Abstract

There is a widely-held scientific conviction that the global climate is changing as a result of the combined anthropogenic forcing due to greenhouse gases, aerosols, and land surface changes. Many pieces of evidence have concluded with a high degree of probability that human activities have exerted a substantial net warming influence on climate. This study provides a comprehensive report on mass concentrations, statistical and geostatistical characterizations of PM$_{10}$ atmospheric aerosols in the Gulf of Gabès, in south Tunisia. Knowledge of source strengths and locations is also a valuable aid for interpreting observations and model results and ultimately choosing appropriate mitigation strategies. For these reasons we have developed a particulate matter emission inventory for Gabès for the year 2007. After knowing the principal source of atmospheric aerosols in the Gulf of Gabès, which is the industrial complex, PM10 was measured at 18 locations (sample points in urban zones with industrial influence). Principally, they were located near the industrial complex (within a distance of 1000-6000 meters), with a mobile monitoring unit equipped with real-time analysers, which generated a mean value of each pollutant for an interval of 15 min. The duration of this measurement campaign was 20 days successive in 2007.

In this study, statistical and geostatistical techniques were used to estimate PM10 atmospheric pollution throughout the experimental area. After analysing data and obtaining a good variogram, multivariate data analysis, cartography via ordinary kriging, was used to estimate PM$_{10}$ concentration at unsampled locations.

1. Introduction

Atmospheric particulate matter (PM) has raised severe concerns in many respects. Elevated PM levels have been associated with an increase of respiratory and cardiovascular diseases (Pope and Dockery, 2006) and allergies (Monn, 2001), with the reduction of visibility (Horvath, 1993) and with acidification and eutrophication of ecosystems (UNECE, 2004). It was further recognized that atmospheric PM plays an important role in the climate system (IPCC, 2007), and it has been shown that the elemental composition of PM has a strong influence on its effects on human health and on the environmental behaviour (de Kok et al., 2006; Harrison and Yin, 2000; Heeb et al., 2008; Lighty et al., 2000; Muller et al., 2010) [1-7].

The Mediterranean basin is considered one of the most controversial regions for aerosol transportation due to its location at the intersection of air masses circulating among the three continents. The Mediterranean basin is characterized by a cross road of different kinds of atmospheric particulate matter (PM), due to the variety of
In this study, statistical, inventory and geostatistical techniques were used to estimate $PM_{10}$ atmospheric pollution in the Gulf of Gabès in south Tunisia.

2. Materials and methods

2.1. Study area: Gabès region

The governorate of Gabès is located in southeast Tunisia on the coast of the Gulf of Gabès, which is part of the Mediterranean Sea (Latitude 33°53’ longitude 10°07’), 376 km south of the capital, Tunis (see Fig.1). It is a governorate (provinces) with 350,000 inhabitants (2005 estimate) and an area of 7,175 km². It has a warm-summer Mediterranean climate, characterized by a hot and dry season and a cool and arid season.

This region is one of the biggest industrial cities in Tunisia. Most industries are chemical oriented. The main industries are: Cement, Chemical products, Brick Factories and Oil refinery.

Gabès has also one of the biggest ports in Tunisia; it is used usually to ship the mineral products from the city of Gafsa.

The fast growing numbers of factories has resulted in fairly serious pollution of the area and gulf of Gabès.

A recent study by the Facility for Euro-Mediterranean Investment and Partnership (FEMIP) and the World Bank pinpointed the Gabès region as one of the most polluted in the Mediterranean Basin. For that, in recent years the government is working on new programs and laws to decrease the amount of pollution.

![Fig.1: Map of Tunisia with Gabès highlighted](image)

2.2. Emission inventory methodology

2.2.1. General methodology
We have considered all the major compounds which are emitted from anthropogenic sources (mainly industries and road traffic). The emissions issued from the anthropogenic sources result mainly from the use of the different fossil fuel types and from the evaporation of solvents. The levels and the composition of these emissions depend on several main parameters such as combustion processes, temperature, filtration devices, etc. (combustion) and on the conditions of using and recovering procedures, when they exist (solvents). Finally, the compounds which compose our emission inventory are explained below.

2.2.1.1. Industrial classification

The information on industries included details of industries based on consumption of fuel and power. The data showed that there are a total 14 air polluting industries in the Golf of Gabès.

The other industries may be either water polluting or hazardous waste generating and/or nonpolluting types. Industrial sector was subdivided into power plant, liquefied petroleum gas (LPG) plant; cement manufacturing, chemicals industries, brick plant, and paper industry.

The available information on industries was analysed with respect to their locations in different industrial cluster/areas and products and is presented in Table 1, respectively. Amongst the air polluting industries, major industries like thermal power plant, chemical and fertilizer industries.

2.2.1.2. Fuel consumption data

Emission estimates for combustion sources are generally based on emission factors developed from fuel composition data and fuel consumption. Information on fuel consumption in industries with regard to light diesel oil (LDO), liquefied petroleum gas (LPG), natural gas (NG), coal... was obtained from various administrations in Tunisia (ANME, Industry ministry...). The latest fuel consumption data was available for 2007, which was chosen as the base year.

2.2.1.3. The different compounds of the emission inventory

2.2.2. Calculation method for each category of sources

2.2.2.1. Industries emissions

The methodology of a bottom up approach of CORINAIR emission is selected to prepare the PM emission inventory.

In CORINAIR emission inventories, sources are broken down over 11 SNAP categories. SNAP stands for selected nomenclature for sources of air pollution. CORINAIR guidebooks give the European continental, national and local authorities a set of standard reference tools and methods to estimate pollutants production in a given area and to report it under the SNAP nomenclature.
The emissions of pollutants depend primarily upon the energy consumption, production of goods, solvent uses, type of transports, etc. but also upon emission factors that relate the primary data to the emission of pollutants in the atmosphere. These emission factors which are among the most sensitive parameters in emission inventories depend on the characteristic of the fuels or solvents and on the processes in which they are involved.

### 2.2.2.2. Industries emission factors

We have used two kinds of emission factors:

The first concerns all the combustion processes (mainly fossil fuels) while the second takes into account all the evaporation processes. For the industry, most of the emission factors used in this study are issued from the CORINAIR guidebooks. However, it should be remembered that, for a given activity, they are average values and are generally valid only for ‘normalized’ installations. Due to lack of information on technical characteristics of the processes, we often had to consider that these emission factors could be applied to the real installations. Nevertheless, we frequently had to correct them to take into account the specificity of the fuels used in Tunisia (sulfur content) as well as the characteristics of the processes when more information was available.

### 2.2.2.3. Emissions from road traffic

Road traffic is one of the most significant anthropogenic sources of PM. To perform this part of the emission inventory, we had to make several assumptions, according to the characteristics of the traffic. We first distinguished two types of traffic: urban and rural.

The vehicles themselves have been divided into several categories according to their weight and their engine type. We then distinguished five categories of cars: passenger cars; light duty vehicles (total wt. < 3.5 tons); heavy duty trucks (total wt. > 3.5), buses and Motorcycles and three engine fuels: gasoline, diesel and LPG. The various percentages for these different categories were provided by the ‘General direction of bridges and chausses’.

Despite their importance, road traffic emissions are very difficult to estimate and they are affected by significant uncertainties.

The uncertainties are both intrinsic to the emission factor equations (which depend on pollutant, vehicle type, fuel type and formulation, inspection and maintenance programs, etc.) and are also due to the many variables needed for their estimation.
(fuel consumed, mileage, driving patterns, climatic factors, etc.) and the uncertainties of these variables.

Total distances travelled, on the main and secondary road networks, were subsequently used to calculate emissions, according to EU-official COPERT methodology. The COPERT methodology is part of the EMEP/CORINAIR Emission Inventory Guidebook, being fully consistent with the Road Transport chapter of the Guidebook (EMEP/CORINAIR, 2007). COPERT is also a software program aiming at the calculation of air pollutant emissions from road transport (Gkatzoflias D. et al., 2007). COPERT IV was used: this approximation was acceptable as the target year for the regional fleet was 2007 and COPERT IV covers all the emission standards related to this year (up to the EURO 4 vehicle emission standards).

COPERT estimates emissions of all major air pollutants (CO, NOx, VOC, PM, NH3, SO2, heavy metals) produced by different vehicle categories (passenger cars, light duty vehicles, heavy duty vehicles, mopeds and motorcycles) as well as greenhouse gas emissions (CO2, N2O, CH4) and fuel consumption. The methodology also provides speciation for NO/NO2, elemental carbon and organic matter of PM and non-methane VOCs, including PAHs and POPs. Emissions estimated are distinguished in three sources: Emissions produced during thermally stabilized engine operation (hot emissions), emissions occurring during engine start from ambient temperature (cold-start and warming-up effects) and NMVOC emissions due to fuel evaporation. Non-exhaust PM emissions from tyre and break wear are also included. The total emissions are calculated as a product of activity data provided by the user and speed-dependent emission factors calculated by the software.

3. Results and discussions

3.1 Statistical characterization of atmospheric PM\textsubscript{10} concentrations

In this section the evolution of PM\textsubscript{10} atmospheric pollution in Gabès is discussed, in this research, monitoring records were obtained from the National Air Quality Monitoring Network (RNSQA) in Tunisia. The box plots in Fig.2 were obtained from averages and maximum of PM\textsubscript{10} of 24 hours; the measuring stations installed in Gabès recorded the highest values of PM\textsubscript{10} compared to other stations during 2010.
(a). Yearly averages of PM$_{10}$ of 24 h  
(b). Yearly maximum of PM$_{10}$ of 24 h

**Fig.2.** Comparison between Gabès and others regions

According to measurements made by the RNSQA in Tunisia, the concentration of suspended particles, in Gabès, is relatively high because of natural factors; Tunisia has some of the wind transporting sand with a few volatile particles. In addition, Gabès’s climate is semiarid, generating an atmosphere for dust emissions. (See Fig.3).

![Temporal evolution of PM$_{10}$](image)

**Fig.3.** Temporal evolution of PM$_{10}$

Fig.3. shows that the highest values of PM$_{10}$ in Gabès were recorded in the winter season, when the wind speed is very important.

To better evaluate the situation of PM$_{10}$ atmospheric aerosols in the Gulf of Gabès, we have compared the concentration of PM$_{10}$ in Gabès station during two years with the Tunisian Limiting values and the Guide Values recommended by the World Health Organisation. (See Table 1).

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of exceedances of the Tunisian Limiting values</th>
<th>Number of exceedances of the Guide Values recommended by the World Health Organisation</th>
</tr>
</thead>
</table>
In 2010, 5% of days exceeded the Tunisian Limiting values and 42% exceeded the Guide Values recommended by the World Health Organisation.

3.2. PM Inventory emissions

3.2.1. PM Inventory emissions of traffic roads

3.2.1.1. Fleet Distribution

Another parameter of importance for the traffic emission calculation is the distribution of the circulating fleet into COPERT vehicle categories.

For the present work, statistics provided by the ATTT (“Agence Technique des Trasports Terrestres”, Tunisia) was used. The percentages of vehicles divided into different emission standards, vehicle categories and fuels are given in figure 4.

![Fleet Distribution Per Categories](image)

![Fleet Distribution Per Fuel](image)

**Fig. 4.** Gabès 2007 vehicle fleet distribution categories (left) and fuel (right)

The results shows that 52% of categories of vehicles in Gabès are light Duty vehicles and 33% are passengers cars. Also, you con note that 74% of vehicles used gasoline.

3.2.1.2. Results of PM Inventory emissions

Table 2 presents the emission results. Thanks to the availability of regional data on fuel consumption for road traffic it is possible to compare the methodology results with observations, the results are quite satisfactorily.
The small difference could be explained by the uncertainties in the distribution of traffic densities and vehicle fleet as well as on the hypothesis made on the vehicle speeds. (See figure 5).

**Table 2.** PM emission results

<table>
<thead>
<tr>
<th>pollutant</th>
<th>TRAFIC (T/an)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM10</td>
<td>20.8</td>
</tr>
<tr>
<td>PM2.5</td>
<td>17.12</td>
</tr>
<tr>
<td>TSP</td>
<td>13.47</td>
</tr>
</tbody>
</table>

Fig. 5. PM Road Traffic Emission (%)

The major PM road traffic emission, in Gabès, is the PM$_{10}$ with 41% and PM$_{2.5}$ with 33%.

We must know that breathable fractions of airborne ambient particulate matter (PM$_{10}$) specifically those fractions that are less than 2.5µm (PM$_{2.5}$) in size. Fine particles have been identified as potential risk of general public. It has been one the largest occupational problem.

They are small enough to penetrate into lungs, where they may exacerbate conditions such as bronchitis and asthma and have also been associated with visibility degradation and climate change.

It causes lung damage such as pneumoconiosis and in particular silicosis, asbestosis, damage to the noise; throat and eyes and damage to the skin; it may cause various types of dermatitis, which are a widespread and often serious problem or even skin cancer [8].

Table 3 presents the PM (exhaust) road traffic emission in Gabès per categories of vehicle and nature of road. (See figure 6).

**Table 3.** PM (exhaust) road traffic emission
As you can see, Buses in Gabès are the principal source of PM (exhaust) and this is can be justified by the age of these buses (Technology euro II).

3.2.1.3. Results of PM 2.5 Inventory emissions
The results of PM\textsubscript{2.5} road traffic Inventory emissions in Gabès are given by table 4 and figure 7.

**Table 4.** PM\textsubscript{2.5} road traffic emission

<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>YEAR</th>
<th>SECTOR</th>
<th>URBAN [t]</th>
<th>RURAL [t]</th>
<th>HIGHWAY [t]</th>
<th>TOTAL [t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2.5</td>
<td>2007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passenger Cars</td>
<td>1.33</td>
<td>1.06</td>
<td>0.00</td>
<td>2.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline 1.4 - 2.0 l</td>
<td>0.08</td>
<td>0.07</td>
<td>0.00</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel &lt;2.0 l</td>
<td>1.20</td>
<td>0.95</td>
<td>0.00</td>
<td>2.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPG</td>
<td>0.05</td>
<td>0.04</td>
<td>0.00</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Duty Vehicles</td>
<td>0.26</td>
<td>0.30</td>
<td>0.00</td>
<td>0.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline &lt;3.5 l</td>
<td>0.26</td>
<td>0.30</td>
<td>0.00</td>
<td>0.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel &lt;3.5 t</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Duty Trucks</td>
<td>2.70</td>
<td>3.52</td>
<td>0.00</td>
<td>6.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rigid 7.5 - 12 t</td>
<td>2.21</td>
<td>2.91</td>
<td>0.00</td>
<td>5.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Articulated 14 - 20 t</td>
<td>0.50</td>
<td>0.61</td>
<td>0.00</td>
<td>1.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buses</td>
<td>7.31</td>
<td>0.58</td>
<td>0.00</td>
<td>7.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Buses Standard 15 - 18 t</td>
<td>7.31</td>
<td>0.58</td>
<td>0.00</td>
<td>7.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motorcycles</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-stroke &gt;50 cm\textsuperscript{3}</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-stroke &lt;250 cm\textsuperscript{3}</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

More than 80% of PM\textsubscript{2.5} Road Traffic Emission are rejected by Buses and Heavy Duty Trucks. Also 70% of these emissions are recorded in urban roads.

**3.2.1.4. Results of PM\textsubscript{10} Inventory emissions**
The results of PM$_{10}$ road traffic Inventory emissions in Gabès are given by table 5 and figure 8.

### Table 5. PM$_{2.5}$ road traffic emission

<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>YEAR</th>
<th>SECTOR</th>
<th>URBAN [t]</th>
<th>RURAL [t]</th>
<th>HIGHWAY [t]</th>
<th>TOTAL [t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM10</td>
<td>2007</td>
<td></td>
<td>13.96</td>
<td>6.84</td>
<td>0.00</td>
<td>20.80</td>
</tr>
<tr>
<td>Passenger Cars</td>
<td>0.14</td>
<td>1.27</td>
<td>0.00</td>
<td>2.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline 1.4 - 2.0 l</td>
<td>0.14</td>
<td>1.27</td>
<td>0.00</td>
<td>2.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel &lt;2.0 l</td>
<td>1.36</td>
<td>1.08</td>
<td>0.00</td>
<td>2.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPG</td>
<td>0.08</td>
<td>0.07</td>
<td>0.00</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Duty Vehicles</td>
<td>0.47</td>
<td>0.49</td>
<td>0.00</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline &lt;3.5t</td>
<td>0.47</td>
<td>0.49</td>
<td>0.00</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel &lt;3.5t</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Duty Trucks</td>
<td>3.36</td>
<td>4.39</td>
<td>0.00</td>
<td>7.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rigid 7.5 - 12 t</td>
<td>2.77</td>
<td>3.64</td>
<td>0.00</td>
<td>6.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Articulated 14 - 20 t</td>
<td>0.60</td>
<td>0.75</td>
<td>0.00</td>
<td>1.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buses</td>
<td>8.51</td>
<td>0.67</td>
<td>0.00</td>
<td>9.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Buses Standard 15 - 18 t</td>
<td>8.51</td>
<td>0.67</td>
<td>0.00</td>
<td>9.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motorcycles</td>
<td>0.05</td>
<td>0.02</td>
<td>0.00</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-stroke &gt;50 cm$^3$</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-stroke &lt;250 cm$^3$</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 8.** PM$_{10}$ Road Traffic Emission per categories (%)  

Same note of PM$_{2.5}$; more than 80% of PM$_{10}$ Road Traffic Emission are rejected by Buses and Heavy Duty Trucks. Also 70% of these emissions are recorded in urban roads.

#### 3.2.2. PM Inventory emissions of industries
The results of PM Inventory emissions of industries in Gabès proved that the particle size distribution of PM industries emissions is given as below:

As you can see 43% of PM industries emissions are TSP.

This figures confirmed that the principal industry sources of PM in Gabès are chemical industries (approximately more than 95%) and cement plant with 5%.
3.2.3. PM Inventory emissions of industries & Traffic roads

The total PM inventory emissions in Gabès for both industries and road traffic is given in the next figure.

![Fig.11. PM Inventory Emission in Gabès](image)

All the result of Particular matter inventory emissions in Gabès confirmed that the industries complex in Ghannouch is the principal sources of Particullar matter with different size.

For this reason, a special PM monitoring campaign near this industrial source is very important.

3.3. Geostatistical analysis of PM$_{10}$ near industrial complex

3.3.1. PM$_{10}$ sampling and chemical characterisation

Measurement took place at 18 locations, (points in urban zones with industrial influence). Principally, they were located near the industrial zone of Gabès (within a distance of 1000-6000 meters).

At each point, PM$_{10}$ was measured, with a mobile monitoring unit equipped with real-time analysers, which generated a mean value of each pollutant for an interval of 15 min. The duration of this measurement campaign was 20 days successive.

The UTM coordinates and description are listed in Table 6.

| Table 6. Locations of ambient air quality monitoring |
### 3.3.2. Spatial analysis

Fig. 12 shows the location of the 18 monitoring stations. These locations are expected to be highly polluted due to industrial zone of Gabès. The spatial results in Fig. 12 were obtained from averages of PM$_{10}$ of 24 hours.

![Geographical distribution of PM$_{10}$](image)

**Fig. 12.** Geographical distribution of PM$_{10}$
The measuring stations installed in near the industrial complex in Gabès (points 7, 11, 12 and 17) recorded the highest values of PM$_{10}$ compared to other sites.

### 3.2.3. Cartography of PM$_{10}$

In this section, as a geostatistical interpolation technique, we have used the ordinary Kriging. First of all, the spatial distribution of the variable was analysed.

Spatial correlation or dependence was quantified with semivariograms, and the covariance (see Fig 14).

Then the cartography of PM$_{10}$ concentration is established using the Ordinary kriging (see Fig. 15).

**Fig.13.** Analysis result

**Fig.14.** Spatial correlation

**Fig.15:** Ordinary Kriging prediction map of PM$_{10}$
This cartography confirmed that the industrial complex of Gabès is a principal source of dusts (PM$_{10}$). This industrial site recorded the highest values of PM$_{10}$ compared to other sites.

4. Conclusion

The Gabès regional PM emission inventory for road traffic and industrial sectors was fed via a bottom-up approach, thanks to this inventory emissions methodology, we have confirmed that industrial sources in Gabès represent the main contribution to the PM atmospheric emissions, then near industrial complex, the PM$_{10}$ level was assessed. Geostatistical interpolation method was used, the final results provide detailed geospatial information of PM$_{10}$ emissions in Gabès, this study showed that some measurements exceeds the Tunisian Limiting values of the ambient air quality and the Guide Values recommended by the World Health Organisation WHO for PM$_{10}$.

It is highly recommended to keep a healthy distance between the industrial complex of Gabès and urban areas to reduce the exposure of population to contaminants.

Acknowledgment

We are thankful to the National Agency for Environmental Protection (ANPE) in Tunisia for providing the air quality data.

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