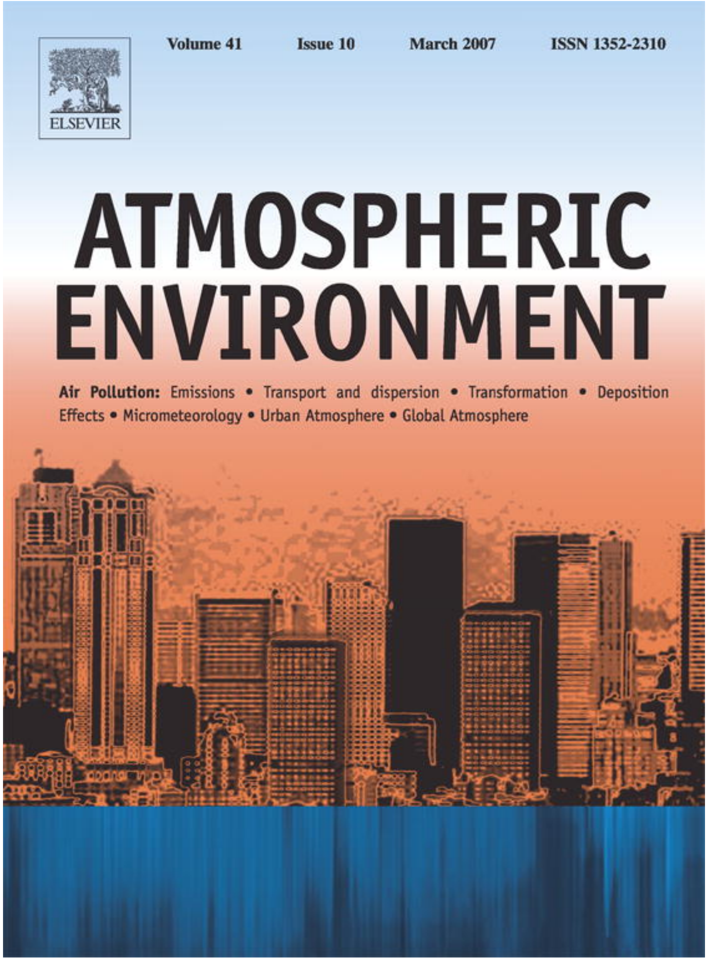
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Assessment of the impacts on health due to the emissions of Cuban power plants that use fossil fuel oils with high content of sulfur. Estimation of external costs

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Abstract

Fossil fuel electricity generation has been demonstrated to be a main source of atmospheric pollution. The necessity of finding out a balance between the costs of achieving a lower level of environmental and health injury and the benefits of providing electricity at a reasonable cost have lead to the process of estimating the external costs derived from these impacts and not included in the electricity prices as a quantitative measure of it that, even when there are large uncertainties involved, can be used by decision makers in the process of achieving a global sustainable development.

The external costs of the electricity generation in three Cuban power plants that use fossil fuel oils with high sulfur content have been assessed. With that purpose a specific implementation of the Impact Pathways Methodology for atmospheric emissions was developed. Dispersion of atmospheric pollutants is modeled at local and regional scales in a detailed way. Health impacts include mortality and those morbidity effects that showed relation with the increment of selected pollutant concentration in national studies. The external cost assessed for the three plants was 40,588,309 USD yr^{-1} (min./max.: 10,194,833/169,013,252), representing 1.06 USD Cent kWh^{-1}. Costs derived from sulfur species (SO_2 and sulfate aerosol) stand for 93% of the total costs.

Keywords: External costs; Electricity generation; Dispersion modeling; Health impacts; Sulfur

1. Introduction

The impacts of electricity generation on the environment and human health are a matter of interest and concern throughout the world. Fossil fuels are one of the energy sources of more undesirable effects on the environment, but this energy is still one of the most competitive at the market, especially for the developing countries. However, it is necessary to find out a balance between the costs of achieving a lower level of environmental and health injury and the benefits of providing electricity at a reasonable cost. A promising way of doing so is to internalize the costs derived form environmental and human health

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damage into the prices of electricity, making fossil energy less competitive; a first step is to assess the external costs (derived from electricity production but not included in electricity price). This approach has weaknesses like the difficulties in assigning a cost for the damage to an ecosystem or to a human life. In spite of many factors not completely included yet, external costs could be an important tool for decision makers in order to achieve a sustainable development.

Many efforts have been made in this sense, especially at developed countries. Within the framework of ExternE project (European Commission. ExternE, 1998) the Impact Pathways Methodology and the corresponding software EcoSense were developed. It has been applied in the European countries, US, Thailand and other countries around the world. This methodology was created by and for developed countries and its application is limited for developing countries due to the complementary studies and large data requirements needed to estimate the impacts. Nevertheless, some data can be transferred from developed countries and other can be calculated or estimated by indirect ways, when no local data is available or the information is incomplete. The importance of the methodologies for doing so, allowing the implementation of detailed methodologies in developing countries, is increased by the fact that these countries usually have less clean technologies and consume more pollutant energy sources than developed nations.

In Cuba the evaluation of the technology impacts on environment and health has, from the Government's point of view, a special significance. Thanks to the concern of decision makers, many national projects aimed to have a measure of these impacts, have been conducted, especially those for electricity generation, which have proved to be a major source of them. External costs, as a quantitative measure of impacts, have the advantage of being more objective than other approaches, even when not all the impacts are included.

In Cuba, fossil fuels supply nearly 92% of the total generated electricity. The most part of these fossil fuels are fuel oil with high sulfur content—around 3.5%—and domestic crude oil, with higher sulfur content that fuel oil—among 5% and 7%. The present work was aimed to present the implementation done in a developing country to estimate the external costs of electricity generation associated with the health impacts caused by atmospheric emission loads and, at the same time, to assess the influence of the use of fossil fuel with high sulfur content.

For the current study, the selected power plants were the ones located in the western area of the country. These power plants include, in their local domains of influence, Havana City, Cuba's capital and the most populated city in the country. The power plant Este de la Habana (300 MW), located in Santa Cruz, has the highest stack; the power plant Máximo Gómez (450 MW), in Mariel, has the biggest emissions and small stacks; both burn domestic crude oil. On the other hand, the power plant Otto Parellada (64 MW) burns fuel oil with a high sulfur content, and it is located at Tallapiedra, which is a centric locality in Havana City.

The assessment was carried out for the year 2003.

2. Methodology

In the assessment of the dispersion of pollutants two different models were used: Industrial Source Complex (ISCST3) Dispersion Models (Environmental Protection Agency, 1995b) for local dispersion and Windrose Trajectory Model (WTM) (Trukenmüller and Friedrich, 1995) for regional dispersion. The use of these models combined ensures that national priorities in this kind of study are considered taking into account the available data.

The selection of the WTM for the evaluation of the regional dispersion obeys the need for a modeling domain big enough to cover the area of influence of the regional dispersion, which has been found to be over 100–1000 km (European Commission. ExternE, 1998, 2005). Nevertheless WTM, as most regional dispersion models, is not intended to describe adequately the processes that occur near the source, which have a significant value in Cuban geographical conditions. Other known regional models as CALPUFF (Scire et al., 2000) covers a reduced domain (50–300 km). The use of 3D model, capable of "nesting" one or more finer-scale subgrids within a coarser overall grid, as REMSAD (ICF Consulting, 2005), is also unsatisfactory for the moment, to describe dispersion below 50 km from the source with the necessary precision due to the data demand of the fine-scale subgrid. REMSAD is the modeling solution implemented in BenMAP (Environmental Protection Agency, 2005) for the whole domain.

Table 1 summarizes power plant technical and emission data required for dispersion modeling. The

Table 1
Power plant information required for ISCST3 modeling

Power plant/generation blocks	Stack height (m)	Stack diameter (m)	Emissions ($g\,s^{-1}$)			Flue gas exit speed ($m\,s^{-1}$)
			SO_x	NO_x	PM_{10}	
Máximo Gómez 82.75W, 23.02N						
1 block of 50 MW	47.0	5.07	129.85	5.00	5.38	1.3
4 blocks of 100 MW	65.0	6.00	2979.60	114.75	123.50	21.3
Este de la Habana 81.95W, 23.16N						
3 blocks of 100 MW	180.0	7.00	2269.93	82.15	93.95	14.5
Otto Parellada 82.35W, 23.12N						
1 block of 64 MW	45.7	4.56	196.94	17.00	8.59	6.0

emissions for SO_2 were assessed using the combustion equations for oil steam boiler technology and the fuel composition; for NO_x and particulate matter 10 μm diameter or less (PM_{10}) emissions were estimated starting from emission factors for oil steam boiler burning residual oil no. 6.

In order to avoid a double counting in impact assessment, the output of the local and regional dispersion models is fed to the externalities estimation separately, regional results are not taken into account in the local domain.

The details for the estimation of local and regional dispersions, health impacts and monetary evaluation are stated in Sections 2.1–2.5.

2.1. Local dispersion modeling

The local dispersion was modeled with ISCST3 Dispersion Models using complex terrain, dry and wet deposition and regulatory options (Environmental Protection Agency, 1995a) for the year 2003. The modeling was carried out separately in three domains of 20 × 20, 5 km cells (100 × 100 km), centered at the power plants; estimating the concentration and deposition (wet and dry) of NO_x, SO_2 and PM_{10}. The common characteristic of these domains is that they include Havana City, Cuba's capital, so the health impacts caused by local increments in concentration of selected pollutant might be important compared with other power plants in the country.

The complete hourly meteorological data for the year 2003 was obtained from the nearest local station with similar geographical conditions, that is, Bahía Honda meteorological station for power plant Máximo Gómez, and Casa Blanca meteorological station, located in Havana City, for the power plants Otto Parellada and Este de la Habana. Missing secondary meteorological data was calculated using methodologies adapted for tropical climatology (see Soltura et al., 2005).

The vertical resolution of the ISCST3 is the mixing layer height, which is calculated using PCRAMMET.

From the point of view of cost assessment, the relevant results are the annual average concentration increments.

2.2. Regional dispersion modeling

The regional dispersion of NO_x, SO_2, PM_{10}, and secondary species (nitrate and sulfate aerosols) was modeled for the year 2003 over a domain that covers the Caribbean, Mexico and Central America, in a 120 × 60, 55 km grid, defined through Lambert Conformal Projection (Evenden, 1995)[1]. The model used was the WTM (Trukenmüller and Friedrich, 1995) which is based on the approach of Derwent et al. (1988) and is also the model used in ExternE (European Commission. ExternE, 1998, 2005).

WTM is a Lagrangian, climatological, receptor oriented trajectory model which allows the prediction of yearly averages for concentration and deposition values. The model is bi-dimensional, so 3D patterns are not predicted, but in contrast with Eularian models, the data required is relatively modest, and contributions from individual sources can be rapidly assessed.

[1]The parameters used were: Ellipsoid Clarke 1866, Central meridian lon_0 = −90W, Central parallel lat_0 = 20N, First parallel lat_1 = 25N, Second Parallel lat_2 = 15N, False origin x_0 = 3,410,816.45, y_0 = 1,375,443.41, Scale at the central meridian k_0 = 0.99995696.

Following Trukenmüller et al. (2001) methodology, a parameterization more suitable for the domain was made, based on revised values of ozone (Logan, 1998) and hydroxyl radical (Spivakovsky et al., 2000) concentrations, temperature and pressure (based on NCEP Reanalysis Data, see Kistler et al., 2001), and expressions for reaction rates (Atkinson et al., 1997). Table 2 contains the new rate constants obtained for the reactions included in the chemical mechanism.

The data requirements of the model were implemented as a geo referenced database, including the following information for each cell of the domain: wind rose. (24 directions), mean annual precipitation, low and high emissions for NO_x and SO_2, and NH_3 emissions.

The meteorological data was obtained taking into account data for the 5 yr period 2000–2004 and the values are intended to represent an annual climatology. Wind roses were obtained from pgb.f00 Reanalysis Data, which contain 6 h data, whereas precipitation data was obtained by a combination of GPCC Monitoring Product (Rudolf et al., 1994) and GPCP Version 2 Combined Precipitation Data Set (Adler et al., 2003).

Emission data, classified in low and high according to its heights, for NO_x and SO_2 was obtained from EDGAR emission database (Olivier et al., 1996) and improved using Cuban emission data when applicable. The criterion followed to classify the emission heights was to consider as high those emissions that originated in the stacks with a height of 100 m or more.

For NH_3, two datasets were used (see Bouwman et al., 1997, 2002). The more updated and accurate data (Bouwman et al., 2002), corresponding to NH_3 derived from animal waste and inorganic fertilizer, was considered using the data for all the other sectors (NH_3 sources) as in Bouwman et al. (1997).

2.3. Health impacts

The revision of the studies conducted in Cuba in the period 1983–2003, that showed relation between air pollution and health impacts, leads to the conclusion that the information was insufficient for the establishment of specific exposure–response functions (ERF) (Molina and Meneses, 2003a). However, the correlations found were consistent and in the range reported internationally.

As a first approach in the assessment of health impacts derived from criteria pollutants, ERF obtained from international studies were used for those effects that showed significant associations with that pollutant in national studies; in addition, the selection process took into account if exposure ranges were comparable with those reported in Cuban studies (Molina and Meneses, 2003b).

Assuming that an ERF varies linearly in the whole exposure range with no threshold value (Spadaro, 1999) leads to

$$\mathrm{ERF}(r, C(r,Q)) = \mathrm{SERF}(r)\ \ C(r,Q), \qquad (1)$$

where $C(r,Q)$ is the incremental change in background concentration $\mu g\,m^{-3}$ for an emission rate Q, at vector location r and SERF is the slope of ERF.

Table 2
Reaction rates used in the chemical mechanism, for the regional dispersion modeling

No	Reaction	Reaction rates	Units, remarks
1	$NO+O_3 \rightarrow NO_2+O_2$	1.74×10^{-14}	cm^3/(molecules s)
2	$NO_2+h\nu \rightarrow NO+O$	2.46×10^{-3}	$1\ s^{-1}$
3	$O+O_2+M \rightarrow O_3+M$	Immediate	
4	$NO_2+OH+M \rightarrow HNO_3+M$	1.31×10^{-11}	cm^3/(molecules s)
5	$HNO_3+NH_3 \rightarrow NH_4NO_3$	1.00E−14	cm^3/(molecules s)
6	HNO_3 + aerosol → Nitrate Aerosol (pNO_3)	3.00×10^{-5}	$1\ s^{-1}$
7	$NO_2+O_3 \rightarrow NO_3+O_2$	3.25×10^{-17}	cm^3/(molecules s)
8	$NO_3+h\nu \rightarrow NO_2+O$	Immediate	Daytime only
9	$NO_3+NO_2+M \rightarrow N_2O_5+M$	Immediate	Only at night
10	N_2O_5 → Nitrate Aerosol (pNO_3)	Immediate	
11	$SO_2 \rightarrow H_2SO_4$	8.99×10^{-6}	$1\ s^{-1}$
12	$H_2SO_4+NH_3 \rightarrow NH_4HSO_4$	1.00×10^{-14}	cm^3/(molecules s)
13	$NH_4HSO_4+NH_3 \rightarrow (NH4)_2SO_4$	Immediate	

SERF equals

$$\mathrm{SERF} = \mathrm{IRR}(\%\,\mu g^{-1}\,m^{-3}) \times \mathrm{Baseline(cases/receptor\ year)} \times \mathrm{fpop}. \quad (2)$$

Here the increment of the relative risk (IRR) is the change in the rate of occurrence of a disease (mortality or morbidity) for a population exposed to the pollutant, by unit of change in the environmental concentration for given average exposure time; fpop, corresponds to the fraction of the population affected. The incidence natural rate of a disease is the baseline, which is expressed in cases/year normalized by person. For mortality, the baseline is the annual rate of mortality for the group of risk.

Using Eq. (2), by the knowledge of the reference level of incidence or baseline, and the fraction of population affected, the ERF selected for this study were modified to fit Cuban conditions transferring only the IRR when it is reported independently, as suggested in Spadaro (1999).

The pollutants assessed in this study were primary particles, sulfur oxide and aerosols of sulfate and nitrate.

In the case of SO_2, the available bibliography is considerably lesser than for particles. In spite of the fact that some of these studies show relation between SO_2 environmental concentration and its effects on human health, sometimes this relationship disappears when in the statistical models other pollutants are controlled (Sunyer et al., 2003a, b). For Cuba, as for many developing countries, this pollutant has special importance due to the high contents of sulfur present in the used fuels. The national studies showed relation between the increments in SO_2 concentration and hospital admissions due to respiratory causes.

Sulfates and nitrates are treated as particles, assuming for sulfates the toxicity of PM_{10} and for nitrates, half the toxicity of sulfates (European Commission. ExternE, 2005).

Based on the fact that life expectancy and epidemiological death profile in Cuba are similar to the developed countries standards; mortality functions reported by these countries were used.

To assess the mortality impact (acute and chronic) the Year of Life Lost (YOLL) approach (Leksell and Rabl, 2001) was used. A reason for using this criterion is that air pollution is not a primary cause of death but a contributory; according to this the loss of life expectancy is a more meaningful indicator than the number of deaths due to pollution. In this study an average value of 10 yr of life expectancy lost is considered as acute mortality and 0.5 yr for chronic mortality, as suggested in Airpacts model (Spadaro, 2002a).

The complete set of SERF used is presented in Table 3. All the effects caused by PM_{10} are extended to sulfate and nitrate aerosols in the way explained previously.

Mortality rates were obtained from the Cuban Statistical Health Yearbook for the year 2002. Cuban population fractions were taken from the Cuban Statistical Yearbook for the year 2002. The asthmatic population fraction was obtained from the Cuban Public Health Ministry (MINSAP, Ministerio de Salud Pública).

2.4. Mortality costs evaluation

The unit cost from Europe was transferred to Cuba using the following relation (Spadaro, 2002b):

$$\text{Unit Cost in country} = \text{Unit cost in EU} \times (\mathrm{PPP_{GNP\_COUNTRY}}/\mathrm{PPP_{GNP\_EU}})^{\gamma}, \quad (3)$$

Table 3
SERF used in health impact assessment

Health effect	SERF, cases or YOLL $\mathrm{receptor}^{-1}\,\mathrm{yr}^{-1}\,\mu g^{-1}\,m^{3}$	Source
Chronic mortality in adults (>30 yr old), PM_{10}	9.5760×10^{-5}	Pope et al. (2002)
Acute mortality, SO_2	1.0500×10^{-5}	Stieb et al. (2002)
Chronic bronchitis in adults (>30 yr old) , PM_{10}	1.6416×10^{-5}	Abbey et al. (1995)
Hospital admissions for respiratory causes, PM_{10} and SO_2	2.8400×10^{-6}	Spix et al. (1998)
Restricted activity days in adults (>18 yr old) , PM_{10}	4.5030×10^{-2}	Ostro (1987)
Emergency room visits , PM_{10}	3.1000×10^{-3}	Rosales-Castillo et al. (2001)
Acute asthma crisis (asthmatic population), PM_{10}	6.3437×10^{-4}	Rosales-Castillo et al. (2001)

where PPP_{GNP} stands for the Purchasing Power Parity of the Gross National Product normalized per capita (see values) and γ is the income elasticity coefficient, taken as 1.

As the PPP_{GNP} for Cuba is not available, the reported value for Latin America and the Caribbean for the year 2003 was taken (6950 USD) (World Bank, 2004). The value for EU (25,700 USD) was taken from the same source. The value of a YOLL was taken from Spadaro (2002b), and converted from Dollars of the year 2000 to Dollars of the year 2002 (taken as a base for costs evaluation) using an annual inflation rate of 3%.

Table 4 presents the values for unitary costs used for both mortality and morbidity effects.

2.5. Morbidity costs evaluation

A Cuban detailed study of the cost associated to acute effects in asthmatics, from the health provider's point of view, and referred to the year 2002, assessed the cost of an acute crisis of asthma. The costs compiled in the MINSAP official statistics and the productivity loss, were considered for other morbidity effects, as detailed in Meneses et al., 2004. In this study, the exchange rate between USD and pesos was considered as 1, as published by the Cuban National Bank for the year 2002.

The cost of a chronic bronchitis in adults was estimated as 4516.8 USD case^{-1}, transferring the cost reported by Spadaro (2002b) for the EU.

The costs associated with productivity loss, are based on the average number of hospitalization days and average salary. Productivity lost was estimated by multiplying the cost of a restricted activity day by the average number of days lost due to emergency room visits, hospital admissions for respiratory causes or acute asthma crisis, obtained in European Commission. ExternE (1998).

3. Results

3.1. Dispersion modeling

The annual average increments in concentrations obtained through local dispersion modeling with ISC3-ST for power plant Máximo Gómez shows a maximum of 0.601 $\mu g\,m^{-3}$ for PM_{10}, 19.228 $\mu g\,m^{-3}$ for sulfur dioxide and 0.744 $\mu g\,m^{-3}$ for nitrogen oxides (results for SO_2 can be seen in Fig. 1). For power plant Otto Parellada, increment in concentration values shows a maximum of 0.190 $\mu g\,m^{-3}$ for PM_{10}, 11.164 $\mu g\,m^{-3}$ for sulfur dioxide and 0.170 $\mu g\,m^{-3}$ for nitrogen oxides. Power plant Este de la Habana increment values present a maximum of 0.280 $\mu g\,m^{-3}$ for PM_{10}, 8.388 $\mu g\,m^{-3}$ for sulfur dioxide and 0.034 $\mu g\,m^{-3}$ for nitrogen oxides (results for SO_2 can be seen in Fig. 2, the scale used is the same for Figs. 1 and 2 and it can be seen that increments are lower for the latter).

On the average, the plumes follow west–south-west direction in all cases. Power plant Otto Parellada increments are negligible beyond the local modeling limits, according to the small stack and the low emissions, but increments near the source are important. Results were higher for power plant Máximo Gómez, but with low influence in Havana City. For power plant Este de la Habana, significant increments in the concentrations of the pollutants can be found beyond the limits of the local modeling domain.

Increments for sulfate aerosols obtained by the regional dispersion modeling for power plant Este de la Habana are shown in Fig. 3. Higher increments in concentration can be found in west–northwest direction for all cases, so pollutants are extended mainly over the Gulf of Mexico area; this behavior is consistent with the wind roses for the cells in the area and the statistics from available soundings.

Table 4
Unitary costs used in health impact assessment

Health effect	USD_2002 per Case or YOLL	Source
Chronic mortality in adults (>30 yr old)	25,658.34	Spadaro (2002b)
Acute mortality	44,203.48	Spadaro (2002b)
Chronic bronchitis in adults (>30 yr old)	4,516.88	Spadaro (2002b)
Hospital admissions for respiratory causes	677.10	Meneses et al. (2004)
Restricted activity days in adults (>18 yr old)	10.20	
Emergency room visits	63.88	
Acute asthma crisis (asthmatic population)	22.74	

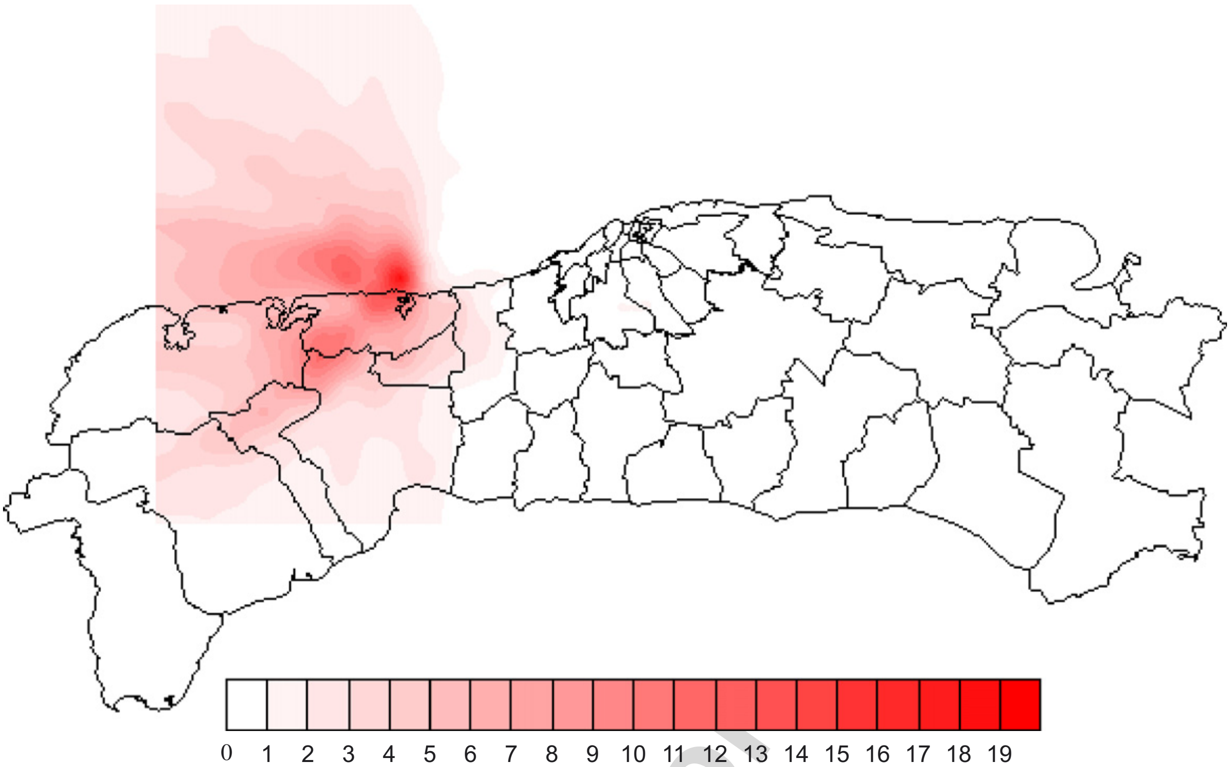

Fig. 1. Distribution of increment in SO_2 concentration levels ($\mu g\,m^{-3}$) obtained from the local dispersion modeling for Máximo Gómez power plant.

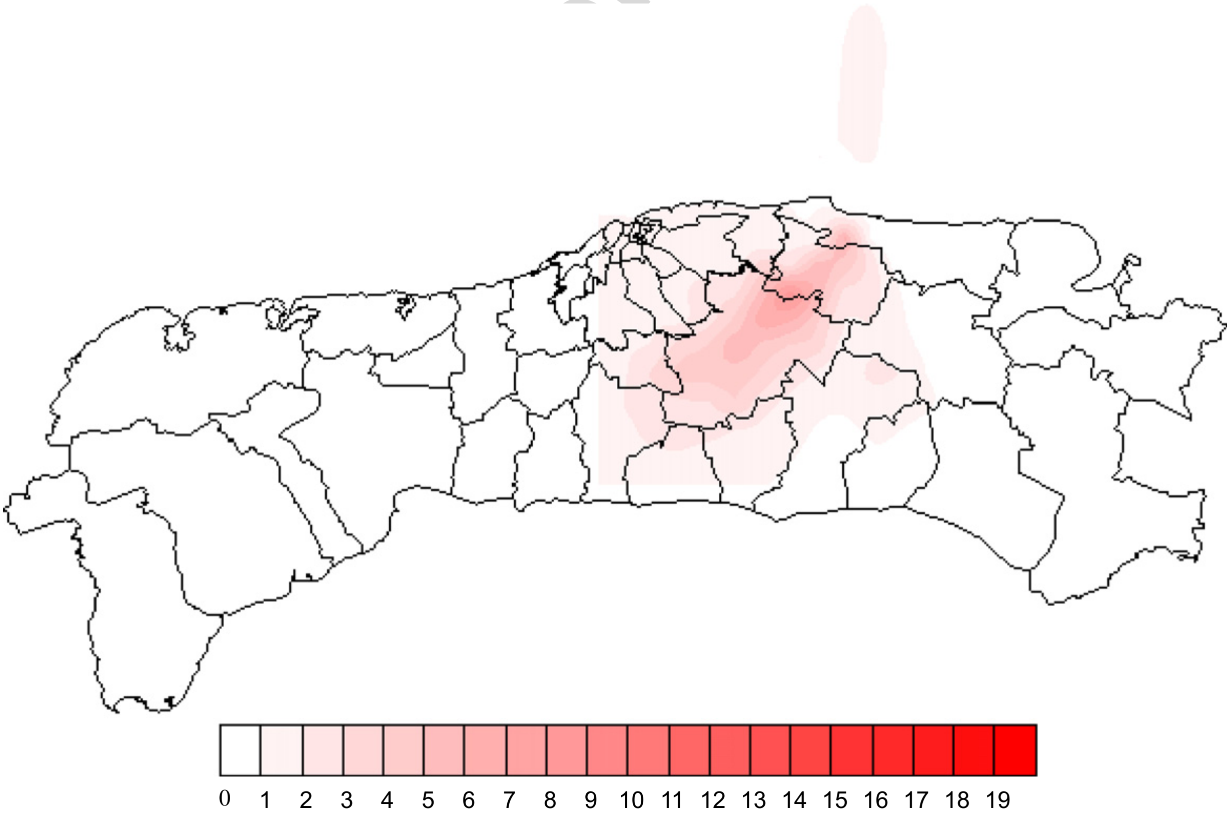

Fig. 2. Distribution of increment in SO_2 concentration levels ($\mu g\,m^{-3}$) obtained from the local dispersion modeling for Este de la Habana power plant.

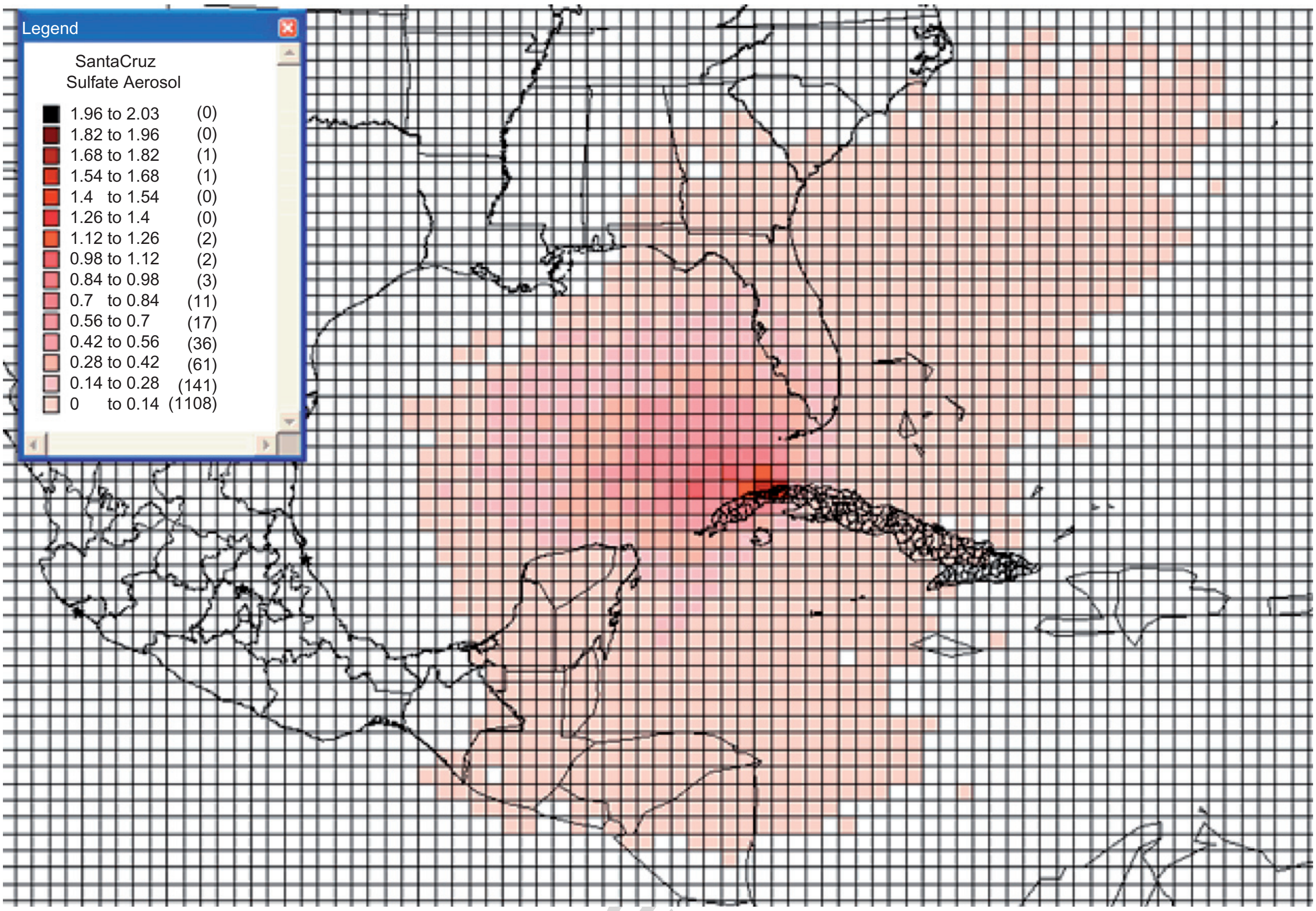

Fig. 3. Distribution of increments in sulfate aerosols concentration levels ($\mu g\,m^{-3}$) obtained from the regional modeling for Este de la Habana power plant.

For secondary species, the increments are spread over a larger area than for PM_{10}, NO_x and SO_2 as expected. For each species the increments decayed ten times at similar distance from the source, evidencing their closeness in space at the modeling scale, which also implies that similar conditions are more important that the emission of each independent source. Increments for primary species are more important near the source, decreasing rapidly with distance.

Concentration values obtained for power plant Máximo Gómez are the highest. For power plant Otto Parellada increments in secondary species are the lowest, in correspondence with the small spread founded at the local modeling.

3.2. Health impacts and external costs

Table 5 resumes the morbidity and mortality effects due to the power plants. The range of impact and subsequent cost was estimated using a confidence interval of 68%.

In Table 6 are presented the total costs by power plants. The total cost assessed was 40,588,309 USD yr^{-1} (min./max.: 10,194,833/169,013,252), representing 1.06 USD Cent kWh^{-1}.

The cost obtained from local dispersion represents 4.8% of the total cost for Máximo Gómez power plant and 10.7% for Este de la Habana. For Otto Parellada it is 53.5% of the total cost obtained, as a result of its centric location, and to a lesser degree by its low regional impact.

Costs derived from sulfur species (SO_2 and sulfate aerosol) represent 93% of the total costs; from it, SO_2 costs account for 19%. The ones derived from mortality effects represent 81.50% of the total.

4. Uncertainties

There are many uncertainties associated with the health effects and costs obtained. The most important ones are discussed in this topic.

Table 5
Health impacts (cases or YOLL yr^{-1}) produced by the power plants

Health effect	Otto Parellada	Este de la Habana	Máximo Gómez	Total
Chronic mortality in adults (>30 yr old)	39	426	531	996
Acute mortality	25	83	55	164
Chronic bronchitis in adults (>18 yr old)	7	73	91	171
Hospital admissions for respiratory causes	8	35	31	74
Restricted activity days in adults (>16 yr old)	18,116	200,548	249,571	468,236
Emergency room visits	1247	13,806	17,181	32,235
Acute asthma crisis (asthmatic population)	255	2825	3516	6596

Table 6
Total costs for the three power plants studied

Power plant	Expected cost (USD yr^{-1})	Lower value (USD yr^{-1})	Higher value (USD yr^{-1})	Cost (USD Cent kWh^{-1})
Máximo Gómez	20,200,171	5,193,973	81,501,147	0.95
Este de la Habana	17,971,734	4,464,831	75,907,242	1.29
Otto Parellada	2,416,405	536,029	11,604,863	0.82
Total	40,588,309	10,194,833	169,013,252	1.06

The minimum and maximum values were estimated using a confidence interval of 68%.

Emissions from the power plants were calculated for SO_2 using a methodology based on the combustion efficiency; for NO_x and PM_{10} emissions were estimated using emission factors for USA (AP-42). In addition, for local dispersion modeling, emissions were considered invariable in time.

The results used in health impact assessment were annual average concentrations, but the effects caused by hourly pollutant concentrations, which often exceed the yearly average concentration, are not considered.

For regional modeling, annual average values are considered for all data and results, intending to represent a statistical behavior. The large cells of regional domain are also a source of uncertainties, because the resolution affects the results with more importance at the cells near the source. The emission data, except for Bouwman et al. (2002), was interpolated from a lower-resolution data and improvement was possible only for Cuba. The precipitation and wind data are also interpolated. In addition, the emission inventory data used corresponds to the year 1995.

Results from the regional dispersion modeling at the local domain are not considered for health impact and cost assessments. The effects of including the increments of the secondary species estimated for the local domain are an increase in final costs of 119% for power plant Máximo Gómez, 162% for power plant Este de la Habana and 146% for power plant Otto Parellada, leading to a total increment of 140%, so including these increments affects in a significant way all results, affected also by the population at the local domain which is large at the three domains. The decision of not considering was based on the little confidence of WMI results at the local cell; comparison with local dispersion results leads to the finding that these results for primary pollutants are closer to the maximum than to the average, so they are overestimated.

Only health impacts were evaluated. Ozone formation and global warming are not calculated.

The ERF were assumed to be linear, without threshold, behavior. The national studies were insufficient for the establishment of ERF; instead, international studies were used, transferring the values of IRR. Sulfates and nitrates were treated as particles, estimating its toxicity in terms of the toxicity of PM_{10}.

The PPP_{GNP} of Cuba used to transfer the unitary cost does not correspond to the country but to the area, introducing an important uncertainty that can be grossly estimated when comparing the economic and social characteristics.

The average number of days lost due to the different morbidity effects was taken as in European Commission. ExternE (1998).

5. Discussion of results and conclusions

In spite of the large number of uncertainties the results obtained in this study represent an important step forward as an externalities assessment study that, for the first time in Cuba, includes results from both local and regional dispersion modeling, resolved in a detailed way, and considers morbidity and mortality health effects. The study proves that it is possible to have an appropriate description of electricity generation impacts in terms of external costs, with a reasonable accuracy, even when the available data is not complete. "It is better to be approximately correct than completely wrong!!" (Spadaro, 1999). Such is the general case of the developing countries, in which larger impacts from electricity generation result from the lower quality of energy sources and the common use of out of date technologies.

The methodologies implemented have been taken as a base for future improvements of Cuban environmental normative for emission and air quality. They have been also used in environmental impact assessment and mitigation studies which are considered in the grant of environmental licenses for new electric generation facilities and in decision making concerning the existing ones.

The health impact analysis for the selected pollutants covered all the impacts that show significant associations with concentration level increments in national studies. The costs were adapted to the country as much as possible with the available data. A domestic value for the cost of an acute asthma crisis was used.

Referring to results, it has to be stressed that the contribution of sulfur species to final costs stands for a 93%, obtaining a 92.52% contribution for the costs of power plant Este de la Habana, 94.28% for power plant Máximo Gómez and 85.74% for power plant Otto Parellada. The lower contribution found for Otto Parellada is owing to the fact that this power plant uses a high sulfur content fuel, as against the domestic crude oil, richer in sulfur, and also due to the high local impact of its PM_{10} emissions.

The costs obtained for power plant Máximo Gómez are the highest, due to the larger emissions of this plant. However, the most elevated cost per kWh was found for power plant Este de la Habana, because the impact of this power plant in Havana City is bigger. The cost per kWh of Otto Parellada is high in spite of its lower impact, since the generation is not so elevated and the impact of its emissions is mainly over Havana city.

Mortality costs stand for the 80.8% of the total costs obtained, as a result of 1159 YOLL yr^{-1}. Morbidity impacts are significant, in spite of its lower contribution to total costs, finding an elevated increment in the number of restricted activity days in adults, and an increment of 171 in the number of cases per year of chronic bronchitis in adults, representing the main contribution to morbidity costs. The increments in occurrence of acute asthma crisis and emergency room visits are also important.

The impacts on health derived from these power plants show that their influence is not only at their locations, but also in an extended area covering the western part of the country, including Havana city.

In order to reduce the uncertainties it is necessary to continue the efforts to establish specific data, especially for health and cost values. The use of the methodology described in this work has been extended for diverse studies that contribute information to the Cuban decision makers and it might be useful as an example for other developing countries.

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References

Abbey, D.E., Lebowitz, M.D., Mills, P.K., Petersen, F.F., Lawrence Beeson, W., Burchette, R.J., 1995. Long-term ambient concentrations of particulates and oxidants and development of chronic disease in a cohort of nonsmoking California residents. Inhalation Toxicology 7, 19–34.

Adler, R.F., Huffman, G.J., Chang, A., Ferraro, R., Xie, P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J., Arkin, P., 2003. The version 2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979–Present). Journal of Hydrometeorology 4, 1147–1167 (also available at HTTP) 〈http://www.icess.ucsb.edu/gem/Adler.et.al2003.J.Hydrology.GPCP.monthly.pdf〉.

Atkinson, R., Baulch, D.L., Cox, R.A., Hampson Jr., R.F., Kerr, J.A., Rossi, M.J., Troe, J., 1997. Evaluated kinetic and photochemical data for atmospheric chemistry: supplement

VI. Journal of Physical and Chemical Reference Data 26 (6), 1329–1498.

Bouwman, A.F., Lee, D.S., Asman, W.A.H., Dentener, F.J., Van Der Hoek, K.W., Olivier, J.G.J., 1997. Global high-resolution emission inventory for ammonia. Global Biogeochemical Cycles 11 (4), 561–587.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Estimation of global NH_3 emissions from synthetic fertilizers and animal manure applied to arable lands and grasslands. Global Biogeochemical Cycles 16 (2).

Derwent, R.G., Dollard, G.J., Metcalfe, S.E., 1988. On the nitrogen budget for the United Kingdom and north-west Europe. Quarterly Journal of the Royal Meteorological Society 114, 1127–1152.

Evenden, G.I., 1995. Cartographic projection procedures release 4 interim report. Technical report, United States Department of the Interior Geological Survey, Coastal and Marine Geology Program, Woods Hole Field Center, Woods Hole, MA. Also available at HTTP: 〈http://kai.er.usgs.gov/ftp/PROJ.4/PROJ.4.3.ps.gz〉.

Environmental Protection Agency, 1995a. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Vol. I—User Instructions EPA-454/B-95-003a. US Environmental Protection Agency, Research Triangle Park.

Environmental Protection Agency, 1995b. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Vol. II-Description of Model Algorithms EPA-454/B-95-003b. US Environmental Protection Agency, Research Triangle Park.

Environmental Protection Agency, 2005. BenMAP environmental benefits mapping and analysis program, user manual. Prepared for Office of Air Quality Planning and Standards, US Environmental Protection Agency, Research Triangle Park. Abt Associates Inc., Bethesda, MD, 〈http://www.abtassociates.comwww.abtassociates.com〉.

European Commission. ExternE, 1998. Externalities of Energy, vol. 7: Methodology 1998 Update (EUR 19083); vol. 8: Global Warming (EUR 18836); vol. 9: Fuel Cycles for Emerging and End-Use Technologies, Transport and Waste (EUR 18887); vol. 10: National Implementation'' (EUR 18528). Directorate-General XII, Science Research and Development. Office for Official Publications of the European Communities, Luxembourg, Paris, Cedex 06, France.

European Commission. ExternE, 2005. Externalities of energy: methodology 2005 update (EUR 21951). Directorate-General XII, Science Research and Development. Office for Official Publications of the European Communities, Luxembourg, Paris, Cedex 06, France.

ICF Consulting, 2005. User's Guide to the Regional Modeling System for Aerosols and Deposition (REMSAD) Version 8.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., Fiorino, M., 2001. The NCEP/NCAR 50-year reanalysis. Bulletin of the American Meteorological Society 82 (2), 247–267.

Leksell, I., Rabl, A., 2001. Air pollution and mortality: quantification and valuation of years of life lost. Risk Analysis 21 (5).

Logan, J.A., 1998. An analysis of ozonesonde data for the troposphere: recommendations for testing 3-D models, and development of a gridded climatology for tropospheric ozone. Journal of Geophysical Research 104 (D13), 16115–16149.

Meneses, E., Álvarez, M., Morales, M., Turtós, L., Díaz, N., 2004. Estimación de los costos en salud para la evaluación de externalidades. Memorias del Segundo Taller Nacional de Gestión del Conocimiento en Energía. ISBN: 959-7136-25-2. Also available at HTTP 〈http://www.energia.inf.cu/evento-gce/trabajos-2.htm〉.

Molina E., Meneses, E., 2003a. Análisis de estudios epidemiológicos nacionales para la Obtención de funciones exposición-Respuesta. Contribución a la Educación y la Protección Ambiental, IX Taller, ISBN: 959-7136-20-1.

Molina E., Meneses, E., 2003b. Evaluación epidemiológica del impacto de los contaminantes del aire. Propuesta metodológica. Revista Cubana de Higiene y Epidemiología. Volumen 41. Números 3-2. Also available at HTTP 〈http://bvs.sld.cu/revistas/hie/vol41_2-3_03/hiesu2-3203.htm〉.

Olivier, J.G.J., Bouwman, A.F., Van der Maas, C.W.M., Berdowski, J.J.M., Veldt, C., Bloos, J.P.J., Visschedijk, A.J.H., Zandveld, P.Y.J., Haverlag, J.L., 1996. Description of EDGAR version 2.0. A set of global emission inventories of greenhouse gases and ozone depleting Substances for all Anthropogenic and Most Natural Souces on a per Country Basis and on 1×1 Degree Grid. RIVM Report 771060 002. RIVM, Bilthoven.

Ostro, B.D., 1987. Air pollution and morbidity revisited: a specification test. Journal of Environmental Economics and Management 14, 87–98.

Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. Journal of the American Medical Association 287, 1132–1141.

Rosales-Castillo, J.A., Torres Mesa, V.M., Olaiz-Fernández, G., Borja-Aburto, V., 2001. Los efectos agudos de la contaminación del aire en la salud poblacional: evidencias de estudios epidemiológicos. Salud Pública México 43 (6).

Rudolf, B., Hauschild, H., Rueth, W., Schneider, U., 1994. Terrestrial precipitation analysis: operational method and required density of point measurements. In: Desbois, M., Desalmond, F. (Eds.), Global Precipitations and Climate Change. NATO ASI Series I, Vol. 26. Springer, Berlin, pp. 173–186.

Scire, J.S., Strimaitis, D.G., Yamartino, R.J., 2000. A User's Guide for the CALPUFF Dispersion Model (Version 5.0). Earth Tech, Inc., Concord, MA.

Soltura, R., Turtós, L., Sánchez, M., 2005. Un nuevo algoritmo para el cálculo de algunos parámetros de la capa superficial atmosférica y estimación del perfil vertical del viento bajo condiciones de clima tropical húmedo. Comparación con el método de balance de energía usado por la EPA. XI Congreso Latinoamericano e Ibérico de Meteorología, Cancún, 27 de Febrero al 5 de Marzo. (Organization responsible: Organización Mexicana de Meteorólogos, A. C. Oklahoma 85 primer piso, Col. Nápoles, México, D.F. C.P. 03810).

Spadaro, J.V., 1999. Quantifying the health impacts of air pollution. Prepared for the International Atomic Energy Agency (IAEA), Planning and Economics Studies Section, Nuclear Division, Vienna, Austria.

Spadaro, J., 2002a. AirPacts Manual (versión 1.0). A Tool for Assessing the Environmental Impacts and Damage Costs to Human Health, Agricultural Crops and Man-made Structures from Exposure to Routine Atmospheric Emissions. International Atomic Energy Agency (IAEA), Vienna, Austria.

Spadaro, J., 2002b. INPUT DATA: MONETARY UNIT COSTS (version 1.0). A Tool for Assessing the Environmental Impacts and Damage Costs to Human Health, Agricultural Crops and Man-made Structures from Exposure to Routine Atmospheric Emissions. International Atomic Energy Agency (IAEA), Vienna, Austria.

Spivakovsky, C.M., Logan, J.A., Montzka, S.A., Blkanskt, Y.L., Foreman'Fowler, M., Jones, D.B.A., Horowitz, L.W., Fusco, A.C., Brenninkmeijer, C.A.M., Prather, M.J., Wofsy, S.C., McElroy, M.B., 2000. Three-dimensional climatological distribution of tropospheric OH: update and evaluation. Journal of Geophysical Research—Atmospheres 105 (D7), 8931–8980.

Spix, C., Anderson, H.R., Schwartz, J., Vigoti, M.A., Le Tertre, A., Vonk, J.M., Touloumi, G., Balducci, F., Piekarski, T., Bacharova, L., Tobias, A., Pönkä, A., Katsouyanni, K., 1998. Short term effects of air pollution on hospital admissions for respiratory diseases in Europe: a quantitative summary of APHEA study results. Archives of Environmental Health 53, 54–64.

Stieb, D.M., Judek, S., Burnett, R.T., 2002. Meta-analysis of time-series studies of air pollution and mortality: effects of gases and particles and the influence of cause of death, age, and season. Journal of the Air and Waste Management Association 52 (4), 470–484.

Sunyer, J., Atkinson, R., Ballester, F., Le Tertre, A., Ayres, J.G., Forastiere, F., Forsberg, B., Vonk, J.M., Bisanti, L., Anderson, R.H., Schwartz, J., Katsouyanni, K., 2003a. Respiratory effects of sulphur dioxide: a hierarchical multicity analysis in the APHEA 2 study. Occupational and Environmental Medicine 60 (8), e2.

Sunyer, J., Ballester, F., Tertre, A.L., Atkinson, R., Ayres, J.G., Forastiere, F., Forsberg, B., Vonk, J.M., Bisanti, L., Tenias, J.M., Medina, S., Schwartz, J., Katsouyanni, K., 2003b. The association of daily sulfur dioxide air pollution levels with hospital admissions for cardiovascular diseases in Europe (The Aphea-II study). European Heart Journal 24 (8), 752–760.

Trukenmüller, A., Friedrich, R., 1995. Die Abbildung der großräumigen Verteilung, chemischen Umwandlung und Deposition von Luftschadstoffen mit dem Trajektorienmodell WTM, in Jahresbericht ALS 1995. Stuttgart 1995, pp. 93–108.

Trukenmüller, A., Klamt, C., Krewitt, W., 2001. Revision of WTM parameters for EcoSense China. Sttutgart University, IER, Stuttgart, Germany.

World Bank, 2004. World Development Indicators. World Bank, Washington DC, USA.