Air Quality Study, Comparison Between the Proposed and Actual Scenarios of Generator Sets in Havana, by Using CALPUFF Model

Yasser Antonio Fonseca Rodríguez[1], Leonor Turtós Carbonell[2], Elieza Meneses Ruiz[1], Gil Capote Mastrapa[1] and José de Jesús Rivero Oliva[2]
[1]CUBAENERGIA
[2]Universidade Federal do Rio de Janeiro
[1]Cuba
[2]Brazil

1. Introduction

"Air Pollution" means the introduction by man, directly or indirectly, of substances or energy into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment, and "air pollutants" shall be construed accordingly (18 ILM 1442, 1979[1]).

Among the main reasons of increased air pollution is the expanding use of fossil energy sources, particularly in energy facilities, like the present case. Under the distributed power generation program that is currently being implemented in the country, generator sets (GS) have been installed and are still being installed in urban and sub-urban areas, to generate electricity using fossil fuels, such as in base-load as in emergency cases. During the operation of this equipment pollutants are released to the atmosphere, primarily nitrogen oxides (NO_x), sulphur dioxide (SO_2) and particulate matter (PM), which increase the concentrations of these pollutants in the atmosphere, affecting air quality.

It is essential to control these emissions so that concentrations achieved by each of the released pollutants be below their regulated values; therefore it is necessary to know to what extent air concentrations resulting from emissions from each facility could change. To this end, direct measurements and estimates of their concentrations by using Air Quality Models could be made. The measurements require specialized instrumentation and trained personnel, which increases the cost of the task; however, the use of models is much cheaper. They present algorithms to simulate physical and chemical processes for each pollutant in the atmosphere, allowing us to evaluate their behaviour after them being released. Despite this fact, none of the two methods is self-sufficient; so, it is necessary them be complemented. In many countries, particularly in developing countries, there are insufficient resources to carry out measurements of air quality with the necessary temporal and spatial extent, thus the computational modelling using the Air Quality Models carries the most importance. Moreover, the use of models for assessing air quality, and possible

mitigation measures considering the results, often fall on simplified models due to their few requirements of input data.

The implementation of sophisticated models enables a more accurate assessment, however, their requirements and data complexity grow, and they are not always available in such countries. To this end, solutions to overcome the disadvantage of lack of data were taken.

The Environmental Protection Agency (US EPA) established on October 21st, 2005 the AERMOD modelling system as the model recommended to be used for the dispersion of local pollutants, replacing ISCST3 (Industrial Source Complex Short Term version 3), hitherto used.

AERMOD is a steady state, Gaussian local model, which includes the treatment of surface and elevated sources, both in simple and complex field (Fonseca, 2010)[2]. It is fed with surface hourly meteorological data and upper air. It is used in many countries in accordance with the regulations. The solutions taken in Cuba allow the use of the model even when the upper air data are not available, based only on surface data (Turtós et al., 2010)[3].

CALMET-CALPUFF Modelling System was developed by Earth Tech (Concord, MA) and it is the model proposed since 2003 by the U.S. EPA as the regulatory model to be used to perform detailed modelling of air pollution dispersion processes, in regional domains (at distances between 50 and 200 km from the source, with acceptable values up to 300 km) using three-dimensional wind fields. It is also proposed to be used at local level (from 0 to 50 km away from the source) in case of complex meteorological conditions such as those arising from the presence of hills and large bodies of water within the study area.

CALPUFF is a multi-layer, multi-species, non-steady state puff dispersion model which can simulate the effects of time- and space-varying meteorological conditions on pollutant transport, transformation, and removal. CALPUFF can use the three-dimensional meteorological fields modelled by the CALMET model, or simple, single station winds in a format consistent with the meteorological files used to drive the ISCST3, AUSPLUME or the CTDMPLUS steady-state Gaussian models. However single-station ISCST3, CTDMPLUS or AUSPLUME winds do not allow CALPUFF to take advantages of its capabilities to treat spatially-variable meteorological fields. CALPUFF contains algorithms for near-source effects such as building downwash, transitional plume rise, partial plume penetration, and subgrid scale terrain interactions as well as longer range effects such as pollutant removal (wet scavenging or dry deposition), chemical transformation, visibility effects (Scire et al., 2000)[4]. As the AERMOD, CALMET also requires upper air meteorological data, although the solutions taken in Cuba for AERMOD have not been introduced in CALMET given the complexity in introducing the meteorological data grid. Therefore, it is proposed to feed CALMET with results from the pre-processors of mesoscale meteorological and geophysical data, such as WRF and MM5.

The present chapter assesses the ability of the CALPUFF modelling system to simulate the dispersion of pollutants at local level, instead of using AERMOD, and predict the maximum concentrations each pollutant could achieve. CALPUFF was selected for the local domain as it provides more accurate results under complex meteorological conditions resulting from Cuban modelling domain, since it uses a three-dimensional meteorological grid, thus obtaining a better approximation for each variable as the resolution of each cell is higher. However, the AERMOD (EPA-454/B-03-001)[5] - the most advanced of those used in Cuba and regulatory EPA for local domains – assumes meteorological conditions to be uniform

throughout the domain, what is a potential source of error in the model's input data. Other advantages of the CALPUFF is that it takes into account, although not at the same level of complexity as photochemical models do, the reactions occurring among pollutants in the atmosphere, making it possible to obtain the values of concentrations and deposition of sulphate and nitrate aerosols.

2. Background

As a result of the decision to install GS fed with fuel oil in Havana, a study of the related impacts to air quality that would produce the operation of the 11 planned GS by using the ISCST3 model (Turtós et al, 2006)[6] was carried out. This study concluded that significant amounts of oxides of sulphur and nitrogen will be released into the atmosphere with the simultaneous operation of these devices in a densely populated area, according to data provided by the manufacturer. In the selected modelling domain of 50 x 37 km, average population density is approximately 1240 inhabitants per km2, according to the data of the year 2000 from Population Study Center.

The work showed concentration levels of SO_2 and NO_2 to be achieved in 1850 points of Havana as a result of simultaneous operation of all the generator sets, which exceeds in an appreciable number of receptors the regulated values in the country for one-hour and one-day periods, and even permissible values from the World Health Organization (WHO).

As a result, it was decided to install only five GS with higher stack (from 15 to 37.5 m) and to carry out several studies (INEL, 2008[7]; CUBAENERGIA, 2009[8] and CUBAENERGIA, 2010[9]). The 2009 study was divided into two parts; the first was a comparative study between ISCST3 and AERMOD, and the second one, the modelling of different scenarios by using AERMOD. The 2010 study included measurement of emissions in different sites and modelling with AERMOD. Although five sites were built, only four are finally in operation.

The use of the AERMOD has been questioned since it is a domain that includes a coastline, which is not properly reflected by the uniform meteorology used by the model. Despite its high computational cost, the use of CALPUFF in this case is justified.

3. Methodology

CALPUFF calculates the pollutant dispersion in the receptor sites, taking into account complex three-dimensional wind fields, obtained with CALMET, which is particularly important for emission sources located in coastal areas and near high elevations. CALMET calculates wind structures in the study area from surface and upper air data. WRF outputs - model for calculating and forecasting the meteorological variables- was used as an alternative due to the unavailability of upper-air meteorological data in Cuba.

This system calculates the concentrations in the receptors distributed in the domain of study, at different times, for example, PM_{10}, sulphur dioxide (SO_2) and the species of the nitrogen family (NO_x). It also includes a simple model of chemical transformation to study and calculate some minor species such as sulphates (SO_4^{-2}) and nitrates (NO_3^-), which have a lot of relevance because of their potential effects on human health. Therefore, the system has been used in studies as a conceptual basis for these tests (Fonseca, 2010).

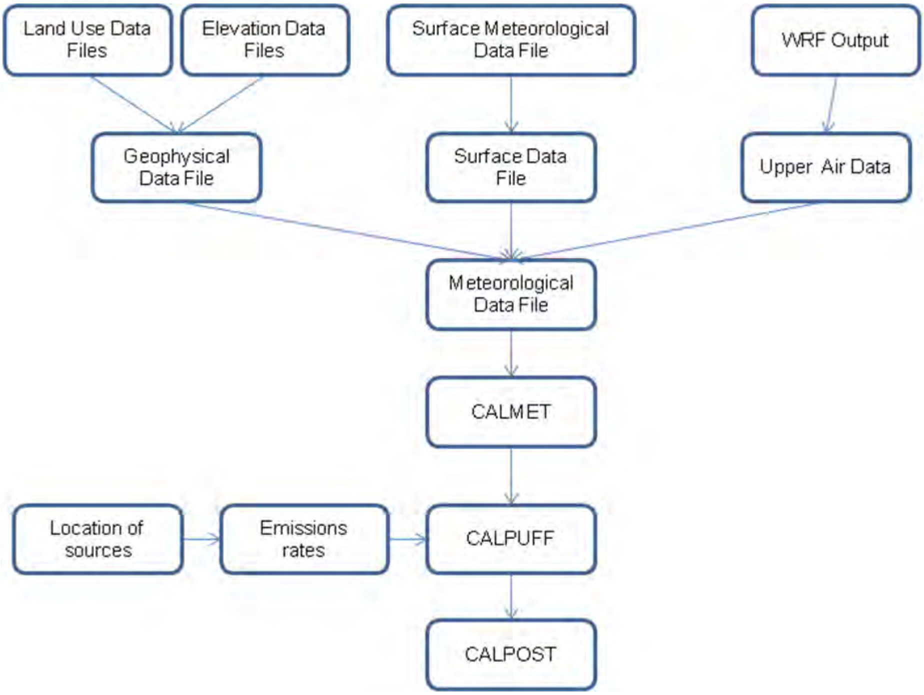

Fig. 1. Flowchart of the modelling with CALPUFF.

3.1 Reference values

The maximum permissible concentrations according to the Cuban Standard (NC) (NC 39:1999[10] and NC 111-2002[11]) and the reference values of the World Health Organization (WHO, 2005)[12] are used as reference for the analysis of results. These concentration values should not be higher than those of the pollutant (in the atmosphere) in the established time interval.

	Maximum permissible concentrations (µg/m³)	
Pollutant	**1 hour**	**24 hours**
SO_2	500	50
NO_x	85	40
PM_{10}	100	50

Table 1. Maximum permissible concentrations (µg/m³) according to the Cuban Standard (NC) and the World Health Organization (WHO).

4. Case study: Modelling scenarios

In this chapter, we used the Air Quality Model CALPUFF in the evaluation of measures related to the design and location of the GS in order to mitigate the possible effects caused by these technologies on air quality.

Two scenarios were defined, which underwent a thorough analysis. The influence of meteorological conditions was assessed in detail, as well as the effective height of emission and power of each facility from a scenario to another.

Scenarios:

- Scenario 1 or proposed scenario (an initial project with 11 GS to be installed).
- Scenario 2 or real scenario (with 4 GS actually installed).

4.1 Modelling period

The modelling period (approximately two months of calculation) was that between January 2nd, 2009 at 00:00 pm and March 7th, 2009 at 23:00 pm.

4.2 Geophysical and meteorological data required for meteorological processing by using CALMET

The characteristics of geophysical and meteorological data used by CALMET for meteorological processing are set out below.

4.2.1 Topography and land use

In order to get information on the relief Digital Elevation Models (DEM) were used while land uses were obtained from the Global Database of Soil Coverage features, both available on the Internet.

4.2.2 Surface meteorological data

Hourly meteorological data of the entire modelling period were processed. They were collected in the seven surface stations located within the meteorological domain. See Table 2.

Station Code	Name	Coordinates	
		Latitude	**Longitude**
78322	Batabano	22.717◦ N	82.267◦ W
78318	Bahia Honda	22.92◦ N	83.17◦ W
78325	Casablanca	23.167◦ N	82.350◦ W
78373	Santiago de las Vegas	22.967◦ N	82,367◦ W
78320	Güira de Melena	22.78◦ N	82.52◦ W
78375	Melena del Sur	22.767◦ N	82.117◦ W
78376	Bauta	22.967◦ N	82.517◦ W

Table 2. Location of surface stations.
(*Source: INSMET, 2008*)

4.2.3 Upper air data – WRF configuration

WRF outputs are used in order to feed CALMET with upper air data. The WRF model was implemented with the configuration shown in the following tables.

Main Data	Domain 1	Domain 2	Domain 3
Cells	45 * 30	34 * 34	34 * 34
Cell Size	27km	9km	3km
Center location (Lambert Conformal Conic)	22.19°N 79.52°W	23.1°N 82.35°W	23.1°N 82.35°W

Table 3. Modelling domain.

Physical Data	Domain 1	Domain 2	Domain 3
Microphysics	WSM5 (A more sophisticated version of WSM3, allows for mixed-phase processes and super-cooled water) (mp_physics=4)	WSM3	WSM3
Cumulus Parameterization	Kain-Fritsch scheme (Deep and shallow convection sub-grid scheme) (cu_physics=1)	Kain-Fritsch scheme (Deep and shallow convection sub-grid scheme) (cu_physics=1)	(Not necessary for domains with cells lower than 4 km)
Shortwave Radiation	RRTMG (a shortwave scheme with Montecarlo Integrated Column Approach (MCICA) method of random cloud overlap) (ra_sw_physics=4)	Dudhia Scheme	Dudhia Scheme
Longwave Radiation	RRTMG (new RRTM scheme that includes MCICA method of random cloud overlap) (ra_sw_physics=4)	RRTM (Rapid Radiative Transfer Model)	RRTM (Rapid Radiative Transfer Model)
Surface Layer	MM5 similarity	MM5 similarity	MM5 similarity
Land Surface	5-layer thermal diffusion	5-layer thermal diffusion	5-layer thermal diffusion
Planetary Boundary layer	Yonsei University scheme	Yonsei University scheme	Yonsei University scheme

Table 4. Physical parameters.

The domains 1, 2 and 3, mentioned in the previous tables, in which the WRF model was implemented, are shown below.

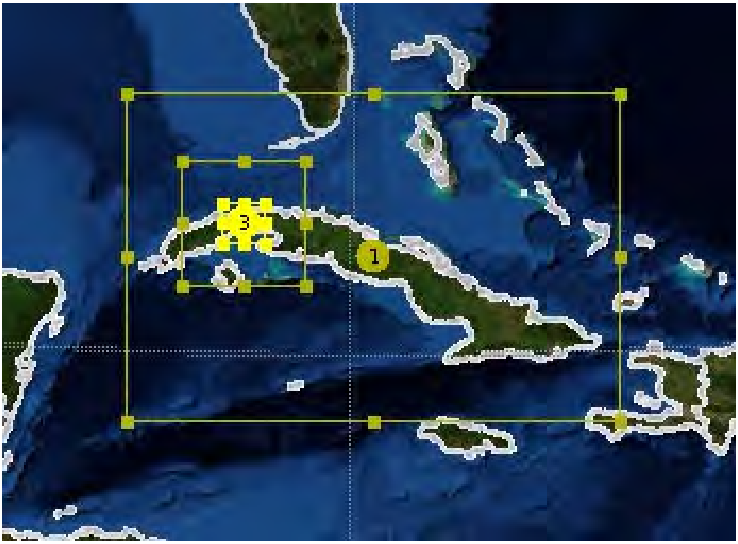

Fig. 2. Domains for WRF modelling.
(*Source: Capote et al. n.d.)*[13]

4.3 Structuring the CALMET meteorological grid

A rectangular grid of 90 x 95 km with a 1 km resolution and centered in X = 340500 Y = 340800 m was set up.

The following values collected by the surface stations within the meteorological domain were used: values of speed and prevailing wind direction, temperature, cloud coverage, height of the cloud base, pressure, relative humidity and precipitation rate. Upper air data obtained from processing WRF and adapted to the needs of CALMET by CALWRF (CALWRF, 2008)[14] pre-processor were added to these data. The description of these meteorological variables used by CALMET was obtained for 10 intervals of different heights (0 to 20, 20 to 40, 40 to 80, 80 to 160, 160 to 320, 320 to 640, 640-1200, 1200 to 2000, 2000 to 3000 and 3000 to 4000 m above ground level), thus obtaining the three-dimensional meteorological grid.

The CALMET meteorological field was simulated for a 1-hour time scale and was obtained by intelligent interpolation mechanisms applied to all the above variables.

Fig. 3 shows a sub-domain of the wind field obtained from CALMET. Examples of the wind direction and speed variability in an area of the modelled domain are given.

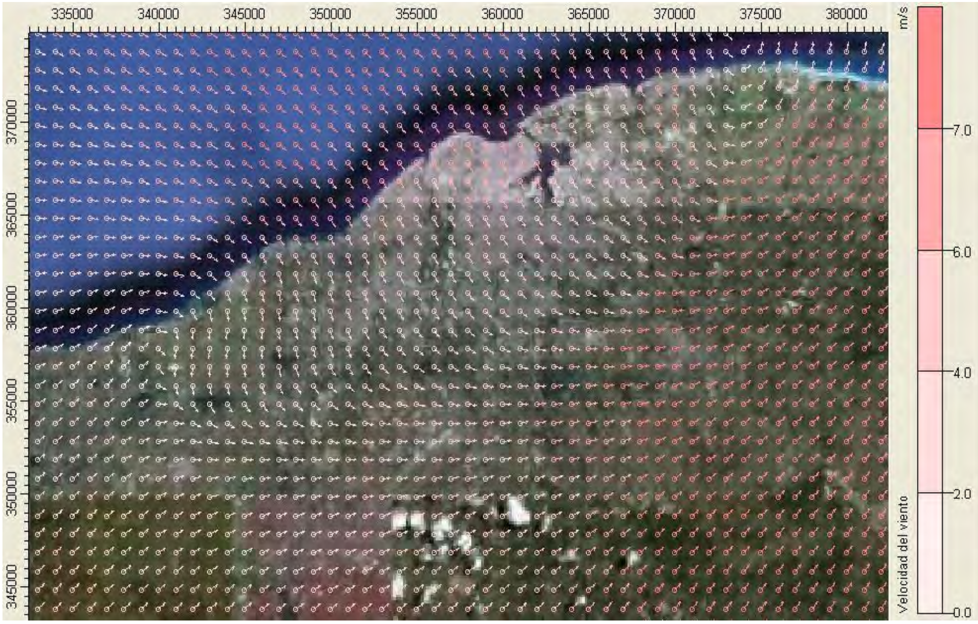

Fig. 3. Speed and direction of winds to 240 m above ground level.
(*Source: Base Map Google Earth*)

The arrows illustrate the wind direction (coinciding with that of the arrows) and speed (color scale) in a study sub-domain.

4.4 Processing by CALPUFF

For processing with CALPUFF two more grids were defined - the calculation and receptor grids - which are made to coincide with the meteorological grid, so that the puff modelling cover a larger area in order to obtain the values of the concentrations and deposition or removal flow of released pollutants. In the calculation grid, puffs are released and transported, allowing their dispersion modelling, and it is in the receptors where the final values of each study are obtained. A total of 8550 receptors, arranged in the shape of a rectangular grid at a distance of 1 km from receptor to receptor, resulted from this configuration.

Calculations were made using a pseudo-first order chemical reaction mechanism for the conversion of SO_2 to SO_4^{-2} and NO_x to nitrate aerosols. This mechanism is based on the chemical transformation scheme used in the MESOPUFF II model (Scire et al., 1984)[15], which introduces the most significant dependencies of transformation rates over varying environmental conditions, in time and space. This scheme models 5 species (SO_2, SO_4^{-2}, NO_x, HNO_3 y NO_3^{-1}) to which the modelling of suspended particles with diameter less than 10 micrometers (PM_{10}) was added.

5. Proposed scenario

Behold the initial project for the installation of 11 in Havana. See Fig. 4.

Fig. 4. Proposed location of the 11 generator sets to be initially installed in Havana.
(*Source: Base Map Google Earth*)

The following tables show the composition of each of the GS to be installed, their technical features and emission rates.

Emission values for the study were those provided by the manufacturer. A fuel with a sulphur content of 2% was assumed to be used.

Nu.	Name of GS	Number of engines making them up	Composition of the GS	Number of stack	Engine power unit (MW)
1	Guanabacoa **(GUA)**	16	4 x 4	4	**1.7**
2	Apolo **(APOLO)**	16	4 x 4	4	**1.7**
3	Naranjito **(NAR)**	16	4 x 4	4	**1.7**
4	Victoria de Giron **(GIRON)**	16	4 x 4	4	**1.7**
5	Diezmero **(DIEZ)**	16	4 x 4	4	**1.7**
6	San Agustin **(SANAG)**	16	4 x 4	4	**1.7**
7	Regla **(REGLA)**	28	7 x 4	7	**1.7**
8	Cotorro **(COTO)**	24	6 x 4	6	**2.5**
9	Parque Metropolitano **(PMA)**	24	6 x 4	6	**2.5**
10	Berroa **(BERROA)**	24	6 x 4	6	**2.5**
11	CUJAE **(CUJAE)**	24	6 x 4	6	**2.5**
	Total	**220**		**55**	**450.8**

Table 5. Composition of GS to be installed.

Nu.	Name of GS	Stack Height (m)	Stack Diameter (m)	Output Speed (m/s)	Output Temperature (°K)
1	**NAR**	15	1.27	14.98-11.23*	520
2	**SANAG**	15	1.27	14.98-11.23*	520
3	**APOLO**	15	1.27	14.98-11.23*	520
4	**CUJAE**	15	1.27	23.1-17.32*	553.5
5	**REGLA**	15	1.27	14.98-11.23*	520
6	**BERROA**	15	1.27	27.7	504.15
7	**COTO**	15	1.27	27.7	504.15
8	**DIEZ**	15	1.27	18.1	477.15
9	**GIRON**	15	1.27	18.1	477.7
10	**GUA**	15	1.27	18.1	477.7
11	**PMA**	15	1.27	27.7	504.15

* In these cases, it was considered that the output speeds change with variations in emission rates.

Table 6. Specifications of the stacks of the GS to be installed.

LCC North Cuba geographic projection (LCC-CN) was used, since it meets the study's needs. The LCC-CN projection parameters are:

- Projection Origin (22.35° of north latitude and 81° of west longitude)
- Standard Parallels (21.7 ° and 23 ° North)
- False North and False East (X = 500000 Y = 280296.016 m)

Nu.	Name of GS	SO_2(g/s)	NO_x(g/s)	PM_{10}(g/s)
1	**NAR**	12.8	13.84	0.1932
2	**SANAG**	12.8	13.84	0.1932
3	**APOLO**	12.8	13.84	0.1932
4	**CUJAE**	18.84	19.44	0.6906
5	**REGLA**	12.8	13.84	0.1932
6	**BERROA**	18.84	19.44	0.6906
7	**COTO**	18.84	19.44	0.6906
8	**DIEZ**	12.8	13.84	0.1932
9	**GIRON**	12.8	13.84	0.1932
10	**GUA**	12.8	13.84	0.1932
11	**PMA**	18.84	19.44	0.6906

Table 7. Emission values for each source (g/s).

Maximum emissions for each engine (by its power) are showed, though it is considered that each set worked with 87.5% availability.

5.1 Analysis of results and comparison with those of the reference values

Table 8 shows the maximum modelled concentrations by each pollutant species in the atmosphere for each of the intervals of importance in the study.

	Maximum concentrations		
Pollutant	**1 hour**	**24 hours**	**the whole period (1559 hours)**
SO_2	558	168	53
SO_4^{-2}	8.1	2.4	0.1
NO_x	567	180	56
NO_3^{-1}	27	3.5	0.2
PM_{10}	21	5.4	0.9
HNO_3	23	3.8	0.6

Table 8. Maximum modelled concentrations (μg/m^3) for each pollutant for each time interval.

It is possible to check if the standardized values are exceeded by comparing the maximum modelled concentrations by each species in 1-hour and 24-hour periods with the maximum permissible concentrations (for 1 and 24 hours respectively) according to Cuban standards. It should be noted that there are species for which the standards do not provide maximum permissible concentrations.

Table 9 below shows a ratio between reached maximum concentrations and maximum permissible (for each species and time interval). When this value is greater than 100, then this species exceeds its maximum permissible for that interval of time.

	MC / MPC (%)	
Pollutant	**1 hour**	**24 hours**
SO_2	112	336
NO_x	667	450
PM_{10}	21	11

Table 9. Ratio of the maximum Modelled Concentrations (MC) and the Maximum Permissible Concentrations (MPC) according to the NC and WHO, for different time intervals.

Taking into account the above criteria it can be confirmed that both SO_2 and NO_x (values highlighted in red) go over the MPC in both evaluation periods.

The following table shows the maximum average concentrations reached by the two "critical species".

	Maximum average concentrations	
Pollutant	**1 hour**	**24 hours**
SO_2	66.2	11.9
NO_x	68.8	11.6

Table 10. Maximum average concentrations of SO_2 and NO_x (μg/m^3).

5.1.1 Critical receptors

The following tables show the receptors, in which the maximum concentrations of SO_2 and NO_x are obtained and at the same time exceed the MPC:

Evaluation Period	NuO	Number of Receptors
1 hour	1	3
24 hours	1	31
	2	13
	3	9
	4	3
	5	3
	8	1
	9	1
	10	1
	15	1
	32	1

Table 11. Number of receptors in which SO_2 exceeds the MPC and number of opportunities (NuO) this occurs.

Table 11 shows the number of opportunities SO_2 exceeds its MPC (middle column), as well as the amount of receptors in which this occurs (right column).

Analyzing the maximum hourly concentrations of NO_x, it is observed that exceeds its MPC for 1-hour and for 24-hour periods in many receptors, therefore only the most critical receptors are shown in Table 12. It is worth noting that 687 receptors go over the MPC for 1-hour period, while the most critical receptor exceeds this MPC for 315 hours out of the 1559 modelled hours, which represents approximately 20% of the modelling period.

Evaluation Period	NuO	Number of Receptors
1 hour	112	2
	132	2
	138	1
	149	1
	155	1
	185	1
	188	1
	315	1

Table 12. Number of receptors that NOx exceeds the MPC for 1-hour period (middle column) and the NuO it occurs (right column).

Evaluation Period	NuO	Number of Receptors
24 hours	1	68
	2	20
	3	13
	4	5
	5	6
	6	6
	7	2
	8	2
	10	3
	12	3
	13	1
	18	1

Table 13. Number of receptors that NOx exceeds the MPC for 24-hour period (middle column) and the NuO it occurs (right column).

The following figures show the isolines of the maximum daily and hourly concentration of NO_x and SO_2 respectively.

The sources are identified by red crosses and all locations where the NOx exceeds its MPC by red areas.

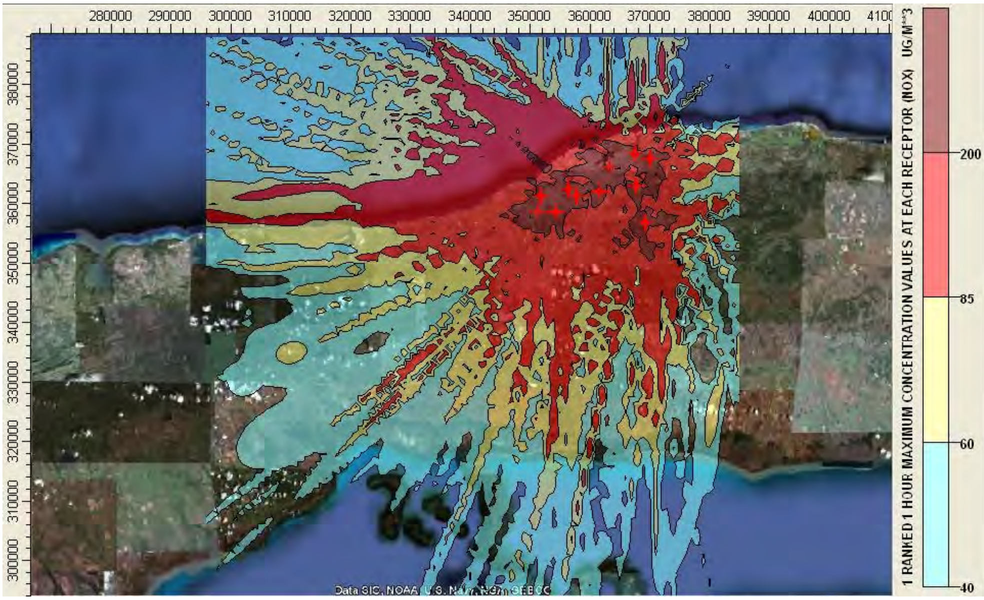

Fig. 5. Isolines of the maximum daily concentration of NO_x.
Source: Base Map Google Earth)

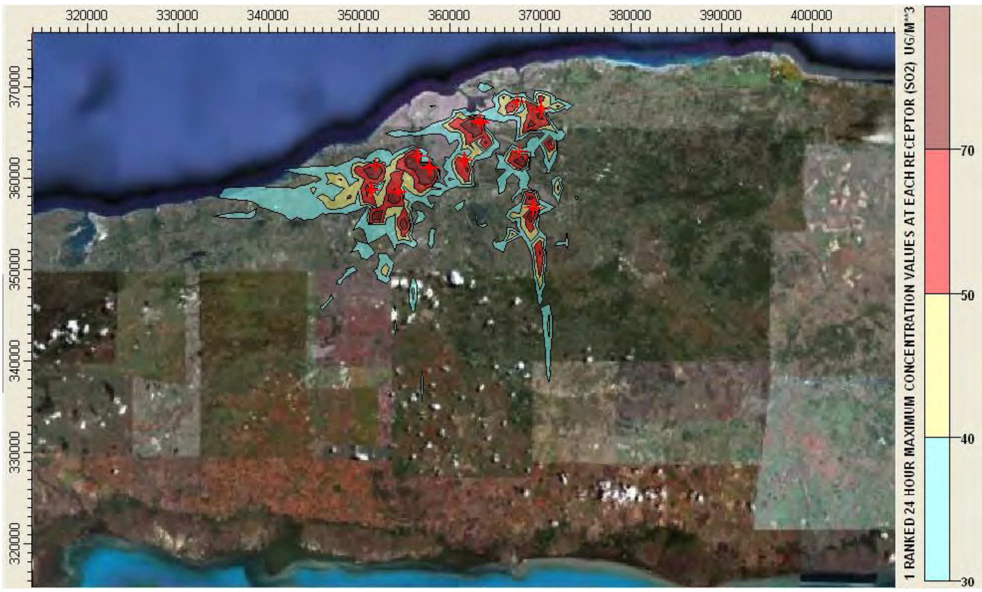

Fig. 6. Isolines of the maximum hourly concentration of SO_2.
(*Source: Base Map Google Earth*)

5.1.2 Depositions

There is general consensus that the deposition of sulphur compounds and nitrogen causes acidification on aquatic and terrestrial ecosystems, which means, among other impacts, less fertile soils and impacts to aquatic organisms which can not tolerate the acidity conditions. In general, these effects appear when the threshold of the critical load is exceeded. The critical load has been defined as "the maximum deposition of acidifying compounds that will not cause chemical changes leading to long term harmful effects on ecosystem structure and function" (Sverdrup et al., 1995)[16].

As there are not critical load values for Cuban conditions, a comparison could be made with the values set in the Air Quality Guide for Europe, WHO, 2000, shown in Table 14.

Compound	Guide values of critical loads	Evaluation Period
S	250–1500 eq/ha/year*	annual
N	5–35 kg N/ha/year*	annual

* Depending on soil type and ecosystem

Table 14. Values set in the Air Quality Guide for Europe.

Table 15 shows the maximum and average deposition values of sulphur and nitrogen, which are considered valid in practice, expressed in µg/m² for each evaluated period, and their respective conversions to eq / ha and to kg N / ha, depending on the species that identify the critical loads for each compound.

		N		S	
Evaluation Period		**(µg/m2)**	**(Kg_N/ha)**	**(µg/m2)**	**(eq/ha)**
1 hour	Maximum	2490	---	5190	---
	Average	77	6.7	355	1944
24 hours	Maximum	11600	---	23000	---
	Average	327	1.2	1520	347
1559 hours	Maximum	111000	6.2	203000	713
	Average	2830	0.2	11900	42

Table 15. Maximum and average deposition values of sulphur and nitrogen.

The table above shows that nitrogen does not exceed critical load values, while the average sulphur for 1-hour period does exceed them.

6. Real scenario

It is the one that takes into account the four GS currently installed in Havana.

Fig. 7. Location of the four generator sets currently installed in Havana.
(*Source: Base Map Google Earth*)

The following table shows the composition of each of the currently installed GS.

Nu.	Name of GS	Number of engines making them up	Composition of the GS	Number of Stack	Engine power unit (MW)
1	**APOLO**	16	4 x 4	4	**1.7**
2	**SANAG**	16	4 x 4	4	**1.7**
3	**REGLA**	28	7 x 4	7	**1.7**
4	**CUJAE**	24	6 x 4	6	**2.5**
	Total	**84**		**21**	**162**

Table 16. Composition of the 4 GS currently installed in Havana.

The technical data of each of the stacks of these 4 GS match those assumed in the initial project, except for the height, since they are 37.5 m. See Table 6.

The emission values of each of these sources are the same as those used in the proposed scenario, since the values provided by the manufacturer were used in both studies. See Table 7.

6.1 Analysis of results and comparison with the reference values

Table 17 shows the maximum concentrations modelled in the atmosphere for each pollutant species for each of the intervals of importance in the study.

	Maximum concentrations		
Pollutant	**1 hour**	**24 hours**	**All Period (1559 hours)**
SO_2	435	105	38
SO_4^{-2}	4.5	1.11	0.045
NO_x	441	112	40
NO_3^{-1}	12.6	1.9	0.068
PM_{10}	16	3.4	0.57
HNO_3	18.7	2.14	0.3

Table 17. Maximum concentrations reached (µg/m^3) by each pollutant for each time interval.

It is possible to check if the standardized values are exceeded by comparing MC with their respective MPC according to Cuban standards.

Table 18 below shows a ratio between MC and the MPC (for each species and time interval), following the same criteria as in the previous scenario, where this value is greater than 100, then this species exceeds its MPC for that time interval.

	MC / MPC (%)	
Pollutant	**1 hour**	**24 hours**
SO_2	87	210
NO_x	519	280
PM_{10}	16	6.8

Table 18. Ratio between MC and MPC according to NC and WHO, for different time intervals.

Given the above criteria, it can be confirmed that both SO_2 for 24-hour periods and NO_x for 1-hour and for 24-hour periods exceed their MPC (values in red).

The following table shows maximum average concentrations modelled in the entire domain compared to the previous scenario.

	Maximum average concentrations	
Pollutant	**1 hour**	**24 hours**
SO_2	33.9	4.5
NO_x	35.5	4.39

Table 19. Maximum average concentrations of SO_2 y NO_x (µg/m^3).

6.1.1 Critical receptors

The following tables show the receptors in which NO_x and SO_2 exceed the MPC and the number of opportunities it happens.

Table 20 shows the number of opportunities the SO_2 exceeds its MPC daily (middle column) and the amount of receptors in which this happens (right column).

Evaluation Period	NuO	Number of Receptors
24 hours	1	6
	2	2
	3	2
	6	1
	25	1

Table 20. Number of receptors in which SO_2 exceeds the MPC and the number of opportunities (NuO) it occurs.

After analyzing the maximum hourly concentrations of NO_x, it can be observed that it exceeds its MPC in many receptors, therefore only the most critical ones will be showed, although it is worth noting that 207 receptors go above MPC for 1-hour period, while the most critical receptor exceeds this MPC for 251 hours out of the total modelled, representing approximately 16% of the modelling period.

Evaluation Period	NuO	Number of Receptors
1h	42	1
	49	1
	59	1
	64	1
	77	1
	90	1
	92	1
	105	1
	251	1

Table 21. The most critical receptors where NOx exceeds for 1-hour period maximum permissible concentrations and the number of opportunities this happens.

The following table shows the days in which MPC are exceeded by NO_x

Evaluation Period	NuO	Number of Receptors
24 hours	1	13
	2	1
	3	7
	5	1
	6	1
	7	1
	32	1

Table 22. The most critical receptors where NOx exceeds in 24 hours maximum permissible concentrations and the number of opportunities this happens.

The following figures show the isolines of the maximum daily and hourly concentration of NO_x and SO_2 respectively.

The sources are identified by red crosses and all locations where the NOx exceeds its MPC by red areas.

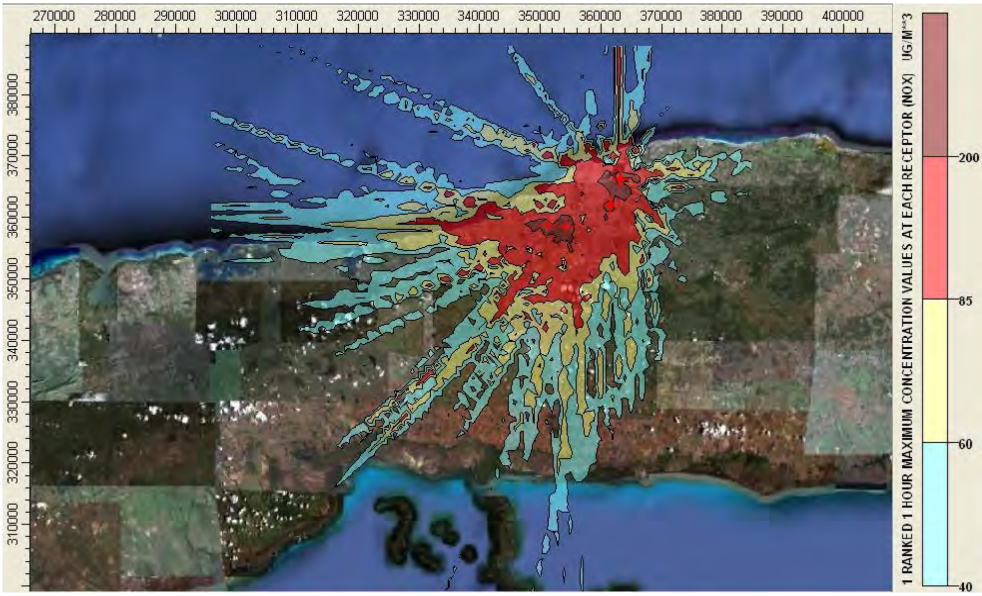

Fig. 8. Isolines of the maximum daily concentration of NO_x.
(*Source: Base Map Google Earth)*

Fig. 9. Isolines of the maximum hourly concentration of SO_2.
(*Source: Base Map Google Earth)*

6.1.2 Deposition

Table 23 shows the maximum and average deposition values of sulphur and nitrogen, which are considered valid in practice, expressed in µg/m² for each evaluated period, and their respective conversions to eq / ha and to kg N / ha, depending on the species that identify the critical loads for each compound.

		N		S	
Evaluation Period		(µg/m²)	(Kg_N/ha)	(µg/m²)	(eq/ha)
1 hour	Maximum	1500	---	3180	---
	Average	40	3.5	185	1013
24 hours	Maximum	8680	---	17500	---
	Average	131	0.5	568	130
1559 hours (All period)	Maximum	83200	4.7	154000	541
	Average	884	0.05	3500	12.3

Table 23. Maximum and average deposition values of sulphur and nitrogen.

The above table shows that neither nitrogen nor sulphur exceeds their critical load values.

7. Comparison between scenarios

The following table shows a ratio between the maximum modelled concentrations by each species in the Scenario 1 (MC1) and the Scenario 2 (MC2).

	MC1/MC2		
Pollutant	1 hour	24 hours	the whole period (1559 hours)
SO_2	1.28	1.6	1.39
SO_4^{-2}	1.8	2.16	2.22
NO_x	1.29	1.61	1.4
NO_3^{-1}	2.14	1.84	**2.94**
PM_{10}	1.31	1.59	1.58
HNO_3	**1.23**	1.78	2

Table 24. Ratio between MC1 and MC2.

The above table shows that all the MC decrease between 1.23 and 2.94 times.

If the ratio between MC1 and MC2 with respect to MPC (see Table 9 y Table 18) is analyzed, it can be observed that SO_2 and NOx exceed their MPC for 1-hour and for 24-hour periods in the scenario 1, while in the scenario 2, NOx exceeds their MPC for 1-hour and for 24-hour periods, but SO_2 only exceeds its MPC for a 24-hour period.

As the MC only show the behaviour in the most critical receptor and there is not a complete analysis of the entire domain, the ratio between MC1 and MC2 really does not show the variation from one scenario to another. Therefore, maximum average concentrations were calculated to qualitatively get a better idea of the critical pollutant dispersion in every scenario (see Table 10 y Table 19). As a result there was a decrease of about half in the concentrations.

The decrease in absolute maximum hourly concentrations of the 2 critical species is mainly due to the elimination of the GS responsible for them, since they are caused by the action of individual sites and not by overlapping plumes of several sites, for example: the maximum hourly concentration of SO_2 and NO_x in the scenario 1 is reached in the vicinity of the **COTO** site, while it is achieved near **CUJAE** in the scenario 2. However, the overall decrease in maximum average concentrations is due to the increase of 22.5m in the height of the stacks in the four currently installed GS. For example, the maximum daily concentration of SO2 reached in the vicinity of the **REGLA** site in the scenario 1 is 168 $\mu g/m^3$, while in the scenario 2 decreases to 105 $\mu g/m^3$.

Analyses carried out to deposition levels showed that only the average sulphur for 1 hour in the scenario 1 is the one which exceeds the critical load values for Europe. See Table 15 y Table 23.

As the critical load depends on the past and present management, of the type of ecosystem and soil conditions, to what extent these critical load values proposed for Europe can be applied in other regions is not known. The information required to properly analyze these results and turn them into physical impacts and external costs is difficult to obtain.

In order to qualitatively compare how much the level of deposition from one scenario to another decrease, ratio of the maximum and average deposition of sulphur and nitrogen in each evaluation period was analyzed.

Period		N	S
1 hour	**Maximum**	1.7	1.6
	Average	1.9	1.9
24 hours	**Maximum**	1.3	1.3
	Average	2.5	2.7
1559 hours	**Maximum**	1.3	1.3
	Average	3.2	3.4

Table 25. Ratio of the maximum and average deposition of sulphur and nitrogen in each evaluation period from one scenario to another.

The table above shows that maximum deposition levels decreases between 1.3 and 1.7 times, while average deposition levels decreased between 1.9 and 3.4 times.

As with maximum concentrations, the highest hourly deposition in the scenario 1 is observed near **COTO** site and in the scenario 2 - in the vicinity of **CUJAE** site. This is also due to the elimination of the site where the maximum emissions occur.

8. Comparison between AERMOD and CALPUFF

The real scenario was modelled using the AERMOD (the same period, the same sources, emission rates, etc.). Results, very similar to those obtained with CALPUFF for the same scenario, were obtained. Because of the similarities in the results, we will analyze only the behaviour of SO_2 in the **REGLA** site.

Table 26 shows the behaviour of some of the maximum concentrations in the vicinity of the REGLA.

Period	Model	Concentration of SO_2 (μg/m³)
1 hour	**CALPUFF**	339
	AERMOD	312
24 hours	**CALPUFF**	93
	AERMOD	141

Table 26. Maximum concentrations of SO_2 (μg/m³) in the vicinity of **REGLA**.

The above table shows that the results are comparable.

This is only a preliminary analysis due to the short temporal modelled interval, but it shows the possibility of using the AERMOD in the evaluation of local pollutant dispersion in Havana despite the existence of the extensive coastline. In order to obtain a final result, an assessment of air quality for a longer modelling period (at least for a year) is recommended to be carried out since this makes it more likely to show all possible synoptic conditions, which does not occur in two-month period.

9. Conclusions

- A refined modelling was performed using the CALPUFF model, following the recommendations for using it at the local level under complex weather conditions. This is considered a significant progress because the AERMOD was the model used for national studies so far.
- The WRF-CALMET-CALPUFF methodology was first used in a real case.
- Significant reductions in air pollution were obtained by replacing the initial project (proposed scenario) with the end project (real scenario) for the installation of generator sets, regarding the following aspects:
  1. Decrease in maximum concentrations with the elimination of the site that produced them, i.e. decrease in absolute maximum hourly concentrations of SO2 and NOx by removing the **COTO**.
  2. Decrease in maximum concentrations by increasing height of the stacks, i.e. decrease in absolute maximum daily concentrations of SO_2 of **COTO.**
  3. Decrease in maximum concentrations by increasing height of the stacks, i.e. decrease in absolute maximum daily concentrations of SO_2 of GS **COTO**.
- Despite the improvements in air quality when using the scenario 2, actions must be taken and new alternatives should be developed to continue reducing emissions so that the maximum concentrations of these pollutants do not exceed their maximum permissible concentrations.
- It was found that the results obtained with CALPUFF and AERMOD, despite the differences between the models and short modelling period, provide comparable results in assessing the dispersion of pollutants at local scale for scenarios in Havana, what makes it possible the use of the AERMOD instead of the CALPUFF model in such scenarios.

- It is recommended to carry out a future local study in Havana (at least one-year assessment) in order to obtain conclusive results about the similarities by using one or the other model in these scenarios.

10. References

[1] 18 ILM 1442 (1979). Convention on Long-Range Transboundary Air Pollution, Article 1(a).

[2] Fonseca,Y. (2010). *Implementación y aplicación del sistema de modelación CALMET-CALPUFF-CALPOST a escala local*. Trabajo de Diploma. Instituto Superior de Tecnologías y Ciencias Aplicadas (INSTEC), Departamento de Ingeniería Nuclear.

[3] Turtós L., J. Rivero, L. Curbelo, M. S. Gácita, E. Meneses & N. Díaz, 2010. *Methodological guide for implementation of the AERMOD system with incomplete local data. Atmospheric Pollution Research,* ISSN: 1309-1042, Vol 1, Issue 2, pp 102-111.

[4] Scire, J. (2000). *User's guide for the CALPUFF Dispersion Model*, July 2011, Available from: www.src.com/calpuff/download/CALPUFF_UsersGuide.pdf.

[5] EPA-454/B-03-001, September 2004. *User's guide for the ams/epa regulatory model – AERMOD*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards Emissions, Monitoring, and Analysis Division Research Triangle Park, North Carolina 27711

[6] Turtós L, N. Díaz, M. Padrón & E. Molina, 2006, *Estudio de calidad del aire por la instalación de los Grupos Electrógenos en Ciudad de la Habana*. Informe de Servicio Científico Técnico entre CUBAENERGIA y la Empresa de Ingeniería para la Electricidad, INEL.

[7] INEL, 2008. *Datos usados en el estudio global pronostico 2008*. Informe Técnico.

[8] CUBAENERGIA, 2009. *Estudios ambientales vinculados a las emisiones de gases y material partículado total de los grupos electrógenos de fuel oil en Ciudad Habana*. Informe de Servicio Científico Técnico CUBAENERGIA-INEL.

[9] CUBAENERGIA, 2010. *Informe de servicio de medición y modelación de dispersión de contaminantes atmosféricos emitidos por los grupos electrógenos de régimen base en La Habana*.

[10] NC 39:1999, NORMA CUBANA. *Sistema de Normas para la protección del Medio Ambiente, Atmósfera, Requisitos higiénicos sanitarios: Concentraciones máximas admisibles, alturas mínimas de expulsión y zonas de protección sanitaria*. Comité Estatal de Normalización.

[11] NC 111: 2002, NORMA CUBANA. *Calidad del aire, Reglas para la vigilancia de la calidad del aire en asentamientos humanos*. La Habana, Oficina Nacional de Normalización.

[12] WHO, 2005, WHO/SDE/PHE/OEH/06.02. *Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide Global update 2005*. Summary of risk assessment.

[13] Capote G., L. Turtós, L. Alvarez, A. Bezanilla & I. Borrajero, (n.d.).*Implementación del modelo meteorológico WRF en Cuba para su uso en modelos de dispersión de contaminantes atmosféricos*.

[14] CALWRF, 2008. Version 1.1. Level 080429. *Atmospheric Study Group in TRC Environmental Corporation*.

[15] Scire et al., 1984. *User' Guide to the MESOPUFF II dispersion Model and related processor programs*. EPA-600/8-84-013. US Environmental Protection Agency. Research Triangle Park. NC.

[16] Air Quality Guidelines for Europe, 2000. World Health Organization. Regional Office for Europe, Copenhagen. WHO Regional Publications. European Series. No. 91. Second Edition.