AMERICAN UNIVERSITY OF BEIRUT

LAGRANGIAN MODELING OF AIR POLLUTION FROM DIESEL GENERATORS INSTALLED INSIDE BEIRUT CITY

by
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AN ABSTRACT OF THE THESIS OF

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Title: Lagrangian Modeling of Air Pollution from Diesel Generators Installed inside Beirut City

Urban areas with high population density are linked with hotspots of air pollution. Since many developing cities do not have enough distributed Air Quality Monitoring Networks (AQMN), air quality modeling becomes an alternative solution to get the pollution map. However, most air quality modeling studies are done at a low spatial resolution and do not capture the intra-urban variability of pollution which makes it difficult for the epidemiological studies to interpret health-related dataset. Therefore, a good air quality modeling will desire reaching the few meter scale resolution taking into account the urban forms of street canyons and the topographic information.

Characterized by an unregulated diesel generators sector, Beirut, the capital city of Lebanon, has witnessed increased pollution events. This study presents for the first time the Beirut pollution map at a 5-m resolution for the installed diesel generators in the city and analyzes the dynamic effects of the stacks location, buildings structure, topography, and atmospheric stability classes on the plume dispersion.

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ABBREVIATIONS

AQMN: Air Quality Monitoring Networks

EEA: European Environmental Agency

EMEP: European Monitoring and Evaluation Programme

GRAL: Graz Lagrangian Model

GRAMM: Graz Mesoscale Model

MOEW: Ministry of Energy and Water

OSM: Open Street Map

$PM_{2.5}$: Fine Particulate Matter

QGIS: Quantum Geographic Information System

WHO: World Health Organization

CHAPTER I

INTRODUCTION

A. General Introduction

Urban areas with high population density are linked with hotspots of air pollution. In fact, more than 80% of people living in urban areas that monitor air pollution are exposed to air quality levels that exceed the World Health Organization (WHO) limit [1]. Among other air pollutants, fine particulate matter ($PM_{2.5}$) is the most critical one affecting human health [2-4] and thus a continuous tracking of $PM_{2.5}$ concentrations have attracted extensive attention of epidemiological studies in urban areas [5-7]

But since many developing cities do not afford having enough distributed Air Quality Monitoring Networks (AQMN), air quality modeling became an alternative solution to get these concentrations as a pollution map [8]. However, most air quality modeling studies are done usually at a low spatial resolution and do not capture the intra-urban variability of pollution which makes it difficult for the epidemiological studies to interpret health-related dataset [9, 10]. Therefore, a good air quality modeling will desire reaching the few meter scale resolution taking into account the topographic information and the urban forms of street canyons.

B. Literature Review

With the lack of efficient urban planning, street canyons are common in most cities. They accumulate air pollutants and deteriorate air quality especially when buildings are tall and streets are narrow [11]. The widely used Gaussian plume model for point sources, which describes the pollutants dispersion as a normal distribution curve, has difficulties in dealing with these complex street canyons configurations where additional parameterizations are required [12]. However, the Gaussian plume model has shown a good performance when dealing with open terrains [13] and explained the effect of the atmospheric stability classes on the plume dispersion [14]. The more unstable the atmosphere is, the more the turbulence brings the plume to the ground resulting in localized high peaks near the stack. But farther downwind, concentrations start to drop off quickly [14].

Driven by three dimensional building-resolving flow simulations, and compared to the Gaussian plume model, Lagrangian particle dispersion models allow for a physically much more accurate representation of pollution transport in the street canyons [15]. The modeling system GRAMM (Graz mesoscale model)-GRAL (Graz Lagrangian model) has been shown to realistically simulate the air flow and air pollution dispersion in complex topography and in cities at resolutions down to a few meters [16-18]. GRAMM, which is a non-hydrostatic model, computes the mesoscale air flow accounting for topography and land-use effects for a larger domain centered on the city. Forced by GRAMM outputs, the GRAL model infers the microscale air flow inside the city, accounting for the effect of buildings on flow and turbulence patterns. This microscale wind field is then used by the dispersion module of GRAL to generate the concentration maps through Lagrangian dispersion computations.

Beirut, the capital city of Lebanon, lying on the eastern shore of the Mediterenean Sea, has witnessed a rapid urbanization phenomenon during the past few years [19]. This uncontrolled urban expansion in Beirut comes at the cost of the residents' health. In fact, the city is characterized by high $PM_{2.5}$ concentration levels [20, 21] exceeding the WHO limits by 150% [22]. These high concentrations are linked with long-range pollution transport such as the dust events originating in the Sahara and Arabian deserts [23], and local-range pollution transport due to emissions from traffic [20, 24], construction sites [21], and diesel generators [25]. Diesel generators are widely spreaded inside Beirut because of daily power outage periods. These generators have been shown to increase the carcinogen exposure in the city [25]. A survey conducted in 2017 [26] for the diesel generators installed in the Hamra neighborhood of Beirut showed that 53% of the buildings were equipped with one diesel generator at least each. Around 469 generators were presented in the Hamra area. The daily fuel consumption of diesel generators installed in the whole city was then estimated (747 metric tons on average) based on the survey data and the imported fuel quantity provided by the ministry of energy and water (MOEW).

C. Research Statement

To our knowledge no previous research work [8, 27] has studied the air pollution for the entire Beirut city at the street canyon resolution. This study presents a Lagrangian modeling for the $PM_{2.5}$ concentration levels originating from the diesel generators installed inside Beirut city. Steady state solutions are given using the GRAMM-GRAL tool at 5-m resolution for the annual averaged dominant meteorological conditions. The prognostic approach was used when buildings were added in the simulations. Effects of topography, buildings, atmospheric stability, diesel generators distribution and the location of their stacks, in addition to the orientation of the street canyons, on the pollution levels are all analyzed.

CHAPTER II

METHODOLOGY

In this chapter, the methodology that was adopted in this study is thoroughly discussed.

A. Digitizing Beirut City

A digital representation was completed for the topography, buildings and streets of Beirut as shown in Figure 1.

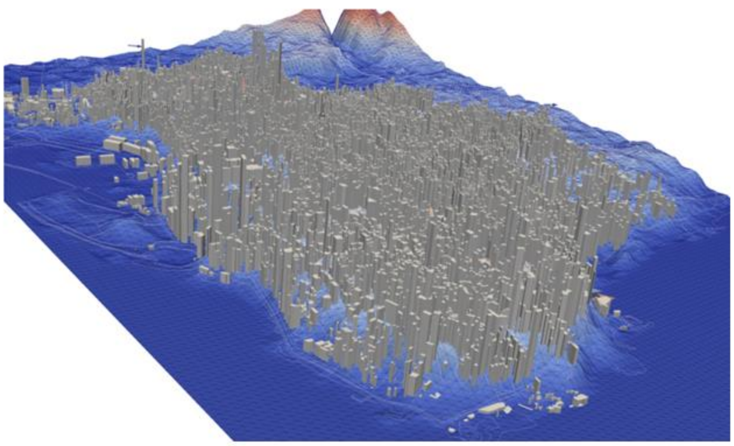

Figure 1: Digital representation for the topography, buildings, and streets of Beirut

1. Topography

Topography data was extracted at 50-m horizontal resolution for Lebanon [28]. In this study, only the topography data for the Greater Beirut area was used as an input to the GRAMM domain.

2. Buildings

A total number of 18478 buildings in Beirut were provided as a shapefile by the Lebanese army. Data about buildings height was also included in the attribute table with an average building height of 19-m.

3. Streets

The streets of Beirut city were downloaded from OpenStreetMap as OSM files and then converted to a shapefile using Quantum Geographic Information System (QGIS).

B. Domain Setup for Pollution Transport Simulations

1. Small Scale Domain

A small scale domain (Figure 2), containing couple of buildings located in Karakas, neighborhood region of Beirut, and assuming a flat terrain (which means that the GRAMM domain was not defined in this case), was taken for the purpose of analyzing the atmospheric stability effect on the plume dispersion for point sources. The buildings structure is complex in this area and the GRAL domain resolution was set to 2-m.

Figure 2: GRAL domain containing couple of buildings in the Karakas neighborhood of Beirut

2. Large Scale Domain

To simulate pollution transport for diesel generators in Beirut, a GRAL domain was defined around the borders of the city, at 5-m resolution, while the GRAMM domain, which has the Beirut airport falling at its boundary, was extended to include parts of the Greater Beirut area with a 50-m resolution. Figure 3 shows the defined domains and the borders of Beirut (white) and Hamra (red).

Figure 3: GRAMM (yellow) and GRAL (blue) domains for Beirut city

C. Diesel Generators Distribution

1. in the Small Scale Domain

Information (Table 1) on six diesel generators in the area (Figure 4) was collected from the janitors. These generators were assumed to work for 3 hours per day and their emission rates were calculated according to the European Monitoring and Evaluation Programme/European Environmental Agency (EMEP/EEA) air pollutant emission inventory guidebook using the Tier 2 method for reciprocating engine applications [29].

Table 1: Information data about the diesel generators distributed in the Karakas neighborhood

LABEL	FUEL CONSUMPTION (LITERS/MONTH)	STACK HEIGHT (M)	NO_X (KG/HOUR)
1	1800	37	0.687
2	1000	38	0.382
3	1500	39	0.573
4	1000	33	0.382
5	1000	29	0.382
6	1800	37	0.687

Figure 4: Six diesel generators distributed in the Karakas neighborhood

2. in the Large Scale Domain

Based on the Hamra survey on diesel generators, half of the buildings in Beirut were assumed to have one generator each. Therefore, 8900 diesel generators were distributed in Beirut city in addition to the collected 469 generators in Hamra. The fuel consumption of the former generators was distributed in a manner that meets the total daily fuel consumption in Beirut. All the diesel generators in Beirut were assumed to work for twelve hours during the day.

a. Best Case Scenario

A best case scenario assumed that all the diesel generators outside the Hamra area have their stacks extended by 2-m above the roof level of the buildings. Two different random distributions for the location of these generators were taken because the information about their exact location is not collected.

b. Worst Case Scenario

A worst case scenario assumed that all the diesel generators in Beirut (8900+469) were placed at the streets level with their stacks being extended 4-m above the ground level. Also two random distributions for the location of these generators were considered in this case.

D. Meteorological Conditions

1. Wind Speed and Wind Direction

The predominant average wind speed (4 m/s at 10-m anemometer level) and wind direction (247° wind blowing from west-southwest) were taken as meteorological inputs for the GRAL boundaries in the small scale domain and for the GRAMM boundaries in the large scale domain. These values come from a wind statistics based on real observations, which were extracted from the weather station at the Beirut Airport, taken between June 2005 and September 2018 daily from 7am to 7pm [29].

2. Atmospheric Stability Classes

a. for the Small Scale Domain

Strongly unstable, unstable, and slightly unstable atmospheric stability classes were taken separately to analyze their effect on the plume dispersed from the point sources.

b. for the Large Scale Domain

Unstable and slightly unstable stability classes were taken as inputs to the GRAMM domain boundary. The choice of these specific stability classes was based on the Pasquill atmospheric stability classes table.

E. Measurements

$PM_{2.5}$ measurements within street canyons were done in a part of the Hamra neighborhood (Figure 5) during the summer months of July and August 2017. Data was gathered throughout 23 days in the morning and 22 days in the afternoon and taken at two different times during the day: between 9 am and 10 am, and between 4pm and 5 pm. These timings were chosen in order to account for the variable conditions of the boundary layer. The sampled days were further classified into weekday runs, Friday runs, and Sunday runs.

A portable DustTrakTM DRX aerosol monitor 8533 was used to measure the concentrations of $PM_{2.5}$, and GPSLogger android application was used to log GPS and time data from GPS satellite. Both the DustTrakTM and the GPS logger were programmed to log data every one second, which allows attributing a GPS location to each $PM_{2.5}$ measurement. The mode of sampling chosen was walking instead of using a bicycle or vehicle in order to eliminate problems of isokinetic sampling faced using the latter methods, where the sampling conditions depend on the speed and flow of the traffic. Therefore, the DustTrakTM was well fitted in a backpack, and carried along the designated pathway (3.79 km circuit) at a constant pace as the devices logged data. Each run took approximately 45 minutes to complete. Measured $PM_{2.5}$ concentrations were overlaid with the recorded GPS coordinates, and mapped using ArcMap by ArcGIS.

Figure 5: Part of the Hamra area where $PM_{2.5}$ measurements were conducted within the street canyons

CHAPTER III

RESULTS AND DISCUSSION

In this chapter, results from simulations are presented and the effect of each parameter on the pollution map is discussed.

A. Effect of the Atmospheric Stability

Figure 6 shows the dispersion of the plume generated when only one diesel generator is operating. The results are in accordance with the Gaussian plume model principles. A small local peak is shown near the stack when the atmosphere is strongly unstable. However, farther downwind, at the leeward side of the building with the downwash effect, the concentrations are larger in the less unstable atmosphere. This aggregate effect can still be seen when all the diesel generators are running together as shown in Figure 7.

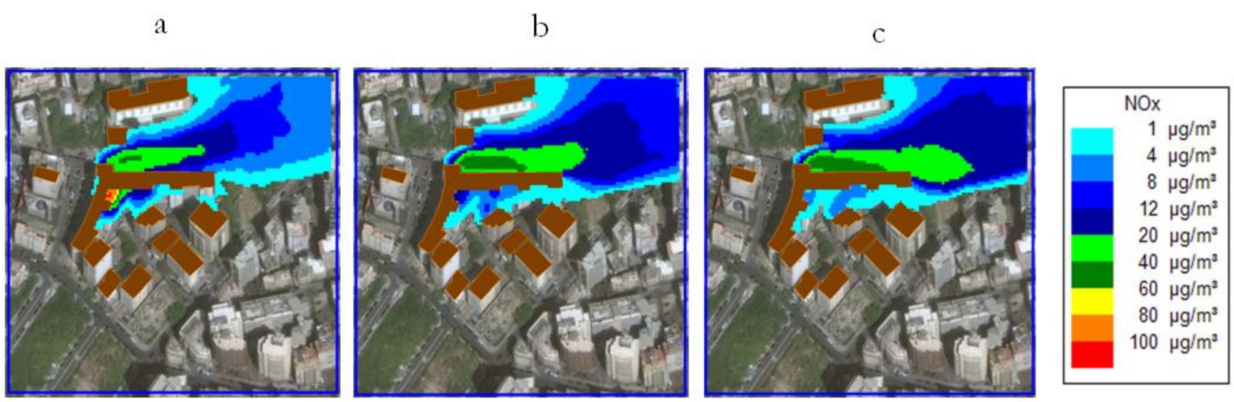

Figure 6: Plume dispersion when only diesel generator #1 is operating for (a) strongly unstable (b) unstable and (c) slightly unstable atmosphere. Solutions are given at 5-m above ground.

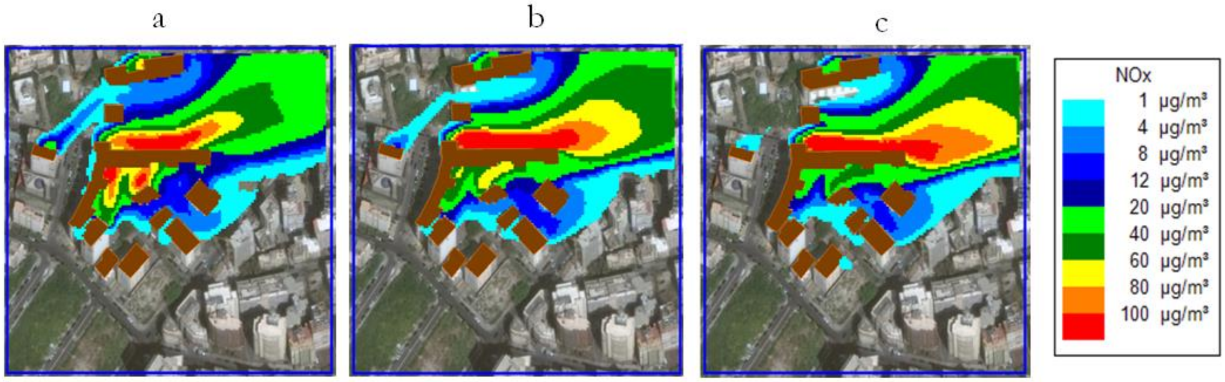

Figure 7: Plume dispersion when all generators are running together for (a) strongly unstable (b) unstable and (c) slightly unstable atmosphere. Solutions are given at 5-m above ground.

B. Effect of the Topography

The topographic map (Figure 8) shows a complex topography in Beirut characterized by two hills, each at approximately 100 m above sea level, separated by a low-elevation pass. Consequently high magnitude wind speed is noticed on the two hills while low magnitude wind speed is found at the low-elevation pass (Figure 9). The east side of the city is characterized by a falling slope created by the river of Beirut that separates the district of Matn in the Mount Lebanon Governorate from the city of Beirut. Accordingly, a deviation in the wind direction was observed in that area resulting in a pollution pocket as seen in Figure 7-a-c. The highest wind speed was at the north-west side near the sea sweeping the pollutants far away from that area as seen in Figure 7-a-c also.

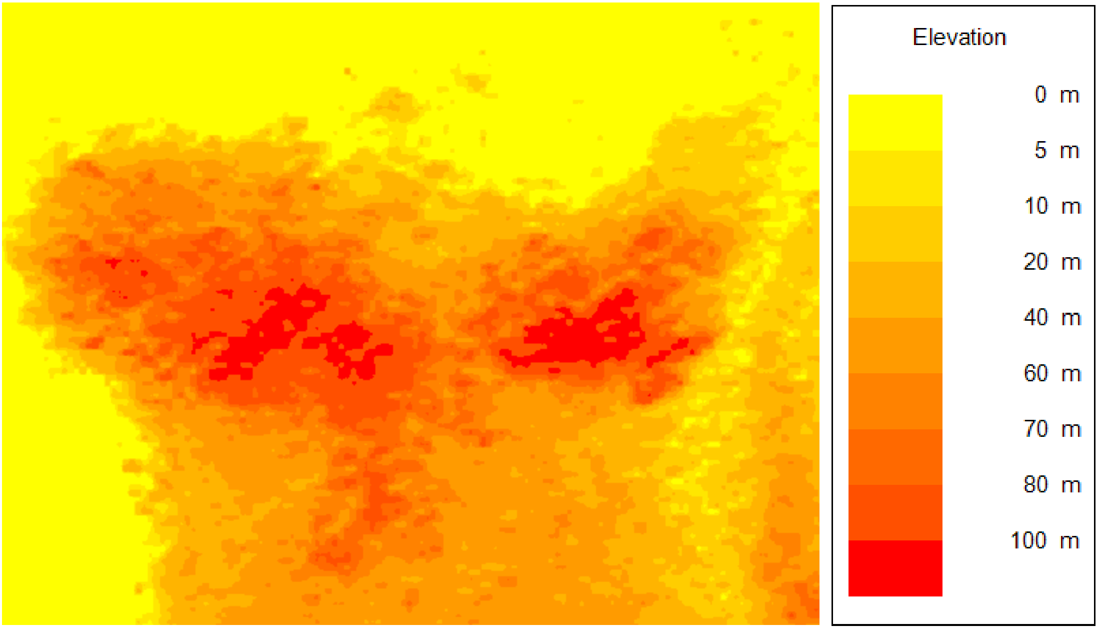

Figure 8: GRAL topography for Beirut city

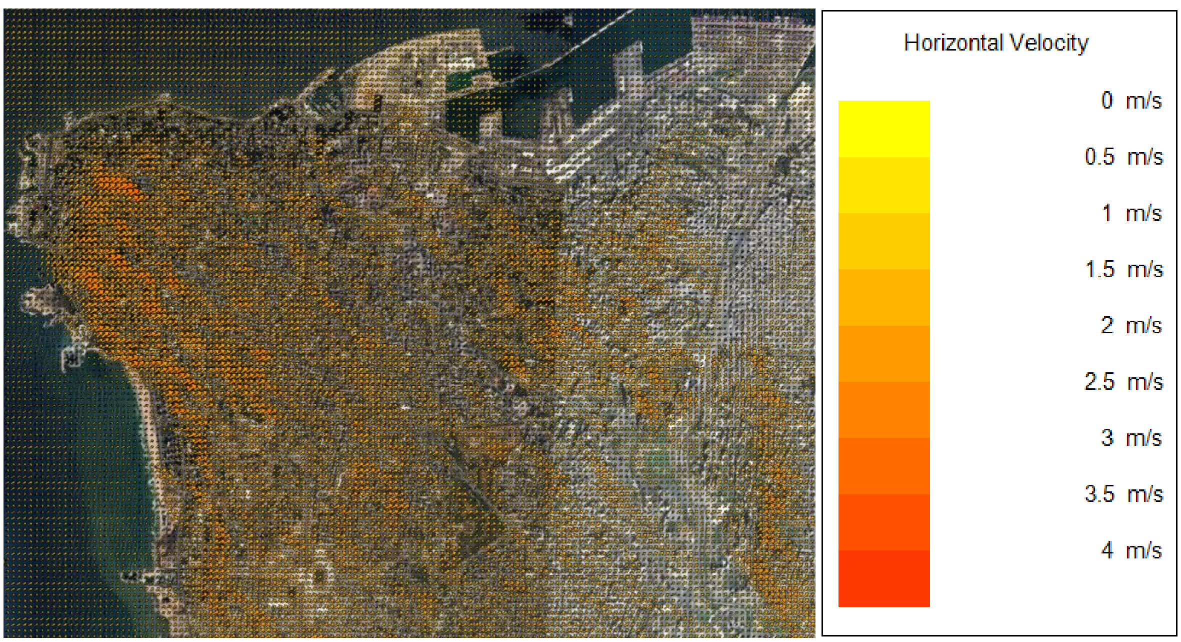

Figure 9: Horizontal wind speed at 2-m above ground computed by GRAMM

C. Effect of the Buildings

Figure 10 shows the downwash effect of the buildings in trapping the pollutants inside the street canyons. Even though the general pattern of the pollution dispersion can be seen, many localized new pockets start to appear in some areas that have been considered clean before adding the buildings. The atmospheric stability effect is clearly shown when comparing Figure 10-a and Figure 10-c. The pollution dispersion is more stretched in the wind direction for the slightly unstable atmosphere than for the unstable one as discussed also previously in the small scale domain.

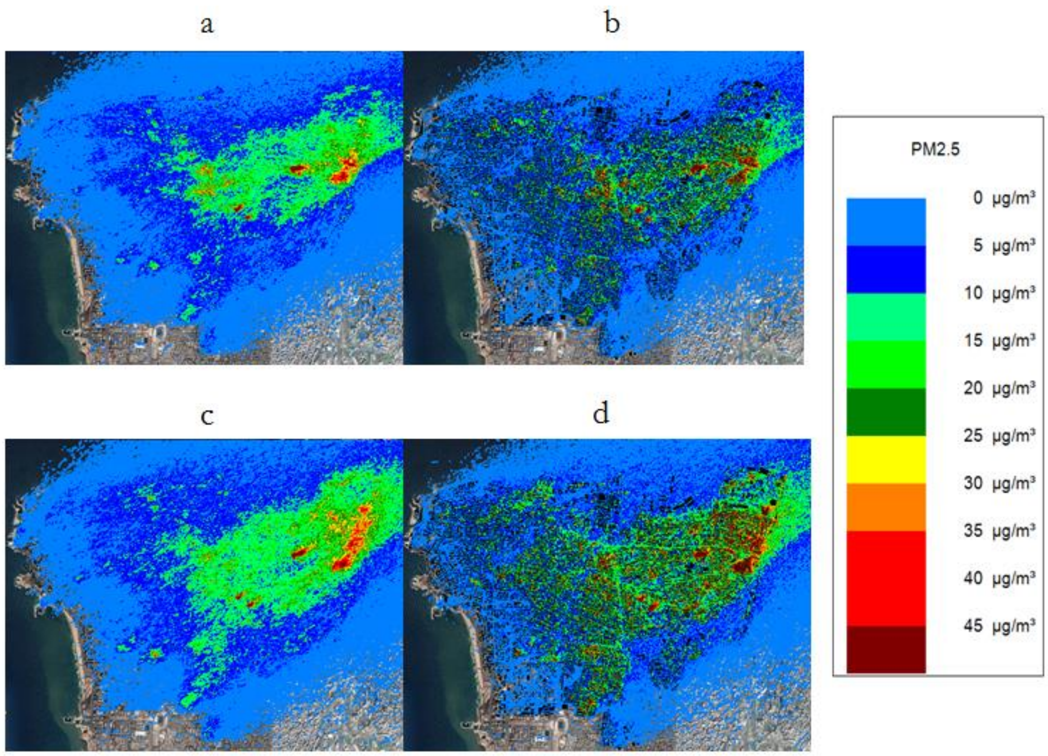

Figure 10: $PM_{2.5}$ concentration maps at 2-m above ground for a) no buildings-unstable atmosphere b) with buildings- unstable atmosphere c) no buildings-unstable atmosphere d) buildings-slightly unstable atmosphere. Generators Stacks outside Hamra are placed on top of the roofs.

D. Effect of the Diesel Generators Distribution and the Location of the Stacks

Figure 11 shows that the two different random distributions of the diesel generators give the same pollution map pattern. This means that the dispersion pattern is highly linked to the buildings, topography and atmospheric stability rather than the exact locations of the point sources. On the other hand, if placed at streets level, concentrations increase dramatically compared to the case where the generators are placed on the roofs.

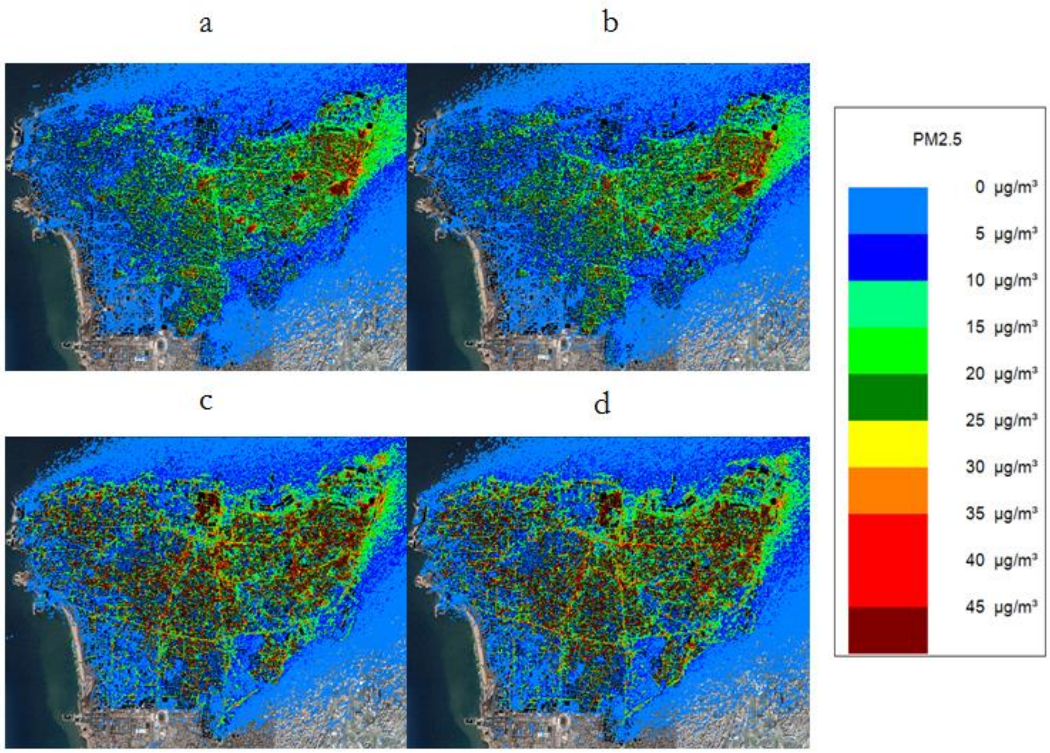

Figure 11: $PM_{2.5}$ concentration maps at 2-m above ground for (a) stacks on roof -first distribution (b) stacks on roof - second distribution (c) stacks at streets level-first distribution (d) stacks at streets level- second distribution. Solutions are for slightly unstable atmosphere.

E. Effect of the Orientation of the Street Canyons

Even though two random distributions were taken in the previous section, pockets and clean areas still show at the same locations. Also some areas remained clean even after adding the buildings in section 4. Analyzing these clean areas reveal a common orientation of their street canyons. In these areas, the wind at the roof level was found to be parallel to the street canyon (Figure 12-a), and tends to be channeled and accelerated through the canyon taking the pollutants far away from the canyon. On the other hand, in the pockets areas, the wind at the roof level was found to be perpendicular to the street canyons (Figure 12-b). According to their aspect ratio, these canyons are classified as deep narrow canyons where the most circular eddy emerges. This kind of regime is known as the skimming flow regime [30]. These results were in line with what was found in the literature [31, 32].

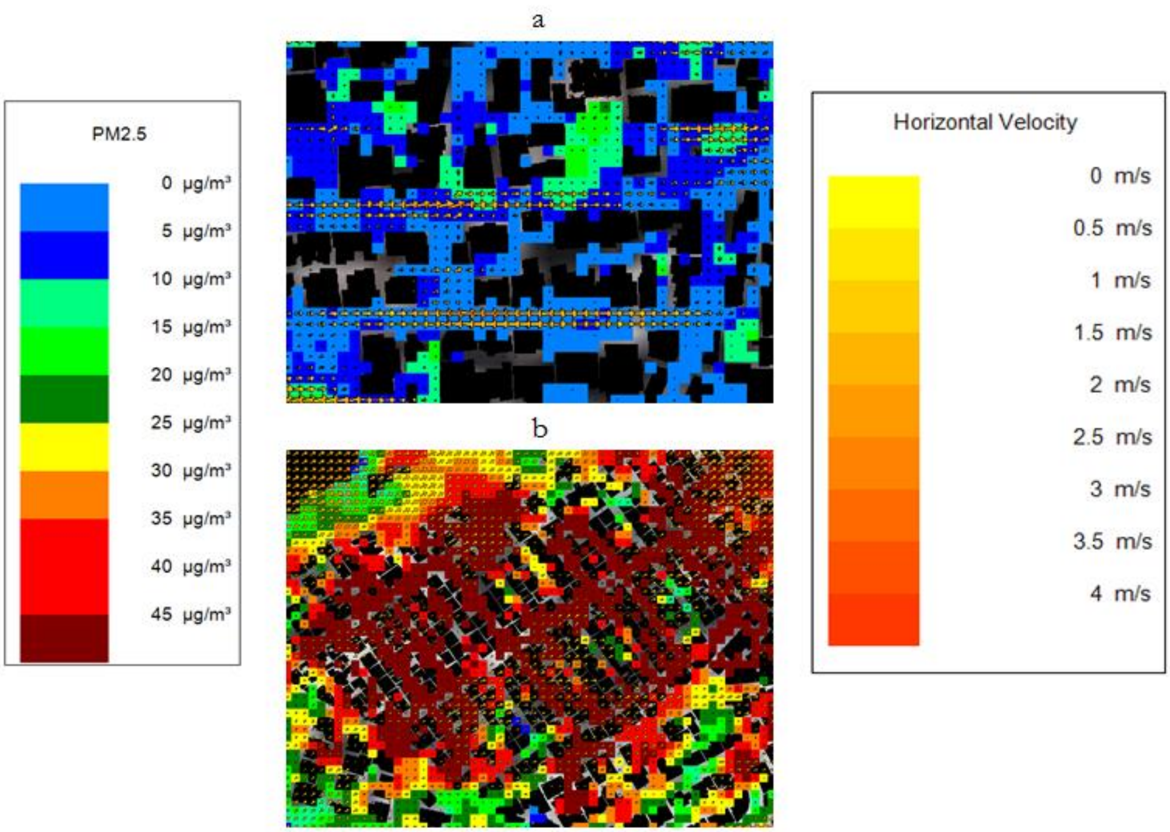

Figure 12: Wind at roof level (19-m) and $PM_{2.5}$ concentrations at 2-m above ground in two different street canyons orientations (a) parallel to the wind flow (b) perpendicular to the wind flow.

F. Comparing with Measurements

As presented in Table 2 and Figure 14 below, the measured weekday variations in $PM_{2.5}$ levels ranged between 25 and 51 μg/m^3 with an average of 36 μg/m^3 in the morning, and between 19 and 51 μg/m^3 with an average of 30 μg/m^3 in the afternoon. Levels decreased during Fridays, and significantly lower levels were observed during Sundays. Morning Sunday values ranged between 63 between 21 and 25 μg/m3 with an average of 23 μg/m^3 for $PM_{2.5}$. Afternoon Sunday values ranged even lower between 19 and 22 μg/m^3 for $PM_{2.5}$ with an average of 20 μg/m^3. The modeled values for the $PM_{2.5}$ concentrations (Table 3) for the diesel generators sources were within the measurements range with a mean of 8.3 μg/m^3 for the slightly unstable atmosphere and 7.6 μg/m^3 for the unstable atmosphere. Small contribution from the diesel generators modeled concentrations was found compared to the total measured concentrations which implies that most $PM_{2.5}$ mass concentrations in Beirut were derived from road traffic exhaust which is in line with what haven been reported in the literature [22]. Not to miss also, that potential hotspots in Figure 14 were noticed near construction sites during weekday's morning and afternoon which could be attributed to the consistent presence of trucks involved in the construction work, such as cranes, steer loaders, bulldozers and excavators. These trucks are large transportation vehicles that remain relatively stationary around the site of construction work, continuously emitting in place the fine particles. With less traffic during Sundays and no work at the construction sites, the major hotspot was found near an agglomeration of diesel generators (Figure 13-f).

Table 2: Summary of the morning and afternoon measured $PM_{2.5}$ concentrations in the Hamra area

Time of the day	**Sampling days**	**Number of sampling days**	**Minimum**	**Maximum**	**Mean**
Morning	Weekdays	16	25	51	36
	Fridays	4	27	37	31
	Sundays	3	21	25	23
Afternoon	Weekdays	14	19	51	33
	Fridays	6	21	33	26
	Sundays	2	19	22	20

Table 3: Summary of the modeled $PM_{2.5}$ concentrations for slightly unstable and unstable atmosphere

Atmospheric Stability	**Minimum**	**Maximum**	**Mean**
Slightly Unstable	3.5	41.1	8.3
Unstable	2.2	36.3	7.6

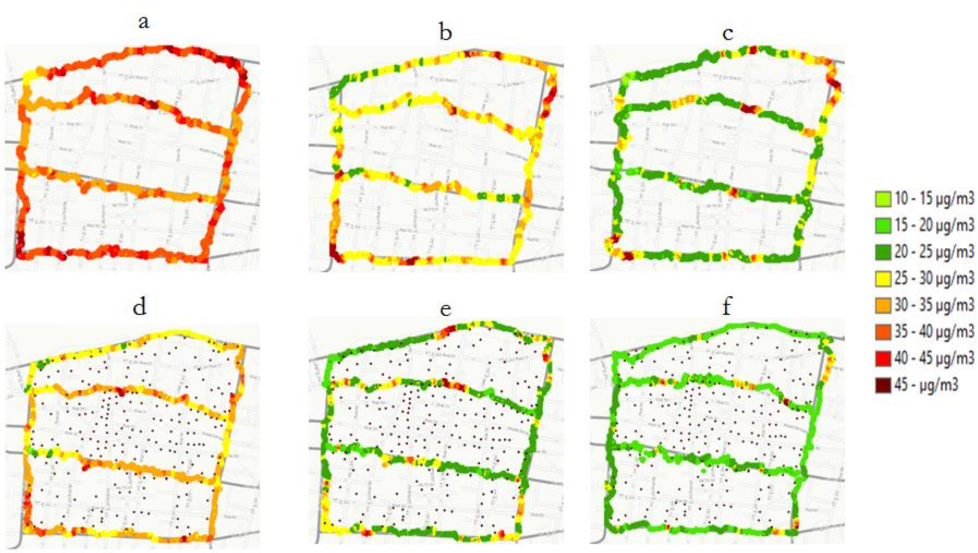

Figure 13: $PM_{2.5}$ measured spatial distribution in the morning for (a) weekdays (b) Fridays (c) Sundays and in the afternoon for (d) weekdays (e) Fridays (f) Sundays

G. Comparing with the WHO limits

From the simulated concentration maps which include the buildings, it was shown that the percentage of the air in Beirut that exceed the WHO annual limit value for $PM_{2.5}$ (10 $\mu g/m^3$), for the unstable atmosphere and the slightly unstable atmosphere, is 25% and 34% respectively in the best case scenario and 37% and 48% respectively in the worst case scenario.

CHAPTER IV
CONCLUSION AND FUTURE WORK

This work studied the concentration distribution of $PM_{2.5}$ originating from the diesel generators sources installed inside Beirut city. The annual averaged meteorological conditions as wind speed, wind direction, and atmospheric stability were taken. A steady-state Lagrangian simulation was carried at 5-m resolution under different scenarios to understand the dynamic effects influencing the plume dispersion. It was shown that the atmospheric stability, topography, and the orientation of the street canyons are highly correlated with the distribution pattern of the air pollutants. On another hand, the distribution of the sources inside the city did not change the pattern, however, the location of the stacks whether placed on top of the building roofs or at the streets level is important to determine the variation in the concentration levels.

The measurements done in the Hamra area showed that the modeled values are within the range of the total exposure levels, suggesting more contribution from the traffic emissions to the total concentrations. When compared to the WHO annual limit value, it was found that around one third of the air of Beirut exceeds that limit just because of operation of the diesel generators sources. This study can be useful for future epidemiological studies especially if the simulations with buildings were taken due to their ability of capturing the intra-urban variability of the concentration gradients.

A future work will include the diesel generators sources installed around Beirut city to estimate the background concentrations. The future model will also study the impact of the diesel generators installed inside Beirut on the pollution levels at the coastal northern cities above Beirut. Measurements for the emission factors of the diesel generators will be also considered to compare with the EMEP-EEA ones. A traffic modeling will be eventually added to the model also. Moreover, an uncertainty assessment study for each parameter in the model will be analyzed separately to ensure robust results.

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