheric transport due to chemical reactions such as gas oxidation on particle surfaces and the formation of secondary compounds. These processes alter key properties including solubility and chemical reactivity. Iron-rich particles, in particular, may play an important biogeochemical role when deposited in marine environments by enhancing biological productivity through the supply of bioavailable iron. [2]

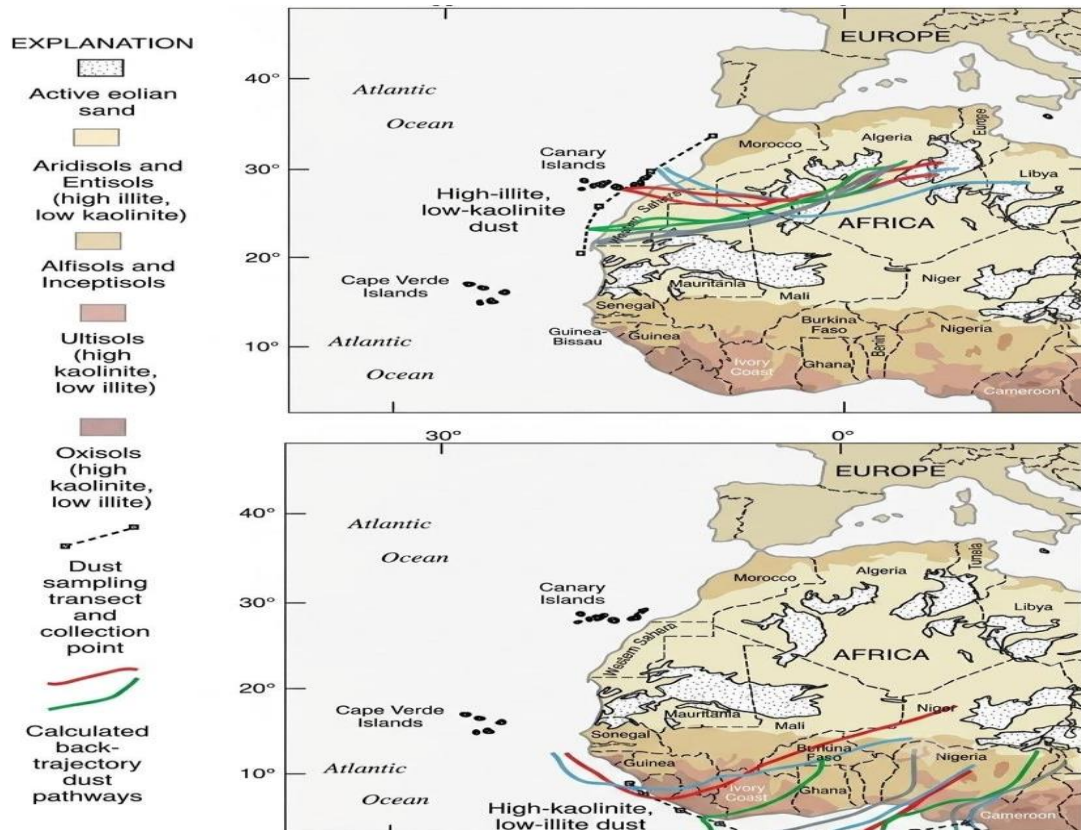


Figure 1.2 – The geographical sources of dust in West Africa and its transport pathways[3]

Regarding particle formation mechanisms, mineral dust originates from multiple geological processes rather than a single source. These include physical rock fragmentation, chemical weathering, volcanic activity, and the inheritance of fine materials from parent rocks. Wind erosion, fluvial processes, salt weathering, and frost weathering are also major mechanisms responsible for generating fine silt-sized particles that can be emitted into the atmosphere and transported over long distances [3]. Studies further indicate that dust production is also linked to surface processes such as glacial grinding in polar regions. However, recent evidence shows that non-glacial desert environments can also generate large quantities of fine particles through wind abrasion, fluvial fragmentation, and combined physical and chemical weathering processes. Thus, dust production is the result of a complex interaction between geological and environmental factors [3]. On a global scale, arid and semi-arid regions represent the dominant source of mineral aerosols, with major deserts such as the Sahara in Africa, regions in the Middle East, Central Asia, and Australia contributing significantly to global dust emissions. North Africa alone accounts for approximately half of the global dust load, while Asian sources also contribute substantially, with the remaining emissions distributed among other regions [4].

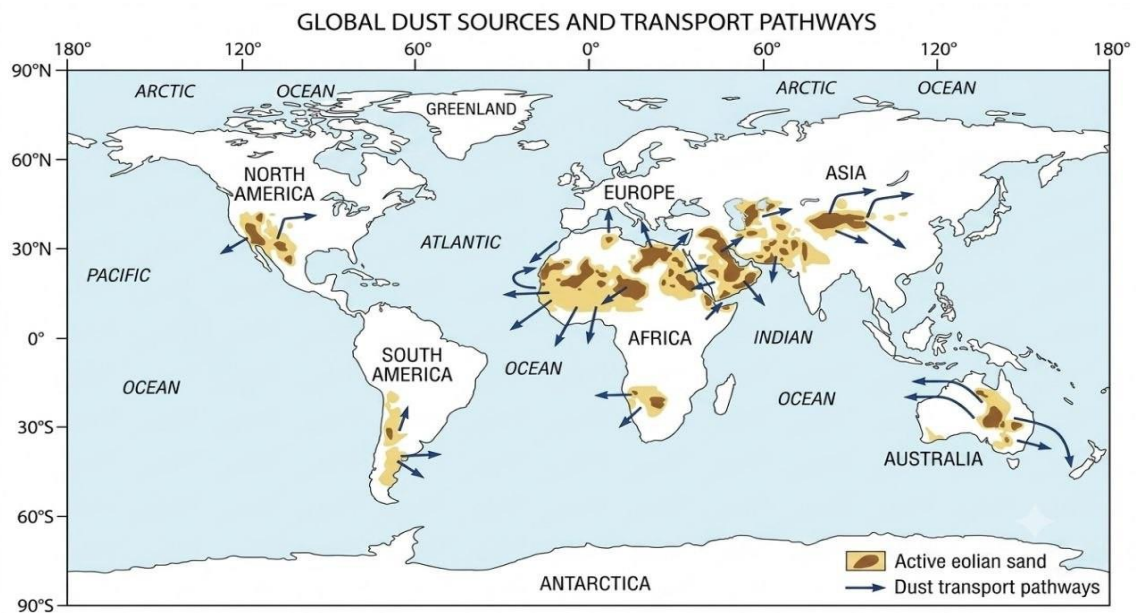


Figure 1.3 – Global distribution of dust sources and their atmospheric transport pathways[3]

Global dust source distribution is not random but is strongly associated with specific geomorphological settings, particularly topographic depressions, dry river basins, seasonal lakes, and salt flats. Bare soils, rangelands, and agricultural lands also play an important role in enhancing dust emissions, especially in regions influenced by human activity [4]. Climatic factors are also critical in controlling dust emission intensity. Conditions such as drought, reduced soil moisture, and increased wind speeds significantly enhance dust activity. Moreover, dust storm frequency is closely linked to hydrological variability and large-scale climate oscillations, including seasonal rainfall patterns and long-term climatic fluctuations, leading to temporal variability in dust emissions over decades [4]. Natural dust sources are further controlled by surface characteristics, where unvegetated dry soils are particularly susceptible to erosion. Dust emission occurs when wind speed exceeds a critical threshold, which depends on particle size, soil moisture, and surface roughness. In the Sahara, this threshold has been estimated to range between approximately 5 and 12.5 m/s depending on local environmental conditions [5]. Traditional observational methods such as horizontal visibility measurements have historically been used to estimate dust activity indirectly, as reduced visibility in desert regions is often associated with increased atmospheric dust concentrations. However, these methods are limited by the sparse distribution of meteorological stations and large spatial gaps in observational coverage [5].

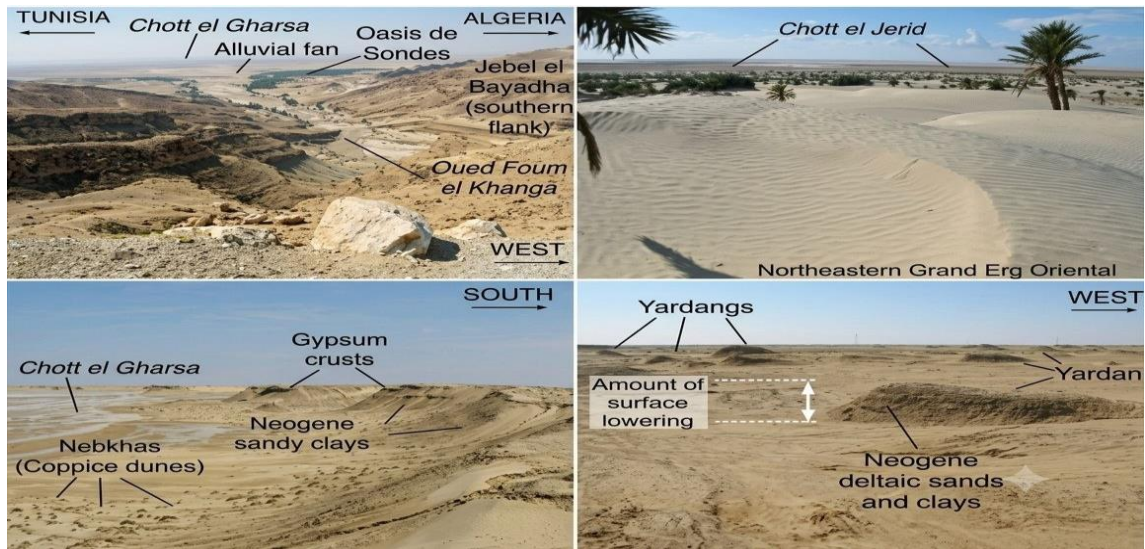


Figure 1.4 – The geomorphological conditions in the Sahara Desert, which are common sources of dust[3]

Remote sensing technologies have significantly improved the understanding of dust sources and distribution, using satellite systems such as TOMS, MODIS, and Meteosat, which enable large-scale monitoring of dust events. Nevertheless, these techniques are subject to limitations including cloud interference, difficulties in distinguishing dust from smoke, and uncertainties in accurately identifying emission sources [5] Anthropogenic sources of dust include intensive agriculture, overgrazing, deforestation, and land-use changes, as well as local modifications of climatic conditions. The contribution of human activity to dust emissions varies widely across regions, ranging from 0% to 50% globally, with stronger impacts observed in agricultural and disturbed land areas compared to natural desert environments [5] Finally, ongoing climate change, including rising temperatures, altered precipitation patterns, and changes in wind regimes, is expected to increase the frequency and intensity of dust storms in the future. This highlights the importance of understanding both sources and emission mechanisms of particulate matter for assessing their environmental and health impacts.

1.2 Temporal variability and long-range transport:

PM_{10} concentrations exhibit pronounced temporal variability across multiple time scales, including daily, monthly, seasonal, and interannual variations, as a result of the complex interplay between emission sources and meteorological conditions.

At the daily scale: PM_{10} levels are strongly influenced by short-term atmospheric dynamics such as wind speed, boundary layer height, temperature, and atmospheric stability. Low wind speeds

and stable atmospheric conditions typically favor the accumulation of particulate matter near the surface, whereas strong winds can either enhance dispersion or promote the resuspension of dust, leading to sudden increases in PM₁₀ concentrations [6].

In desert regions, particularly North Africa, the diurnal cycle of dust emissions is closely linked to boundary layer processes. Observational studies based on visibility records indicate that dust emission peaks typically occur during daytime (between 09:00 and 15:00), when convective activity intensifies and the boundary layer deepens, facilitating vertical mixing and dust uplift. In contrast, minimum dust activity is generally recorded during nighttime (21:00–03:00) due to reduced convection and more stable atmospheric conditions [5].

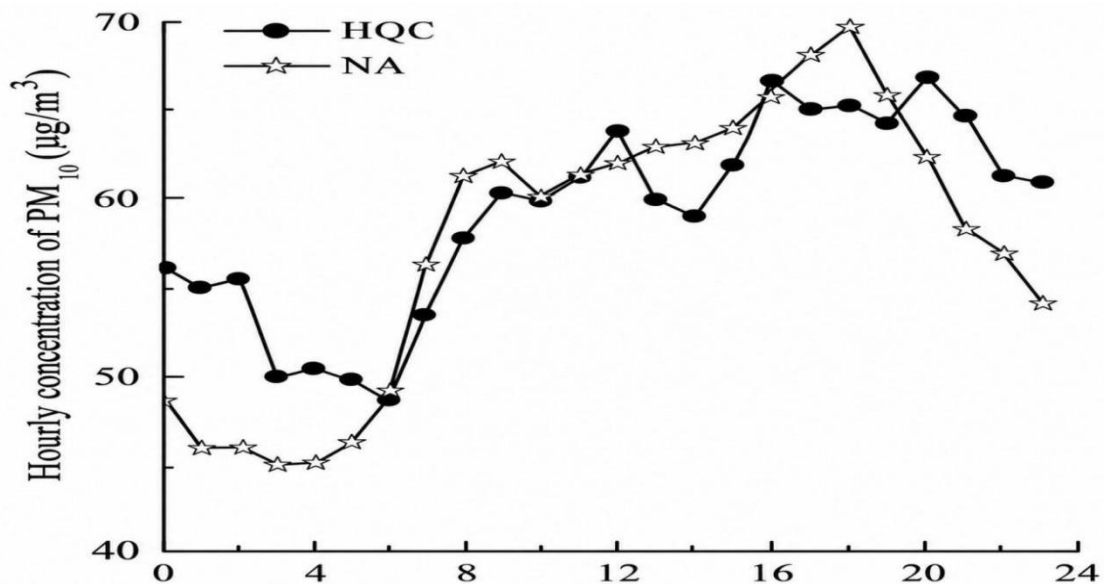


Figure 1.5 – Hourly variation in pm_{10} particles [7]

This image presents a graph illustrating the hourly variation of particulate matter (PM_{10}) concentrations over a 24-hour period, accompanied by an explanation from a scientific text commenting on this graph.

Analysis of the graph elements:

- **Horizontal Axis:** Represents the daily hours from 0 (midnight) to 24.
- **Vertical Axis:** Represents the hourly PM_{10} concentration in $\mu g/m^3$.
- **Curves:** The graph shows two curves representing two different locations or conditions: HQC (with black circular dots) and NA (with empty stars)

illustrates the daily pattern of PM_{10} concentrations, clearly showing the contrast in levels between daytime and nighttime hours and its impact on emission dynamics. At the monthly and seasonal scales: PM_{10} concentrations display well-defined cyclical patterns, often characterized by higher values during winter and spring and lower values during summer. This seasonal variability is largely attributed to increased dust activity and long-range transport during dry periods, reduced precipitation, and more stable atmospheric conditions in colder seasons, which limit pollutant dispersion. In contrast, summer conditions are generally associated with enhanced atmospheric mixing, stronger convection, and more effective wet deposition processes, leading to lower PM_{10} levels [pey2013african].

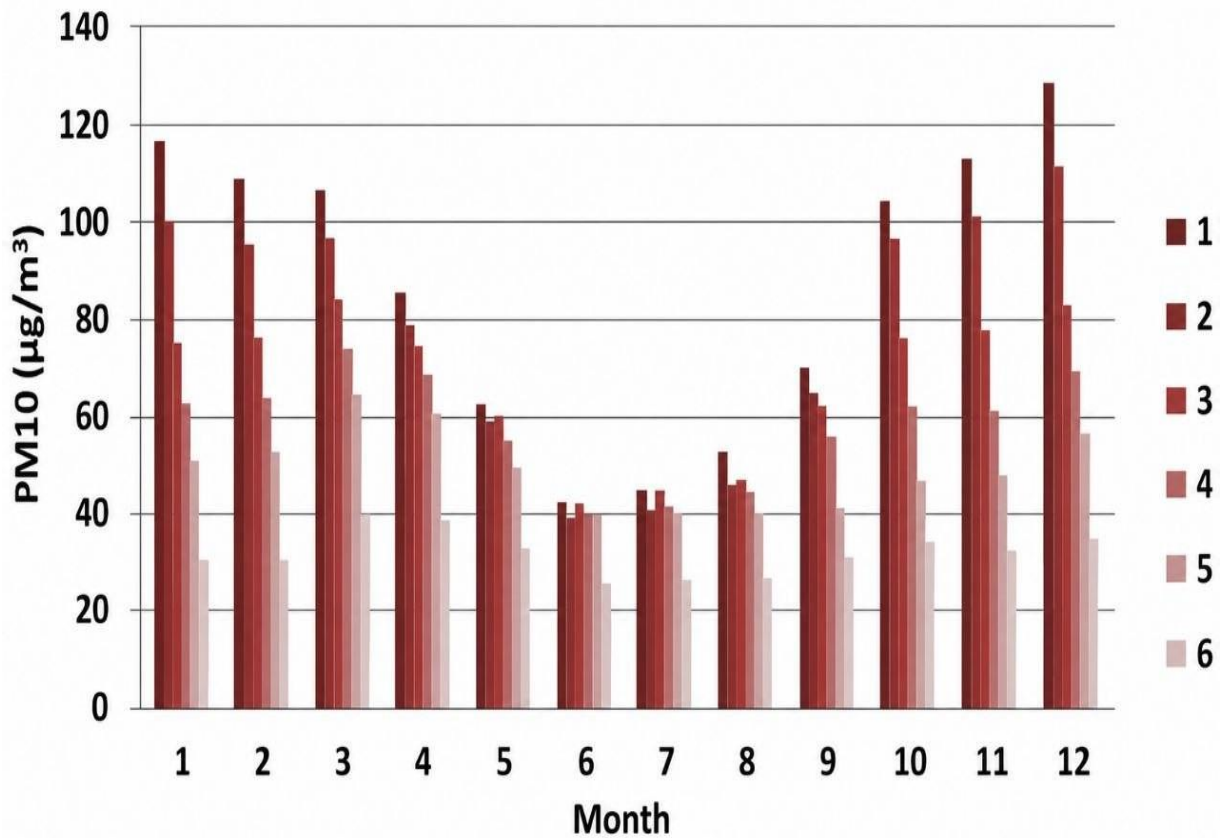


Figure 1.6 – Monthly variation in pm_{10} particles [8]

This graph illustrates the temporal variations in the average concentrations of particulate matter (PM_{10}), measured in micrograms per cubic meter ($\mu g/m^3$), across the twelve months of the year for the six clusters identified in the study.

Here is an analysis of the key points shown in the graph:

- **Horizontal Axis:** Represents the months of the year (1 to 12).
- **Vertical Axis:** Represents the PM_{10} concentration in $\mu g/m^3$.
- **Cluster Classification:** The color gradient, ranging from dark brown to light brown, represents the six clusters; Cluster 1 (the darkest color) represents the highest PM_{10} concentrations, while Cluster 6 (the lightest color) represents the lowest concentrations.

demonstrates the cyclical pattern of PM_{10} concentrations throughout the months, where higher values appear in winter and spring months and lower peaks in summer months, reflecting the influence of seasonal atmospheric processes. Furthermore, regional atmospheric circulation patterns play a key role in modulating these seasonal trends. In addition to seasonal patterns, intraseasonal variability is influenced by synoptic atmospheric systems such as African Easterly Waves (AEWs), which propagate westward and significantly contribute to dust uplift and transport [engelstaedter2006north]. At the interannual scale: PM_{10} variability is characterized by the absence of consistent long-term trends in certain regions, but with the occurrence of episodic peaks associated with intense dust events in specific years.

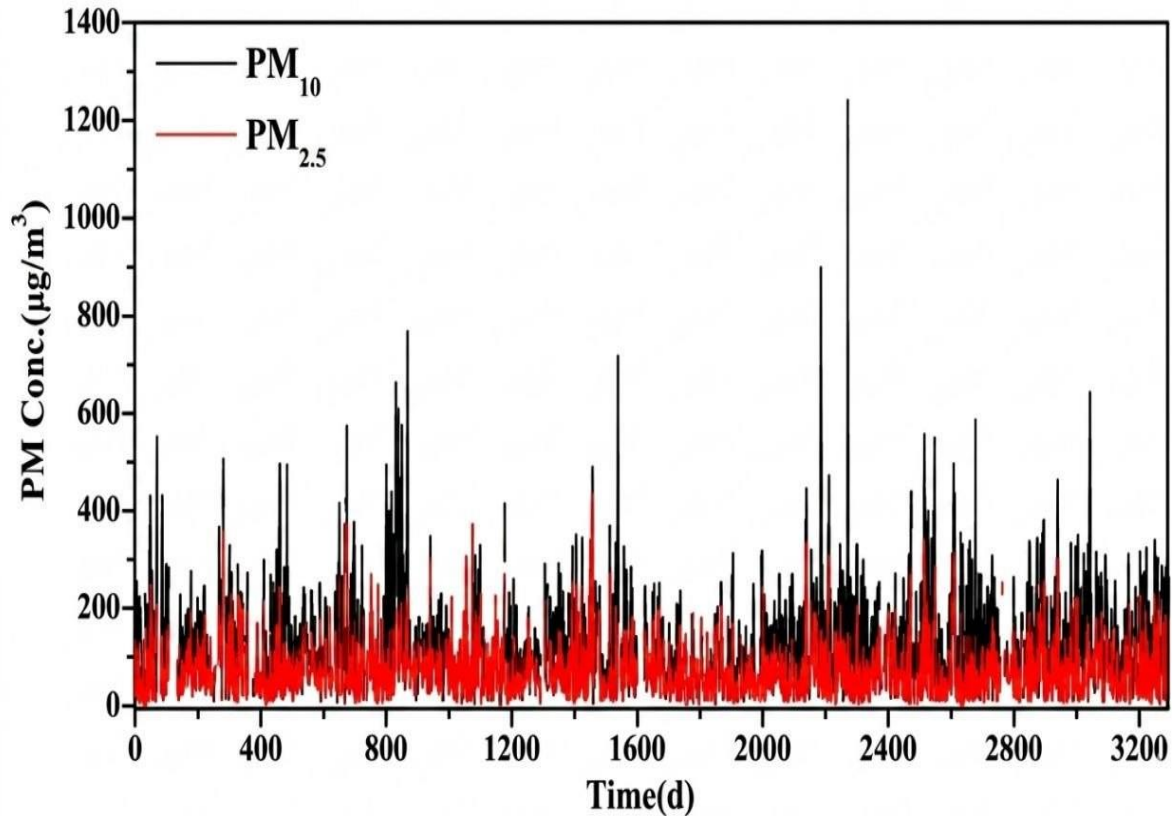


Figure 1.7 – Daily variation in pm10 particles [9]

shows the time series of particulate matter concentrations, where sharp episodic peaks that characterize intense dust events are evident, confirming the absence of fixed long-term patterns. These fluctuations are often linked to climatic variability and large-scale atmospheric circulation systems such as the North Atlantic Oscillation (NAO) [10].

Additionally, to seasonal patterns, intraseasonal variability (on time scales of several days) is influenced by synoptic atmospheric systems such as African Easterly Waves (AEWs), which propagate westward and significantly contribute to dust uplift and transport. These systems are estimated to account for a considerable fraction of dust entrainment and variability over the Atlantic, highlighting the importance of short-term atmospheric circulation patterns in modulating dust emissions and transport [5].

At the interannual scale, PM_{10} variability is characterized by the absence of consistent long-term trends in certain regions, but with the occurrence of episodic peaks associated with intense dust events in specific years. These fluctuations are often linked to climatic variability, including changes in precipitation patterns, drought frequency, and large-scale atmospheric circulation

systems such as the North Atlantic Oscillation (NAO), which influence dust emission and transport processes[10]

Satellite observations further reveal a pronounced annual cycle of dust emissions in North Africa, with distinct seasonal behaviors depending on source regions. For instance, some major sources such as the Bodélé Depression remain active throughout the year but exhibit peak emissions during specific months, while other regions show maximum activity during spring and summer and minimum levels during autumn. These spatial and temporal variations reflect the influence of regional meteorology, surface conditions, and atmospheric circulation patterns on dust emission processes [5].

In addition to temporal variability, long-range transport is a fundamental process controlling PM₁₀ concentrations, particularly in regions located far from primary emission sources. Mineral dust, which constitutes a significant fraction of PM₁₀, can be transported over thousands of kilometers from major source regions such as the Sahara Desert. This transport occurs through large-scale atmospheric circulation systems, most notably the Saharan Air Layer (SAL), a warm, dry, and dust-laden air mass that facilitates the westward movement of dust across the Atlantic Ocean and towards the Mediterranean Basin and Europe [3]. Such transboundary dust transport events can significantly elevate PM₁₀ concentrations on daily to seasonal time scales, even in areas with relatively low local emissions [11].

The efficiency and intensity of long-range transport processes are governed by several atmospheric factors, including wind strength, turbulence, vertical mixing, and boundary layer dynamics, which enable dust particles to be lifted to higher altitudes and remain suspended for extended periods. This enhances their potential for long-distance transport and widespread dispersio [12], Consequently, the interaction between multi-scale temporal variability and long-range transport mechanisms plays a crucial role in shaping the spatial and temporal distribution of PM₁₀ concentrations at both regional and global levels

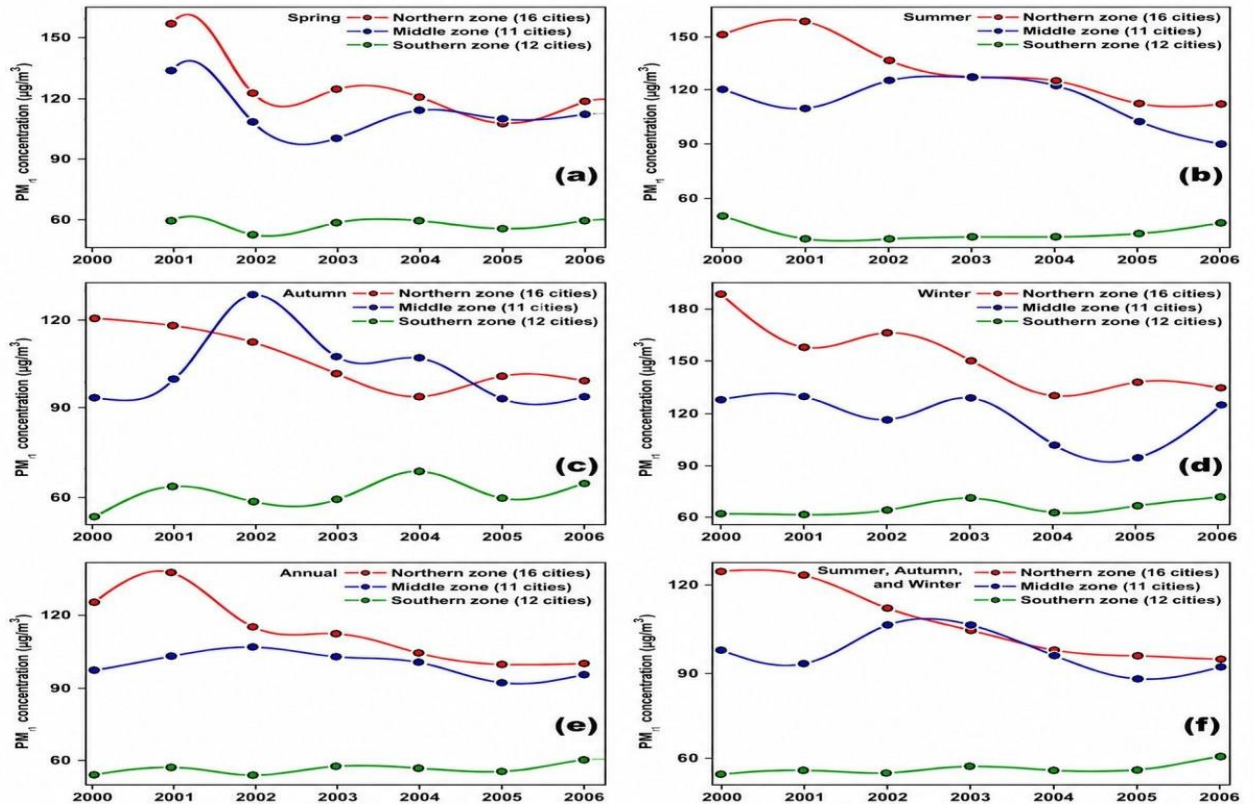


Figure 1.8 – Seasonal and annual variation in PM_{10} concentrations by geographical region (2000–2006) [13]

This image consists of a set of graphs illustrating the interannual variations (between 2000 and 2006) of average PM_{10} concentrations in urban areas of China, divided into three latitudinal zones: the Northern zone (in red), the Middle zone (in blue), and the Southern zone (in green).

Explanation of the image contents:

- **Graphs (a-f):** Display data for each season separately:
 - (a) Spring, (b) Summer, (c) Autumn, (d) Winter.
 - (e) Overall annual average.
 - (f) A combination of summer, autumn, and winter.
- **Horizontal Axis:** Represents the years from 2000 to 2006.
- **Vertical Axis:** Represents the PM_{10} concentration in $\mu g/m^3$.

1.3 Physical, Chemical, and Toxicological Characteristics of PM_{10} :

The physical and chemical properties of PM_{10} particles are the main determinants of their atmospheric behavior and health impacts. From a physical perspective, particulate matter is classified according to its aerodynamic diameter into different size fractions such as PM_{10} , $PM_{2.5}$, PM_1 , and $PM_{0.1}$. This size distribution governs their ability to remain suspended in the atmosphere, undergo long-range transport, and deposit within different regions of the respiratory system [14]. Physical characteristics such as particle size, shape, and density play a crucial role in deposition mechanisms, including impaction, sedimentation, and diffusion, which de-

termine how particles interact with the human respiratory tract [15]. Fine particles are also characterized by a high surface area-to-mass ratio, which enhances their ability to adsorb toxic substances and increases their biological reactivity [16]. Additionally, these characteristics allow particles to remain airborne for extended periods and be transported over long distances [16]. Chemically, PM₁₀ consists of a heterogeneous mixture of components including soluble inorganic species such as sulphates, nitrates, ammonium, and chlorides, as well as organic and elemental carbon [15]. These components originate from both natural sources, such as desert dust and marine or geological processes, and anthropogenic sources including combustion, industrial activities, and traffic emissions [14]. Advanced analytical techniques such as Particle Induced X-ray Emission (PIXE) have identified up to 24 chemical elements within PM₁₀, ranging from crustal elements like silicon, aluminum, iron, calcium, and magnesium, to toxic trace metals such as lead, cadmium, and nickel associated with human activities. Sulphates and nitrates are secondary particles formed through atmospheric oxidation of precursor gases such as SO and NO_x [16]. During dust events, the mineral fraction dominates, consisting mainly of quartz and clay minerals such as kaolinite and illite, with additional contributions from carbonates and iron oxides [17]. These secondary and mineral components may act as surface carriers for toxic compounds such as transition metals and organic pollutants, increasing their overall toxicity [16]. From a toxicological perspective, exposure to PM₁₀ is associated with a wide range of adverse health effects. Acidic components such as sulphates and nitrates can lead to the deposition of hydrogen ions in the respiratory tract, resulting in a reduction of local pH levels and irritation of lung tissues [16]. Epidemiological studies have demonstrated strong associations between exposure to these components and increased mortality as well as respiratory morbidity [16]. Furthermore, crystalline silica (quartz), which is abundant in the respirable fraction of mineral dust, can cause severe lung diseases such as silicosis, commonly referred to as “Desert Lung Syndrome” [17]. The toxicity of PM₁₀ is also strongly linked to oxidative stress mechanisms, where reactive oxygen species (ROS) are generated through redox-active components such as transition metals and organic compounds, leading to inflammation and cellular damage [16],[14]. Overall, the health impact of PM₁₀ is not determined solely by its chemical composition, but rather by the interaction between its physical properties and chemical constituents, which together govern its ability to induce oxidative stress and inflammatory

responses [16], [14].

1.4 The specific health effects of PM₁₀ particles:

Air pollution, particularly particulate matter (PM_{2.5} and PM₁₀), is considered one of the most significant environmental determinants contributing to the global burden of disease. International estimates indicate that approximately 3% of cardiopulmonary deaths and 5% of lung cancer deaths worldwide are directly attributable to exposure to particulate matter. In the European region, these proportions range from 1–3% for cardiovascular diseases and 2–5% for lung cancer [18]. Recent scientific evidence shows a growing health burden. In 2010, fine particulate matter (PM_{2.5}) was responsible for millions of premature deaths globally, contributing significantly to disability-adjusted life years (DALYs). From a population health perspective, exposure to PM_{2.5} reduces life expectancy in highly polluted regions. Conversely, reducing PM_{2.5} concentrations in accordance with World Health Organization guidelines could substantially increase life expectancy in urban areas with high pollution levels [18].

1.4.1 Spectrum of Health Effects:

From Acute to Chronic The health effects of air pollution vary widely, ranging from short-term acute impacts to severe long-term outcomes. Short-term exposure may lead to immediate respiratory and mucosal symptoms, including irritation of the eyes, nose, and throat, coughing, wheezing, and shortness of breath. It can also exacerbate chronic conditions such as asthma and cardiovascular diseases, and increase the risk of acute events such as myocardial infarction [2]. Long-term exposure, on the other hand, is associated with more severe and persistent health effects, including cancer development and structural and functional damage to several vital systems, particularly the respiratory, immune, nervous, and reproductive systems. In severe cases, chronic exposure to high concentrations of air pollutants may lead to premature death [18].

1.4.2 Respiratory Effects

The lungs represent the primary entry point for inhaled particles, and the severity of damage depends on the ability of these particles to penetrate deep into lung tissue. Fine (PM_{2.5}) and ultrafine particles (UFPs) can reach the alveoli and activate immune cells, leading to inflamma-

tory responses, cytokine release, and oxidative stress, resulting in tissue damage [2]. Long-term exposure to desert dust is associated with impaired lung function, increased mucus secretion, and chronic respiratory diseases such as asthma, chronic bronchitis, and chronic obstructive pulmonary disease (COPD) [2].

1.4.3 Cardiovascular Morbidity

The impact of particulate matter (PM₁₀, PM_{2.5}, PM₁) extends to the cardiovascular system through multiple physiological pathways. Epidemiological studies show that increased PM₁₀ concentrations are associated with a higher risk of myocardial infarction, acceleration of atherosclerosis, and vascular dysfunction [19]. Exposure to particulate matter also induces changes in heart rate variability, platelet activation, and coagulation processes, increasing the risk of ischemic stroke and cardiovascular mortality [19].

1.4.4 Proposed Pathophysiological Mechanisms

The toxicity of desert dust is explained by three main mechanisms: Systemic inflammation: caused by the release of inflammatory mediators from the lungs into the bloodstream [2]. Direct translocation: ultrafine particles crossing the air-blood barrier and entering circulation, leading to vascular and DNA damage [19]. Neural mechanisms: involving autonomic nervous system disruption and activation of sensory nerve reflexes due to toxic components in dust [2],[19].

1.4.5 Effects on Vulnerable Populations and Gender Differences

Children are more vulnerable due to incomplete lung development, while the elderly experience reduced clearance of inhaled particles, increasing respiratory complications during dust events [2]. Pregnant women are also at higher risk, as pollutants may cross the placenta and affect fetal development, increasing risks such as low birth weight and preeclampsia [19],[18].

1.4.6 Synergistic Effects and Mortality

Smoking and air pollution act synergistically, increasing cardiovascular risk and mortality by amplifying systemic inflammation and oxidative stress [19]. Air pollution remains responsible for a large number of premature deaths globally, but reductions in PM concentrations can significantly decrease mortality rates and improve public health outcomes [18].

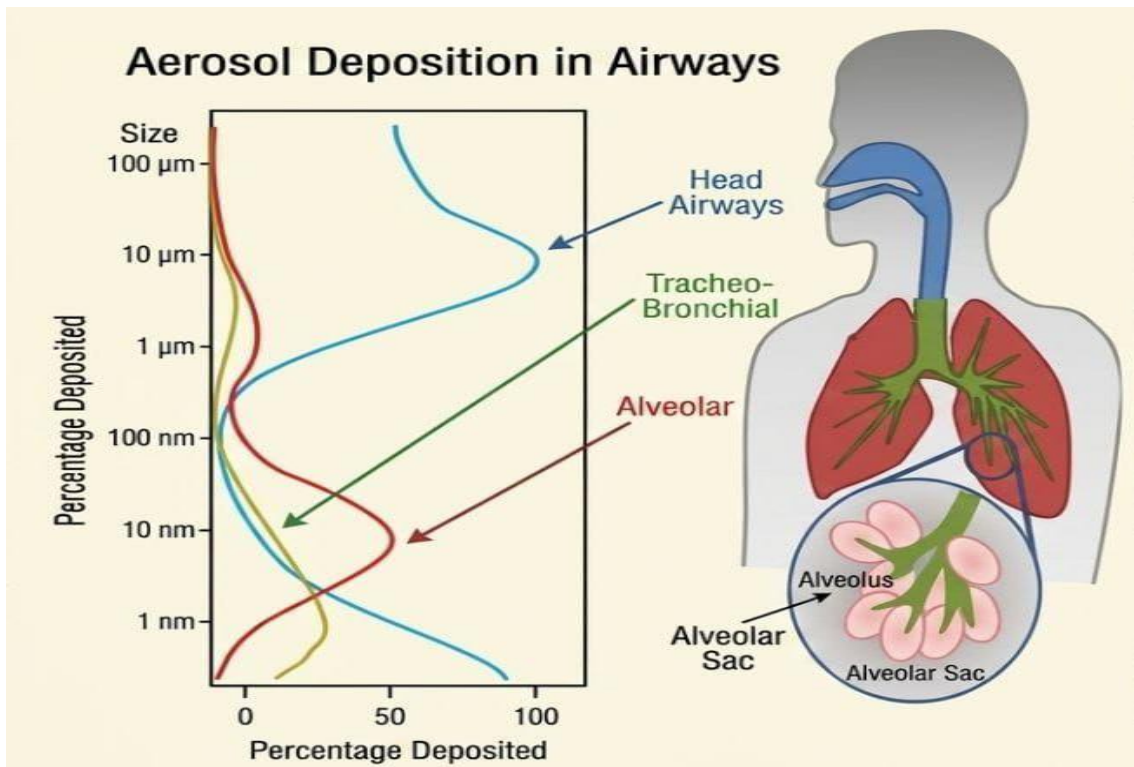


Figure 1.9 – The health effects of PM₁₀ particles on the human respiratory system[18].

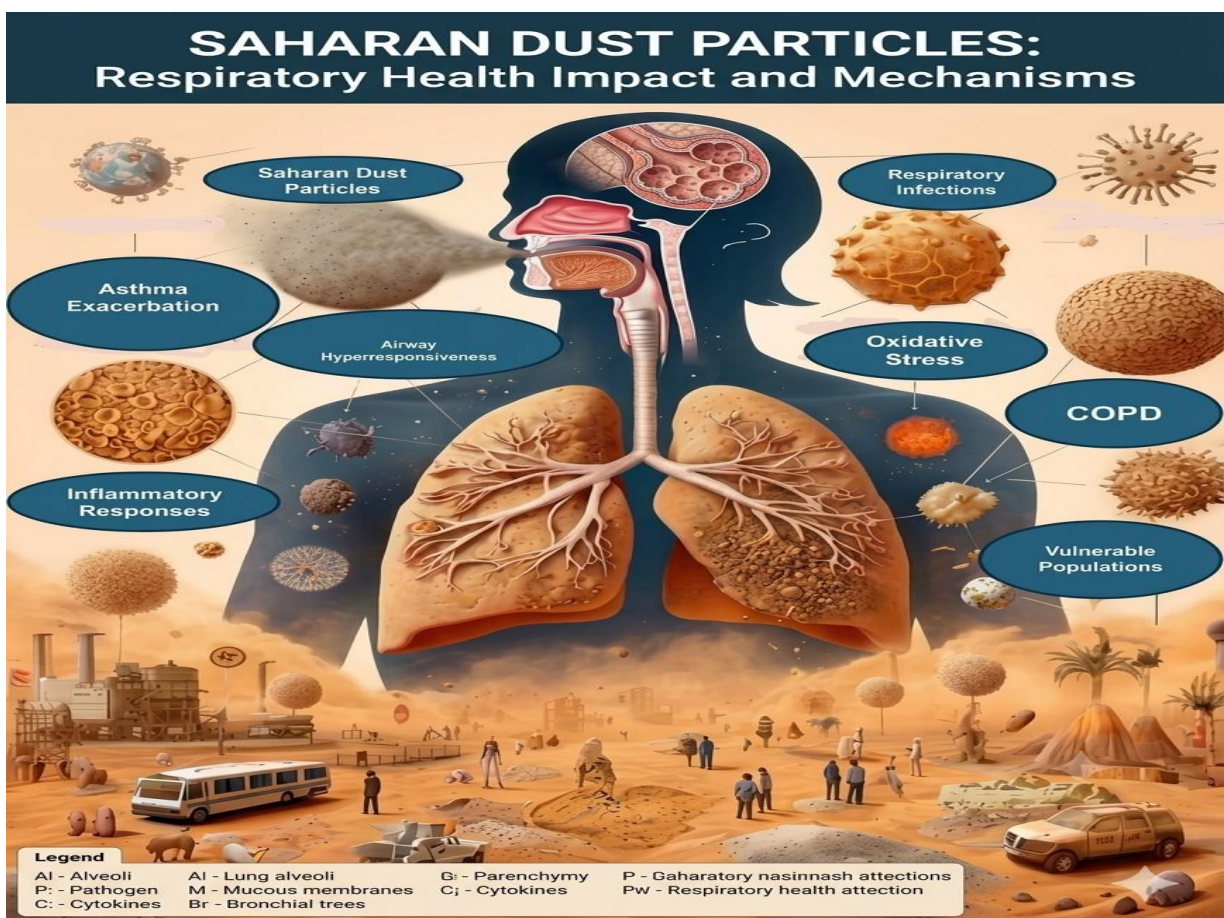


Figure 1.10 – Particle Size-Dependent Deposition in the Human Respiratory Tract [2].

*Theoretical Relations, Physical
Laws, and Health Dynamics of
Particulate Matter (PM_{10})*

2.1 Introduction and Atmospheric Behavior of PM₁₀

Particulate matter (PM₁₀) represents one of the most critical atmospheric pollutants in arid and semi-arid environments. It consists of solid or liquid particles with an aerodynamic diameter of less than 10 micrometers. Because of their microscopic physical size, these particles possess a remarkably low gravitational settling velocity, allowing them to remain suspended in the atmospheric column for extended periods. This aerodynamic stability enables air currents to transport them across vast regional domains, directly threatening air quality and public health in zones adjacent to major desert dust sources [16].

2.2 Soil Mechanical Properties and Particle Emission Dynamics

The initial detachment and emission of suspended mineral dust from the ground surface are strictly governed by the dynamic interaction between atmospheric wind shear stress and surface resistance. Based on the fundamental physical principles established by Bagnold [20], surface particles remain completely immobile until the wind friction velocity reaches a critical threshold, known as the Threshold Friction Velocity (u_{*t}). This threshold represents the minimum aerodynamic force required to overcome both gravitational forces and inter-particle cohesive forces within the soil. [21] demonstrated that this threshold velocity is not a static constant but a highly variable parameter governed by localized surface properties. This physical equilibrium is mathematically expressed through the following formulation:

$$u_{*t=A} = \sqrt{\left(\frac{\rho_p - \rho_a}{\rho_a}\right) g d_p} \quad (2.1)$$

Where:

u_{*t} : Threshold Friction Velocity.

A : A semi-empirical coefficient reflecting surface roughness and soil aggregate cohesion.

ρ_p : The particle density (estimated at approximately 2.65 g/cm³ due to the quartz-rich sandy nature of the Ouargla basin soil).

ρ_a : Ambient air density.

g : Acceleration due to gravity.

d_p : The representative soil grain diameter.

In the hyper-arid environment of the Ouargla region, this emission threshold is driven by four key environmental factors:

- **Wind Speed:** Providing the horizontal kinetic energy and drag forces necessary to initiate particle motion.
- **Soil Moisture:** While highly scarce in the Ouargla basin, moisture exponentially increases intermolecular cohesion between grains, thereby raising the required u_{*t} and suppressing dust generation [21].
- **Surface Vegetation Cover:** The absolute lack of vegetation over the local Erg and Reg landscapes leaves the topsoil highly vulnerable to continuous wind erosion and deflation.
- **Particle Size Distribution:** Controlling the aggregate weight and dictates whether a particle will resist motion or enter atmospheric transport.

2.3 Micro-Mechanical Mechanisms of Wind-Driven Transport

Once the critical friction velocity is exceeded, the movement of mineral dust ceases to be merely an isolated phenomenon; rather, it organizes into a coherent and sequential chain of four distinct mechanical processes [20]; [21]. The initiation and maintenance of these processes are governed by near-surface wind dynamics and physical soil properties, including surface texture, moisture content, and vegetation cover.

The efficiency of particle "entrainment" depends heavily on particle size; while gravitational forces hinder the movement of larger, heavier grains, finer particles require higher threshold wind velocities to overcome cohesive forces. Consequently, particle movement by wind manifests through four size-dependent mechanisms saltation, reptation (or ejection), suspension, and surface creep which are shaped by the interaction between horizontal wind flow and vertical turbulent fluctuations.[22]

2.3.1 Saltation

Saltation serves as the primary dynamic engine driving desert wind erosion. It involves the movement of medium-sized sand grains (ranging between 70 and 500 micrometers) that gain sufficient aerodynamic lift to detach from the surface, traveling along short, ballistic trajectories before gravity pulls them back to the ground [20]. Although saltating grains are too heavy

to remain suspended, their continuous bouncing action transfers massive amounts of kinetic energy back into the surface soil layer upon impact.

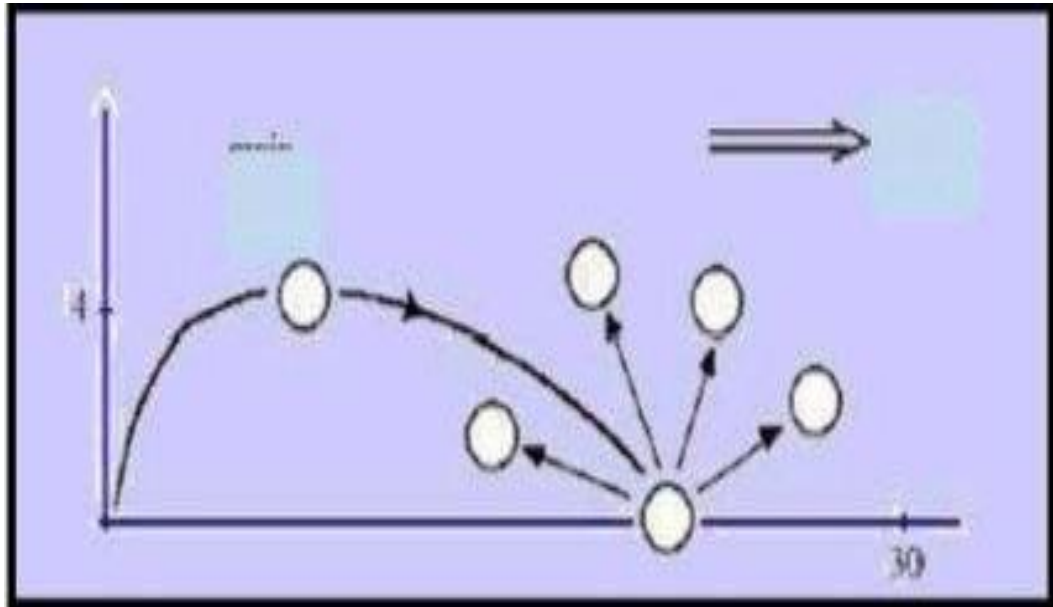


Figure 2.1 – Saltation process[22]

2.3.2 Sandblasting /Ejection :

Because fine particulate matter (PM₁₀) is bound together within the soil by powerful intermolecular forces (such as Van der Waals forces), direct wind force alone is fundamentally incapable of lifting these micro-particles into the air column [15]. Instead, the high-energy kinetic bombardment of saltating grains striking the ground—a process known as sandblasting—mechanically shatters dry clay and silt aggregates. This micro-destructive process releases the highly fine PM₁₀ fraction, making the dust emission flux directly proportional to the intensity of the saltation process [21], [15].

2.3.3 Atmospheric Suspension :

Following their release via sandblasting, fine PM₁₀ particles enter the atmospheric suspension stage. At this point, the terminal settling velocity of these tiny particles is significantly lower than the upward velocity of turbulent eddies and convective thermal currents. Consequently, they are lifted into the upper planetary boundary layer without returning to the ground, a phenomenon highly accelerated by the intense solar radiation and extreme summer thermal convection characteristic of the Ouargla region.

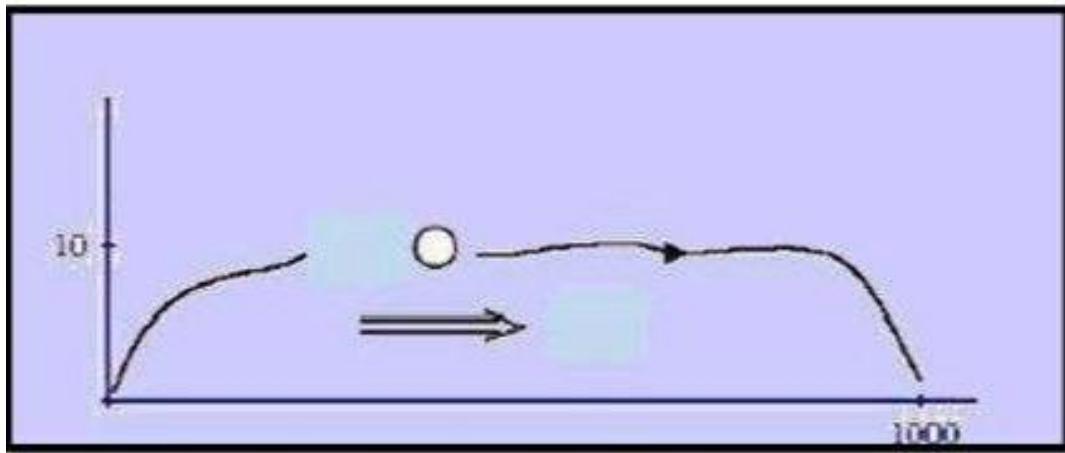


Figure 2.2 – Atmospheric Suspension process[22]

2.3.4 Surface Creep :

Surface creep is the mechanism responsible for the transport of coarse particles in desert environments, where the nature of particle movement varies according to size. For medium-sized particles (exceeding 0.5 mm in diameter), creep occurs via rolling or sliding along the surface, driven by the kinetic energy transferred from saltating grains and the direct impact of wind [23]. In contrast, for larger particles exceeding 2 mm in diameter, they are too massive to be lifted or transported via saltation; instead, they undergo horizontal sliding due to the shear stress exerted by the wind on the soil surface. While strong winds facilitate this sliding, these massive particles play a dual role: they act as a protective factor for the soil by increasing surface roughness, which reduces near-surface wind speed and limits the deflation of fine particles. This makes surface creep a vital component in understanding sedimentary dynamics and the mass balance of sediments in arid regions such as Ouargla, a phenomenon observed in broader studies of desert aerosol optical properties across Southern Algeria[22]

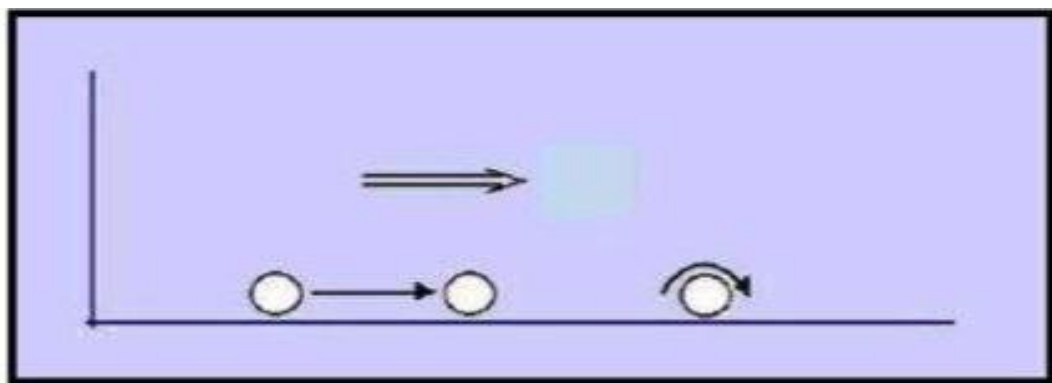


Figure 2.3 – Surface Creep process
[22]

2.3.5 The Sequential Chain

These mechanisms operate in a strictly dependent, cumulative sequence:

Saltation → Sandblasting / Ejection → Suspension → Surface Creep

Any increase in wind speed over the exposed landscapes of Ouargla triggers an exponential, compounded increase across this mechanical chain, directly explaining the massive, abrupt spikes observed in local PM₁₀ concentration data.

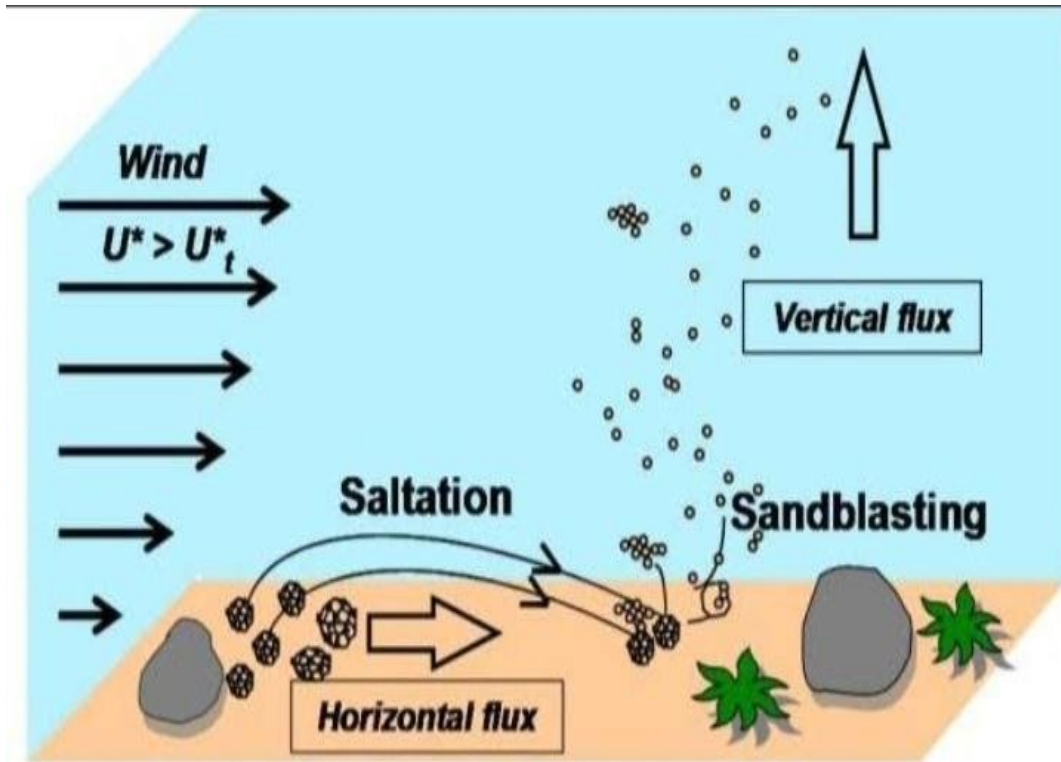


Figure 2.4 – Micro-mechanical stages of dust emission illustrating the sequence of wind-driven saltation, kinetic bombardment (sandblasting), and vertical atmospheric suspension. [21]

2.4 Modeling Particle Flux Emissions

To quantify the volume of fine dust entering the atmosphere, numerical models rely on calculating the vertical emission flux of suspended particles (F_a). This vertical flux is expressed as a direct function of the atmospheric friction velocity and the surface critical threshold [15]:

$$F_a = C(\rho_a/g)u^{*3}(1 - u_t^*/u^*)(1 + u_t^*/u^*)^2; \quad (u^* > u_t^*) \quad (2.2)$$

Where (u_*) represents the current wind friction velocity, and C is an empirical erodibility constant specific to the soil characteristics of the studied zone. This cubic relationship [(u_*)³] highlights that minor escalations in ambient wind speeds generate exponential surges in vertical PM₁₀ emissions during regional dust storm events.

2.5 Emitted Size Distribution Theory

Predicting the precise size distribution of dust aerosols at the moment of emission is a fundamental requirement for accurate environmental modeling. Historically, traditional climate simulations assumed that the size distribution of emitted dust shifted dynamically with changes in wind speed. However, [24] revolutionized this field by establishing a universal scaling theory rooted in the fracture mechanics of brittle materials.

Kok [24] proved that the physical fragmentation of soil aggregates during the sandblasting process yields a stable, invariant particle size distribution that remains independent of ambient wind speeds. This research revealed that older atmospheric models systematically underestimated the volume of coarser dust fractions entering the global cycle. For regional assessments in hyper-arid zones like Ouargla, applying Kok's scaling theory prevents underestimation, ensuring a highly precise tracking of the total suspended mass of PM₁₀ overhead [24].

2.6 The Advection-Diffusion Equation for Atmospheric Dispersion

The continuous spatial-temporal transport, mixing, and dispersion of PM₁₀ across the three-dimensional air basin of Ouargla are mathematically governed by the Eulerian advection-diffusion differential equation [21]:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} = \frac{\partial}{\partial x} K_x \frac{\partial C}{\partial x} + \frac{\partial}{\partial y} K_y \frac{\partial C}{\partial y} + \frac{\partial}{\partial z} K_z \frac{\partial C}{\partial z} + S - R \quad (2.3)$$

Where:

- C: The mass concentration of PM₁₀ at any given spatial coordinate (x, y, z) and time t.
- u, v, w: The components of the fluid wind velocity vector across the three spatial dimensions.

- K_x, K_y, K_z: The turbulent diffusion coefficients of the atmosphere, representing turbulent eddy mixing.
- S: The net source term, representing local mechanical dust emissions from sand dunes and dry basins.
- R: The sink term, representing particle removal through wet or dry atmospheric deposition processes.

2.7 Atmospheric Deposition Mechanisms

Suspended PM₁₀ particles are eventually removed from the atmosphere via dry deposition, which is driven by a balance between gravitational pull and aerodynamic fluid drag resistance. The Terminal Settling Velocity (V_s) for particles in this size range is determined using the Modified Stokes' Law, incorporating a correction factor for micro-scale interactions [15]:

$$V_s = \frac{\rho_p d_p^2 g C_c}{18\mu} \quad (2.4)$$

Where μ represents the dynamic viscosity of air, and C_c is the dimensionless Cunningham Correction Factor. This factor must be integrated because PM₁₀ particles are small enough to physically slip between individual ambient air molecules, calculated as follows:

$$C_c = 1 + \frac{2\lambda}{d_p} \left[1.257 + 0.40 \exp \left(-1.10 \frac{d_p}{2\lambda} \right) \right] \quad (2.5)$$

Where λ is the mean free path of *airmolecules* = 0.066micrometers). Due to the microscopic scale of d_p , the resulting terminal settling velocity (V_s) remains exceptionally low. This mechanical property dictates that PM₁₀ requires extended periods to drop out of suspension by gravity alone, prolonging the duration of human exposure to these inhalable crustal pollutants following a desert storm.

2.8 Remote Sensing Estimation and Aerosol Optical Depth (AOD)

Because ground-based monitoring infrastructure is often limited in expansive desert terrains, tracking spatial-temporal variations of PM₁₀ in the Ouargla region requires a physical

integration of surface measurements with satellite-derived Aerosol Optical Depth (AOD) data. This relationship is modeled through the following vertical physical column formulation:

$$PM_{10} = \frac{AOD}{PBLH f(RH) Q_{ext}} \quad (2.6)$$

Where:

- PBLH: The Planetary Boundary Layer Height, establishing the vertical volume available for dust mixing.
- $f(RH)$: A hygroscopic growth factor adjusting for ambient relative humidity.
- Q_{ext} : The specific mass extinction efficiency characteristic of Saharan mineral dust particles.

2.9 Environmental and Climatic Drivers in Ouargla

The seasonal trends of PM₁₀ concentrations within the Ouargla basin are highly sensitive to regional meteorological conditions. The most dominant driver is the frequent blowing of the "Sirocco"—a highly hot, hyper-dry southerly wind that triggers severe sandstorms during the spring and summer seasons, driving surface dust concentrations to extreme microgram peaks. Conversely, during winter nights, the atmospheric column transitions into high stability, accompanied by intense surface thermal inversion layers that trap localized urban and crustal PM₁₀ emissions close to the ground.

2.10 Epidemiological Dynamics and Public Health Impact Assessment

The severe temporal variations of desert PM₁₀ concentrations in the Ouargla region have a documented, direct impact on human health, manifesting as sharp influxes in daily hospital emergency room admissions for acute respiratory distress. Because these crustal particles possess an aerodynamic diameter under 10 micrometers, they successfully bypass upper respiratory filtration systems, penetrating deeply into the bronchial tubes and triggering severe pulmonary inflammation [25].

According to the World Health Organization [26], chronic and acute exposures to mineral

dust particles are major environmental risk factors for cardiovascular disorders, lung cancer, asthma, and Chronic Obstructive Pulmonary Disease (COPD). To mathematically and statistically quantify these health impacts, three standard biostatistical models are applied:

2.10.1 The Relative Risk (RR) Model

To evaluate the excess probability of a population contracting respiratory illnesses due to a specific incremental increase in dust concentrations (e.g., per 10 micrograms/m³ rise in PM₁₀), epidemiological studies utilize the following exponential dose-response relationship [26]:

$$RR = \exp[\beta(C - C_0)] \quad (2.7)$$

Where:

- Beta: The health risk coefficient derived from local empirical time-series data.
- C: The current daily mass concentration of PM₁₀ measured in the Ouargla atmosphere.
- C₀: The baseline reference concentration deemed safe by international health guidelines [26].

2.10.2 The Attributable Fraction (AF)

To isolate the exact proportion of total medical emergency cases in local hospitals that can be blamed solely on air pollution levels exceeding safe boundaries, the Attributable Fraction is derived [26]:

$$AF = \frac{RR - 1}{RR} \quad (2.8)$$

2.10.3 The Poisson Regression Model for Time-Series Analysis

Given that daily hospital admission counts are discrete, non-negative integer data, the non-linear relationship linking daily patient numbers to temporal PM₁₀ spikes and confounding meteorological variables is modeled using a log-linear Poisson regression framework [25]:

$$\ln(E(Y_t)) = \beta_0 + \beta_1[PM_{10}]_{t-l} + \beta_2(T_t) + \beta_3(RH_t) + ns(\text{time}) \quad (2.9)$$

Where:

- $E(Y_t)$: The expected number of respiratory hospital admissions on day t .
- $PM_{10}(t - l)$: The dust concentration variable integrated with a time-lag (l) of several days, accounting for the delayed physiological response of human lung tissues following exposure to a sandstorm.
- (T_t) and (RH_t) : Co-variables adjusting for ambient daily temperature and relative humidity.
- $ns(\text{time})$: A natural cubic smoothing spline function implemented to isolate and remove confounding long-term seasonal trends that are independent of mineral dust variations.

The life cycle and temporal fluctuations of PM_{10} in the Ouargla air basin are governed by an intricate web of physical laws and mathematical models. They span from initial threshold velocities [20], [21] and mechanical sandblasting emissions [15] to structural size distributions [24] and advection dispersion equations. When these mechanical laws are linked with health risk assessments including Relative Risk and Poisson time-series frameworks they provide a comprehensive, multi-disciplinary paradigm. This framework successfully traces Sa-haran dust from its geomorphic origins on the desert floor directly to its acute and chronic physiological impacts on the exposed human population [26], [25].

*Detection Methods and
Measurement Instruments for
Particulate Matter PM_{10} :*

3.1 Particulate Matter PM₁₀ :

Particulate Matter (PM) is considered one of the most critical air pollutants, significantly impacting human health and the environment. This is especially true for particles with an aerodynamic diameter of less than 10 micrometers PM₁₀, which can penetrate deep into the respiratory system, causing severe respiratory and cardiovascular diseases. Consequently, continuous measurement and monitoring of PM₁₀ concentrations have become essential for evaluating air quality and formulating appropriate environmental policies. The measurement of PM₁₀ relies on a variety of techniques and instruments that differ in their operating principles, accuracy, and response times. These range from traditional filter-based gravimetric methods to modern automated methods that provide continuous, real-time measurements by utilizing the optical, radiative, or oscillatory properties of the particles [27], [28].

3.2 Gravimetric Method

The gravimetric method is recognized worldwide as the primary reference method for measuring PM₁₀ and PM_{2.5} concentrations. It relies on collecting particles onto specific filters and determining their mass by weighing the filters before and after the sampling period. In this method, a known volume of ambient air is drawn by a pump through a filter—typically made of glass fiber or polytetrafluoroethylene (PTFE/Teflon)—causing the particles to deposit on the filter surface. Upon completion of the sampling cycle, the filter is re-weighed using a highly sensitive microbalance. The mass concentration is then calculated from the net mass gain divided by the total volume of sampled air [27], [29], [30]. Academic studies frequently utilize low-volume samplers, such as the U.S. EPA-approved Partisol Model 2000, which operates at a volumetric flow rate of approximately 16.7 L/min and uses Teflon-coated Pallflex TX40 filters. Filters are weighed using analytical microbalances, such as the Mettler Toledo AT201 or the Cahn C-32 microbalance, which feature a sensitivity of up to $\pm 1\mu\text{g}$. Prior to weighing, filters are conditioned in a climate-controlled environment with stabilized temperature and relative humidity to ensure measurement precision [27], chaloulakou2003measurements, [29]. In addition to low-volume systems, High-Volume Samplers operating at significantly higher volumetric flow rates of up to $1.13\text{m}^3/\text{min}$ (1130L/min) are widely deployed. The paramount importance of these high-volume systems lies in their ability to collect substantial dust mass

over short intervals. This is essential for conducting subsequent high-precision chemical and mineralogical analyses (such as X-ray Diffraction [XRD] or Scanning Electron Microscopy [SEM]) to identify the core mineral components of desert dust, such as quartz, kaolinite, and illite [29], [30]. While the gravimetric method is highly accurate and universally accepted as the standard reference, it suffers from a lack of temporal resolution, as sampling periods typically extend over 24 hours. Furthermore, in arid and desert environments, this method faces severe challenges regarding early filter clogging and heavy loading due to extreme dust concentrations during sandstorms. This clogging can induce flow rate drops and compromise subsequent concentration calculations [27], [30].

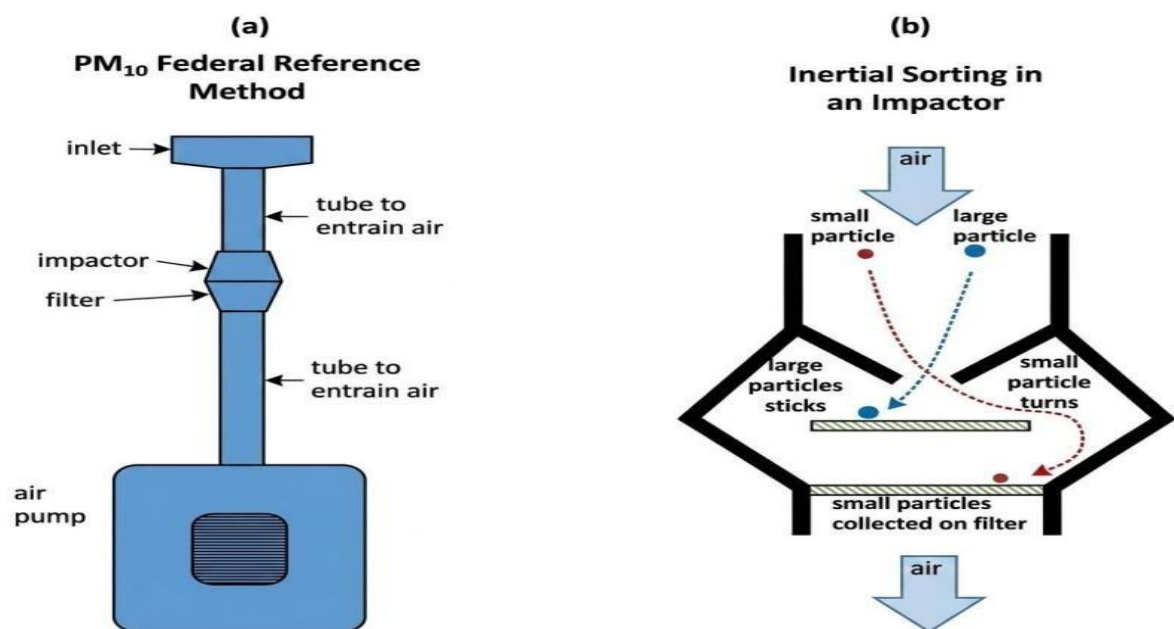


Figure 3.1 – Schematic workflow of the gravimetric reference method for PM₁₀, illustrating the field sampling, filter conditioning, and analytical microgravimetric weighing. [27]

3.3 Optical Methods

Optical instruments rely on the interaction between particles and light, where particles scatter or absorb light as they pass through a light beam. These instruments are highly valued for their ability to provide instantaneous and continuous real-time monitoring of particulate concentrations [31, 30].

3.3.1 Light Scattering Photometers (Nephelometers)

In these instruments, the sample air stream passes through a sensing chamber illuminated by a light source, typically a laser diode. When the light beam hits the particles, light scattering occurs at a specific angle.

Photodetectors measure the intensity of this scattered light and convert it into an electrical signal that is directly proportional to the mass concentration of the particles [31, 30].

Widely used commercial examples include DustTrak, DataRAM 4, and SidePak AM510. The DustTrak monitor provides real-time mass concentrations for PM₁₀ and PM_{2.5} and features an isolated optical chamber that prevents lens contamination. The DataRAM 4, in addition to measuring mass concentration, estimates the median particle size, ambient temperature, and relative humidity [31].

Despite their high temporal resolution, their accuracy is highly dependent on aerosol physical characteristics. In arid and desert regions, a critical drawback emerges: these monitors rely on factory calibrations using standard urban or industrial dust (such as Arizona Road Dust), which differs fundamentally in its refractive index and density from natural desert mineral dust. Consequently, optical instruments frequently overestimate or underestimate actual PM₁₀ mass concentrations during dust events. This necessitates the derivation of a local correction factor via side-by-side field co-location with primary gravimetric reference instruments [31, 30].

3.4 Optical Particle Counters (OPC)

Optical Particle Counters (OPCs) operate by illuminating individual particles one at a time as they pass through a narrowly focused laser beam. The light scattered by each individual particle is collected by a photodetector. The intensity of the resulting electrical pulse is then used to simultaneously determine both the size (diameter) and the number concentration of the particles [31, 30].

These instruments are extensively used to resolve the particle size distribution, particularly in urban and industrial environments. The physical size of the particle is determined based on a pre-established calibration curve that relates the scattered light intensity to an equivalent optical sphere diameter [31].

3.5 Condensation Particle Counters (CPC)

Condensation Particle Counters (CPCs) are designed to measure ultrafine and nanoparticle concentrations that are too small to be directly detected by standard OPCs. The operating principle involves passing the sample through a heated saturator filled with a working fluid vapor (such as butanol or water). The aerosol stream is then cooled in a condenser, causing the vapor to become supersaturated and condense onto the tiny particles, growing them into larger droplets [31, 30].

Once these particles grow to an optically detectable size, they pass through a conventional laser detection block where they are individually counted. This technique is highly efficient for tracking number concentrations down to the nanometer scale [32].

3.6 Tapered Element Oscillating Microbalance (TEOM)

The TEOM monitor is one of the most prominent instruments used for the continuous, real-time measurement of PM₁₀ and PM_{2.5} mass concentrations. It operates on the principle of an oscillatory microbalance, where ambient particles are continuously deposited onto a filter cartridge exchangeably mounted on the tip of a hollow, tapered glass element that oscillates at a fixed natural frequency [31].

As particle mass accumulates on the filter, the total mass of the tapered element increases, causing its oscillating frequency to decrease. The instrument precisely measures this frequency shift and directly converts it into the mass of the deposited particles. The mass concentration is then calculated in real time using the precise volumetric flow rate of the sampling air [27, 31].

However, a known limitation of the standard TEOM system is its potential to underestimate mass due to the loss of volatile and semi-volatile particulate matter because the filter element must be heated (typically to 50°C). Furthermore, under intense desert dust storms, the rapid and massive accumulation of coarse mass on the filter can heavily stress the tapered element and cause rapid filter saturation, demanding frequent manual filter cartridge replacements [27, 31].

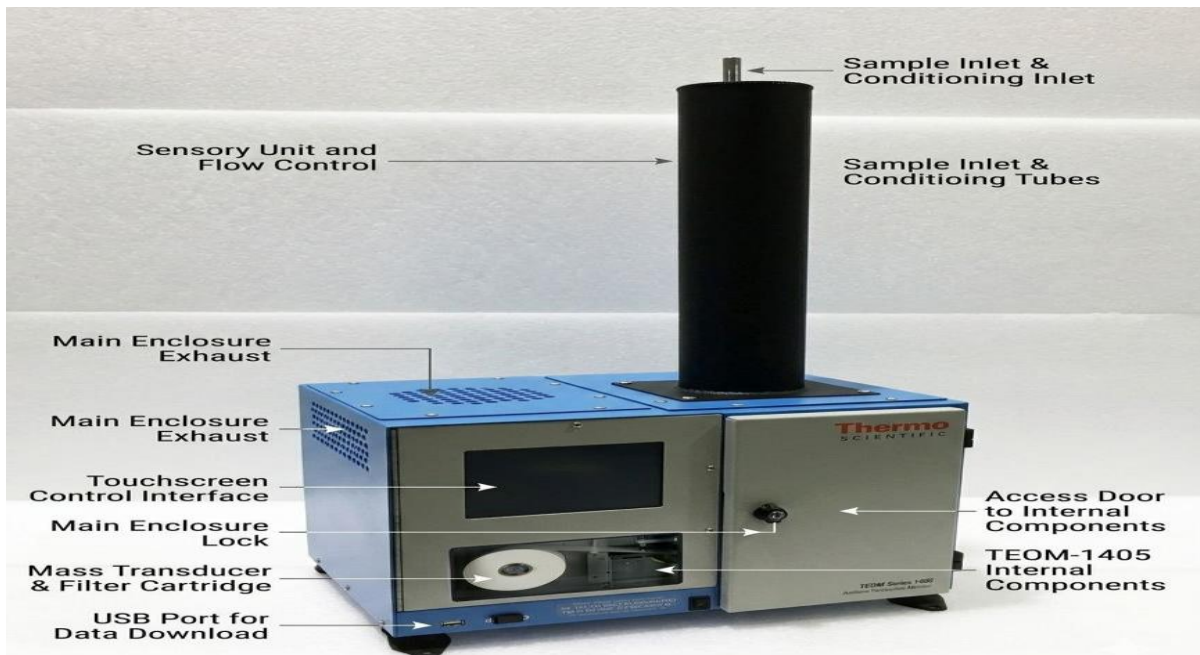


Figure 3.2 – Technical component layout and interface features of the Thermo Scientific TEOM-1405 analyzer. [31].

3.7 Beta Attenuation Monitors (BAM)

The BAM instrument is widely deployed in regulatory ambient air quality monitoring networks globally for continuous, automated PM₁₀ and PM_{2.5} measurements. It is formally designated as a Federal Equivalent Method (FEM) by the U.S. EPA [32].

3.7.1 Operating Principle of the BAM

The BAM utilizes the physics of beta radiation attenuation. It quantifies the mass of ambient particulate matter collected on a continuous fiberglass filter tape by measuring the reduction in beta ray intensity passing through the sample [32].

A beta source—typically Carbon-14 (¹⁴C)—emits beta particles through the clean filter tape to establish a baseline intensity (I_0). Ambient air is then sampled through the size-selective PM₁₀ inlet, depositing particles onto that specific spot on the tape. At the end of the sampling period, the beta ray intensity (I) passing through the dust-laden tape is measured again. The accumulation of particulate mass attenuates (absorbs) the beta particles according to the exponential Beer-Lambert law [32].

The instrument utilizes the following mathematical relationship to calculate the deposited mass density:

$$m = (1/\mu) \ln(I_0/I) \quad (3.1)$$

Where the variables are defined as:

- m : The mass density of the deposited particles per unit area (mg/cm²).
- μ : The beta ray mass attenuation coefficient (cm²/mg).
- I_0 : The initial beta particle count through the clean filter tape.
- I : The final beta particle count through the particle-laden filter tape.

Once the mass density (m) is determined, the internal electronic processor combines it with the total volumetric sample flow rate and sampling time to compute the definitive ambient PM₁₀ mass concentration ($\mu\text{g}/\text{m}^3$) [32].

3.7.2 Instrument Components, Advantages, and Limitations

The BAM system consists of a steady beta source (¹⁴C), a sensitive photodetector, a motorized filter tape mechanism, a regulated volumetric flow system, and an integrated microprocessor control unit. It provides automated, continuous hourly mass concentration updates with minimal field intervention [32].

However, its primary limitation in desert environments involves its susceptibility to elevated relative humidity—which induces hygroscopic growth in collected clay particles—alongside the issue of accelerated filter tape consumption. During severe dust storms, the sudden accumulation of massive dust loads can exceed the linear detection range of the beta counter. To maintain measurement linearity, the instrument is forced to automatically advance the tape and change the sampling spot prematurely. This significantly increases tape consumption and elevates routine field maintenance requirements [32]. Implementing a smart inlet heater that regulates the sample stream's relative humidity to below 35% effectively resolves moisture artifacts and optimizes accuracy [32].



Figure 3.3 – Detailed component layout and assembly of the Met One BAM-1020 particulate monitor. [32].

3.8 Particle Size Distribution Analyzers

3.8.1 Scanning Mobility Particle Sizer (SMPS)

The Scanning Mobility Particle Sizer (SMPS) measures particle size distribution based on the electrical mobility of charged particles. The aerosol sample is first passed through a neutralizer to establish a known steady-state charge distribution. The particles then enter a Differential Mobility Analyzer (DMA), which separates them sequentially according to their electrical mobility by ramping an applied voltage. The classified particles are subsequently counted by a Condensation Particle Counter (CPC) [31, 30].

3.8.2 Fast Mobility Particle Sizer (FMPS)

The FMPS operates on an electrical mobility separation principle similar to the SMPS, but it is optimized for high-speed, transient data collection. Instead of sequentially scanning voltages, the FMPS utilizes a parallel array of highly sensitive electrometers (Electrometer array). This allows the instrument to collect the electrical currents of differently sized particles simultaneously, yielding a complete size distribution profile with a temporal resolution of up to 1 second,

making it ideal for capturing immediate shifts during early dust emissions or combustion plumes [32, 31].

3.8.3 Aerodynamic Particle Sizer (APS)

The Aerodynamic Particle Sizer (APS) evaluates the aerodynamic diameter of particles based on their inertial behavior in an accelerating flow field. The aerosol sample is drawn through an accelerating nozzle, causing particles to exit into a detection zone where they cross two parallel laser beams. The instrument records this “time-of-flight” between the two beams to calculate the aerodynamic size. The APS excels at resolving particles within a size range of 0.5 to 20 micrometers, which is the perfect window for monitoring coarse desert dust dynamics transported via saltation and suspension mechanisms [31, 30].

3.9 Particle Surface Area Monitors

Nanoparticle Surface Area Monitors (NSAM) are specialized instruments designed to evaluate the lung-deposited surface area (LDSA) of ultrafine particles. In this technique, particles are exposed to a cloud of unipolar ions, acquiring an electrical charge that is directly proportional to their available surface area. The total electrical current of the sampled aerosol is then measured using a highly sensitive electrometer. The resulting signal correlates directly with the aggregate surface area concentration of the particles [30].

The instrumentation and methodologies for detecting and measuring PM₁₀ concentrations span a wide spectrum, ranging from classic manual reference techniques to sophisticated, high-resolution automated systems. Ultimately, selecting the optimal instrumentation configuration depends strictly on the specific research objectives, data quality requirements, and ambient environmental conditions of the monitoring site. In arid and desert environments, a comprehensive understanding of optical sensor limitations, the crucial need for localized calibrations, and the mechanics of filter loading in continuous monitors (TEOM and BAM) is vital to ensuring the validity and scientific integrity of recorded atmospheric datasets [27, 31, 30, 32].

3.10 Remote Sensing: Principles, Spaceborne, and Ground-Based Systems

The network uses AERONET, and the missions MODIS and CALIOP to determine the optical thickness and vertical profile of dust.

Remote sensing technologies constitute the fundamental pillar and modern toolkit for atmospheric studies, particularly in investigating aerosols and suspended particulate matter. These techniques enable continuous monitoring and analysis over vast temporal and spatial scales that conventional in-situ ground-based measurements cannot fully cover [33].

These technologies rely on analyzing and interpreting the interaction of electromagnetic radiation with atmospheric particles through absorption and scattering processes, allowing the retrieval of precise physical and optical characteristics of the atmospheric column [33]. Consequently, remote sensing has become an essential component in climate research and air quality applications, integrates to provide critical environmental parameters, including:

- Aerosol Optical Depth (AOD or τ_a).
- Horizontal and geographical distribution of dust and atmospheric pollutants.
- Temporal and spatial variations of dust storms.
- Vertical profiles of particulate matter as a function of altitude.
- Reflectance properties, complex refractive index, and the ecosystem's radiative forcing [34, 35, 36, 33].

3.11 The AERONET Network and Ground-Based Spectroscopic Measurements (Holben et al., 1998)

The AERONET (Aerosol Robotic Network) is considered a global reference network for measuring aerosol properties. It represents the primary worldwide ground-based standard for characterizing particulate matter and validating satellite observations. Developed as a federated network, it unites international scientific institutions under the management of NASA and the French National Center for Scientific Research (CNRS) to provide standardized, unified data [34].

According to Holben et al. (1998), the network consists of automated, robotically controlled Sun/Sky radiometers designed to track the solar disk precisely and withstand extreme weather conditions. These instruments measure direct solar radiance at multiple wavelengths (typically

ranging from 340 nm to 1020 nm). The academic strength of the network lies in its standardization of calibration protocols, centralized data processing, and public access to its real-time archive [34].

3.11.1 Physical Principle of Operation

AERONET relies on the principle of direct spectral measurement of solar radiation. The intensity of solar radiation reaching the Earth's surface is recorded and compared with the calibrated extraterrestrial radiance derived via the "Langley plot" method. By applying the Beer-Lambert-Bouguer law, the Aerosol Optical Depth (AOD) is calculated by isolating the contributions of suspended particulate matter and filtering out the effects of molecular Rayleigh scattering and atmospheric gas absorption (such as ozone and water vapor). The retrieved AOD value expresses the total magnitude of light extinction and serves as a direct proxy for dust loading intensity throughout the atmospheric column [34].

3.11.2 Network Significance and Applications

In addition to AOD, the instrument measures sky radiance at various angles (Almucantar and Principal Plane protocols). These data are utilized in inversion algorithms and within network applications to:

- Monitor global dust storms and determine their microphysical characteristics, such as particle size distribution, to distinguish between the fine mode and the coarse mode—the latter representing the primary mass component of PM₁₀ particles of Saharan origin.
- Calculate the Ångström exponent (α), which expresses the spectral dependence of AOD. Its value approaches zero or becomes negative ($\alpha \approx 0$) during dust storms, serving as definitive remote sensing evidence of large particle sizes and the dominance of PM₁₀, whereas it increases ($\alpha > 1$) in cases of pollution dominated by small combustion and smoke particles (PM_{2.5}).
- Study long-range transcontinental transport pathways of aerosols.
- Provide the essential baseline reference standard for quality assurance and validation of satellite data and imagery [34].



Figure 3.4 – A typical ground-based AERONET Sun photometer station. [34].

3.12 Passive Satellite Remote Sensing: The MODIS System Over Land and Oceans

The MODIS (Moderate Resolution Imaging Spectroradiometer), aboard NASA's Terra and Aqua satellites, is one of the most widely used passive spaceborne sensors globally for mapping horizontal aerosol distributions, thanks to its extensive swath width of approximately 2330 km [35].

3.12.1 Retrieval Algorithms Over Continents

The foundational research by Kaufman et al. (1997) revolutionized remote sensing over land. Since land surfaces exhibit high and variable surface reflectance (albedo) that is difficult to filter, the researchers developed the "Dark Target" algorithm. The core concept relies on observing the surface in the shortwave infrared spectrum (SWIR at $2.1 \mu\text{m}$), where vegetation and non-desert soils appear completely dark and are unaffected by fine particles. By utilizing empirical linear relationships that link surface reflectance in the SWIR band to reflectance in the visible blue and red bands, the surface contribution is precisely determined and subtracted from the total radiance. This isolates the aerosol signal and allows the calculation of AOD over land [35].

3.12.2 Mechanism and Operational Characteristics

According to Remer et al. (2005), MODIS employs advanced processing algorithms that analyze reflected solar radiation from the surface-atmosphere system across multiple spectral bands, comparing it against reference radiative models and Look-up Tables (LUTs) representing a clean surface. The variance is used to estimate particulate impacts and extract official AOD products (MOD04 and MYD04) at a spatial resolution of $10 \times 10 \text{ km}^2$ (and more recently $3 \times 3 \text{ km}^2$) [36].

The system is characterized by:

- Continuous, near-global daily coverage mapping the horizontal distribution of aerosols.
- Tracking the dynamics of Saharan dust storms from their primary sources (such as the Bodélé Depression in Chad) and monitoring their transcontinental transport over oceans, using the "Deep Blue" algorithm specifically designed for arid and desert regions with high surface reflectance in the visible spectrum.
- Constructing particulate matter (PM) distribution maps as a satellite-derived indicator to assess ground-level air pollution, wildfires, and industrial emissions [35, 36].

This linkage between column-integrated AOD values and ground-level PM₁₀ mass concentrations represents a crucial methodological step; it requires advanced statistical algorithms (such as multiple linear regression or machine learning) and chemical transport models to correct for atmospheric humidity and planetary boundary layer height (PBLH) to ensure accurate ground-level estimations.

3.12.3 Methodological Limitations

- Cloud Masking: The presence of clouds obstructs the sensor's view and prevents data retrieval, resulting in spatial gaps in daily imagery.
- Retrieval challenges over highly reflective surfaces: Interference from highly bright surfaces (e.g., snow/ice) elevates the error margin in AOD calculations.
- The continuous requirement for rigorous calibration and adjustment using ground-based reference data from the AERONET network [34, 35, 36].

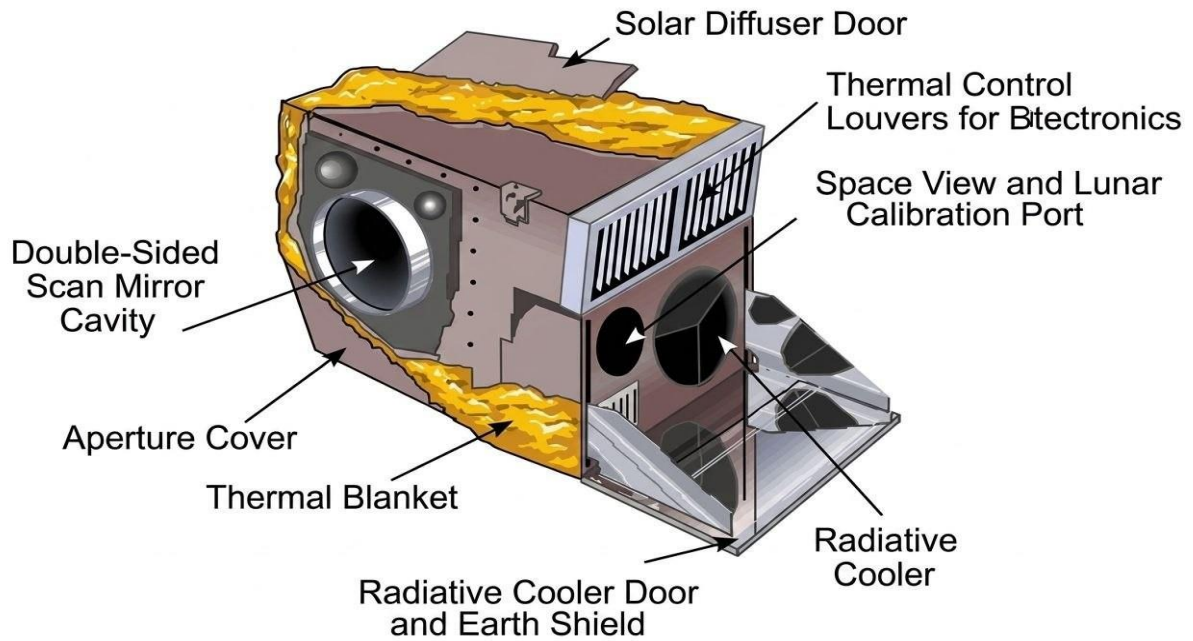


Figure 3.5 – Conceptual illustration of the MODIS satellite instrument. [36].

3.13 Active Satellite Remote Sensing: The CALIOP Lidar Technique

While passive sensors (such as MODIS) are highly efficient, they cannot resolve the actual vertical altitude of dust layers, providing only a column-integrated AOD value. Here, active remote sensing steps in via the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) instrument onboard NASA's CALIPSO satellite. It resolves the vertical structure and visibility of the atmosphere by measuring backscattered light from particles and clouds [33].

According to Winker et al. (2009), the system operates as an active remote sensing platform, emitting synchronized laser pulses into the atmosphere at two wavelengths (532 nm and 1064 nm), and subsequently recording the attenuated backscatter signal as a function of time. Calculating the time delay between pulse emission and reception allows the reconstruction of highly accurate vertical profiles (resolving down to 30 meters in the lower troposphere), illustrating the stratified vertical distribution of particles and clouds [33].

3.13.1 Physical Principle and Typological Discrimination

Level 2 data processing algorithms rely on physical criteria to classify the observed scene. The primary physical advantage of the instrument lies in measuring the volume depolarization ratio at the 532 nm wavelength. Since Saharan dust and sand particles are characterized by irregular, highly non-spherical, and birefringent geometries, they cause substantial depolarization

of the backscattered laser light compared to spherical liquid droplets (such as marine aerosols or sulfates). This physical distinction enables the algorithms to determine:

- The precise altitude and thickness of suspended atmospheric dust layers, identifying their injection levels into the free troposphere.
- The density and attenuation of suspended particles, as well as cloud-aerosol discrimination (CAD) through analyzing backscatter intensity and the spectral dependence of the color ratio between the two wavelengths.
- Advanced physical differentiation and accurate aerosol typing, which allows isolating pure dust—which falls within the PM_{10} size range—and polluted dust from other components like smoke and fine industrial pollution [33].

3.13.2 Operational Limitations

- Signal Attenuation and low penetration capacity: The laser signal cannot completely penetrate the atmospheric column to reach the surface during intense dust storms or thick convective cloud cover.
- Narrow Swath width: The instrument measures strictly along the nadir track directly beneath the satellite, significantly limiting its daily horizontal spatial coverage compared to imaging sensors like MODIS [34].

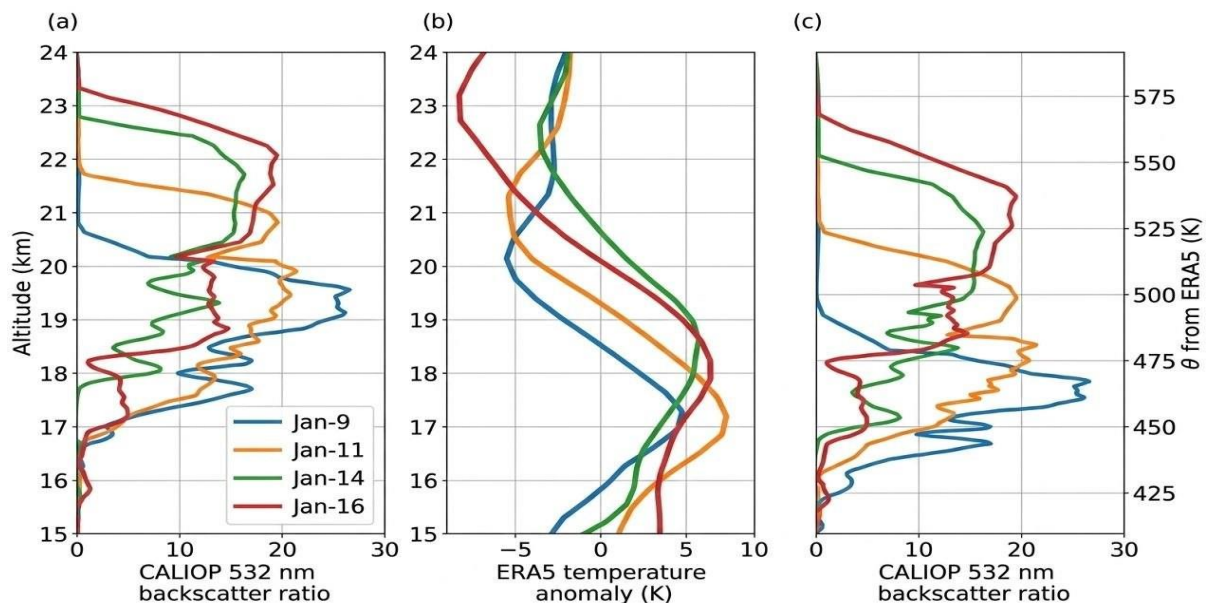


Figure 3.6 – CALIOP Lidar vertical profiling schematic. [33].

3.14 The Role of Remote Sensing in Climate and Air Quality Studies (IPCC Reports)

The Intergovernmental Panel on Climate Change (IPCC), in its successive Assessment Reports, relies on data integration and analytical synergy among AERONET, MODIS, and CALIOP to conceptualize the global climate equilibrium and reduce uncertainty margins through the following dimensions:

- **Direct Radiative Forcing:** Remote sensing aids in precisely determining aerosol optical properties (such as single scattering albedo and AOD). This enables climate models to calculate the amount of solar energy scattered back into space (cooling) or absorbed within the atmosphere (warming) based on vertical layer heights, establishing whether a layer exerts a net cooling or heating effect [33].
- **Indirect Radiative Forcing:** Utilizing the vertical cross-sections from CALIOP alongside horizontal observations from MODIS, scientists investigate dust-cloud interaction mechanisms. Dust particles act as cloud condensation and ice nuclei (CCN/IN), altering cloud microphysical properties, planetary albedo, precipitation cycles, and cloud lifetimes [35, 36, 33].
- **Air Quality and Public Health Policy Formulation:** International reports integrate these spaceborne and ground-based datasets with chemical transport models to estimate global exposure to surface particulate matter (PM_{2.5} and PM₁₀).

This allows for assessing long-term health impacts on human populations and developing early warning systems, particularly in vast regions lacking dense ground-based monitoring networks [33].

Remote sensing technologies demonstrate an advanced, multi-dimensional methodological integration in aerosol research. While ground-based systems like the AERONET network [34] provide precise physical spectral standards and reference validation, the MODIS sensor (Kaufman et al., 1997; Remer et al., 2005) [35, 36] provides a comprehensive, two-dimensional horizontal geographic view of dust transport and distribution. Meanwhile, the CALIOP lidar [33] completes this synergy by revealing the vertical profile (the third dimension). This advanced technological synergy serves as a vital complement and strategic alternative to bridge

spatial gaps resulting from limiting measurements to direct ground stations using mass-based instruments like Beta Attenuation Monitors (BAM) and Tapered Element Oscillating Microbalances (TEOM), thereby contributing to a comprehensive and dynamic characterization of PM₁₀ concentrations that serves climate and air quality assessments in alignment with the strategic framework of the IPCC reports [33].

*The temporal variation of desert
particles:*

4.1 Climatological Summary of Ouargla:

4.1.1 Boundaries of the geographical area (Ouargla)

The Jewel of the Oases is located in the southeastern part of the country and covers an area of up to (163,233) km², which represents (06.85%) of the total area of Algeria. The Province of Ouargla is located about 900 km away from the Algerian capital. It is bordered to the north by the provinces of Djelfa and El Oued, to the east by the Republic of Tunisia, to the south by the provinces of Tamanrasset and Illizi, and to the west by the province of Ghardaia."[Bandour]

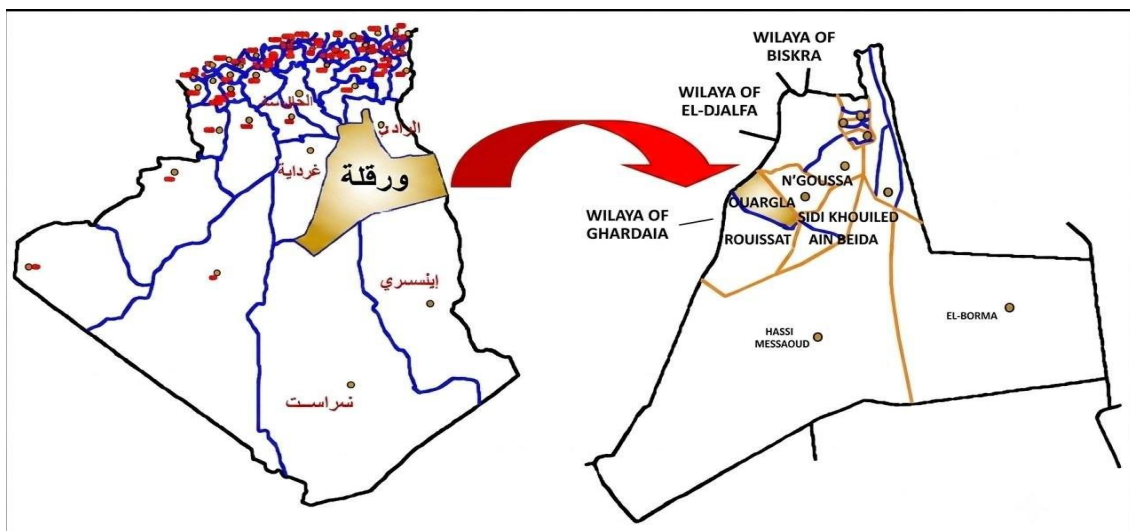


Figure 4.1 – Geographical location map and administrative boundaries of Ouargla Province. [5]

4.1.2 Geographical and Climate

The wilaya of Ouargla, located in the southeast of Algeria in the heart of the northern Sahara, is characterized by an essentially flat relief, dotted with chotts and ergs, which allows the free propagation of wind-driven flows without major obstacles. Far from maritime influences, the region has a hot desert climate (Köppen classification: BWh) marked by very long and scorching summers—where the average maximum temperatures approach 45°C in July—as well as mild-to-cool winters with average minimums falling to 5°C in January. This large thermal range is accompanied by extreme structural aridity.

with precipitation being rare, irregular, and limited to a few millimeters per month. Analysis of Emberger's climagram confirms this by placing Ouargla rigorously in the Saharan stage (desert) with a cool winter (coordinates: $m = 5^{\circ}\text{C}$ and $Q_2 = 2.14$). In addition, applying

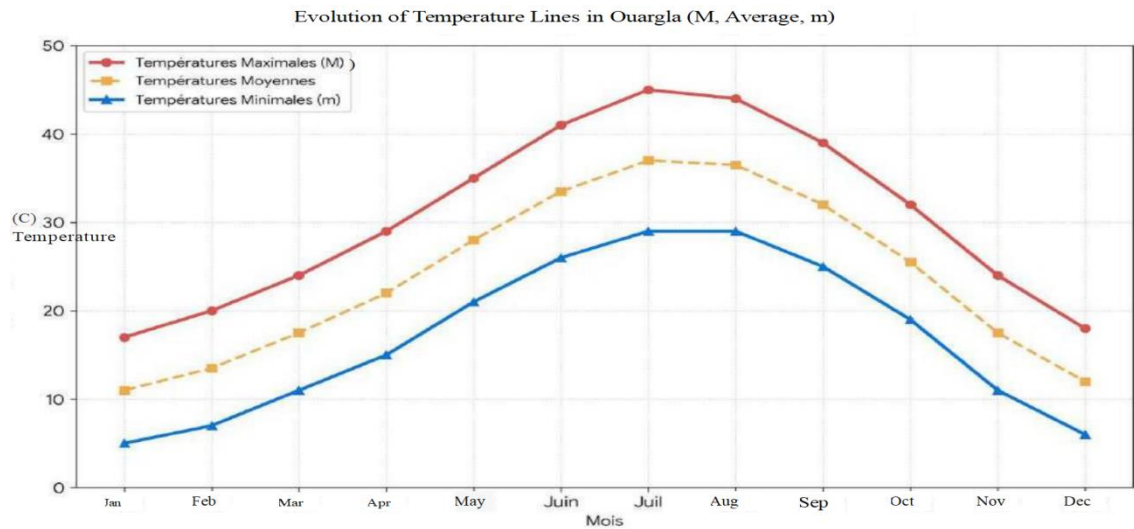


Figure 4.2 – Geographical location map and administrative boundaries of Ouargla Province. [37]

Gausson's rule on the ombrothermic diagram shows that the dryness condition ($P < 2T$) is met 12 months out of 12, which indicates permanent aridity with no humid month during the year.

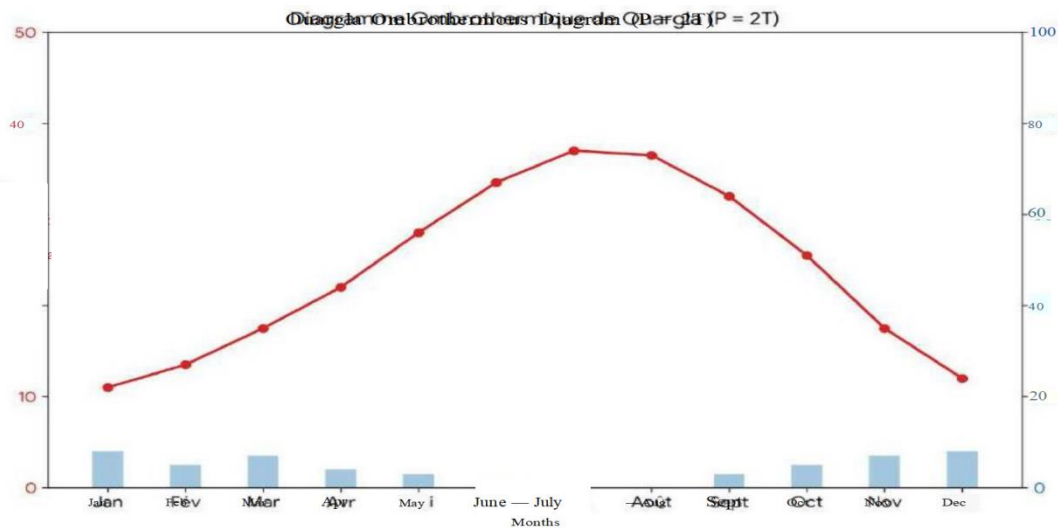


Figure 4.3 – The Ombrothermic Diagram (Gausson Rule: $P = 2T$). [37]

Finally, the region's wind dynamics over the past ten years highlight a clear dominance of winds from the North to North-East (N–NE) sector, blowing at an average speed of 4,23 m/s (for 15,1% of calm time), a regime influenced by regional thermal contrasts and the meeting of Mediterranean and subtropical atmospheric circulations.

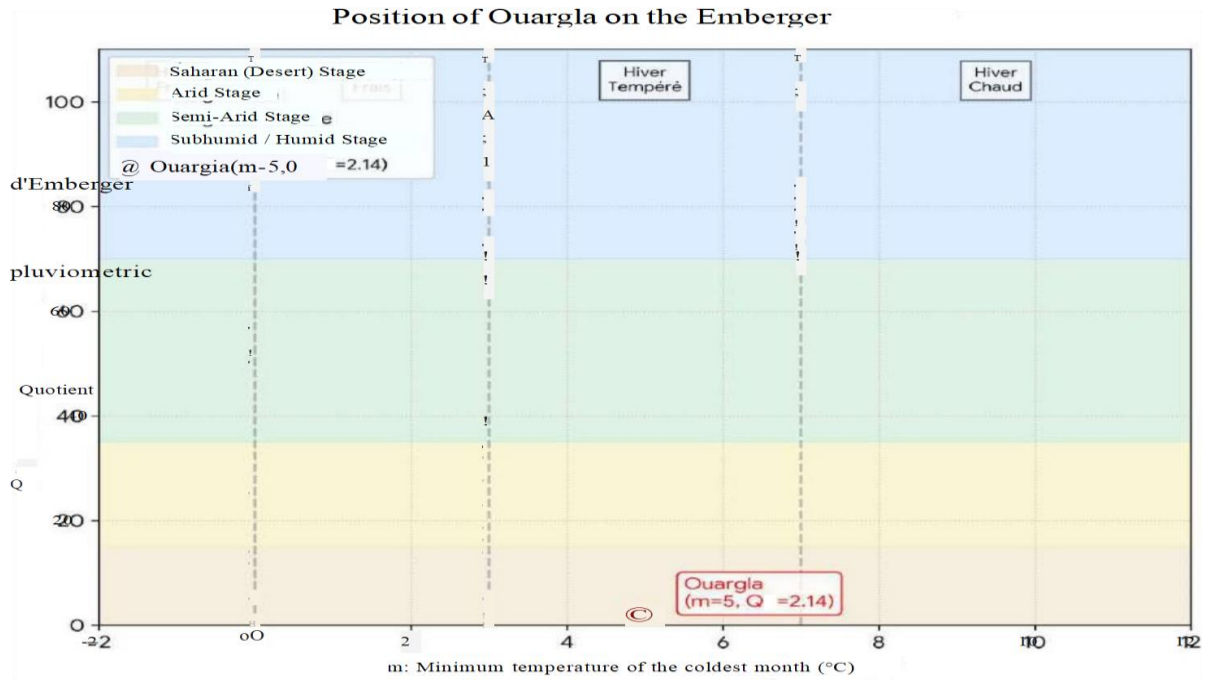


Figure 4.4 – Position of Ouargla on the Emberger [37]

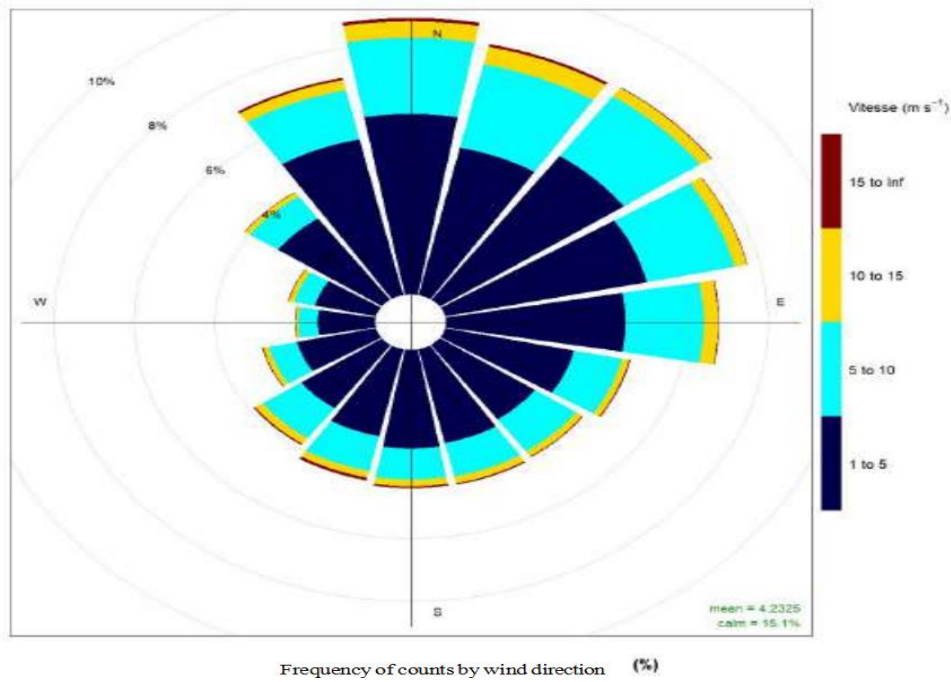


Figure 4.5 – Wind Rose of Ouargla [37]

4.2 Data and method :

For this study, we used the CAMS global reanalysis (EAC4) dataset, This dataset focused on aerosols and reactive chemical species. Currently covers January 2003 to August 2025. which provides consistent, three-dimensional fields of atmospheric composition on a global scale. This dataset is produced by the European Centre for MediumRange Weather Forecasts

(ECMWF) and has a spatial resolution of approximately 80 km, with data interpolated to a regular 0.750.75 latitudelongitude grid. We specifically extracted surface PM₁₀ concentrations at a temporal resolution of 3 hours (analysis times) from the Atmosphere Data Store. To obtain PM₁₀ values at our exact study location, we applied a nearestgridpoint interpolation method. This means that for each time step, we identified the grid cell whose center was closest to the latitude and longitude of the study site and assigned its PM₁₀ value to that location. This approach preserves the original model values without introducing additional smoothing, making it suitable for our analysis. Further details on the CAMS reanalysis system can be found in Inness et al. (2019). Temporel analysis were focused on the the variation of PM₁₀ in different time scales from hourly to inter annual variation of PM₁₀ as shown in the diagram below.

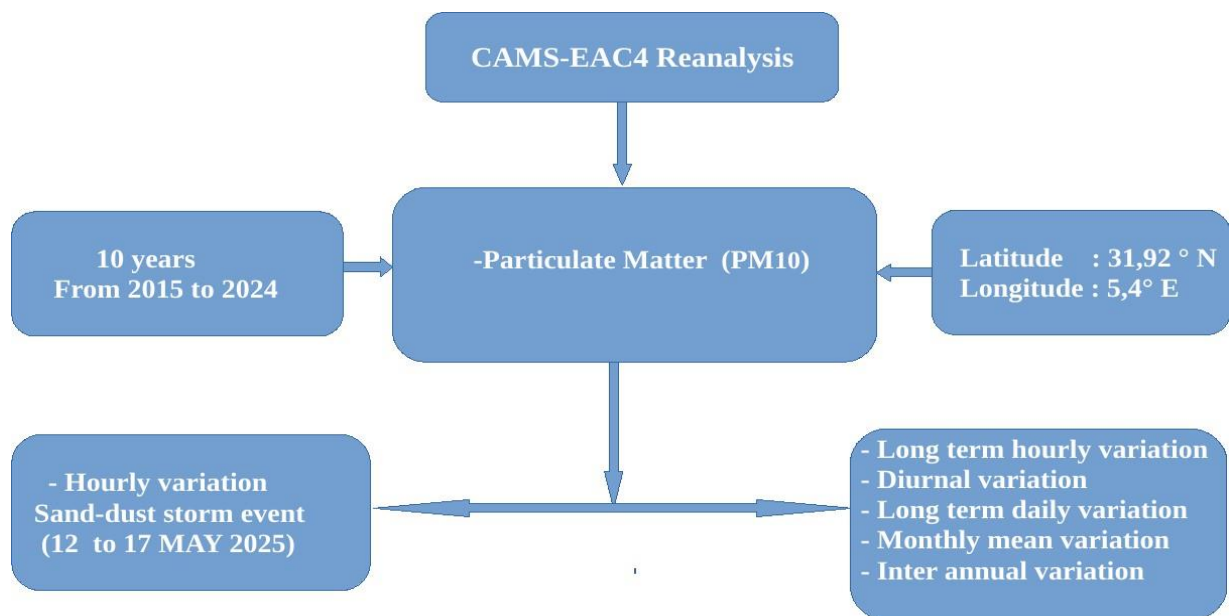


Figure 4.6 – Flow chart

4.3 Results and Analysis

Table 4.1 – Hourly statistics of PM₁₀ concentrations

PM ₁₀	Mean	Median	SD	Min	Max	Date (Min/Max)	
	110.9	66.3	133.6	0.0099	1684.1	23 May 2017 – 12:00 / 23 Feb 2021 – 21:00	
PM ₁₀	Mean	Median	Max	Date (Max)		Min	Date (Min)
	110.9	66.29	1684.09	23 Feb 2021 - 21h		0.0099	23 May 2017 - 12h

4.3.1 Hourly Time Variation

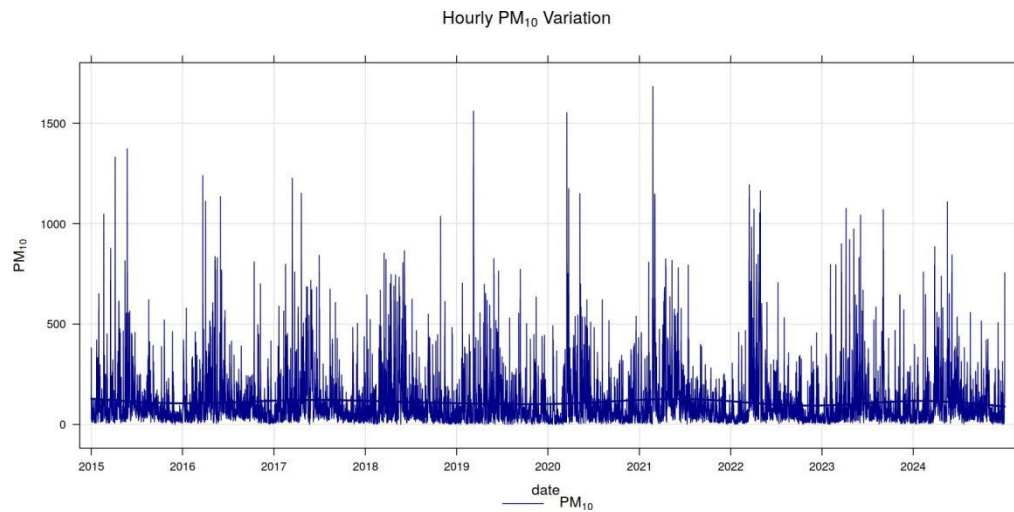


Figure 4.7 – Hourly PM₁₀ evolution for all period (2015-2024)

Figure 4.7- illustrates the hourly temporal variation of PM₁₀ particle concentrations in the Ouargla region between 2015 and 2024, revealing sharp and irregular fluctuations in concentration levels. Despite the recording of extreme peaks that sometimes exceed 1,500 units—often reflecting periods of intense dust activity—the general trend line indicates a relative stability in average concentrations throughout the decade. This pattern reflects the fluctuating and seasonal nature of the PM₁₀ particles focused on by the study, and underscores the importance of monitoring these instantaneous changes and their potential impacts on public health."

4.3.2 Diurnal variation of PM₁₀

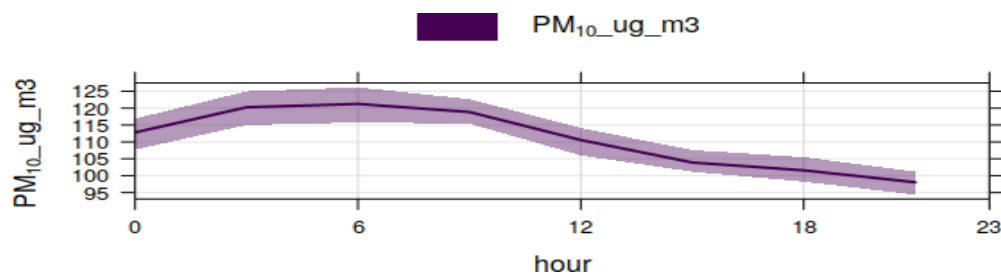


Figure 4.8 – Diurnal variation of PM₁₀

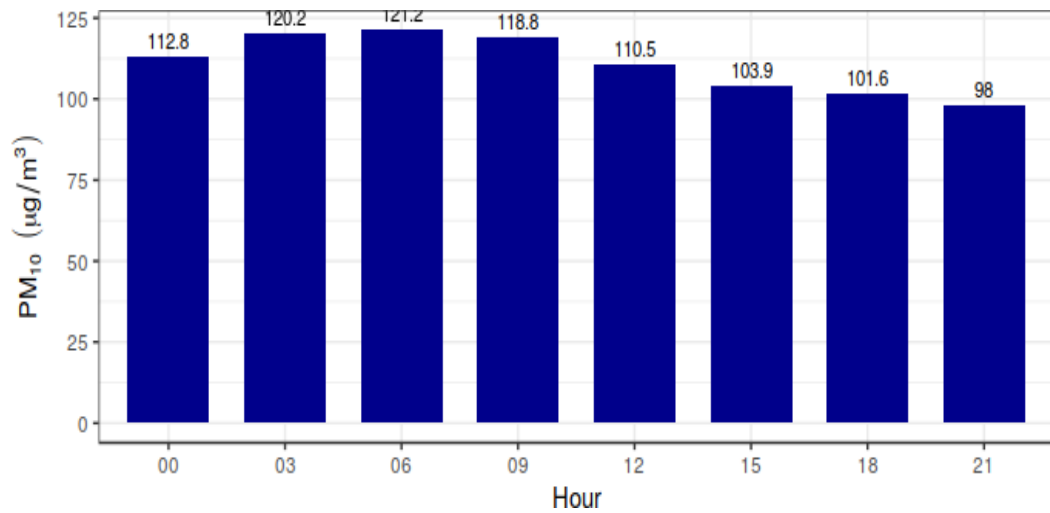


Figure 4.9 – Hourly PM₁₀ evolution for all period (2015-2024)

Figures 4.8 and 4.9 illustrate the daily variation of PM₁₀ particle concentrations in the Ouargla region during the period from 2015 to 2024, revealing a regular pattern that begins with a gradual increase to reach a morning peak at 06:00 with a concentration of 121.2 micrograms/cubic meter. This peak is followed by a continuous decrease in concentration levels throughout the day, reaching its lowest recorded value at 21:00 with a concentration of 98 micrograms/cubic meter. This variation reflects the atmospheric dynamics and local activities that directly affect air quality in the region during different hours of the day."

4.3.3 The Daily Variation:

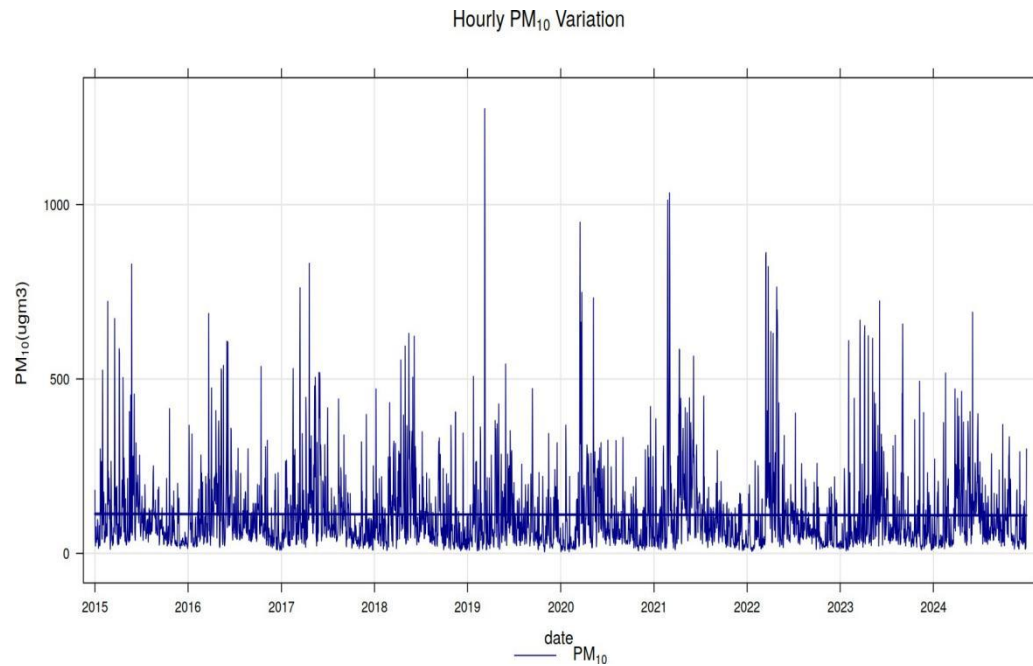


Figure 4.10 – Daily PM₁₀ evolution for all period (2015-2024)

Figure 4.10- illustrates the daily evolution of PM₁₀ particle concentrations in the study area during the period from 2015 to 2024. The curve reveals continuous and irregular daily fluctuations in particulate levels. The graph also highlights sharp and intermittent peaks that sometimes exceed the threshold of $1,000 \mu\text{g/m}^3$, indicating the occurrence of extreme and time-limited dust events. Despite these intense daily variations, the general trend line shows relative stability in average concentrations across the entire decade, reflecting a temporal balance in air quality within the studied region."

4.3.4 Monthly Variation:

PM ₁₀	Mean	Median	Max	Date (Max)	Min	Date (Min)
Jan	77.6	41.9	704	24Jan2019-06h	0.471	17 Jan 2019-12h
Feb	105	55.0	1684	23Feb2021-21h	0.114	01 Feb 2023-21h
Mar	147	71.3	1561	09Mar2019-18h	0.862	01 Mar 2020-21h
Apr	183	126	1332	06Apr2015-21h	0.462	23 Apr 2019-12h
May	167	102	1373	25May2015-00h	0.00989	23 May 2017-12h
Jun	152	111	1135	01Jun2016-03h	1.61	23 Jun 2019-12h
Jul	95.7	75.0	794	15Jul2021-12h	0.124	21 Jul 2019-12h
Aug	92.1	71.9	674	13Aug2017-12h	0.384	06 Aug 2019-12h
Spt	95.3	65.2	1070	03Spt2023-12h	3.32	29 Spt 2018-12h
Oct	78.7	50.5	1037	29Oct2018-12h	0.230	30 Oct 2019-12h
Nov	70.0	38.7	700	07Nov2016-21h	1.43	14 Nov 2024-21h
Dec	67.5	36.2	755	31Dec2024-21h	0.340	01 Dec 2015-21h

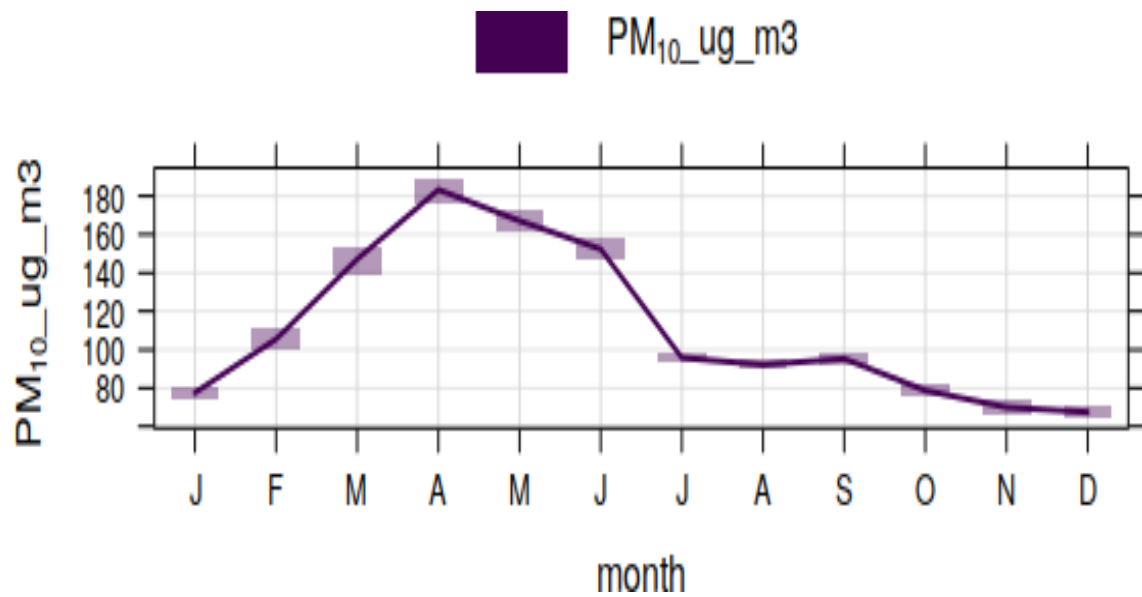


Figure 4.11 – Monthly variation of PM₁₀

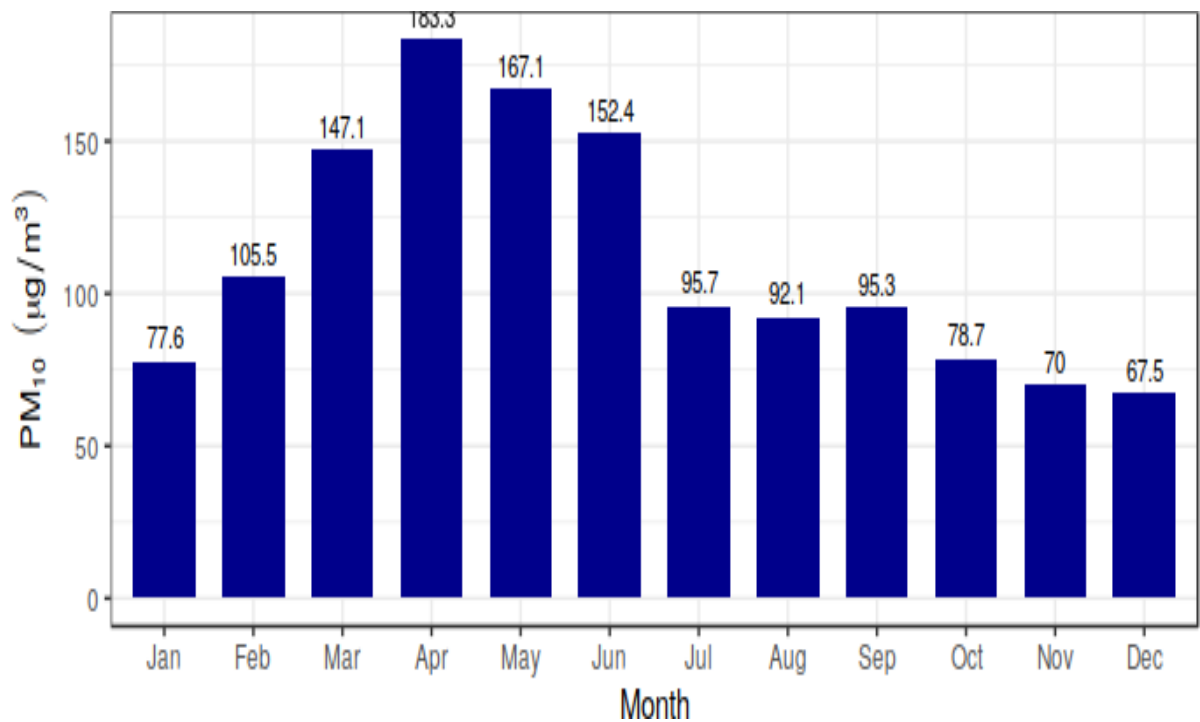


Figure 4.12 – Histogram of Monthly PM₁₀ Variation

Figures 4.11 and 4.12 illustrate the monthly variation of PM₁₀ particle concentrations in our region during the study period 2015–2024. The monthly variation of PM₁₀ concentrations shows a clear seasonal pattern, with values peaking during the spring season (April and May), exceeding the threshold of 160 micrograms/cubic meter, which is often associated with the dynamic activity of seasonal winds in the desert environment. This is followed by a gradual and continuous decrease in concentrations starting from June, reaching its lowest annual levels during the winter months

(December and November). This pattern reflects the direct impact of climatic fluctuations and periodic weather phenomena on air quality in the study area."

4.3.5 seasonal variation

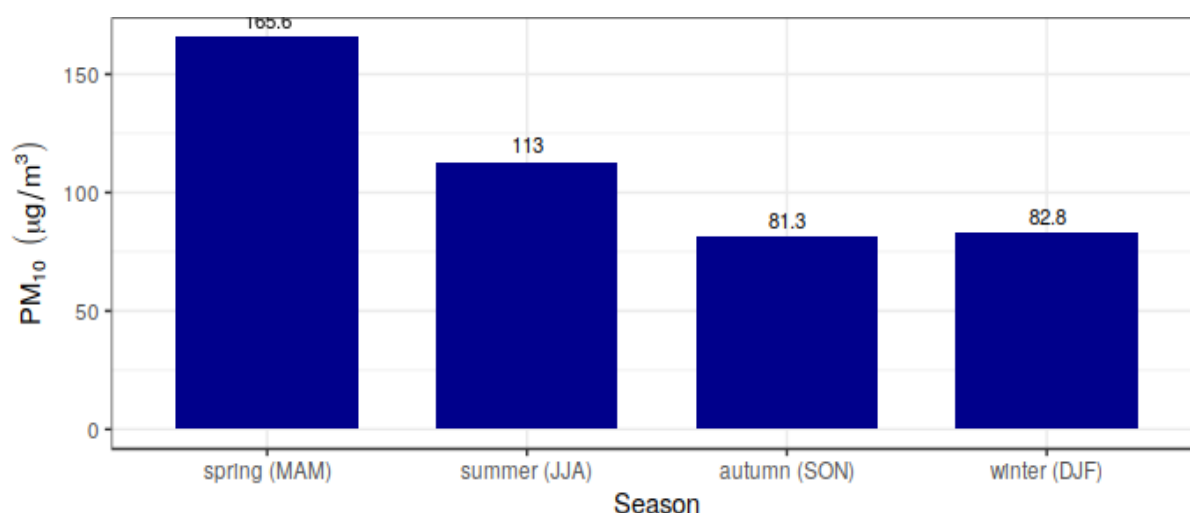


Figure 4.13 – Histogram of Seasonal PM₁₀ Variation

Figure4.13 illustrates the seasonal variation of PM10 particle concentrations in our region during the study period 2015–2024, showing a clear contrast between the seasons. Spring dominates the scene with high concentrations reaching 165.6 micrograms/cubic meter, reflecting the strong impact of climatic factors and dust-laden winds during this period. In contrast, the data for autumn and winter show a notable stability in particulate levels, with concentrations dropping to nearly half compared to spring, indicating a relative improvement in air quality outside the spring dust storm season."

4.3.6 Annual PM₁₀ Statistics

Table 4.2 – Yearly statistics

PM ₁₀	Mean	Median	Max	Date (Max)	Min	Date (Min)
2015	105	65.5	1373	05May2015-00h	126	01Dec2015-21h
2016	114	75.2	1240	22Mar2016-06h	122	19Dec2016-21h
2017	118	71.2	1226	14Mar2017-21h	135	23May2017-12h
2018	114	69.1	1037	29Oct2018-00h	129	22May2018-21h
2019	105	62.1	1561	09Mar2019-18h	134	21Jul2019-12h
2020	104	56.6	1553	16Mar2020-21h	136	03Feb2020-18h
2021	124	77.9	1684	23Feb2021-21h	152	20Feb2021-21h
2022	106	57.7	1194	16Mar2022-09h	145	20Jan2022-21h
2023	106	57.8	1076	07Apr2023-03h	138	01Feb2023-21h
2024	111	74.6	1109	16May2024-18h	114	26Dec2024-21h

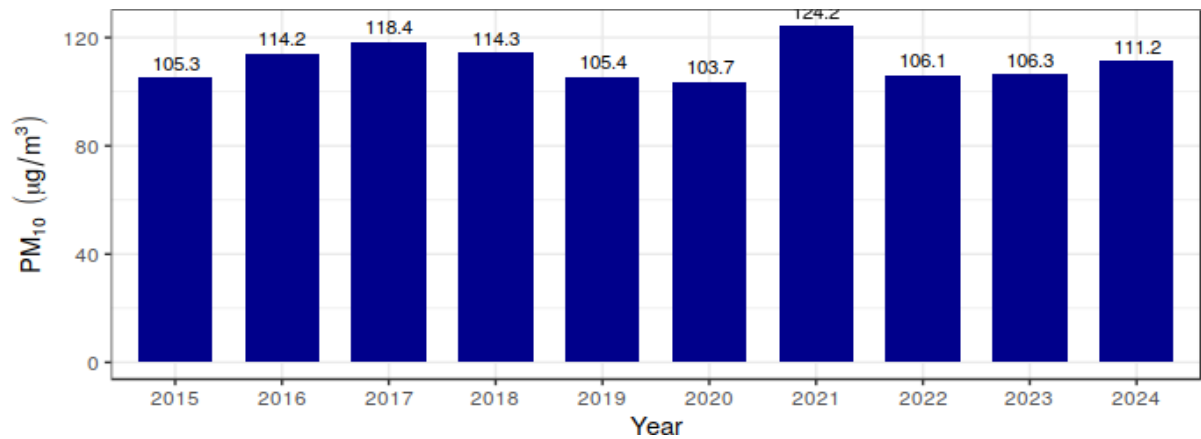


Figure 4.14 – Hystogram of Yearly PM₁₀ Variationnn

Figure 4.14 illustrates the annual variation of PM₁₀ particle concentrations in our region during the study period 2015–2024. The data show a relative stability in annual pollution levels, with values fluctuating within a close range for most years of the decade. The annual peak was recorded in 2021 with an average of 124.2 micrograms/cubic meter, while the remaining years maintained balanced measurement levels. These results reflect that the variation in air quality in the region is primarily linked to natural and seasonal fluctuations, with the absence of a long-term upward or downward trend, confirming the dominant climatic nature governing particle distribution in the area."

Part II:

Conclusions General

General conclusion

Based on the findings of this study, it is evident that atmospheric particles with an aerodynamic diameter of less than 10 micrometers (PM_{10}) of Saharan origin represent a key factor in determining air quality in arid regions, particularly in the Ouargla area during the period from 2015 to 2024. The results, based on the integration of multiple data sources including reanalysis data, satellite observations, and field measurements, show that the observed variations in PM_{10} concentrations are mainly driven by natural dynamic factors governed by wind emission processes, atmospheric transport, and the stability and instability conditions of the atmosphere, confirming the dominance of climatic factors over this type of air pollution.

The study also demonstrates that the temporal behavior of PM_{10} is characterized by significant variability across different time scales. Background concentrations remain relatively stable, interrupted by sharp and short-lived peaks associated with dust storm events. On a daily scale, higher concentrations are recorded during nighttime and early morning hours due to atmospheric stability and thermal inversion, while lower values occur during the daytime as a result of atmospheric mixing and dispersion. At seasonal and interannual scales, the highest concentrations are observed during spring, particularly in April, while the overall trend remains relatively stable, reflecting the predominantly natural character of the variability rather than direct anthropogenic influence.

The use of multi-source datasets, combining reanalysis products and field observations, has enabled a detailed representation of the temporal and seasonal patterns of PM_{10} concentrations, providing a valuable scientific reference for air quality assessment and its implications for public health and the local environment. These findings not only describe the current situation but also highlight that PM_{10} risks in the study area are mainly episodic and seasonal rather than continuous, making short-term dust event monitoring essential for environmental risk manage-

ment strategies.

In conclusion, this work opens new research perspectives for a deeper understanding of the complex interactions between Saharan dust and the regional climate system. It emphasizes the need to develop more accurate and integrated local monitoring networks and to intensify studies linking climate variability with extreme weather phenomena in the Algerian Sahara. It also highlights the importance of adopting science-based strategies to address future environmental challenges, thereby improving air quality and ensuring sustainability in arid environments.

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