Impacto de la contaminación atmosférica en las edificaciones patrimoniales de La Habana, Cuba. Efectos para un futuro climático

Impact of environmental pollution in the historical buildings of Havana, Cuba. Effect of future climate change

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Abstract

In the last decades, the quality of the air on the Old City of La Habana has become a growing concern regarding the durability and the aesthetics of the historical buildings. The aim of this work is to assess the impact of atmospheric pollutants on the conservation of the historic buildings of La Habana, declared World Heritage Site by UNESCO in 1982. The city located between 20-2600 m from the north coast is constantly exposed to increasing levels of atmospheric pollutants mainly from anthropogenic sources. The future projections on climate for the Caribbean area reflect changes in temperature, humidity and rainfall levels, which will have implications for the preservation of the heritage buildings.

Keywords: *Historical buildings, environmental pollution, corrosion, material recession*

Resumen

La calidad del aire en la Habana Vieja ha venido siendo desde las últimas décadas una preocupación creciente en cuanto a durabilidad y estética de las edificaciones históricas. El objetivo de este trabajo es evaluar el impacto de la contaminación atmosférica en la preservación de las edificaciones históricas de La Habana, declarada Patrimonio de la Humanidad en 1982 por la UNESCO. La ciudad, ubicada entre 20-2600 m de la costa norte, está constantemente expuesta al incremento en los niveles de contaminación atmosférica, fundamentalmente de fuentes antropogénicas. Las proyecciones futuras del clima para el área del Caribe reflejan cambios en la temperatura, humedad y precipitaciones, los cuales tendrán implicaciones para la preservación del patrimonio construido.

Palabras clave: Edificaciones históricas, contaminación atmosférica, corrosión, degradación de los materiales

1. Introduction

Since the middle of last century to the present, there have been climate events that resulted in increases in global temperature, changes in precipitation, sea levels, soil conditions and the occurrence frequency of extreme weather events (IPCC, 2007; Kumar & Imam, 2013). As a result of the above mentioned phenomena, the historic buildings have suffered a detriment in the aesthetics and the durability of their materials.

The deposition of chemical compounds and particulate matters (PM) on the surface of buildings, are revealed in terms of deterioration, yellowing and blackening of architectural and structural elements (Belfiore et al., 2013; Bonazzaa et al., 2005; Brimblecombe & Grossi, 2010; Ghedini et al., 2006; Inkpen, 2004). These impacts are considered chronic (Kucera, 1995; Screpanti & De Marco, 2009) and often irreversible, exerting their action during long periods of time.

Of the range of atmospheric pollutants present on the air, sulfur compounds (SOx), tropospheric ozone (O_3), carbon dioxide (CO_2), nitrogen compounds (NO_x), chloride ions (Cl^-), and PM are the most influents in the deterioration of buildings materials. The negative impact of these elements can range from a local to a global environment (Kumar & Imam, 2013; Rao et al., 2014).

The rapid urban and industrial growth influencing the air quality of the regions is the fundamental cause of the deterioration and accelerated aging found on most modern buildings (Bonazzaa et al., 2005; Helene & Borges, 2009; Jacob & Winner, 2009; Kucera, 1995). These alterations have caused damage to metals and plastics for an increase in the corrosion rates by exposure to aggressive environments, deterioration of the façades by deposition of suspended particles in the air (Brimblecombe & Grossi, 2010; Grossi & Brimblecombe, 2008; Grossi & Brimblecombe, 2016), among other causes.

The knowledge of the pollutants presents in the air, levels of concentration, transport mechanisms and deposition rates are vital to an efficient environmental management in order to extend the life time of modern and historical buildings and infrastructures.

Almost all architectural and structural elements become barriers to air currents, acting as reservoirs of atmospheric pollutants (Ozga, 2009). As consequence, this allows the rising to the formation of black crust (Di Turo et al., 2016), crystals of gypsum among other chemical compounds that propitiate aerosols, spores and the PM remain trapped in the mineral structures present in the pores of the stone. On these elements exposed to sources of emissions and aggressive atmospheres, act mechanisms of wet and dry deposition (Ozga, 2009). Those that have greater retention capacity (capitals, under cornices, under balconies, canes, and many others), show greater damages

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because they do not receive the direct impact of sun, air and rain.

The Historical Center of Havana, located between 20-2600 m from the north coast, was declared a World Heritage Site by UNESCO in 1982. Gradually the historic buildings have begun to show signs of deterioration, reflected in blackening and yellowing of the façades, cracks, corrosion and biodeterioration. The color pattern observed on buildings façades is a darker tone on the first levels with a gradually decrease as the level increase. The main sources of the present atmospheric pollution are industrial and anthropogenic.

Monitoring and measurement of air quality in Havana has been going on since the 70s' of the last century (Véliz & Machado, 1999). Since 1990, the monitoring stations have registered emissions of greenhouse gases, in particular compounds of SO_2*,* NO_x *and* PM_{10} *(Reyes et al., 2011). Based on these records, other studies have been developed to promote environmental programs and policies but mainly focused on the health status of the inhabitants, agriculture and biodiversity (Almoguea, 2008; CITMA, 2005; Peñalver & Lara, 1998; Véliz & Machado, 1999).*

The housing fund is over 50 years of age and heritage buildings is almost five centuries old since the first foundations, however there is still no efficient mechanism to estimate the direct and indirect losses related to corrosion damage and deterioration of materials (Castañeda & Rodriguez, 2014). Some studies have been carried out on the relationship between the climatic parameters and the concentration levels of atmospheric pollutants in the Capital (Castañeda et al., 2012; F. Corvo et al., 2009; Oroza, 2016) but deeper knowledge about the effect of air pollution on the preservation of historic buildings in Havana still lacking. Consequently, the possibility of implementing preventive strategies for the durability of the built heritage and the new buildings remains limited.

2. Materials y Methods

2.1 Data collection

The collection of data was made on buildings façades and sculptures affected by the formation of black crusts, yellowing, soiling, cracks and other related to atmospheric aggressiveness. The study begun in 2016 and ended on august of 2017. The assessment has coverage several avenues and streets of the Center of Havana, including the Old Havana City (Figure 1).

Figure 1. *Representation map of the assessed area*

2.2 Identification of the type of environment

A correlation was made between reported atmospheric pollutants for Havana City and their level of concentration on the air for the last decade (Castañeda et al., 2012; Placeres et al., 2004; Varona et al., 2011). From these results, the classification of the atmosphere and time of wetness (TOW) were established (ISO, 2012). For climate parameters (temperature, relative humidity and wind velocity), 14 years of data from the National Forecast Institute (INSMET) were used (figure 2).

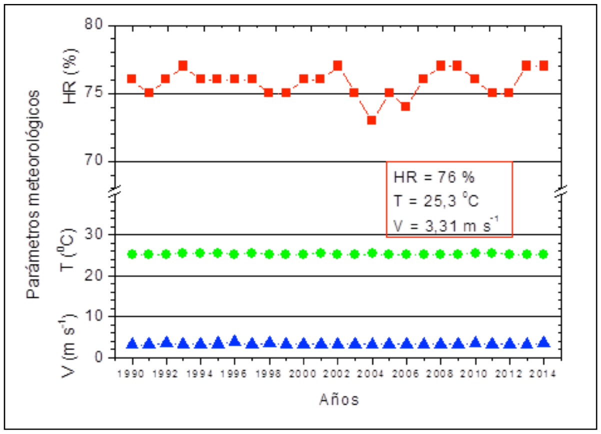

Figure 2. *Climate data reported by INSMET from 1990 to 2014*

2.3 Calculation of corrosion loss of metals (r_{corr})

The estimation of mass loss by corrosion attack was made for carbon steel, copper, zinc and aluminium for one year of exposure, according to ISO 9223:2012. For chloride (Cl^-), sulfur (SO_2) deposition rate (S_d and P_d respectively) and TOW, the data (Castañeda et al., 2012) were derived for the distance between 20-2600 m from northern coast line (Table 1). For mathematical calculations, the computer software used was Wolfram Mathematica version 9.0. Graphics were constructed by the computer software Origin Pro version 8.0.

Table 1. *Variables measured in Havana*

Variables	***Value***
TOW (hours/year)	*4966-3782*
D_{Cl} (mg/m^2d)	*719.5-2.7*
[SO_2] (μg/m^3)	*32.7*

Equations proposed by ISO 9223:2012 for the estimation of mass loss from environmetal paremeters, for the first year of exposure:

Carbon steel:

$$r_{corr} = 1.77P_d^{0.52} * exp(0.020HR + f_{St}) + 0.102S_d^{0.62} * exp\,(0.033HR + 0.040T)$$
$$f_{St} = -0.054(T-10)$$

Copper:

$$r_{corr} = 0.0053P_d^{0.26} * exp(0.059HR + f_{Cu}) + 0.01025S_d^{0.27} * exp\,(0.036HR + 0.049T)$$
$$f_{Cu} = -0.080(T-10)$$

Zinc:

$$r_{corr} = 0.0129P_d^{0.44} * exp(0.046HR + f_{Zn}) + 0.0175S_d^{0.57} * exp\,(0.008HR + 0.085T)$$
$$f_{Zn} = -0.071(T-10)$$

Aluminum:

$$r_{corr} = 0.0042P_d^{0.73} * exp(0.025HR + f_{Al}) + 0.018S_d^{0.60} * exp\,(0.020HR + 0.094T)$$
$$f_{Al} = -0.043(T-10)$$

where:

r_{corr}: corrosion rate for the first year of atmospheric exposure; μm/year.
T: air temperature; °C
RH: relative humidity; %
P_d: deposition rate of SO_2; mg/m^{2}day
S_d: deposition rate of Cl^-, mg/m^{2}day

2.4 Analysis of future climate change scenario

The estimation of the mass loss of materials for future projection was based on the developed weather data (Jacob & Winner, 2009) for the Caribbean zone. In the obtained climatic model an increase of the regional temperature of 2°C is expected for the next 80 years. For this future scenario a dose-response function model (Klinesmith et al. 2007) were applied for the following metals:

Carbon steel:

$$R = 13.4t^{0.98}\left(\frac{TDH}{3800}\right)^{0.46}\left(1+\frac{[SO_2]}{25}\right)^{0.62}\left(1+\frac{[D_{Cl}]}{50}\right)^{0.34} e^{0.016(T+20)}$$

Copper:

$$R = 0.46t^{0.15}\left(\frac{TDH}{3800}\right)^{0.02}\left(1+\frac{[SO_2]}{25}\right)^{0.38}\left(1+\frac{[D_{Cl}]}{50}\right)^{0.46} e^{0.02(T+20)}$$

Zinc:

$$R = 0.16t^{0.36}\left(\frac{TDH}{3800}\right)^{0.24}\left(1+\frac{[SO_2]}{25}\right)^{0.82}\left(1+\frac{[D_{Cl}]}{50}\right)^{0.44} e^{0.05(T+20)}$$

Aluminium:

$$R = 0.094t^{0.05}\left(\frac{TDH}{3800}\right)^{0.23}\left(1+\frac{[SO_2]}{25}\right)^{1.14}\left(1+\frac{[D_{Cl}]}{50}\right)^{0.42} e^{0.01(T+20)}$$

where:

R: mass loss by corrosion attack; μm/year.
[SO_2]: annual mean of gaseous concentrations; μg/m^3.
[D_{Cl}]: chloride deposition; mg/m^{2}d.
TOW: time of wetness; hours/year.
T: mean annual temperature; °C
t: exposure time; years.

3. Results y discussion

The figure 3 demonstrates the behavior of air pollutants for measurements taken in Havana between the years 1998-2011. The results show the concentrations of SO_2 and soot in the air increasing gradually. Conversely, the presence of PM_{10} reflects a decrease between the two periods. In the case of atmospheric NH_3, the measured levels exceed the normal category (ISO, 2012) with a value of 54.10 μg/m^3. Based on these results the concentrations of atmospheric contaminants measured in the Capital are categorized in the Urban/Industrial environment.

The first reports about the impact of pollutants and coastal climate on the buildings of Cuba were registered in 1995 (F. Corvo et al., 1995). In the V Summit of Environment and Development, the Ministry of Science, Technology and Environment (CITMA, 2005) published values of NO_2 of 3.3 μg/m^3, NH_3 of 5.6 μg/m^3 y SO_2 of 0.8 μg/m^3 for the Capital. Statements about impacts of acid rains were also issued. In the Casa Blanca station (INSMET) measurements of acid rain of 5.3 pH scales were recorded.

Studies published by Varona et. al. (2011) showed an increase in contamination levels with maximum values of NO_2= 120.3 μg/m^3, NH_3= 54.1 μg/m^3 and SO_2= 32.7 μg/m^3. In this research was provided as additional data the concentration of PM_{10} with 41.08 μg/m^3 and soot with 30 μg/m^3. With respect to tropospheric O_3, measurements of this element have only been made for the field of agriculture (Almoguea, 2008). The results obtained showed concentrations between 40 and 120 ppb. Similar concentrations of this element were obtained in a study made on historical sites and monuments in Italy (Screpanti & De Marco, 2009), demonstrating the effect of this element in the deterioration of materials such as copper and limestone. For the Historical Center of Havana, there have been no studies of tropospheric O_3 levels; therefor there is no knowledge of the impact on the historic buildings.

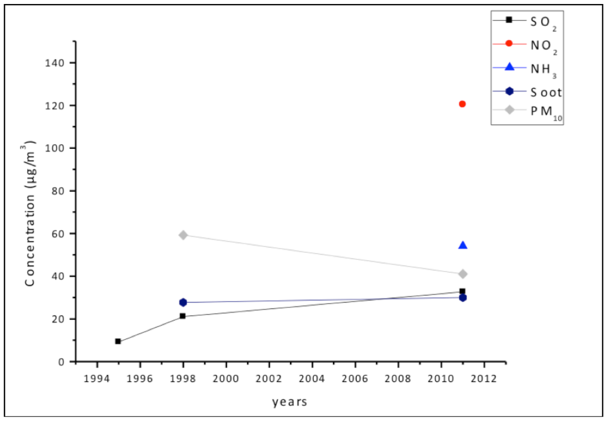

Figure 3. *Progression of air pollution levels in Havana*

As a result of the increasing concentrations of air pollutants in Havana, almost all buildings and sculptural elements show signs of blackening, acidification, loss of materials, growth of microorganisms and presence of higher plants (Figures 4 & figure 5). Table 2 shows the most common damages present on the historical buildings of Havana related to atmospheric pollution.

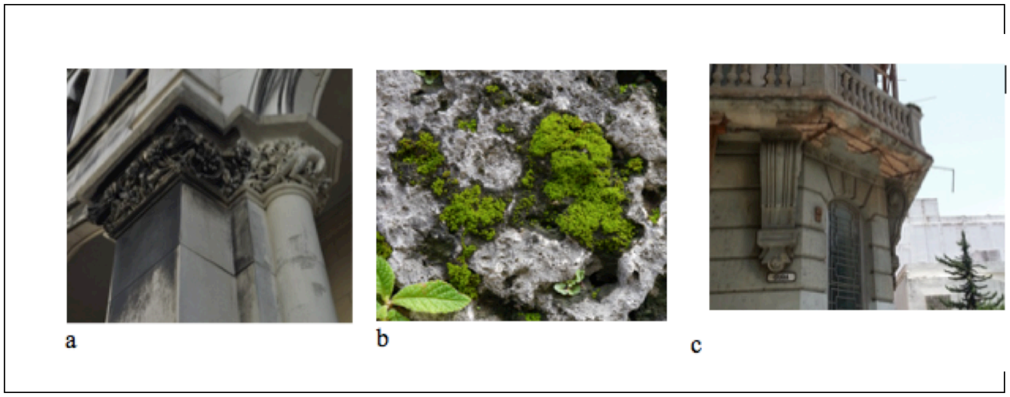

Figure 4. *Historical buildings in Havana with signs of deterioration. a) Columns of the Church of Queen, at Queen Avenue. b) Growing of higher plants and algae on the walls of the Havana's Cathedral. c) Balconies of a 1950' edifice at Cuba Street, heavily affected by carbonation and corrosion of the reinforcing steels*

Figure 5. *Sculptures located in Old Havana City affected by black crust and dust due to environmental pollution. a) Atlantes, Embassy of Spain. b) Atlantes, Cueto Palace. c) Saint Charles statue, Havana's Cathedral*

Table 2. *Common damages present on the historical buildings in Havana*

Building	***Damage type***	***Date of construction***	***Substrate***	***Past restoration work***
Church of Queen	*Black crust*	*1923*	*Reinforced concrete*	*No information available*
Church of Carmen	*Black crust*	*1825*	*Reinforced concrete*	*No information available*
Havana's Cathedral	*Loss of material, dust deposit, grow of higher plants and algae*	*1773*	*Limestone*	*2015*
San Francisco de Asís's Convent (main facade)	*Loss of material, heavily blackened*	*1580*	*Limestone*	*No information available*
Finlay's Science Museum (façade)	*Yellow crust, dust deposition*	*1925*	*Limestone*	*No information available*
Palace of the Captains and Generals	*Yellow crust, dust deposition*	*1792*	*Limestone*	*The cleaning of the main facade is in progress*
Church of Paula	*Soot deposition, loss of material*	*1730*	*Limestone*	*No information available*
National Capitol	*Yellow crust, dust deposition, corrosion, acidification*	*1929*	*Reinforced concrete*	*In progress*
Edifice of Commerce	*Black crust, dust deposition*	*1939*	*Reinforced concrete*	*No information available*
Dionisio Velasco's Palace	*Black crust, dust deposition*	*early XX century*	*Reinforced concrete*	*2016*

The annual average values of RH and the frequency of precipitations, lead to the wet deposition of atmospheric pollutants on the surface of buildings. The wind speed allows the transport of particles for several kilometers, extending atmospheric aggressiveness to areas with lower levels of emissions. The wetting of carbonations material with RH over 65% enables the activation of transport mechanisms of pollutants such as carbon dioxide (CO_2) and sulfur compounds, increasing the porosity and acidifying the base substrate (Castañeda, 2013; Howland, 2012). The presence of black crusts and dust deposition is most found on buildings located near high vehicular traffic avenues. In a study made at San Francisco de Asís's Convent (Reyes et al., 2011), located next to Port Avenue, average sulphur compounds deposition were superior to 12 $mg.m^{-2}d^{1}$ and nitrous compounds deposition were over 16 $mg.m^{2}d^{-1}$. As impact on reinforced concrete buildings, loss of alkalinity in the cement paste implies loss of passivity of reinforcing steel, thereby initiating the corrosion phenomenon.

The types of deterioration previously discussed are widely visible in almost all of the existing buildings in the old side of the capital with a marked impact on heritage buildings and sculpture pieces. The major structural and aesthetic damages are found in the most densely populated areas, avenues with high vehicular traffic and buildings located on the front line of the Havana seawall. Especially in the latter, being approximately at 20 m from the northern coastal strip, the durability of the materials due to the effect of the marine aerosol and the emissions from mobile sources passing through the avenue of Malecón, is extremely low and the materials deteriorates at a high rate.

Table 3 shows the exposure categories for the levels of air pollutants reported in Havana. The categories of atmospheric corrosive aggressiveness indicated by ISO 9223:2012 are given as reference.

Table 3. *Relationship of pollution variables and categories in Havana*

References	**Maximum concentrations of atmospheric pollutants ($\mu g/m^3$)**				
	SO_2	NO_2	PM_{10}	NH_3	Soot
(Placeres et al., 2004)	21.5	-	59.2	-	-
(Varona et al., 2011)	32.7	120.3	41.09	54.10	21.86
Intervals ISO 9223:2012	**5-100**	**20-150**	**30-70**	**<20**	**-**
Category	**Urban**	**Urban**	**Urban/Industrial**	**Normal**	**-**

** (-) on reported*

The r_{corr} results obtained from the application of the models (ISO, 2012) for the first year of exposure show an increase in the category of corrosive aggressiveness according to what was reported by Castañeda et al. (2012) for the distances between 20-4500 m from the north coast of Havana (Table 4). For the case of carbon steel and zinc, the obtained corrosion level is CX (extreme) for the distance of 20 m, and is maintained at C5 (very high), for copper. The Figure 6 shows the mass loss of the metals with respect to the distance of the north coast. The categories of atmospheric corrosive aggressiveness are shown in Table 4.

Table 4. *Corrosivity of atmosphere in Havana for the studied metals*

Material	**Carbon steel**						
Distance from sea (m)	20	360	615	1500	1600	2678	4500
r_{corr} (μm/y)	269.2	42.2	28.2	42.3	25.6	23.7	23.9
Interval ISO 9223:2012 (μm/y)	200-700	25-50				1.3-25	
Category	CX	C3	C3	C3	C3	C2	C2
Material	**Copper**						
Distance from sea (m)	20	360	615	1500	1600	2678	4500
r_{corr} (μm/y)	4.3	1.8	1.4	1.7	1.3	1.2	1.2
Interval ISO 9223:2012 (μm/y)	2.8-5.6	1.3-2.8				0.6-1.3	
Category	C5	C4	C4	C4	C4	C3	C3
Material	**Zinc**						
Distance from sea (m)	20	360	615	1500	1600	2678	4500
r_{corr} (μm/y)	12.9	2.1	1.3	2.0	1.2	1.1	1.1
Interval ISO 9223:2012 (μm/y)	8.4-25	2.1-4.2	0.7-2.1				
Category	CX	C4	C3	C3	C3	C3	C3
Material	**Aluminium**						
Distance from sea (m)	20	360	615	1500	1600	2678	4500
r_{corr} (μm/y)	5.21	0.66	0.37	0.64	0.32	0.29	0.28
Interval ISO 9223:2012 (μm/y)	-	-	-	-	-	-	-
Category	-	-	-	-	-	-	-

For the distances covered by the Historical Center of Havana, the behavior of metallic materials recession is as follows:

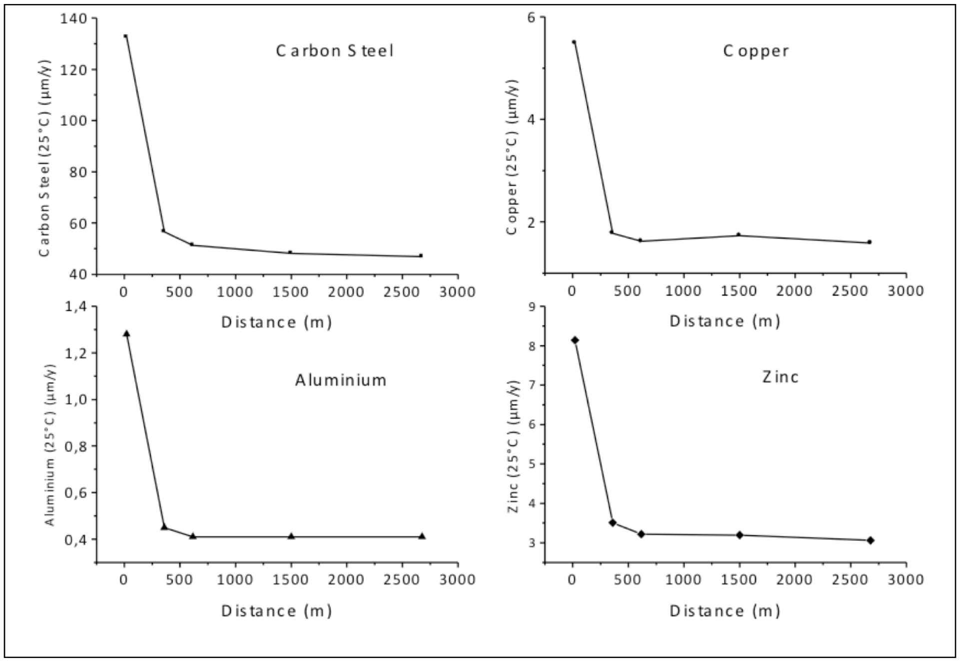

Figure 6. *Metal recession for the area covered by the Historical Center of Havana*

3.1 Possible effects for climate change scenario

Since the last century, emissions in Havana have increased gradually. The negative impact of air pollutants on the heritage buildings is undeniable and requires the implementation of actions, policies and durability-based mitigation strategies. The occurrence of extreme weather events and the effect that has on the city is most devastating annually. These have an increasing impact in the speed of deterioration of the historic buildings, especially those located in the proximity of the north coast.

Climate models for the XXI century (Jacob & Winner, 2009) indicate changes in the global climate. For the future conditions of Cuba, the simulation shows an increase between 1-2°C, while rainfall will tend to decrease in a 10%. Based on this prediction the weather in the region of Central America will tend to a drier and warmer environment.

The increase in regional temperature will cause a warming of the ocean and the air which increases the possibility of hurricane formation. In the city of Havana, if current emission levels are maintained combined with the predicted scenario, the climate variations will increase the drying of urban vegetation, higher dust content in the air, greater contents of carbonate particles, increasing rates of materials recession (Figure 7), among other consequences.

As predicted by Grossi and Brimblecombe (2007), increase in solar radiation may accelerate deterioration of organic materials, such as stone conservation treatments or paint coatings. Changes in temperature can also affect wetting-drying cycles and therefore the deposition rate of acidic gases. The historical buildings and the metals of carbon steel, copper and zinc, will be the most affected. Consequently, the speed of dissolution of the materials, especially calcareous ones, will be increased. As the frequency of precipitation decreases, there will be more deposition of soil and dust on the façades of the buildings.

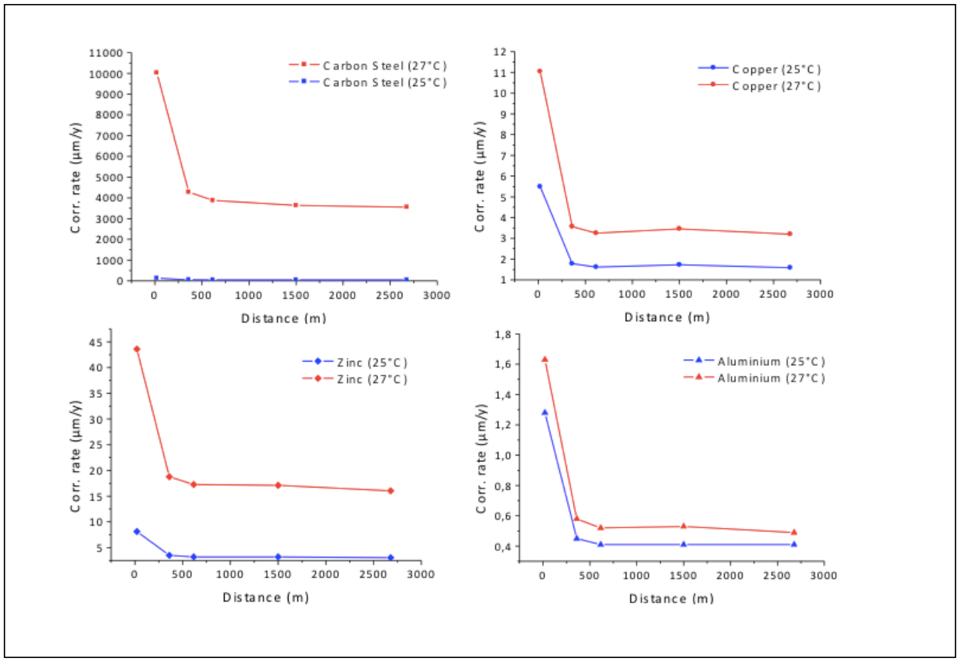

Figure 7. *Behavior of metals recession at 25°C and 27°C in possible climate change event*

Variations in the regional climate will favor an increase in O_3 concentration levels. The entry of the seasons of the year, the residence time and the levels of NOx compounds will have a significant influence. The aesthetic and structural condition of the buildings will therefore be also affected by the concentration levels of tropospheric O_3.

4. Conclusions

This study demonstrated the effect of atmospheric pollution in Havana on the deterioration of monuments and historic buildings. The formation of black crust, corrosion and dust deposition are the most common damages found on building facades, especially on those located near to urban areas with heavy traffic. The results obtained from the applied mathematical models proved the extreme atmospheric corrosivity for the first 20 m of the northern coastal strip. The concentrations of the pollutants present in the air of the Capital are in the category of Urban/Industrial according to ISO 9223: 2012.

The Historic Center of Havana, located very close to the north coast, presents a high vulnerability. The buildings show an accelerated aesthetic and structural deterioration due to the high levels of atmospheric contaminants present in the city, mostly from anthropogenic sources.

It is imperative to apply actions and mitigation strategies focused on durability, in order to adapt to future climate change processes.

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