

2 **Tropical Atmospheric Corrosion of Galvanized Steel, in a light urban atmosphere in**  
3 **the San José Valley of Costa Rica**

4 **Corrosión atmosférica tropical de Hierro Galvanizado en una atmósfera urbana leve,**  
5 **en el Valle de San José de Costa Rica**

6 J. Rodríguez-Yáñez<sup>1,\*</sup>, J. Uruchurtu Chavarín<sup>2</sup>, J. Sanabria-Chinchilla<sup>3</sup>

7  
8 <sup>1</sup>Laboratorio de Ecología Urbana, Universidad Estatal a Distancia, CP 474-2050, San  
9 José, Costa Rica, ORCID <https://orcid.org/0000-0001-5539-3153>, jrodriguezy@uned.ac.cr

10 <sup>2</sup>Centro de Investigaciones en Ingeniería y Ciencias Aplicadas, Universidad Autónoma del  
11 Estado de Morelos, Avenida Universidad 1001, Chamilpa, 62209 Cuernavaca, Morelos,  
12 México, ORCID <https://orcid.org/0000-0001-5539-3153>, juch25@uaem.mx

13 <sup>3</sup>Centro de Electroquímica y Energía Química, Escuela de Química, Universidad de Costa  
14 Rica, CP 11501-2060, San José, Costa Rica, ORCID [https://orcid.org/0000-0002-9597-](https://orcid.org/0000-0002-9597-7636)  
15 7636, jean.sanabria@ucr.ac.cr

16  
17 Sent date: 15/03/2022

18 **Abstract:**

19 *Costa Rica imports most of the metallic materials it uses. In construction, Galvanized Steel*  
20 *(GS) is one of the most used elements in urban areas, where atmospheric corrosion is the*  
21 *main problem of its environmental deterioration. The area of greatest population and*  
22 *economic activity in Costa Rica is the San José Valley, which has a tropical monsoon climate*  
23 *with low pollution, defined under ISO 9223 as light urban. The present study of the*  
24 *atmospheric corrosion of the GS, proposes a high correlation for simple linear models, with*  
25 *climatic parameters as main components and SO<sub>2</sub> as secondary component. Seasonality and*  
26 *sampling sites are partially significant at the beginning of the oxidation process, but this*  
27 *effect is damped over time. The average corrosion rate after 2 years is in the order of 0.4 μm*  
28 *y<sup>-1</sup>, which represents a low level (C2 according to ISO 9223). Complex annual corrosion*  
29 *models, such as those indicated by ISO 9223, overestimate the real corrosion value.*

30 **Keywords:** atmospheric corrosion, galvanized steel, mathematical modelling, monsoonal  
31 climate, air pollutants, rain, time of wetness

---

32  

---

\* Corresponding author. E-mail: [jrodriguezy@uned.ac.cr](mailto:jrodriguezy@uned.ac.cr)  
Tel. (+506) 83-40-07-94

33

34 **Resumen:**

---

35 *Costa Rica es un importador de la mayoría de los materiales metálicos que utiliza. En la*  
36 *construcción el Hierro Galvanizado (HG) es uno de los elementos de mayor uso en áreas*  
37 *urbanas, donde la corrosión atmosférica es el principal problema de su deterioro ambiental.*  
38 *El área de mayor población y actividad económica en Costa Rica es el Valle de San José, el*  
39 *cual tiene un clima tropical monzónico de baja contaminación, definido bajo la norma ISO*  
40 *9223(2012) como urbano leve. El presente estudio de la corrosión atmosférica del HG,*  
41 *plantea una alta correlación para modelos lineales simples, con parámetros climáticos como*  
42 *principales componentes y SO<sub>2</sub> como componente secundario. La estacionalidad y los sitios*  
43 *de muestreo son parcialmente significativos al inicio del proceso de oxidación, pero dicho*  
44 *efecto se amortigua con el tiempo. La velocidad de corrosión media luego de 2 años es del*  
45 *orden de 0.4  $\mu\text{m año}^{-1}$ , lo que representa un nivel bajo (C2 según la norma ISO 9223). Los*  
46 *modelos complejos de corrosión anual como los indicado por la norma ISO 9223,*  
47 *sobrestiman el valor de corrosión real.*

48

49 *Palabras clave:* Corrosión atmosférica, acero galvanizado, modelos matemáticos, clima  
50 monzónico, contaminantes del aire, lluvia, tiempo de humectación

---

51

52

# 1. Introduction

Galvanized steel (GS) is one of the most widely used materials in Costa Rica for construction, especially for roofing and drainage (Apuy, 2016). Atmospheric corrosion is one of the main problems for the definition of durability for these materials (NACE International Impact, 2016). The Costa Rican standard INTE C405 (2019) sets out the basic levels of alloy coating thicknesses on steel sheets, being a basis for the production of GS and similar or associated products. The current minimum value is 150 g m<sup>-2</sup> of zinc, considering both sides.

The central area of Costa Rica, and in particular the San José Valley (SJV), concentrates most of the country's population and economic activity (PRUGAM, 2009; INEC, 2011; Estado de la Nación, 2014). The SJV is a mountain valley surrounded by the volcanic mountain range to the NE and by the Talamanca mountain range to the SW. It has a tropical monsoon climate, with a dry season from December to April and a rainy season from May to November with an average of 2 300 mm m<sup>-2</sup> of rainfall. The climate presents slight variations depending on the altitude, with an average temperature of 20 °C and a relative humidity of 75 %, with main winds from the NE (Solano & Villalobos, 2000; Muñoz, Fernández, Gutiérrez, & Zárate, 2002; IMN, 2008).

The levels of atmospheric pollution are low, so that the classification of the SJV according to ISO 9223 (2012) is of the light urban type. This makes the dependence of corrosion to a large extent associated with climatic parameters, with a corrosion level generally expected to be of the type C2 or C3 (Morcillo, Chico, de la Fuente, & Simancas, 2012; Robles, 2013; Almeida, Morcillo, & Rosales, 2000; Neurohr, Monge-Nagera, & González, 2011).

Atmospheric corrosion of GS on a seasonal basis has not been studied for the SJV, with only a single reference in the MICAT project (Morcillo, Almeida, Rosales, Uruchurtu, & Marrocos, 1998), with a value of 0.708 µm y<sup>-1</sup>, but without establishing any kind of corrosion model. Subsequently, the PATINA Thematic Network (Morcillo, Almeida, Fragata, & Panossian, 2002) carried out a study for different Zn coatings, where the atmospheres like those of SJV, present corrosion levels between C2 and C3, with corrosion values somewhat higher than those presented by MICAT for Zn.

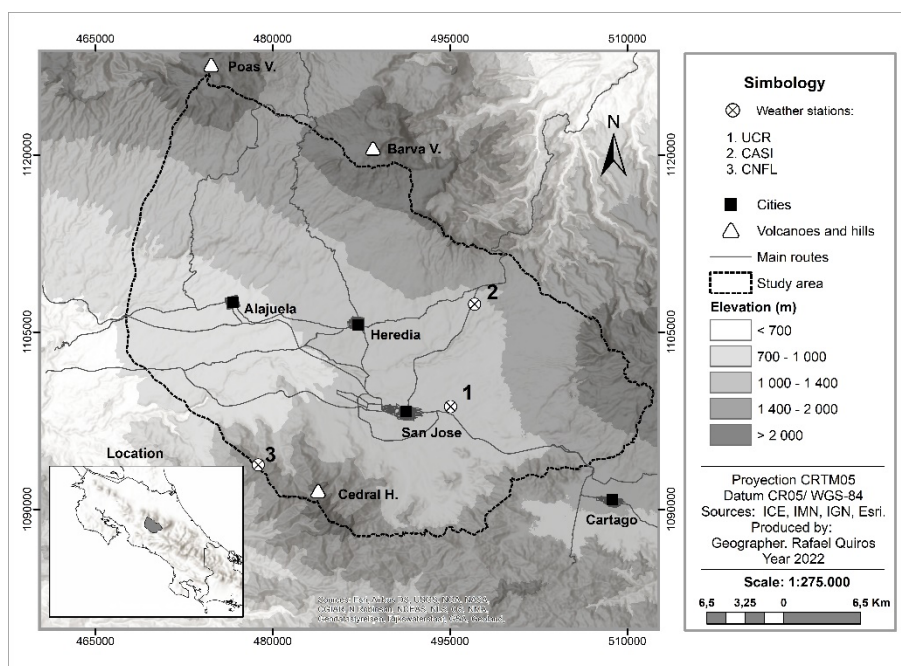
The prediction of atmospheric corrosion of Zn (or as GS) was initially approached with linear models, associated with atmospheric and pollution parameters. Subsequently, depending on the availability of data, statistical methodologies of dose-response analysis and neural networks were considered. (Feliu, Morcillo, & Feliu, 1993; Morcillo, Almeida, Rosales, Uruchurtu, & Marrocos, 1998; Mariaca, Genesca, Uruchurtu, & Salvador, 1999; Díaz, Martínez-Luaces, & Guineo-Cobs, 2003; Mikhailov, Strekalov, & Panchenko, 2007; de la Fuente, Castaño, & Morcillo, 2007; Vera, y otros, 2017; Yikun Cai, Yu Zhao, Xiaobing Ma, Kun Zhou, & Hao Wa, 2019) These methodologies allowed to establish general behavioural generalities for atmospheric corrosion depending on pollution levels, atmospheric parameters and the time considered. For low pollution atmospheres at short times, the dependence became more important on atmospheric parameters, which allowed a quick approximation with meteorological information only. This situation allows a quick visualization of the atmospheric corrosion of Zn in tropical areas with low pollution, as well as its adaptability to climate change. Due to this lack of information, it is proposed to evaluate the seasonal

96 atmospheric corrosion of zinc from GS sheets at the SJV. This will also establish basic  
97 models of GS corrosion, as well as considerations for its protection and durability against  
98 atmospheric corrosion.

99

## 2. Methodology

The insert in Figure 1 shows the map of Costa Rica. The grey area in this map corresponds to the SJV. A detailed view of the valley is shown in the main frame of Figure 1, emphasizing the main urban areas, the topographical relief, the location of the weather and corrosion stations and the outline of the studied area. The position of the weather and corrosion stations were selected in function of the wind direction passing through the SJV (from the NE to the SW).



**Figure 1.-** The study area in San José Valley, Costa Rica

### 2.1. Materials and parametric data

The galvanized steel (GS) used is produced in Costa Rica by immersion of a steel sheet in hot zinc, having more than  $200 \text{ g m}^{-2}$  of zinc, considering both sides. The gravimetric analysis according to ASTM A90/A90M (2013) indicates an average of  $236 \text{ g m}^{-2}$  of zinc. In proportion, the upper side had an average of  $29 \text{ }\mu\text{m}$  of zinc, while the lower side had an average of  $12 \text{ }\mu\text{m}$ , measured by ultrasound, with a Kocour H-10M equipment. The GS sheet was 1.2 mm thick (18 gauge). GS is used with a minimum coating level of  $10 \text{ }\mu\text{m}$  on either side, to only have effects on Zn during the study period.

The GS samples were cut into  $100 \text{ mm} \times 50 \text{ mm}$  coupons. They were initially cleaned with soap and water to remove grease and dirt. Chemical cleaning was performed according to ASTM G1 (2013), method C 9.1. After, the sample is cleaned in an ultrasonic bath and rinsed with distilled water and acetone before dried in air. The edge of the coupons is coated with paint to prevent corrosion of the steel and to ensure that this process does not affect the corrosion level of the zinc. All the coupons were weighed and prepared for the exposure test (ASTM G50-20, 2020; ASTM G33 - 99(2020), 2020).

Corrosion monitoring stations were built based on ASTM G50-20 (2020) and ASTM G92-20 (2020) standards. Their installation sites are shown in Figure 1. CASI station is located at 1341 m.a.s.l.; UCR station, at 1210 m.a.s.l.; and CNFL, at 1772 m.a.s.l.

For the classification of corrosive atmospheres proposed by ISO 9223 (2012), climate parameters were evaluated based on meteorological data provided for stations near to the sampling sites by the Instituto Meteorológico Nacional (IMN). The parameters considered are Temperature (T), Relative Humidity (RH), precipitation (P) and wind (W). The time of wetness (TOW) is estimated according to the ISO 9223 (2012) counting the quantity of hours when the RH is higher or equal to 80 %.

Atmospheric pollutants were evaluated according to ISO 9225 (2012), using wet candles for chlorides (Cl<sup>-</sup>) and passive monitoring such as Passam AG (2012), for sulfur dioxide (SO<sub>2</sub>). These methods are robust, low contamination and reliable in low pollution tropical environments. Vulcanological data on the dispersion of contaminants emitted by nearby volcanoes (Irazú, Turrialba and Poás), provided by public data from the Observatorio Vulcanológico y Sismológico de Costa Rica (OVSICORI) are also being analyzed in relation to possible acid gases (HCl and SO<sub>2</sub>), as well as particulate material. In similar way are considered the influence for tropical storms through the IMN, especially their influence on precipitation (OVSICORI, 2021).

Corrosion assessment of GS samples is performed using the gravimetric method of mass loss by chemical pickling according to ISO 8407 (2013), using the method C 9.1 Previously to the pickling the film of paint in the edges is removed with thinner. Two series are exposed during a period of two years. The first series starts the corrosion process in rainy season (September 2018 to September 2020), and the second starts in the dry season (March 2019 to March 2021).

The samples of the 12 months were analyzed by Scanning Electronic Microscopy (SEM) and X-ray Diffraction (XRD), to characterize the sample in terms of corrosion products and their availability on the surface. The SEM microscope corresponds to a Carl Zeiss model Sigma 300 and the diffractometer corresponds a Bruker XDS model D8 Focus.

## 2.2. Corrosion models

The basic typical model proposed for atmospheric corrosion is that of a potential function whit time (Feliu, Morcillo, & Feliu, 1993; González, y otros, 2008; Garita, Rodríguez Yáñez, & Robles, 2014; Morcillo, 2017), expressed as follows:

$$Corr = A t^n \quad (1)$$

Where,

Corr = corrosion accumulated in the time,  $\mu\text{m}$

t = accumulated time, in years

Although this equation is heuristic, the principal interest in this type of equation is in the value of n which is inversely associated with the level of protection of the surface oxide. The same form, A constant is associated with the Corr of the corrosion in the first year.

Secondary are the lineal equations models (Roberge, Klassen, & Haberecht, 2002; Santana, Santana, & González, 2003; Mikhailov , Tidblad, & Kucera, 2004; Ríos-Rojas, Aperador-Rodríguez , Hernández-García, & Arroyave, 2017), in their different variants (equations 2 to 4) according to:

$$Corr = a + b Cl + c SO_2 + d TOW + e P \quad (2)$$

$$Corr = a + b Log Cl + c Log SO_2 + d Log TOW + e Log P \quad (3)$$

$$\log Corr = a + n \log t + b Cl + c SO_2 + d TOW + e P \quad (4)$$

where,

Corr = corrosion accumulated in the time,  $\mu m$

t = accumulated time, in years

SO<sub>2</sub> = accumulated SO<sub>2</sub> deposition,  $mg\ m^{-2}$

Cl = accumulated Cl<sup>-</sup> deposition,  $mg\ m^{-2}$

TOW = accumulated time of whiteness, hours

P = accumulated precipitation,  $mm\ m^{-2}$

This type of linear equations is widely used for a general interpretation of the influence of each parameter on atmospheric corrosion from small data sets.

Recently, the fusion of the different groups of corrosion studies (Mikhailov , Tidblad, & Kucera, 2004; Morcillo , Chico, de la Fuente, & Simancas, 2012; Chico, de la Fuente, Díaz, Simancas, & Morcillo, 2017) present a general equation for estimating the annual value of corrosion for base metals, as a function of the annual levels of contamination and the climatic parameters of the studied site. These equations are included in the ISO 9223 (2012) and in the case of zinc, proposed equation has the form:

$$Vcorr = 0.0129 P_d^{0.44} \exp (0.046 RH + f_{St}) + 0.0175 S_d^{0.57} \exp (0.008 RH + 0.085 T) \quad (5)$$

$$f_{St} = 0.038 \times (T - 10), \quad \text{if } T \leq 10$$

$$f_{St} = -0.071 \times (T - 10), \quad \text{if } T > 10$$

$$N=114 \quad R^2= 0.78$$

Note: N is the number of sites used for the equation (5), R<sup>2</sup> is the Pearson coefficient, f<sub>St</sub> is a factor of steel, associate to the T effect.

Where,

Vcorr = corrosion rate in the first year,  $\mu m\ y^{-1}$

Pd = annual average SO<sub>2</sub> deposition,  $mg\ m^{-2} \cdot d^{-1}$

Sd = annual average Cl<sup>-</sup> deposition,  $mg\ m^{-2} \cdot d^{-1}$

T = annual average temperature, °C

RH = annual average relative humidity, %

These models are evaluated in the different sites and seasons.



213

214 *2.2.1. Control parameters of models*

215 Before analyzing the models, a study of principal components and comparative tests between  
216 sites and time periods is carried out (Pearson factor correlations, Mann Whitney U, Kruskal  
217 Wallis) (Miller & Miller, 2002; Wilks, 2011). According to the results of these tests, specific  
218 considerations are made for equations 2 to 4, considering that they should have more data  
219 than variables to be modeled.

220 Three indicators of the level of error are taken as control parameters: Pearson's correlation  
221 coefficient ( $R^2$ ), the sum of squared residuals (RSS) and Fisher's index (F). In them, it is  
222 taken as a consideration of a good adjustment that they must comply with  $R^2 > 0.7$ , RSS  
223 minimum and  $F > 100$  (Miller & Miller, 2002; Díaz , Martínez-Luaces, & Guineo-Cobs,  
224 2003).

225 The statistical process was run in SPSS Statistical Analysis Software.

226



### 3. Results and discussion

#### 3.1. Corrosion and associated parameters.

The assessment of corrosion at the sampling sites and the meteorological and contamination data is shown in Tables 1 and 2, for starting processes in rainy and dry seasons respectively.

**Table 1.-** Corrosion data (Corr) and accumulated parameters for the first series (starting in rainy season)

Sites	Time (days)	Corr ( $\mu\text{m}$ )	P ( $\text{mm m}^{-2}$ )	Cl ( $\text{mg}\cdot\text{m}^{-2}$ )	SO <sub>2</sub> ( $\text{mg}\cdot\text{m}^{-2}$ )	TOW (h)
UCR	29	0.016	305.4	109.29	199.06	540
	62	0.064	384.2	299.69	519.91	1054
	123	0.071	404.0	534.36	1659.25	1738
	179	0.095	404.0	819.56	2208.10	2272
	277	0.184	1077.2	1354.54	3157.23	3544
	368	0.186	1640.6	1408.70	3678.90	4992
	487	0.294	2211.6	1691.37	5204.95	6770
	606	0.358	2354.8	1926.04	6815.10	7984
	732	0.502	3619.0	2035.90	8348.36	10013
CASI	29	0.036	241.8	20.65	448.13	645
	62	0.048	294.4	26.81	667.84	1284
	123	0.065	354.3	174.75	2160.61	2489
	179	0.066	381.5	249.75	2637.83	3297
	277	0.146	717.8	658.49	3772.59	5147
	364	0.153	1113.3	1311.70	4906.55	7117
	487	0.384	1718.1	1870.71	6421.23	9803
	606	0.390	1827.5	2083.26	8221.96	12128
	732	0.520	2731.0	2443.93	11290.33	14830
CNFL	31	0.139	496.8	50.79	205.94	685
	64	0.171	573.0	56.32	456.26	1270
	125	0.200	591.6	498.99	1632.35	2058
	184	0.220	613.2	926.47	2404.61	2683
	279	0.302	1728.1	1314.47	3279.63	4168
	369	0.327	2205.4	1458.34	3916.48	5855
	489	0.394	3016.6	1854.26	5542.85	8042
	608	0.446	3259.3	2149.62	8667.44	9547
	734	0.657	4688.8	2437.85	10063.68	12008

**Table 2.-** Corrosion data (Corr) and accumulated parameters for the second series (starting in dry season)

Sites	Time (days)	Corr ( $\mu\text{m}$ )	R ( $\text{mm m}^{-2}$ )	Cl <sup>-</sup> ( $\text{mg}\cdot\text{m}^{-2}$ )	SO <sub>2</sub> ( $\text{mg}\cdot\text{m}^{-2}$ )	TOW (h)
UCR	29	0.068	17.8	358.40	441.00	319
	57	0.196	244.8	418.47	853.13	769
	120	0.205	816.0	541.59	1081.68	1754
	183	0.234	1236.6	589.14	1470.80	2720
	268	0.359	1803.2	825.34	2748.25	4079
	393	0.448	1883.6	1083.68	3765.11	5328
	729	0.607	4103.6	1656.87	7750.28	10048
CASI	35	0.022	47.5	230.53	582.75	552
	63	0.034	190.5	344.88	1039.76	1145
	126	0.049	492.8	809.26	1480.71	2488
	185	0.142	728.7	1061.95	2268.73	3747
	274	0.358	1261.4	1611.88	3463.30	5686
	399	0.462	1402.1	1835.24	4630.04	8164
	735	0.775	2719.1	2475.43	9448.11	15336
CNFL	32	0.165	226.5	363.47	299.60	338
	60	0.182	622.2	413.73	639.01	870
	123	0.188	1203.7	466.36	968.51	2034
	185	0.193	1592.2	563.02	1511.86	3172
	271	0.336	2402.0	867.60	2839.86	4830
	396	0.461	2505.9	1239.56	4413.69	6414
	732	0.670	5373.0	2045.85	10450.29	12483

The Table 3 show the annual mean values of Cl<sup>-</sup>, SO<sub>2</sub>, RH and T.

**Table 3.-** Annual mean values of Cl<sup>-</sup>, SO<sub>2</sub>, RH and T, in each season

Site	Cl <sup>-</sup> ( $\text{mg m}^{-2} \text{ day}^{-1}$ )		SO <sub>2</sub> ( $\text{mg m}^{-2} \text{ day}^{-1}$ )		RH (%)		T (°C)	
	<i>Rainy</i>	<i>Dry</i>	<i>Rainy</i>	<i>Dry</i>	<i>Rainy</i>	<i>Dry</i>	<i>Rainy</i>	<i>Dry</i>
UCR	3.8	2.7	10.0	9.4	80.2	76.5	20.4	20.5
CASI	3.6	4.6	13.5	11.6	87.5	90.1	17.8	18.2
CNFL	3.9	3.1	10.6	11.2	84.4	83.9	17.6	17.6

According to ISO 9223 (2012) the annual average values of Cl<sup>-</sup> and SO<sub>2</sub> correspond to categories S1 and P0, respectively. These are indicated as low pollution values and therefore the SJV is considered as a light urban type of atmosphere.

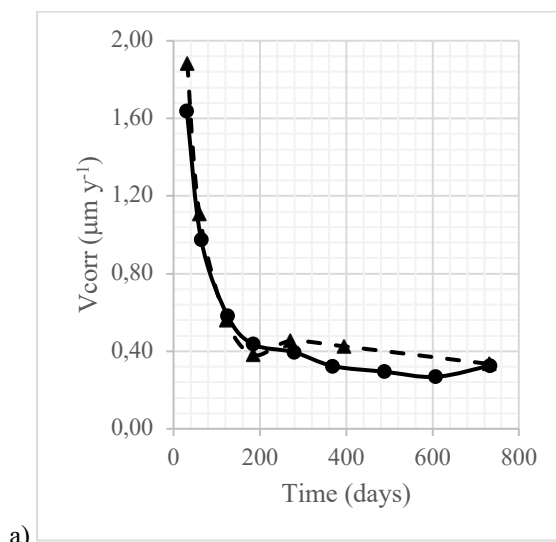
The atmospheric parameters of T and RH are typical of tropical environments, with mean values of RH above 80 % and T above 17 °C, While the accumulated rainfall has a downward pattern in direction NE (Solano & Villalobos, 2000; IMN, 2008).

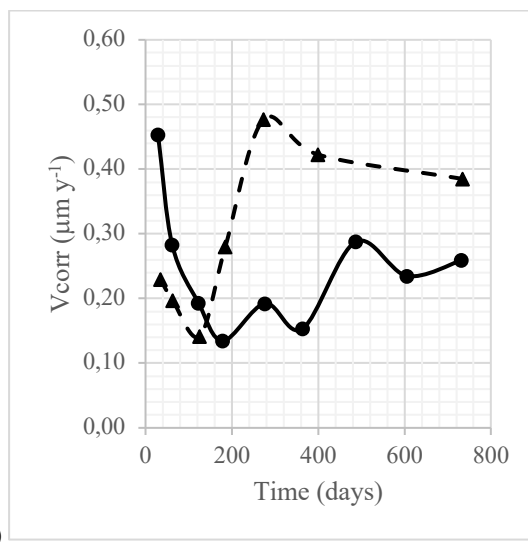
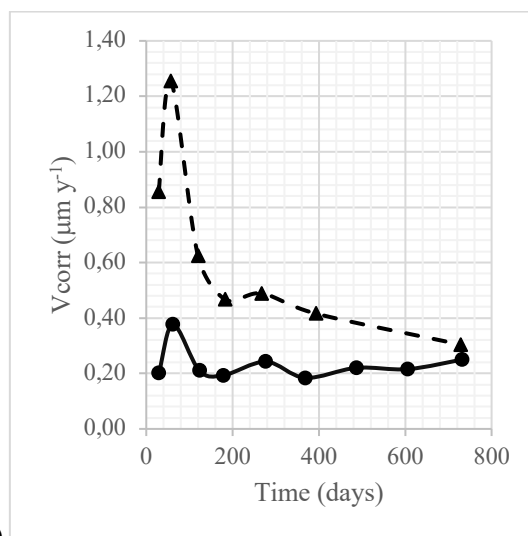
In accordance with the previous TOW values the ones shown here are high, being generally higher than 5000 hours ( $\tau$  5), with important effect in the Corr (ISO 9223:2012, 2012; Rodríguez Yáñez, Garita, & Saborío, 2015; Corvo, y otros, 1997; Corvo, y otros, 2008). The annual Corr values obtained in both seasons are associated with a category C2 ( $0.1$  to  $0.7 \mu\text{m y}^{-1}$ ) according to ISO 9223 (2012), although with different final values, by season and site. These values are consistent with the general consideration of GS or zinc in rural or light urban atmospheres (Almeida, Morcillo, & Rosales, 2000; Morcillo, Chico, de la Fuente, & Simancas, 2012; Restrepo, Botero, & Correa, 2007).

Alisios winds dominate the main wind component over the NE quadrant (Neurohr, Monge-Nagera, & González, 2011; Neurohr, Monge-Najera, & Mendez Estrada, 2013; Rodríguez-Yáñez & Chaves Villalobos, 2019).

### 3.2. Relationship between seasons

At all sites the general trend of Corr seems to indicate a lineal growth, while Vcorr has an exponential decay. This can be seen in Figure 2, for all sites.





**Figure 2.-** V<sub>corr</sub> in both season: rainy (—●—) and dry (—▲—) in a) CNFL and b) UCR, c) CASI sites respectively

Corr is dependent on site characteristics but not so much on the onset season, while V<sub>corr</sub> is affected by the onset season in the first months of corrosion.

The V<sub>corr</sub> values tend to be in the order of 0.3 to 0.4 μm y<sup>-1</sup>. Being only the CNFL site the one with a linear trend in the relationship between V<sub>corr</sub> in different seasons. The initial V<sub>corr</sub> values in the rainy season increase when moving from the SW to NE of the valley (see Figure 2). The sites UCR and CASI are clearly affected for this effect. This is possibly because the decrease in the strength of the Alisios winds (from NE) brings moisture from the Pacific coast (from SW) that concentrates in the center and north side of the SJV due to the higher altitude of the volcanic mountain range (Muñoz, Fernández, Gutiérrez, & Zárate, 2002).

The relationship of the Corr in each season in the first year, is relatively lineal (with the format  $\text{Corr (dry)} = a \text{ Corr (rainy)} + b$ ) and with different slope depending the site (see Table 4). The slope values are greater than 1, which would indicate that more corrosion occurs if the process starts in the dry season. This situation is especially important for the CASI site where the rainy season accelerates the corrosion again. These sites have the highest  $\text{SO}_2$  values, with a high TOW, with a moderate level of rainfall. This combination of factors, associated with a low level of initial corrosion, could lead to the loss of the protective corrosion products at the change of season, reactivating the surface.

**Table 4.-** Linear fit for the correlation between Corr dry vs Corr rainy for the first year  
( $\text{Corr (dry)} = a \text{ Corr (rainy)} + b$ )

Sites	a	b	R <sup>2</sup>
CNFL	1.500	-0.0856	0.8676
UCR	1.895	0.0571	0.9492
CASI	3.6143	-0.1318	0.9552

### 3.3. Volcanic activity and tropical storms

The volcanic activity during the studied period was low, being mainly from the Turrialba volcano in eruptive emissions between September and December 2018, April and September 2019 and March to July 2020. Part of these emissions were directed to the SJV in November and December 2018 and April to May 2020 but did not have a significant influence in the global values. There were also slight emissions from Poás volcano between November and December 2018, but the main direction was towards areas west of the SJV (OVSICORI, 2021).

Tropical storms ETA and IOTA affected indirectly the SJV during November 2020 (IMN, 2021; NOAA, 2021).

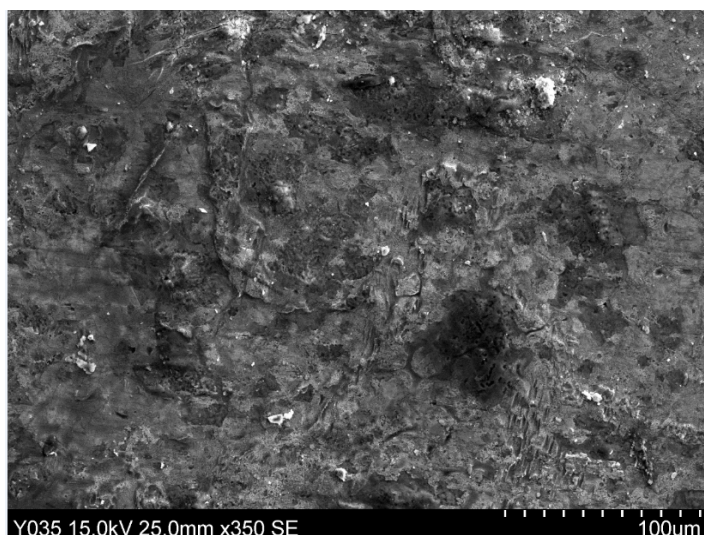
### 3.4. SEM and DRX

XRD study of the plates at one year showed no specific crystalline structures. This may be because the average pH of the rain is of the order of 6 to 5, at which many of the corrosion products are dissolved (Rodríguez-Yáñez & Chaves Villalobos, 2019; Herrera Murillo, Rodríguez, Rojas Marin, & Baez, 2012).

The expected corrosion products are ZnO (zincite), which eventually hydrates and forms hydroxides ( $\text{Zn(OH)}_2$ ) and  $\text{Zn}_5(\text{CO}_3)_2(\text{OH})_6$  (hydrozincite), established in small surface films with growth granules at points of dust or contaminant accumulation. Both products are soluble in slightly acidic media such as those present in the rain at the SJV (Almeida, Morcillo, & Rosales, 2000; de la Fuente, Castaño, & Morcillo, 2007; Leygraf & Wallinder, 2016).

SEM micrographs showed homogeneous corrosion but with an effect on the grain boundaries (see Figure 3).

315



316

317 **Figure 3.-** GS surface in SEM, UCR site, month 12, rainy series

318

319 **3.5. Data Models**

320 The models give the following values per site, per equation.

321

322 **3.5.2. Corr vs, time model (equation 1)**

323 Tables 5 and 6 show the correlations associated with equation 1 in the logarithmic form, for  
 324 the stations in the different seasons for two years data, where Log Corr are the actual values  
 325 obtained at each site associated with Log A.

326 **Table 5.-** Parameters of equation 1, in the rainy season

Site	Log A	n	R <sup>2</sup>	Log Corr
UCR	-0.6518	0.9609	0.9619	-0.7305
CASI	-0.6735	0.8604	0.8869	-0.8153
CNFL	-0.4454	0.4463	0.9152	-0.4855
<b>General</b>	-0.5902	0.7559	0.9213	

327

328 **Table 6.-** Parameters of equation 1, in the dry season.

Site	Log A	n	R <sup>2</sup>	Log Corr
UCR	-0.3821	0.6141	0.9201	-0.3487
CASI	-0.4546	1.2902	0.9475	-0.3354
CNFL	-0.4078	0.4550	0.8097	-0.3363
<b>General</b>	-0.4148	0.7864	0.8924	

329

All sites and all times show Pearson coefficients greater than 0.8, while the Log A values are different from Log Corr for one year at all sites and seasons.

Corrosion aggressiveness is linked to the inverse values of the constant n, which has site-dependent values. While at CNFL it is relatively independent of season, with values in the order of 0.45, at UCR and CASI their values are much higher (0.6 to 1.2) and dependent to the season. This difference is more important between stations when the corrosion starts in dry season. These values would indicate a partial protection for GS in CNFL, while for the UCR and CASI sites the protection would be minimal. This observation would be consistent with the fact that no protective corrosion products were found by XRD. The general equations by season are similar, so a simplified estimate of GS corrosion in the SJV could be generalized with the equation:

$$\text{Log Corr} = 0.7416 \text{ Log } t - 0.5214 \quad R^2 = 0.660 \quad (6)$$

The  $R^2$  value in the equation 6, falls because there are significant differences between sites for the Log A and constant n values. Therefore, such a generalization is inappropriate.

### 3.5.3. Lineal and logarithmic models (equation 2 and 4)

Pearson correlation coefficients for each parameter in relation to corrosion are calculated ( $p > 0.01$ ) for two years. The values, with all parameters, are showed in the Table 7, and have a good correlation (more than 0.8) where  $\text{SO}_2$  and P have the best correlations, followed in second order by TOW and  $\text{Cl}^-$ .

**Table 7.-** Pearson correlation coefficient between variables

	Corr ( $\mu\text{m}$ )	P ( $\text{mm m}^{-2}$ )	$\text{Cl}^-$ ( $\text{mg m}^{-2}$ )	TOW (h)	$\text{SO}_2$ ( $\text{mg m}^{-2}$ )
Corr	1	0.893	0.858	0.862	0.884
Rain		1	0.825	0.875	0.839
$\text{Cl}^-$			1	0.934	0.938
TOW				1	0.978
$\text{SO}_2$					1

Comparisons between sites (Kruskal Wallis,  $p > 0.05$ ) as well as the comparisons by season (U Mann Witney,  $p > 0.05$ ) show no significant differences for two years. However, the same study for one year (less 400 days), mark differences between sites, especially for CASI and CNFL.

Since there is no significant difference by season, the modelling is considered globally by site and in the SJV, with different number of variables for two years.

The best results for equation 2 and 3, in its lineal and logarithmic forms, are:



$$\text{Corr} = 3.873\text{E-}2 + 9.788\text{ E-}5 \text{ P} - 5.120\text{ E-}5 \text{ SO}_2 + 5.392\text{ E-}5 \text{ TOW} \quad (7)$$

$$R^2 = 0.8772 \quad \text{RSS} = 0.197 \quad F = 112.96$$

and

$$\text{Corr} = -0.8025 + 0.1471 \text{ Log SO}_2 + 0.1939 \text{ Log P} \quad (8)$$

$$R^2 = 0.6807 \quad \text{RSS} = 0.523 \quad F = 51.11$$

The most basic equations with minimum meteorological parameter are with TOW and P; expressed as a lineal regression (Restrepo , Botero , & Correa, 2007; Corvo, y otros, 2008; Vera , y otros, 2017)

$$\text{Corr} = 4.655\text{ E-}2 + 2.123\text{ E-}5 \text{ TOW} + 7.707\text{ E-}5 \text{ P} \quad (9)$$

$$R^2 = 0.8552 \quad \text{RSS} = 0.237 \quad F = 139.80$$

These equations show that the contribution of chloride (Cl<sup>-</sup>) is not significant, possibly due to its low values. While P and TOW are presented as the main variables, followed by SO<sub>2</sub>.

For the equation 4, the Table 8 presents the coefficients for the equations with different number of variables for the SJV.

**Table 8.-** The best correlation obtained for the SJV, in general for the equation 4

# variables	a	Log t n	P b	Cl <sup>-</sup> c	SO <sub>2</sub> d	TOW e	R <sup>2</sup>	F	RSS
5	-1.82	3.51E-01	1.72E-04	2.21E-04	-1.45E-04	6.69E-05	0.722	25.447	1.957
4	-1.99	4.70E-01	1.69E-04		-1.28E-04	8.20E-05	0.712	30.007	2.079
3	-2.14	5.66E-01	1.47E-04		-2.67E-05		0.691	36.050	2.280
2	-1.98	4.74E-01	1.16E-04				0.691	53.525	2.333
1	-2.42	7.42E-01					0.652	88.963	2.687

Equation 4 is a combination of Equation 1 and 2. It does not present a substantial improvement and increases the complexity, since it requires the measurement of more parameters, Additionally, the reduction of variables in the equation decreases the values of the Pearson coefficients, which are already lower than those of equations 2 and 3 or their simplified version (Garita, Rodríguez Yáñez, & Robles, 2014).

The main variable in this system is time, which already presented a high correlation in equation 2, This factor is followed by P in a similar way as analyzed for equations 2 and 3.

### 3.5.3. Model ISO (equation 5) and Measured values

The values of equation 5 of ISO 9223 (2012) always present values higher than the measured values obtained for the SJV (see Table 9). This may be associated with the tropical conditions

and low contamination levels in the SJV, which are a situation where the equation is not as adequate (Morcillo , Chico, de la Fuente, & Simancas, 2012; Garita, Rodríguez Yáñez, & Robles, 2014; Restrepo , Botero , & Correa, 2007; Vera , y otros, 2017).

**Table 9.-** Annual Vcorr values in ( $\mu\text{m y}^{-1}$ ) according to the ISO 9223 (eq, 5), and Measured value obtained in each site

Site	ISO 9223		Measure	
	<i>Rainy</i>	<i>Dry</i>	<i>Rainy</i>	<i>Dry</i>
UCR	1.0823	0.8784	0.186	0.448
CASI	1.6366	1.7402	0.153	0.462
CNFL	1.3649	1.3241	0.327	0.461

In low contaminated tropical atmospheres, such as that of the SJV, defined as rural or light urban by ISO 9223(2012), zinc (or GS) corrosion is mainly linked to environmental factors (Almeida, Morcillo, & Rosales, 2000). Of special attention in these cases are the wetting and drying cycles, as well as the averaged values of T, RH, TOW and the levels and intensity of rainfall (de la Fuente, Castaño, & Morcillo, 2007; Leygraf & Wallinder, 2016). Increasing T has a counteracting action, by increasing the reaction rate, but decreasing the effective evaporative wetting time, as well as the solubility of oxygen and other atmospheric gases. While the increase in RH (or TDH) increases the possibility of dew generation on the metal surface and with it the dissolution of the salts deposited on the surface. In contrast, rain generates a washing process of these salts, as well as some labile corrosion products, or the dragging of non-adherent ones, particularly in cases like this, where the pH is slightly acidic (Morcillo , Chico, de la Fuente, & Simancas, 2012; Del Angell, Vera, & Corvo, 2015; Odnewall Wallinder & Leygraf, 2017; Graedel, 1989; Feliu, Morcillo , & Feliu, 1993).

Of particular importance is the level of SO<sub>2</sub> contamination in any type of atmosphere since a direct correlation between these and corrosion rate in zinc is proposed. Whereas, for Cl<sup>-</sup>, the correlation is clearer in marine environments, from S1 levels according to ISO 9223 (2102) (Morcillo , Chico, de la Fuente, & Simancas, 2012). On the other hand, the particulate material deposited on the zinc surface favors oxidation by differential aeration, generating localized corrosion and/or accumulation points of oxidation products (de la Fuente, Castaño, & Morcillo, 2007). In this sense, the levels of PM in the SJV are low, so it is not considered as a parameter in the possible modelling (Herrera Murillo, Rodríguez , Rojas Marin, & Baez, 2012; Herrera, Rojas, Beita, & Chaves, 2014; Herrera-Murillo, Soto-Murillo, Rojas-Marin, Beita-Guerrero, & Hidalgo-Gutierrez, 2020; DIGECA - MINAE, 2013).

In this sense, the values obtained for equation (1) show moderate to high correlations with time and medium to high n values. This is associated with the specific corrosion process of the zinc surface by charge transfer, but without the formation of a stable protective film that decreases the corrosion rate. (Natesan , Venkatachari, & Palaniswamy, 2006; Morcillo, Almeida, Rosales, Uruchurtu, & Marrocos, 1998).

There are high correlations between atmospheric and pollution parameters with corrosion of zinc. From this the linear models based on equations 2 to 4 correlate well with the main meteorological parameters mentioned for mild urban atmospheres, such as TDH and rainfall,

as well as with SO<sub>2</sub>, secondarily. The simplification to meteorological parameters for the linear equations (equation 9) maintains good correlation levels, avoiding the need to evaluate pollution, especially SO<sub>2</sub> (Restrepo , Botero , & Correa, 2007; Santana, Santana, & González, 2003; Corvo, y otros, 2008; Mikhailov , Strekalov, & Panchenko, 2007; Yikun Cai, Yu Zhao, Xiaobing Ma, Kun Zhou, & Hao Wa, 2019; Castaño, Botero, & Peñaranda, 2007; Corvo, y otros, 1997; Mariaca , Genesca, Uruchurtu, & Salvador , 1999; Rosales, 1997).

The approximation equation proposed by ISO 9223 (2012) is not suitable for estimation in tropical and/or low pollution atmospheres. This situation has already been expressed by other authors for zinc, as well as for other materials (Garita, Rodríguez Yáñez, & Robles, 2014; Mikhailov , Tidblad, & Kucera, 2004; Chico, de la Fuente, Díaz, Simancas, & Morcillo, 2017; Yikun Cai, Yu Zhao, Xiaobing Ma, Kun Zhou, & Hao Wa, 2019; Morcillo, 2017).

## 4. Conclusions

The SJV's atmosphere is dominated by its warm monsoon climate with seasonal rainfall and high RH that generates high TOW values. From this it is classified as mild urban C2 level, according to ISO 9223 (2012).

Initial corrosion growth is site dependent and to some extent dependent on the time of onset, but over 2-year average periods the sites and times become equivalent for the whole SJV, with an estimated average corrosion level of  $0.4 \mu\text{m y}^{-1}$  (conservative).

The morphology of the attack is associated with a process of homogeneous surface zinc weathering, with some grain-edge damage, but no significant generation of corrosion products. This may be because they are mostly labile (soluble) in slightly acid rain (pH 6 to 5).

The models applicable to a global 2-year system show that the best approximation is of a linear polynomial type (equation 7), without the effect of chlorides due to their low level in the SJV. The simplification with meteorological parameters is based on P and TOW (equation 9), while for the one-year analysis the simplified evaluations with time according to equation 1 can be site- and epoch-specific (see table 8 and 9),

The corrosion estimation model proposed by ISO 9223 (2012) is not applicable for tropical climates such as the SJV.

Based on the above, materials that comply with the INTECO C405 standard could have a long life, but this will also depend on the construction systems used, volcanic activity (especially  $\text{SO}_2$  emissions), and the environmental effects of the site.

## Acknowledgements

Special thanks to the National Meteorological Institute and the Costa Rican Electricity Institute for providing the meteorological data of the Western Central Valley, The actual corrosion data was obtained from measuring sites located at facilities of the National Power and Light Company and the Ministry of Security, This study was funded by the National Council of University Presidents (CONARE) of Costa Rica, as part of a collaborative project among the State Distance University (UNED-VINVES-6-10-50), the University of Costa Rica (UCR-VI-805-B8-650 and 804-B9-264), the National High Technology Center (CeNAT-VI-269-2017), the National University (UNA- SIA: 0600-17), and the Costa Rica Institute of Technology (ITCR-VIE 1490-021).

Rodríguez-Yáñez acknowledges the support of the Innovation and Human Capital for Competitiveness Program (PINN) of the Ministry of Science, Technology and Telecommunications (MICITT) of Costa Rica.

## References

- Almeida, E., Morcillo, M., & Rosales, B. (2000). Atmospheric corrosion of zinc. Part 1: Rural and urban atmospheres. *British Corrosion Journal*, 35:4, 284-288. doi:<https://doi.org/10.1179/000705900101501353>
- Apuy, E. (2016). *Caracterización de la Industria Metal Mecánica en Costa Rica*. Retrieved from PROCOMER: <http://servicios.procomer.go.cr/aplicacion/civ/documentos/Caracterizacion%20de%20la%20industria%20metalmecanica%20costarricense.pdf>
- ASTM A90/A90M - 2021. (2021). *Standard Test Method for Weight [Mass] of Coating on Iron and Steel Articles with Zinc or Zinc-Alloy Coatings*. West Conshohocken, PA, USA: American Society for Testing and Materials, International.
- ASTM G1 - 03(2017)e1. (2017). *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. West Conshohocken, PA, USA: ASTM International. doi:10.1520/G0001-03R17E01
- ASTM G33 - 99(2020). (2020). *Standard Practice for Recording Data from Atmospheric Corrosion Tests of Metallic-Coated Steel Specimens*. West Conshohocken, PA, USA: ASTM International. doi:ASTM International
- ASTM G50-20. (2020). *Standard Practice for Conducting Atmospheric Corrosion Tests on Metals*. West Conshohocken, PA, 2020: ASTM International. doi:10.1520/G0050-20
- ASTM G92 - 20. (2020). *Standard Practice for Characterization of Atmospheric Test Sites*. West Conshohocken, PA, USA: ASTM International. doi:10.1520/G0092-20
- Castaño, J., Botero, C., & Peñaranda, S. (2007). Corrosión atmosférica del zinc en ambientes exteriores e interiores. *Revista de Metalurgia*, 43 (2) 133-145. doi:<https://doi.org/10.3989/revmetalm.2007.v43.i2.60>
- Chico, B., de la Fuente, D., Díaz, I., Simancas, J., & Morcillo, M. (2017). Annual atmospheric corrosion of carbon steel worldwide. an integration of ISOCORRAG, ICP/UNECE and MICAT Databases. *Materials*, 10(6):601. doi:<https://doi.org/10.3390/ma10060601>
- Corvo, F., Haces, C., Betancourt, N., Maldonado, L., Veleza, L., Echeverría, M., . . . de Rincón, A. (1997). Atmospheric corrosion in the Caribbean area,. *Corrosion Science*, 39, 823–833. doi: [https://doi.org/10.1016/S0010-938X\(96\)00138-2](https://doi.org/10.1016/S0010-938X(96)00138-2)

513 Corvo, F., Perez, T., Martin, Y., Reyes, J., Dzib, L., González-Sánchez, J., & Castañeda, A.  
 514 (2008). Time of wetness in tropical climate: Considerations on the estimation of  
 515 TOW according to ISO 9223 standard. *Corrosion Science*, 50 (1): 206-219.  
 516 doi:<https://doi.org/10.1016/j.corsci.2007.06.012>

517 de la Fuente, D., Castaño, J., & Morcillo, M. (2007). Long-term atmospheric corrosion of  
 518 zinc. *Corrosion Science*, 49 (3) 1420-1436,.  
 519 doi:<https://doi.org/10.1016/j.corsci.2006.08.003>

520 Del Angell, E., Vera, R., & Corvo, F. (2015). Atmospheric Corrosion of Galvanised Steel  
 521 in Different Environments in Chile and Mexico. *International Journal of*  
 522 *Electrochemical Sciencie*, 10, 7985-8004.

523 Díaz , V., Martínez-Luaces, V., & Guineo-Cobs, G. (2003). Corrosión atmosférica:  
 524 validación de modelos empleando técnicas estadísticas. *Revista Metalurgia*,  
 525 39(4):243-251. doi:<https://doi.org/10.3989/revmetalm.2003.v39.i4.335>

526 DIGECA - MINAE. (2013). *Informe de calidad de aire GAM 2012*. Retrieved from  
 527 DIGECA : <http://www.digeca.go.cr/informe-calidad-aire>

528 Estado de la Nación. (2014). *Vigecimo Informe del Estado de la Nación*. Retrieved from  
 529 Estado de la Nación: <http://www.estadonacion.or.cr/20/#inicio2>

530 Feliu, S., Morcillo , M., & Feliu, S. (1993). The prediction of atmospheric corrosion from  
 531 meteorological and pollution parameters, I Annual Corrosion. *Corrosion Science* 34  
 532 (3), 403-4014. doi:[https://doi.org/10.1016/0010-938X\(93\)90112-T](https://doi.org/10.1016/0010-938X(93)90112-T)

533 Garita, L., Rodríguez Yáñez, J., & Robles, J. (2014). Modelado de la Velocidad de  
 534 Corrosión de Acero de baja aleación en Costa Rica. *Revista Ingenieria*, (24), 2, 79-  
 535 90. doi:<https://doi.org/10.15517/RING.V24I2.14624>

536 González, P., Mos, D., Santana, F., Vaswani, J., Santana Rodríguez, J., & González  
 537 González, J. (2008). Modeling of the Atmospheric Corrosion of Copper in the  
 538 Province of Las Palmas. Studies Using Classic and Electrochemical Techniques.  
 539 *Portugaliae Electrochimica Acta*, (26): 125-145.25.  
 540 doi:<https://doi.org/10.4152/pea.200801125>

541 Graedel, T. (1989). Corrosion Mechanisms for Zinc Exposed to the Atmosphere. *Journal of*  
 542 *the Electrochemical Society* , 193 - 203.

543 Herrera Murillo, J., Rodríguez , S., Rojas Marin, J., & Baez, A. (2012). Relations Between  
 544 Bulk Precipitation, PM10 Composition and Meteorological Conditions in the  
 545 Metropolitan Area of Costa Rica. *The Open Journal of Atmospheric Sciences*, 6: 19-  
 546 32. doi:<http://dx.doi.org/10.2174/1874282301206010019>



- 547 Herrera, J., Rojas, J., Beita, V., & Chaves, M. (2014). Composición química de muestras de  
548 depositación total colectadas en el área metropolitana de Costa Rica en 2012.  
549 *Ciencias Ambientales*, (48) 30 - 38. doi:<https://doi.org/10.15359/rca.48-2.3>
- 550 Herrera-Murillo, J., Soto-Murillo, T., Rojas-Marin, J., Beita-Guerrero, V., & Hidalgo-  
551 Gutierrez, M. (2020). Water-Soluble Anions in PM10 Samples Collected in the  
552 Metropolitan Area of Costa Rica: Temporal and Spatial Variations. *Atmosphere*, 12,  
553 1264 . doi:<https://doi.org/10.3390/atmos12101264>
- 554 IMN. (2008). *Segunda Comunicación sobre Clima, variabilidad y cambio climático en*  
555 *Costa Rica*. San José, Costa Rica: MINAET, IMN, PNUD, CRRH.
- 556 IMN. (2021). *Instituto Meteorológico Nacional de Costa Rica*. Retrieved from Boletines  
557 meteorológicos: <https://www.imn.ac.cr/en/boletin-meteorologico> [Accesed 21th  
558 november 2021]
- 559 INEC. (2011). *Anuario Estadístico 2010*. San José, Costa Rica: Instituto Nacional de  
560 Estadística y Censos, Ministerio de Hacienda.
- 561 INTE C405-2021. (2021). *Productos planos de Acero recubiertos con zinc (galvanizados)*  
562 *o recubiertos con aleación hierro zinc (galvano recocido) mediante procesos de*  
563 *inmersión en caliente*. San José. Costa Rica: Instituto Costarricense de Normas  
564 Técnicas.
- 565 ISO 8407:2013. (2013). *Corrosion of Metals and Alloys - Removal of corrosion products*  
566 *from corrosion test specimens*. Ginebra, Suiza: ISO.
- 567 ISO 9223:2012. (2012). *Corrosion of Metals and Alloys - Corrosivity of Atmospheres -*  
568 *Classification*. Ginebra, Suiza: ISO.
- 569 ISO 9225. (1992). 6. *Corrosion of Metals and Alloys – Corrosivity of Atmospheres –*  
570 *Measurement of pollution*. Ginebra, Suiza: ISO.
- 571 Leygraf, C., & Wallinder, I. (2016). The Atmospheric Corrosion Chemistry of Zinc -  
572 Appendix J. In J. Tidblad, & T. Graedel, *Atmospheric Corrosion, Second Edition*.  
573 (pp. 348 - 359). Hoboken, NJ. USA: John Wiley & Sons, Inc. Published.
- 574 Mariaca , L., Genesca, J., Uruchurtu, J., & Salvador , L. (1999). *Corrosividad Atmosferica*  
575 *(MICAT - Mexico)*. Mexico, Mexico: Plaza y Valdez.
- 576 Mikhailov , A., Strekalov, P., & Panchenko, Y. (2007). Atmospheric Corrosion in Tropical  
577 and Subtropical Climate Zones: 3. Modeling Corrosion and Dose–Response  
578 Function for Structural Metals. *Protection of Metals*, 43(7):619–627.  
579 doi:<https://doi.org/10.1134/S0033173207070028>

- 580 Mikhailov , A., Tidblad, J., & Kucera, V. (2004). The Classification System of ISO 9223  
581 Standard and the Dose–Response Functions Assessing the Corrosivity of Outdoor  
582 Atmospheres. *Protection of Metals*, (40):541-550.  
583 doi:doi.org/10.1023/B:PROM.0000049517.14101.68
- 584 Miller, J., & Miller, J. (2002). *Estadística y Quimiometría para química analítica*. Madrid,  
585 España: Pearson.
- 586 Morcillo , M., Chico, B., de la Fuente, D., & Simancas, J. (2012). Looking Back on  
587 Contributions in the Field of Atmospheric Corrosion Offered by the MICAT Ibero-  
588 American Testing Network. (Hindawi Publishing Corporation, Ed.) *International*  
589 *Journal of Corrosion*, Volume 2012, Article ID 824365, 1-24.  
590 doi:doi:10.1155/2012/824365
- 591 Morcillo, M. (2017). *Fundamental and research frontier of atmospheric corrosion*. Madrid,  
592 Spain: Materials. doi:https://doi.org/10.3390/books978-3-03842-642-4
- 593 Morcillo, M., Almeida, E., Fragata, F., & Panossian, Z. (2002). *Corrosión y Protección de*  
594 *Metales en las Atmósferas de Iberoamérica, Parte II: Protección Anticorrosiva de*  
595 *MEtales en las Atmósferas de Iberoamérica (PATINA)*. Madrid, España: Programa  
596 CYTED, CSIC.
- 597 Morcillo, M., Almeida, E., Rosales, B., Uruchurtu, J., & Marrocos, M. (1998). *Corrosion y*  
598 *Proteccion de Metales en las Atmósferas de Iberoamerica, Parte I: Mapas*  
599 *Iberoamericanos de Corrosion Atmosferica (MICAT)*. Madrid, España: Programa  
600 CYTED.
- 601 Muñoz, A. C., Fernández, W., Gutiérrez, J. A., & Zárate, E. (2002). Variación estacional  
602 del viento en Costa Rica y su relacion con los regímenes de lluvia. *Tópicos*  
603 *meteorológicos y oceanográficos*, 9 (1), 1 - 13.
- 604 NACE International Impact. (2016). *International measures of prevention, application and*  
605 *economic of corrosion technology study* . Houston, TX, USA: NACE International.
- 606 Natesan , M., Venkatachari, G., & Palaniswamy, N. (2006). Kinetics of atmospheric  
607 corrosion of mild steel, zinc, galvanized iron and aluminium at 10 exposure stations  
608 in India. *Corrosion Science*, 48, 3584–3608.  
609 doi:https://doi.org/10.1016/j.corsci.2006.02.006
- 610 Neurohr, E., Monge-Nagera, J., & González, M. (2011). Air pollution in tropical city. The  
611 relationship between wind direction and lichen bio indicators in San José, Costa  
612 Rica. *Biologia Tropical*, (59) 899 - 905.  
613 doi:https://www.doi.org/10.15517/RBT.V0I0.3148

- 614 Neurohr, E., Monge-Najera, J., & Mendez Estrada, V. (2013). Use of geographic  
615 informatioin system and lichens to map air pollution in tropical city, San José, Costa  
616 Rica. *Biologia Tropical*, 61 (2), 557- 563.  
617 doi:<https://www.doi.org/10.15517/RBT.V61I2.11148>
- 618 NOAA. (2021). *Atlantic Hurricane Season*. Retrieved from National Hurricane Center and  
619 Central Pacific Hurriacan Center:  
620 <https://www.nhc.noaa.gov/data/tcr/index.php?season=2020&basin=atl>
- 621 Odnewall Wallinder, I., & Leygraf, C. (2017). A Critical Review on Corrosion and Runoff  
622 from Zinc and Zinc-Based Alloys in Atmospheric Environments. *Corrosion*, 73 (9)  
623 1060-1077. doi:<https://www.doi.org/10.5006/2458>
- 624 OVSICORI. (2021). *Boletin semanal Vulcanologia*. Retrieved from Observatorio  
625 Vulcanologico y Sismologico de Costa Rica:  
626 [http://www.ovsicori.una.ac.cr/index.php/vulcanologia/informes-y-boletines/boletin-](http://www.ovsicori.una.ac.cr/index.php/vulcanologia/informes-y-boletines/boletin-semanal-vigilancia-volcanica)  
627 [semanal-vigilancia-volcanica](http://www.ovsicori.una.ac.cr/index.php/vulcanologia/informes-y-boletines/boletin-semanal-vigilancia-volcanica)
- 628 Passam AG. (2016). *Productos*. Retrieved from Passam AG:  
629 <http://www.passam.ch/products.htm>
- 630 PRUGAM. (2009). *Planificación Regional Urbana del Gran Área Metropolitana,*  
631 *Ministerio de Vivienda y Asentamientos Humanos, San José, Costa Rica*. Retrieved  
632 from Ministerio de Vivienda y Asentamientos Humanos:  
633 <http://www.mivah.go.cr/PRUGAM.shtml>
- 634 Restrepo , A., Botero , C., & Correa, E. (2007). Corrosión del acero al carbono, acero  
635 galvanizado y aluminio en diferentes atmósferas colombianas. *Scientia et Technica*,  
636 (36):7-12. doi:<https://doi.org/10.22517/23447214.4857>
- 637 Ríos-Rojas, J., Aperador-Rodríguez , D., Hernández-García, E., & Arroyave, C. (2017).  
638 Annual atmospheric corrosion rate and dose-response function for carbon steel in  
639 Bogotá. *Atmósfera*, (30):53-61. doi:<https://doi.org/10.20937/atm.2017.30.01.05>
- 640 Roberge, P., Klassen, R., & Haberecht, P. (2002). Atmospheric corrosivity modeling-A  
641 review. *Materials and Design*, (23):321-330. doi:[https://doi.org/10.1016/S0261-](https://doi.org/10.1016/S0261-3069(01)00051-6)  
642 [3069\(01\)00051-6](https://doi.org/10.1016/S0261-3069(01)00051-6)
- 643 Robles, J. (2013). *Evaluacion de la Corrosion Atmosferica en Tres Zonas Geograficas de*  
644 *Costa Rica por Medio de Tecnicas Electroquimicas y Gravimetricas*. Heredia,  
645 Costa Rica: Tesis de Grado para Licenciatura en Quimica Industrial, Universidad  
646 Nacional.

- 647 Rodríguez Yáñez, J., Garita, L., & Saborío, E. (2015). Mapas estimativos de la corrosión  
648 atmosférica de acero de baja aleación en Costa Rica. *Cuadernos de Investigación,*  
649 *UNED, Costa Rica.*, 7 (2): 181-191. doi:<https://doi.org/10.22458/urj.v7i2.1144>
- 650 Rodríguez-Yáñez, J., & Chaves Villalobos, M. (2019). Análisis de deposición total en la  
651 zona protectora de los cerros de Escazú en Costa Rica. *Yulök*, 3(1), 28-37.  
652 doi:<https://doi.org/10.47633/yulk.v3i1>
- 653 Rosales, B. (1997). *Mapa de Corrosividad Atmosférica de Argentina*. Buenos Aires,  
654 Argentina: CITEFA.
- 655 Santana, J., Santana, F., & González, F. (2003). The effect of environmental and  
656 meteorological variables on atmospheric corrosion of carbon steel, copper, zinc and  
657 aluminium in a limited geographic zone with different types of environment.  
658 *Corrosion Science*, 45(4):799-815. doi:[https://doi.org/10.1016/S0010-](https://doi.org/10.1016/S0010-938X(02)00081-1)  
659 [938X\(02\)00081-1](https://doi.org/10.1016/S0010-938X(02)00081-1)
- 660 Solano, J., & Villalobos, R. (2000). *Regiones y Subregiones Climáticas de Costa Rica*. San  
661 Jose, Costa Rica: Instituto Meteorológico Nacional.
- 662 Vera , R., Troconi de Rincón, O., Bagnara , M., Romero, N., Araya, R., & Ossandón, S.  
663 (2017). Tropical/non-tropical marine environments impact on the behaviour of  
664 carbon steel and galvanised steel. *Materials Corrosion*, (69):614-625.  
665 doi:<https://doi.org/10.1002/maco.201709873>
- 666 Wilks, D. (2011). *Statistical Methods in the Atmospheric Sciences*. New York, USA:  
667 Academic Press.
- 668 Yikun Cai, Yu Zhao, Xiaobing Ma, Kun Zhou, & Hao Wa. (2019). Application of  
669 hierarchical linear modelling to corrosion prediction in different atmospheric  
670 environments,. *Corrosion Engineering, Science and Technology*, 54(3):266-275.,  
671 doi:<https://doi.org/10.1080/1478422X.2019.1578067>

672