

TITLE

Wind Effects on the Dispersion of SO₂ and PM₁₀ around a Coastal Industrial Complex: The Case of Gabès (Southeastern Tunisia).

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Abstract

This article analyzes the influence of winds on the atmospheric dispersion of sulfur dioxide (SO₂) and fine particulate matter (PM₁₀) in the industrial zone of Gabès, southern Tunisia. This study uses data from the ANPE monitoring network and instantaneous measurements. These data were used to model pollutant dispersion using AERMOD. The results highlight the structuring role of synoptic winds (particularly ENE) in the spatial distribution of concentrations. The major contribution of the Tunisian Chemical Group (GCT) is confirmed by the analysis of mass fluxes and the spatialization of regulatory threshold exceedances. The article offers a geographical and environmental analysis of the impacts associated with industrial development in a densely populated coastal environment. Keywords: Gabès, Pollution, Modeling, Winds, SO₂, PM₁₀.

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Introduction

The Gabès region (southern Tunisia) is home to one of the largest chemical complexes in the country. It is located in a coastal area, close to urban areas (towns such as Ghannouch, Bouchamma, and Chott Essalem), agricultural areas, and ports (figure 1).

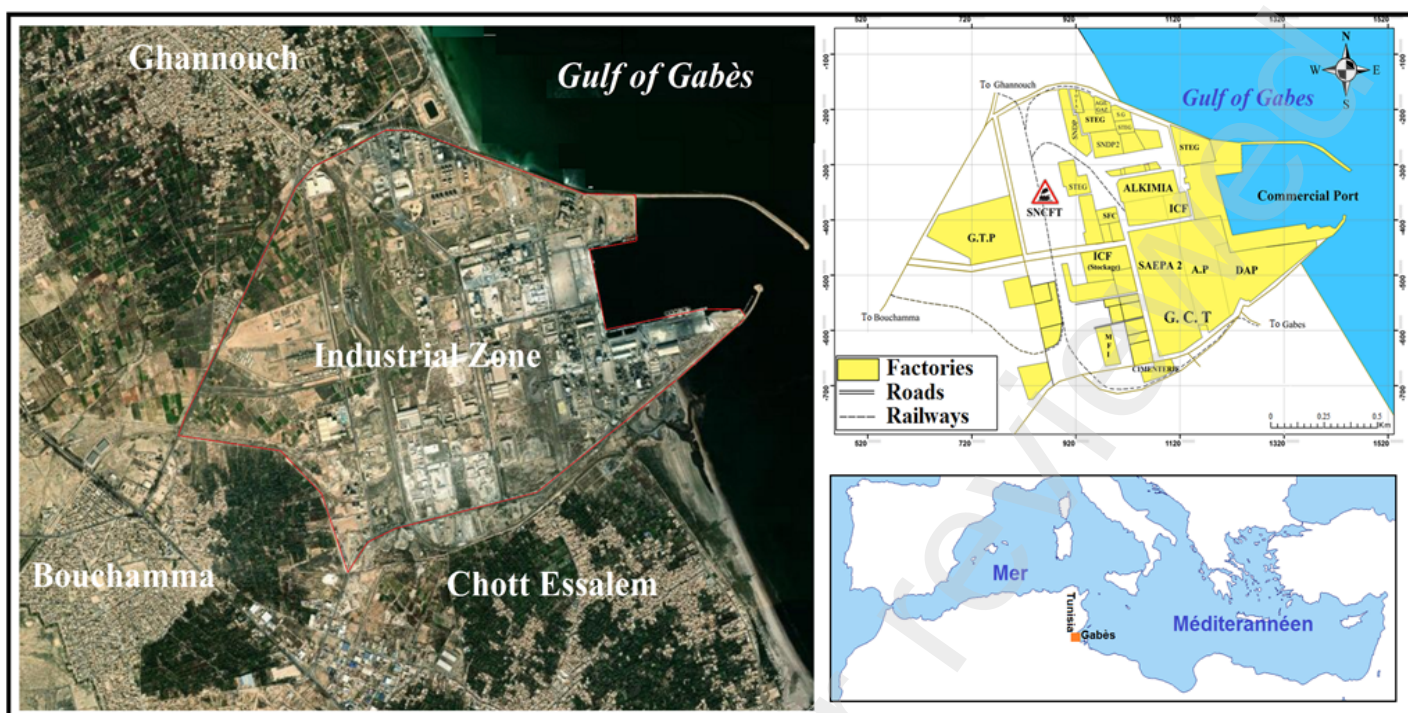


Figure 1: Location of the Gabès industrial zone (source Google Earth and field visits)

This complex raises major issues in terms of air pollution, particularly emissions of sulfur dioxide (SO_2) and fine particulate matter (PM_{10}), mainly from phosphate processing and fertilizer production. These gaseous emissions can have repercussions on health and the environment, the extent of which depends on various factors such as the concentration and toxicity of the emissions, the duration of exposure, and the socioeconomic characteristics of the exposed populations. This research therefore aims to:

- Identify the main industrial sources of SO_2 and PM_{10} ,
- Model their dispersion according to prevailing winds,
- Analyze the links between the geography of emissions and exposure in populated areas.

I. Methodology

The atmospheric dispersion of pollutants was simulated using AERMOD software (version 8.9.0), developed by the United States Environmental Protection Agency (EPA). This model is designed to estimate the dispersion of air pollutants over a radius of up to 50 km from stationary sources, integrating the effects of topography, meteorological conditions, and the characteristics of the emitting sources. AERMOD can model different types of emissions: point (industrial chimneys), linear (roads), and surface (diffuse industrial zones).

Input data relating to the physical characteristics of the chimneys (location, height, diameter, temperature, and discharge velocity) were obtained from the region's main industrial units: the Tunisian Chemical Group (GCT), ICF, and ALKIMIA. Table 1 presents a representative excerpt of these technical parameters used to input the model.

Table 1: Stack characteristics for chemical plants (source: GCT, 2022)

Characteristics	GCT	FCI	ALKIMIA	Cement plant
Stack position (X, Y) UTM (m)	601175 3753090	600800 3753480	600624 3753792	599756 3754965
Number of stacks	26	1	2	1
Stack height (m)	50	28	37- 52.5	30
Stack diameter (m)	3	1.8	2.5	2.6
Discharge temperature (°C)	90	38	64	70
Discharge velocity (m/s)	22.8	9.1	10	13.1
Gas flow m ³ /s	161.2	24.17	48.2	69.5

Furthermore, the hourly meteorological data required for the simulation were provided by the French National Environmental Protection Agency (ANPE) and the National Institute of Meteorology (INM). These data cover the period from January 1, 2002 to December 31, 2023, and come primarily from the Ghannouch station, including wind speed and direction, temperature, and cloud cover. Analysis of the prevailing winds showed a preponderance of ENE to NNE flows, which are highly influential in the trajectory of pollution plumes.

The measurement points were taken from the three measurement campaigns conducted by the ANPE, the series of hourly pollutant measurements between 2008 and 2021 at the Ghannouch station (Ghannouch-West primary school), and instantaneous measurements taken at 50 measurement sites. Three ad hoc measurement campaigns were carried out by the ANPE:

- ✓ Campaign 1 (June–July 2007): mobile measurements at 18 sites within a 6 km radius of the industrial complex; main pollutants measured: SO₂, HF, PM, H₂S.
- ✓ Campaign 2 (March–April 2013): measurements at 5 sites around the planned university campus; pollutants: O₃, SO₂, NO_x, CO, PM₁₀; prevailing NE winds.

- ✓ Campaign 3 (July–September 2018): 69 days of measurements at 16 sites spread across 7 delegations within a 30 km radius; pollutants measured: SO₂, NO_x, CO, H₂S, O₃, PM₁₀; Frequent winds from the E to ENE sector with speeds > 5 m/s.
- ✓ Continuous series of measurements from the Ghannouch fixed station, operational since 2007, were used for spatial-temporal analysis of SO₂ and PM₁₀ concentrations.
- ✓ Instantaneous measurements were carried out using PM₁₀ and SO₂ measuring instruments provided by the Faculty of Sciences of Gabès. PM₁₀ concentrations were measured using a DustTrak aerosol monitor (model 8532), while SO₂ concentrations were monitored using a single-gas detector specific to sulfur dioxide.

In summary, this work is based on data collected from 40 fixed points and more than 50 instantaneous measurements, taken at different distances from the pollution sources and on various dates.

Spatial interpolation of the measured concentrations was carried out using the IDW (Inverse Distance Weighting) method, in order to produce pollutant distribution maps in the study area.

II. Results

1. Main Sources of Pollutants

The table 2 below lists the quantities emitted per pollutant and per stack for the production units of three main sources of pollution: the GCT plants, ALKIMIA, and the ICF.

Table 2: Mass flow rates or emissions from GCT, AL KIMIA, and ICF (source: GCT, 2022)

polluants	GCT		ALKIMIA		ICF		Total Gabès	
	Kg/hour	%	Kg/hour	%	Kg/hour	%	Kg/hour	%
SO ₂	2214	99.3	0.8	0.03	11.78	0.47	2228.4	100
HF	13	90.2	0.04	11.92	0.007	0.68	14.4	100
PM ₁₀	253.8	58.5	18	4.1	0.22	0.05	433.8	100
NH ₃	38.5	98.2	0.7	1.8	0	0	39.2	100
HC (Hydrocarbons)	57.5	94.55	2.95	4.85	0.37	0.6	60.82	100

The data show that the dominant pollutants in the various discharges are SO₂, dust (PM) and hydrocarbons (HC). The first two pollutants account for 98% of the flows: 82% for SO₂ and 16% for PM. The average annual quantities emitted are around 19,520.7 metric tonnes of SO₂,

3,800 metric tonnes of fine particles, 343.4 tonnes of ammonia (NH₃). In addition, GCT units (DAP Units, DCP Unit, Sulphuric Unit, Nitric Unit, Ammonitrate Unit, etc.) discharge the highest mass flow rates or pollutant flows.

2. Spatial distribution of air pollution from field measurements

The results of the spatial interpolation of SO₂ and PM₁₀ concentrations (figure 2 and 3), based on measurements taken between 2007 and 2023 and processed using ArcMap (IDW method), highlight a gradual decrease in pollution levels as one moves away from the industrial complex, particularly from the main emitting sources located within the perimeter of the Tunisian Chemical Group (GCT).

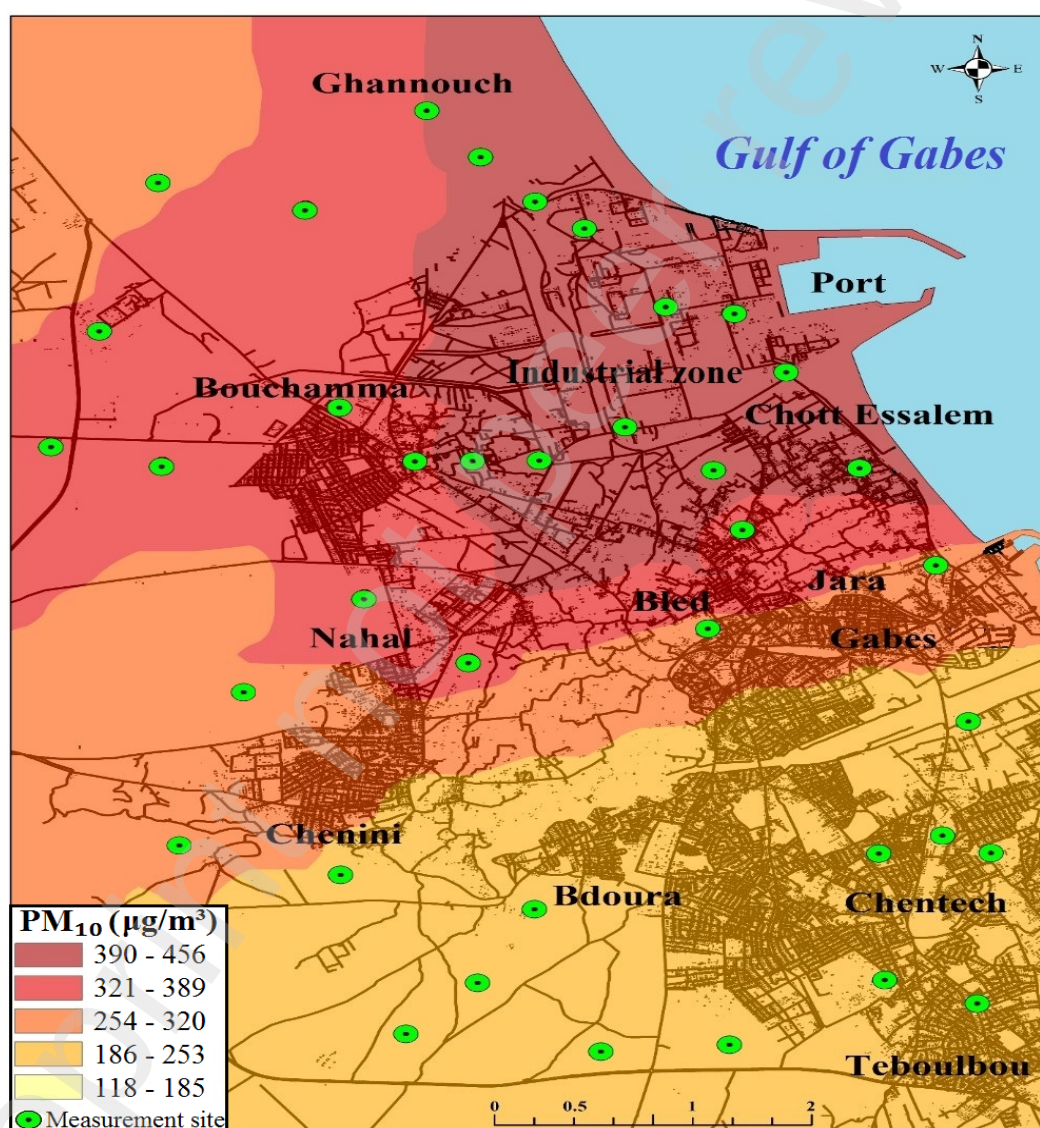


Figure 2: Spatial distribution of PM₁₀ concentrations based on ANPE data and instantaneous field measurements.

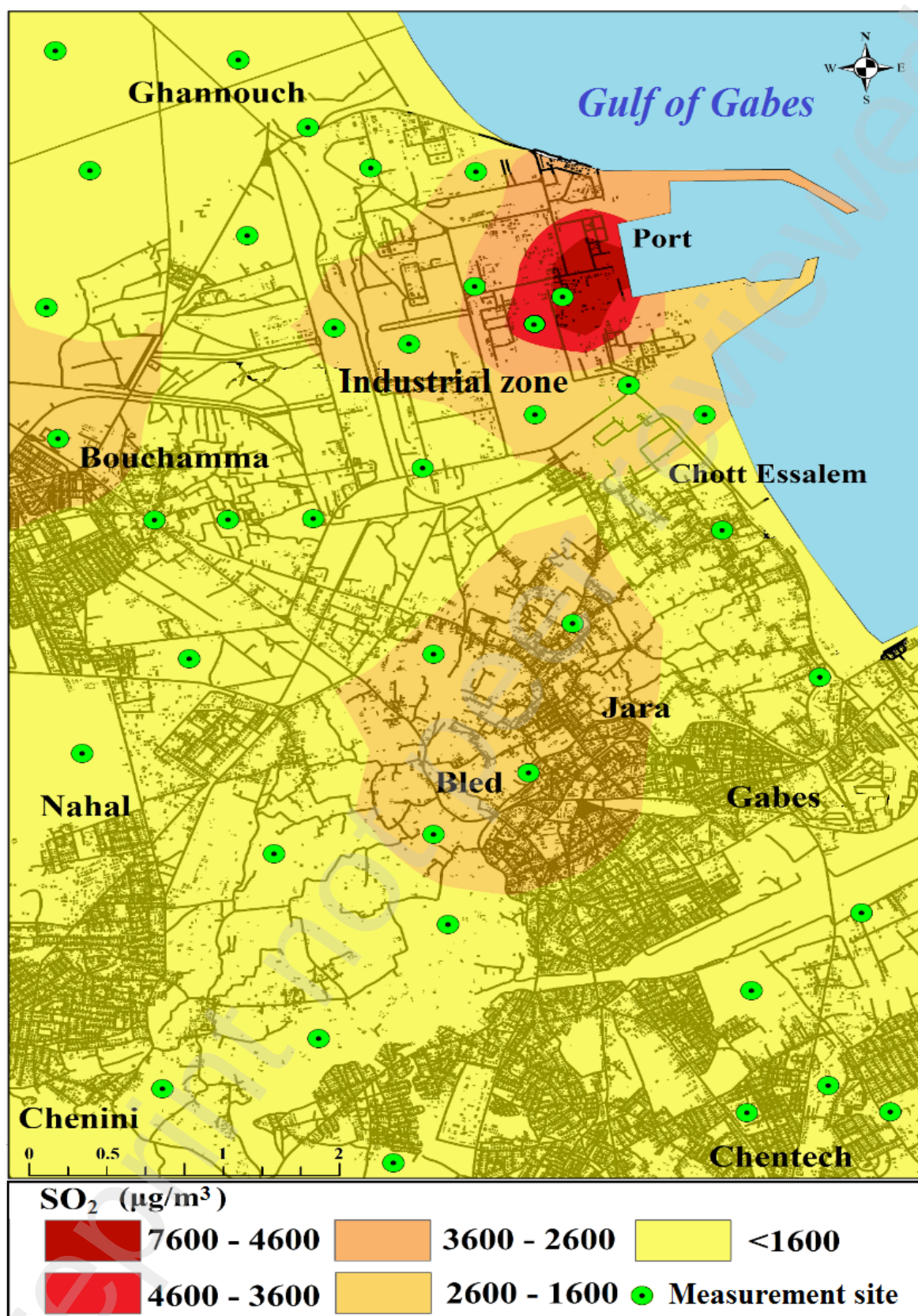


Figure 3: Spatial distribution of SO₂ concentrations based on ANPE data and instantaneous field measurements.

Sites located less than 300 meters from the GCT units (DAP, DCP, sulfuric unit, nitric unit, and ammonium nitrate) have particularly high cumulative concentrations, related to the frequency of exposure to the plume emitted by the stacks. These emissions are strongly influenced by the prevailing easterly to ENE winds (average speed: 3.2 km/h) and the sea breeze, which contribute to channeling pollutant flows toward densely populated areas.

However, it has been observed that points very close to the stacks (<200 m) sometimes have low concentrations, which can be explained by the height of the stacks (on average 30–50 m) and the initial velocity of the releases, which propel the plumes beyond the immediately surrounding air layer. At 2 km from the sources, cumulative SO₂ concentrations range between 3600 and 4600 µg/m³, while more distant areas (3 to 6 km) record levels below 1600 µg/m³. However, at all the measured points, SO₂ concentrations consistently exceed 500 µg/m³, which exceeds both the Tunisian limit value (380 µg/m³) and, in some cases, the alert threshold (500 µg/m³ for 3 consecutive hours), established by standard NT 106.04 (2014).

Significant concentration differences are observed between sites located equidistant from the sources, which can be explained by directional factors, particularly wind direction, which determines the presence or absence of the site under the plume. The dispersion of PM₁₀ has a more widespread spatial distribution than that of SO₂. This is explained by the multiplicity and geographic dispersion of particulate matter sources, unlike SO₂ sources, which are more concentrated in the southeast of the industrial complex. Three main concentration areas have been identified:

The first covers the entire industrial zone, the southern neighborhoods of Ghannouch (notably Cité Taha Hossein and Cité Essbouï), and the northern neighborhoods of Chott Essalem (Ennazla, Errouajhia).

The second area extends west toward Bouchemma, including areas near the RN1 highway.

The third extends southward, toward Gabès-City (Bled, Jara, Beb Bhar neighborhoods) and Gabès-West (Nahal, Chenini, etc.). Beyond these areas, a relative decrease in SO₂ and PM₁₀ concentrations is observed, due to the mitigating effect of several geographic factors: local topography, the presence of built-up areas, and especially oases (particularly those of Bouchemma and Chott Essalem), whose palm groves act as a vegetation barrier by partially filtering suspended particles and contributing to the purification of ambient air.

3. Modeling Pollutant Dispersion: SO₂ and PM₁₀

Numerical modeling is a central tool for assessing the dispersion dynamics of air pollutants from industrial sources. In this study, the AERMOD model was used to simulate the dispersion of two major pollutants emitted by the Gabès-industrial-complex: sulfur dioxide (SO₂) and fine

particulate matter (PM₁₀). The modeling required the precise definition of sources (industrial chimneys, diffuse emissions), the characterization of releases (emission rates, height and diameter of chimneys, temperature and flow speed), as well as the integration of meteorological parameters (wind speed and direction, temperature, humidity, pressure, etc.).

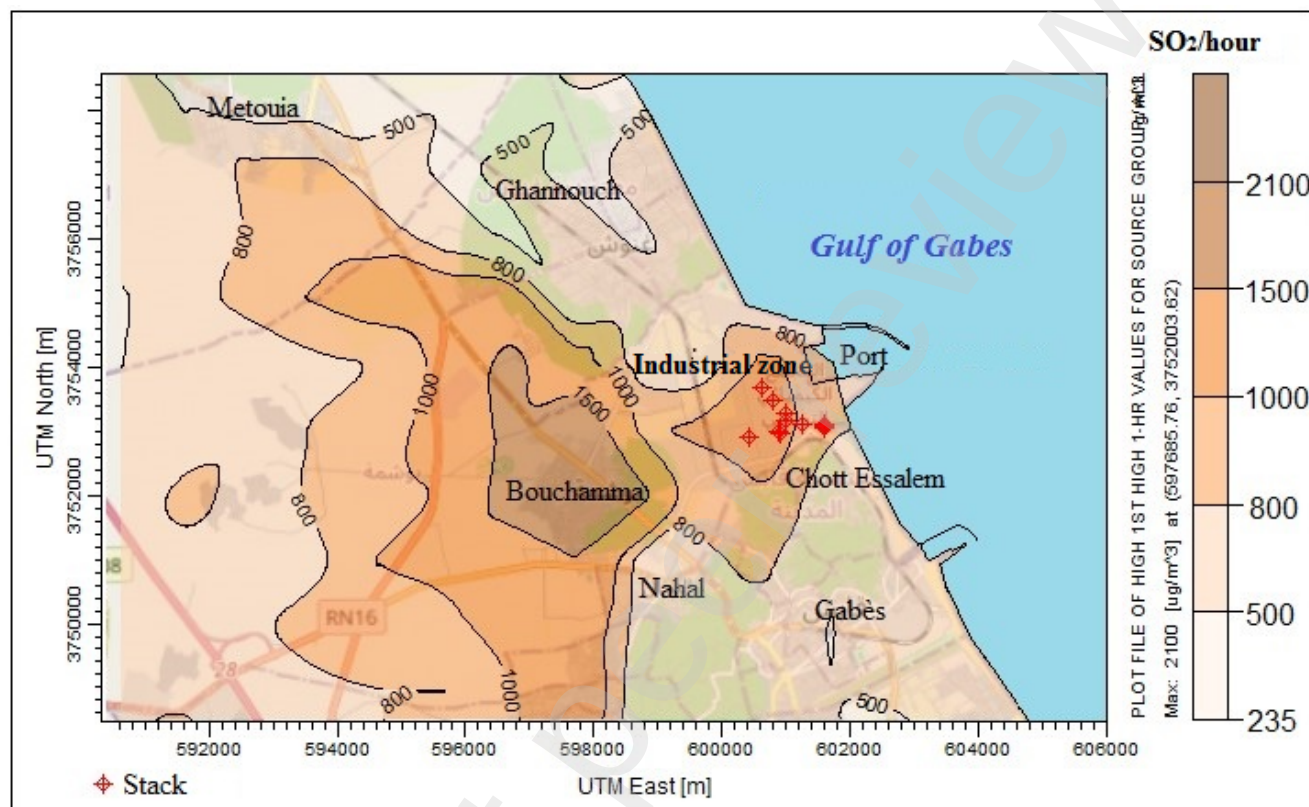


Figure 4: Iso-concentration curves for hourly SO₂ dispersion, source: ANPE raw data.

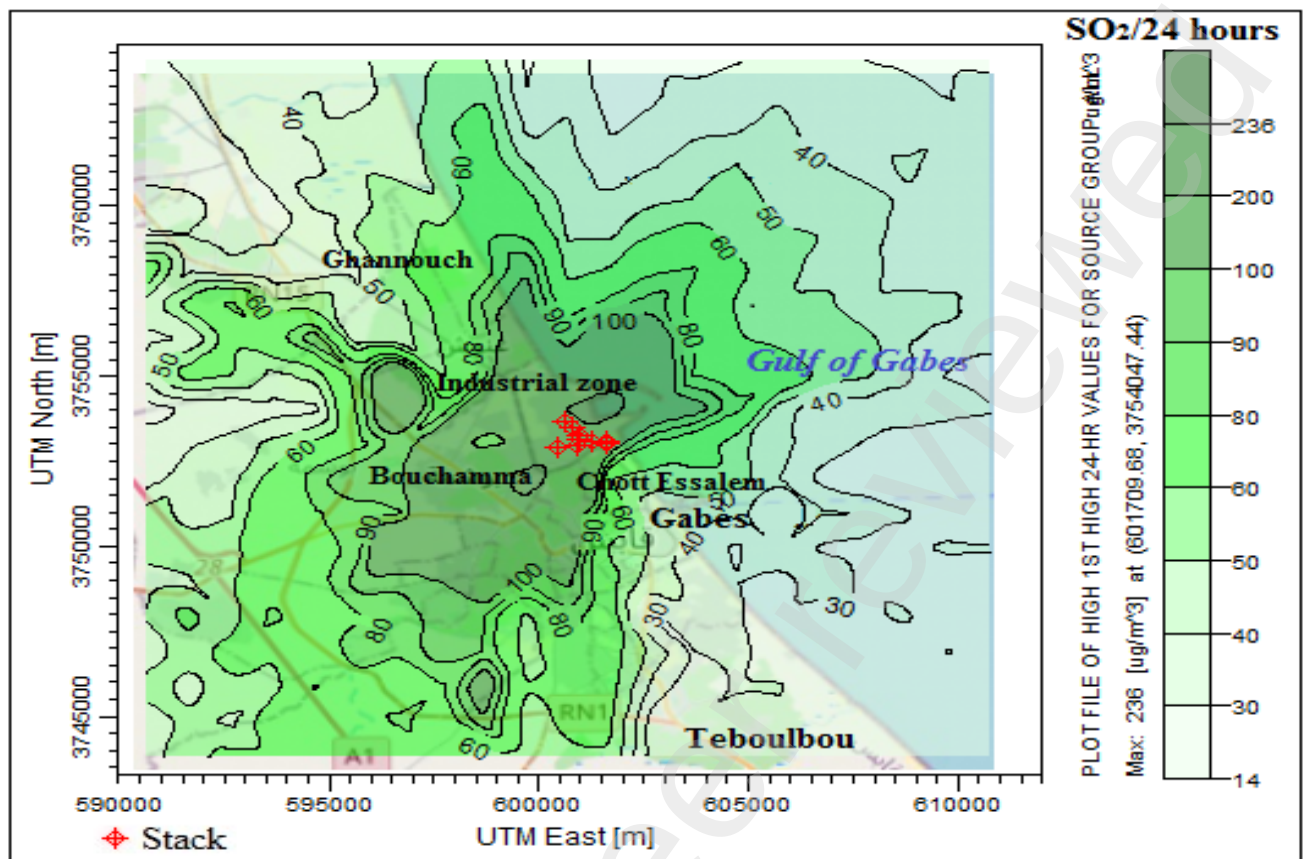


Figure 5: Iso-concentration curves for daily SO₂ dispersion, source: ANPE and GCT raw data.

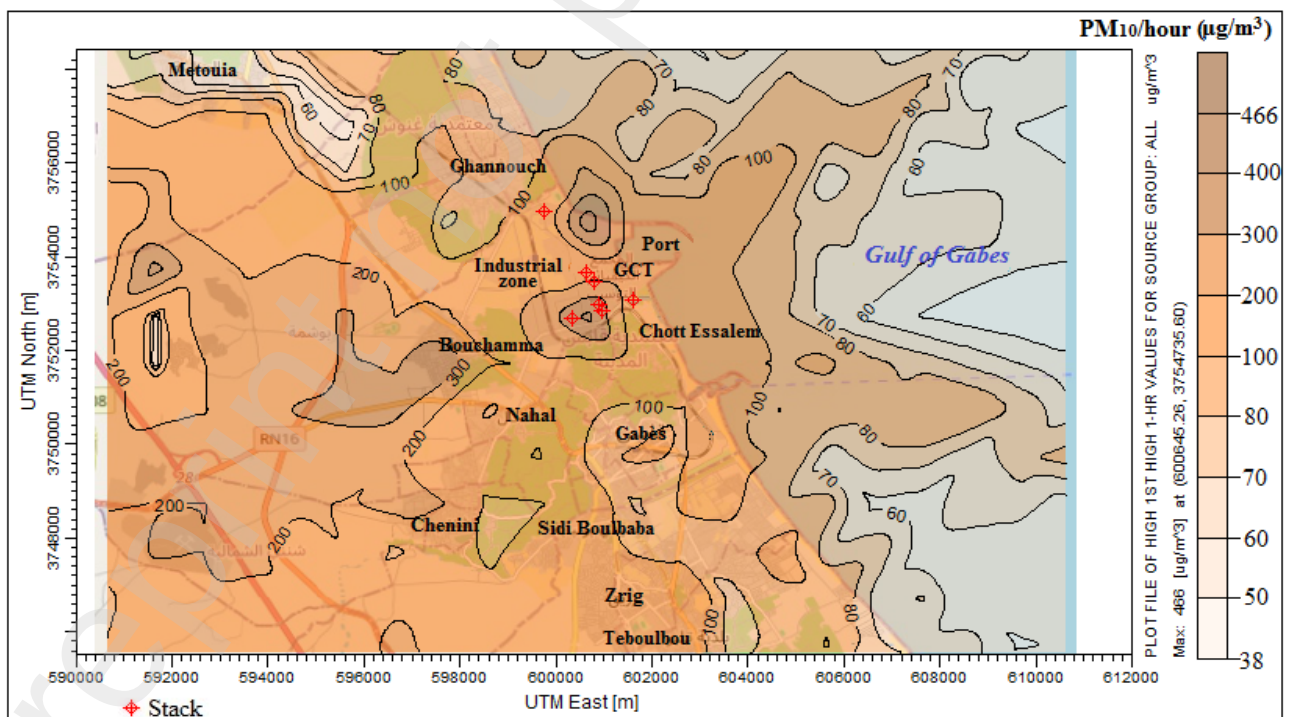


Figure 6: Iso-concentration curves for hourly PM₁₀ dispersion, source: ANPE and GCT raw data

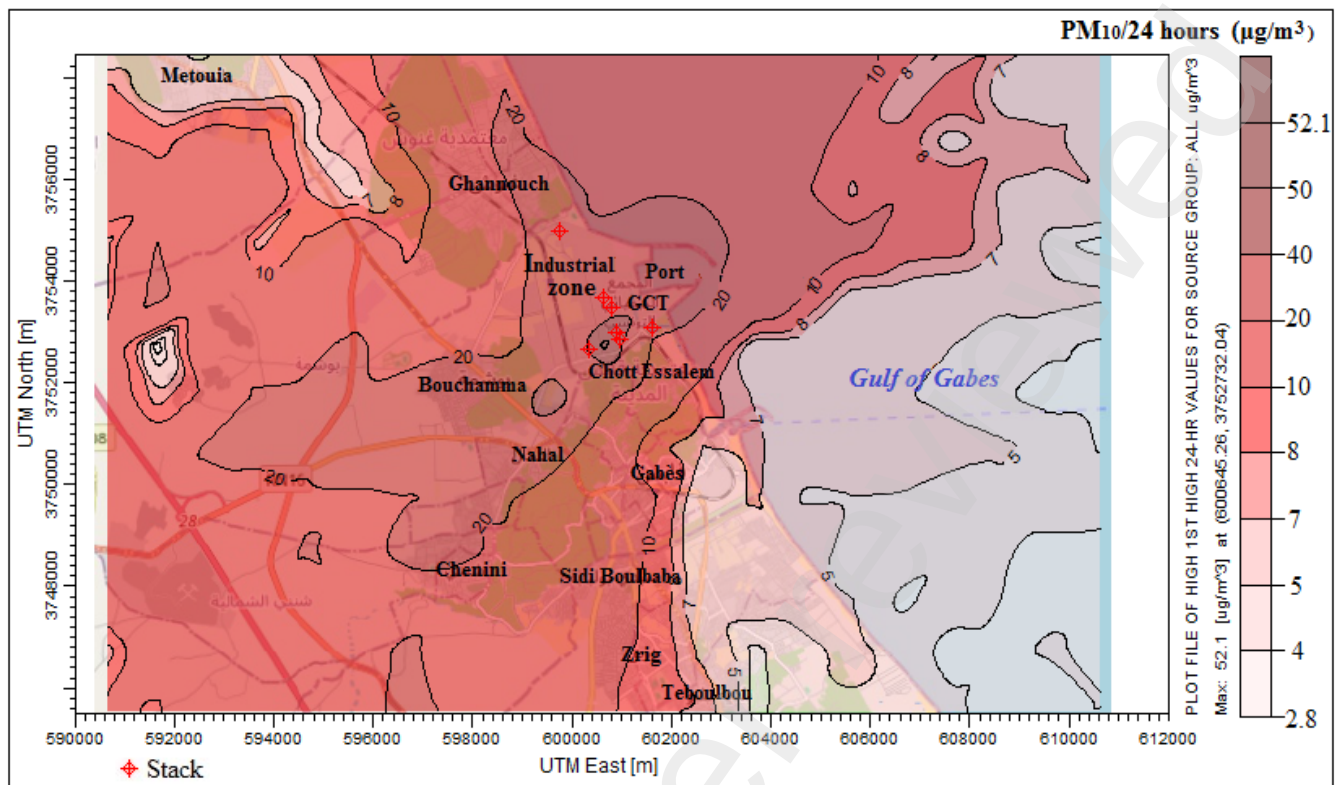


Figure 7: Iso-concentration curves for daily PM_{10} dispersion, source: ANPE and GCT raw data.

Analysis of the modeling results (figures 4,5, 6 and 7) allows the following observations:

- The results from AERMOD show good spatial consistency with the maps produced by interpolation (IDW) on ArcMap, particularly for PM_{12} , whose simulated values are very close to field measurements (instantaneous measurements and measurements provided by the ANPE).
- For SO_2 , the AERMOD model tends to underestimate the measured concentrations. The difference between the simulated values and the empirical values reaches up to 300% at certain points, suggesting increased sensitivity of the model to meteorological parameters and emission characteristics (particularly stack height).
- Regarding PM_{12} particles, the relative differences between modeling and measurement are less than 30% in the majority of cases, demonstrating greater model stability for this type of pollutant.
- Both approaches—modeling and interpolation—identify similar peak concentration areas, with a spatial shift of around 1 to 2 km for SO_2 . This shift is likely related to local variations in prevailing winds and topographical effects.

- Peak SO_2 and PM_{10} concentrations are logically located near the main industrial sources. However, at distances greater than 3 km, AERMOD simulations indicate higher concentrations than those measured, particularly in the Bouchemma and Ghannouch areas, where iso-concentration curves show a resurgence of pollution levels ($\text{SO}_2 > 1500 \mu\text{g}/\text{m}^3$; $\text{PM}_{10} > 300 \mu\text{g}/\text{m}^3$).
- Finally, the spatial representation of concentrations differs depending on the method: the measured data show an organization in decreasing circular zones around the sources (such as a "crown" or buffer), while the AERMOD simulation results reveal a multiple-core structure, depending on the location of the stacks and plume trajectories.

These results confirm the importance of combining empirical data and dispersion models to better understand the exposure zones and the spatial-temporal dynamics of air pollution in a complex industrial context.

4. Influence of winds on atmospheric dispersion

Wind is a determining factor in the spatial-temporal dispersion of air pollutants, particularly in coastal industrial areas. Analysis of data from the Gabès-Médina (Gabès-City) meteorological station over a 22-year period (2002–2023) allows us to characterize the structure of the prevailing winds, their speeds (figures 8 and 9), and their contribution to the exposure of neighboring communities.

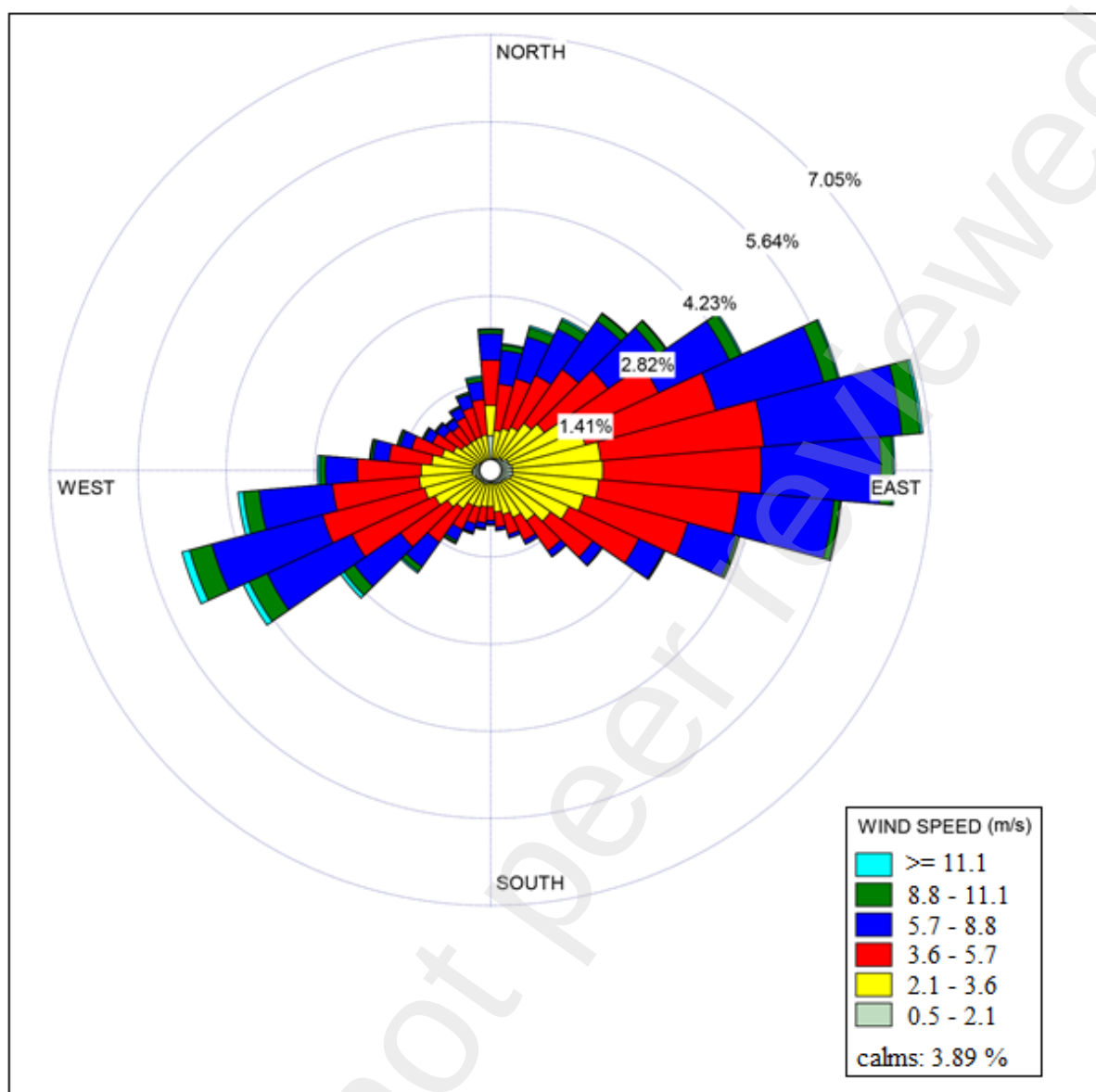


Figure 8: General wind rose for the Gabès Medina station, source: raw data INM 2002-2023

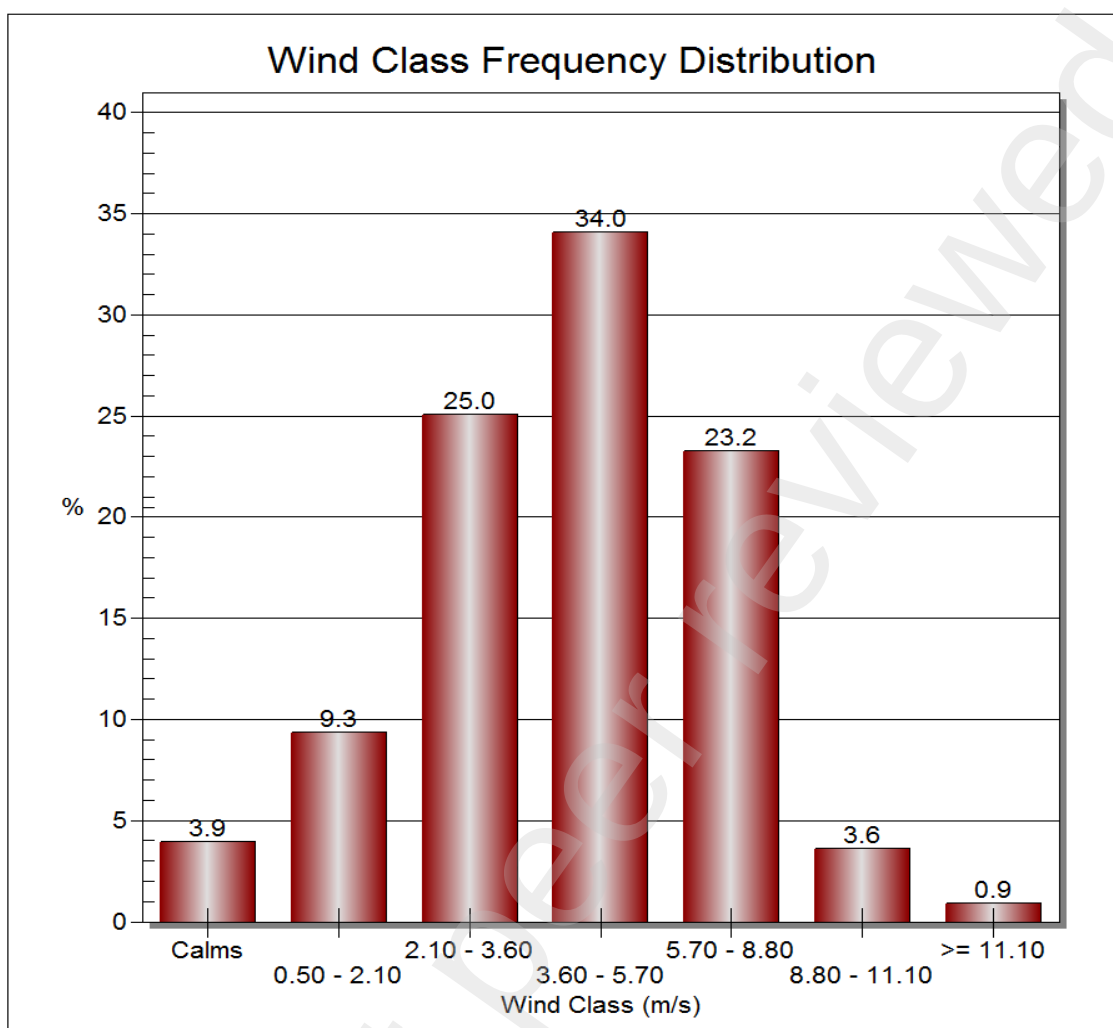


Figure 9: Wind speed classes at the Gabès Medina station, source: raw data INM 2002-2023

Prevailing winds originate mainly from the East-Northeast (ENE) and East-Southeast (ESE) sectors, i.e., from the coast, directing pollutant plumes inland, particularly towards the towns of Ghannouch, Chott Essalem, Bouchamma, Nahal, Chenini, and Gabès-City, within a radius of 3 to 6 km. Conversely, West/Southwest winds, although less frequent, can reach higher speeds (up to 10–14 m/s), promoting better vertical dispersion of pollutants.

On average, 82.2% of the observed winds had speeds between 2.1 and 8.8 m/s, including 34% between 3.6 and 5.7 m/s. Very light winds (<0.5 m/s) account for 3.9%, while winds above 11 m/s, although the most effective at dispersing pollutants, account for only 0.9% of annual occurrences.

❖ Seasonal Wind Variability

According to Figure 10, during winter and part of autumn, the Gabès metropolitan area is primarily subject to strong winds from the west-southwest. These winds, which can reach

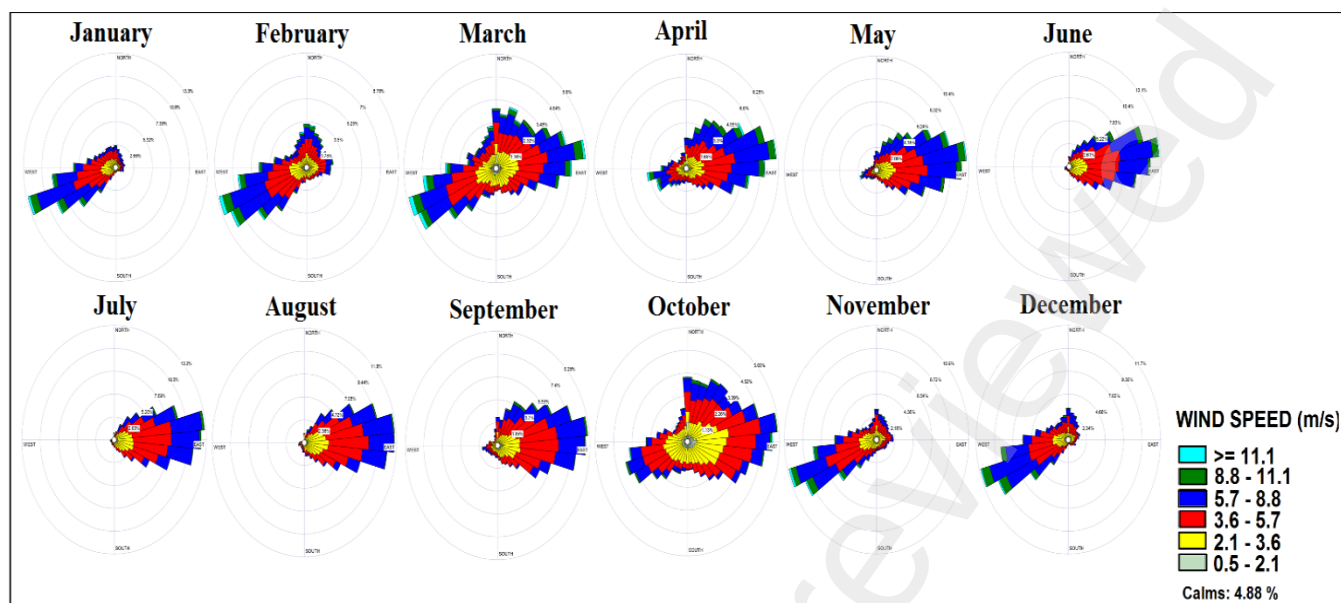


Figure 11: Monthly wind rose at Gabès-Medina station, source: raw data INM 2002-2023

Analysis of monthly winds (figure 11) reveals an annual bimodal structure:

- From March to October, prevailing east-northeast to east-southeast winds, combined with a daytime sea breeze, carry plumes inland, causing high pollutant concentrations in urban areas near the industrial zone.
- From November to February, west-southwest winds direct industrial discharges toward the sea or northeast coastal areas, generally reducing atmospheric concentrations on land.

The effect of the sea breeze, particularly active between April and September, accentuates this dynamic. By blowing perpendicular to the coast with low intensity, it tends to trap pollutants in the lower layers of the atmosphere, limiting their dispersion and increasing their accumulation in nearby towns such as Ghannouch, Bouchamma, and Chott Essalem.

❖ Exposure by Wind Regime

Winds orient the plumes according to their direction and persistence, resulting in differentiated exposure of urban neighborhoods (table 3):

- Ghannouch is exposed year-round, due to its immediate proximity to industrial units and its geographical location downstream of the dominant wind direction, whether marine or continental.
- Bouchamma (to the west) and Chott Essalem (to the south) experience moderate exposure, mainly between March and October, with lower concentrations in winter.
- Gabès-City and Chenini-Nahal are affected occasionally, depending on monthly wind variability.

Table 3: Air Pollution Exposure Levels by Dominant Wind Patterns in Residential Areas Near the Gabès Industrial Complex

Location	Exposure period	Wind source	Exposure level
Ghannouch	All year round	East, ENE, West/South-West	Very high
Bouchamma	April – October	East, South-East	High
Chott Essalem	April – October	East, South-East	Moderate

Source: measurement results

❖ Observed Health Consequences

The direct impact of these aerological conditions on public health has been highlighted by several incidents:

- On October 13, 2023, a steady north-northwest wind between 9 a.m. and 12 p.m. directed a plume of ammonia gas (NH_3) toward the Chott Essalem primary school, causing the asphyxiation of 16 people, including 10 students and educational staff.
- On May 18, 2024, a south-southeast wind, combined with a butane gas purge from a British Gaz storage sphere, caused the suffocation of 15 middle school students in Ghannouch, located less than 500 m from the chimney. Summary: Exposure by Wind Regime

5. Gabès and Air Pollution: Comparative Analysis and Threshold Exceedances

Analysis of monthly concentrations of sulfur dioxide (SO_2) and fine particulate matter (PM_{10}) measured at the Ghannouch fixed station (Figure 12) reveals a marked seasonal trend. From January to September, pollution levels gradually increase, peaking in August at $58 \mu\text{g}/\text{m}^3$ of SO_2 and $185.6 \mu\text{g}/\text{m}^3$ of PM_{10} . This altitude is closely linked to summer weather conditions: rising temperatures, light winds, and sea breezes, which limit the dispersion of pollutants in the lower atmosphere.

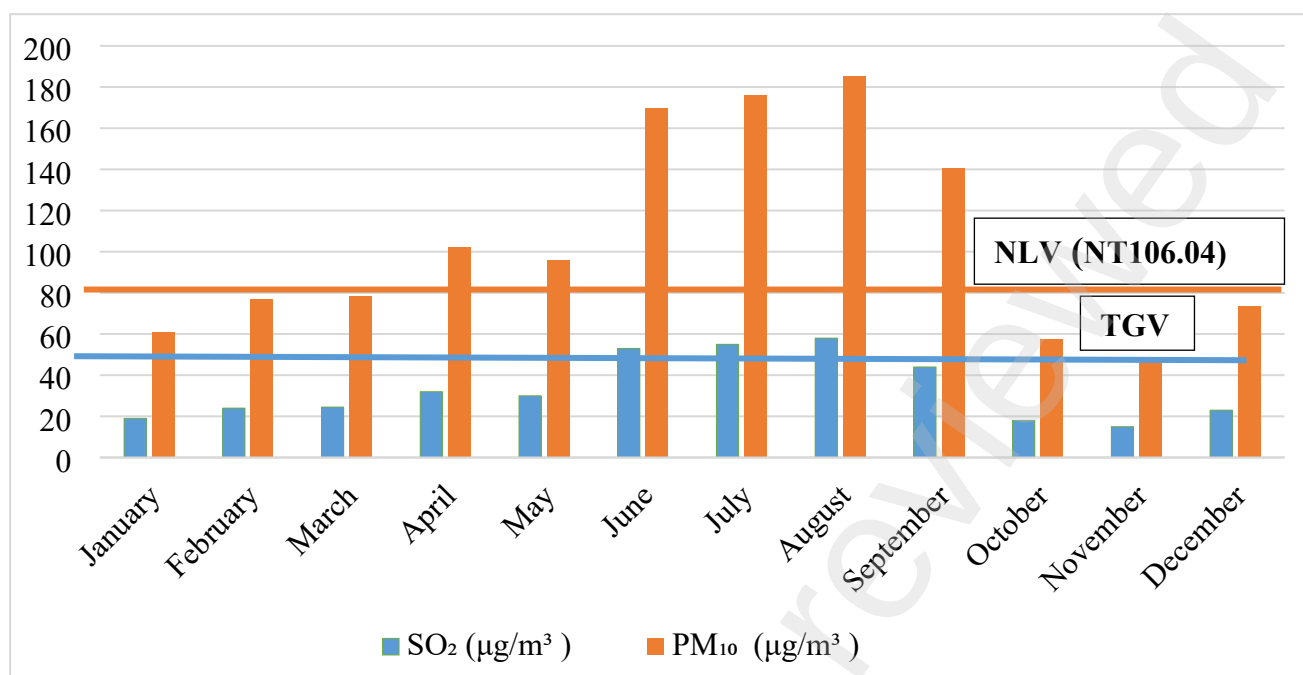


Figure 12: Monthly concentrations of SO₂ and PM₁₀ at the Ghannouch monitoring station.

Conversely, the months of October and November record a relative decrease in concentrations, before a slight increase in December. This dynamic is explained by the return of stronger westerly winds, favoring the vertical diffusion of emissions. The data reveal that:

SO₂ concentrations exceed Tunisian guideline values (TGV: 50 µg/m³) and World Health Organization (WHO) recommendations throughout the summer, particularly between June and August.

For PM₁₀, the entire year—with the exception of November—shows concentrations automatically exceeding regulatory thresholds, with frequent exceedances of the national limit value (NLV: 80 µg/m³).

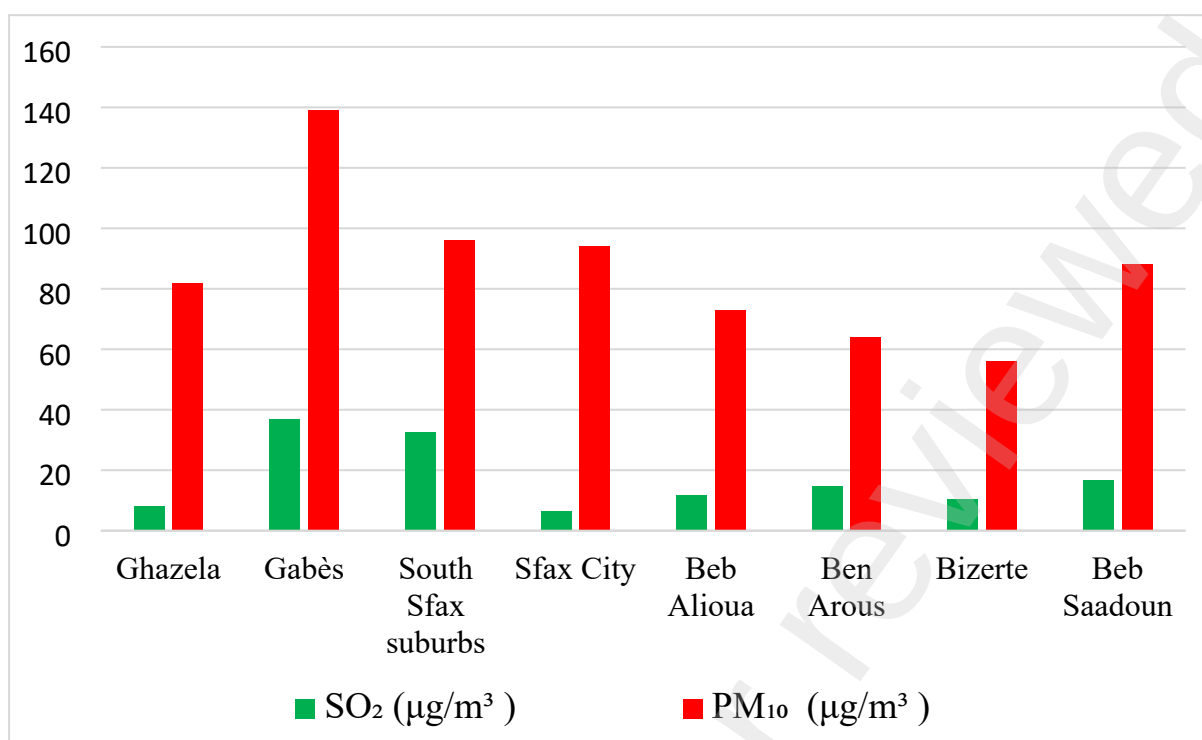


Figure 13: SO₂ and PM₁₀ concentrations at selected monitoring stations, ANPE, 2022 (annual average, 2022)

According to Figure 13, Gabès has the highest air pollution levels among all stations belonging to the National Air Quality Monitoring Network (RNSQA) managed by the National Agency for Environmental Protection (ANPE). While Sfax has high levels of air pollution by fine particles PM₁₀ and sulfur dioxide (SO₂), particularly in its southern suburbs, Gabès records the highest levels of SO₂ (36.75 µg/m³) and PM₁₀ (139 µg/m³), indicating more severe air pollution. Among these stations, the PM₁₀ concentration in Gabès significantly exceeds the recommended thresholds, it is 2.8 times higher than the Tunisian guideline value and 1.7 times higher than the Tunisian limit value. In conclusion, Gabès can be considered a disaster city due to its alarming levels of air pollution.

Conclusion:

The study of air pollution in the industrial zone of Gabès reveals that the main sources of pollution are phosphate processing plants and chemical fertilizer production facilities, particularly those operated by the Tunisian Chemical Group (GCT). Dispersion models and

field measurements confirm that pollution primarily affects areas near the industrial installations but can also spread over several kilometers, impacting adjacent residential and agricultural zones. Synoptic winds play a key role in pollutant dispersion, carrying plumes toward neighboring localities. Field-measured concentrations frequently exceed national standards, posing serious risks to both public health and the environment.

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