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Authors: Camila Aldereguía-Sánchez, Ingrid Fernández-Lorenzo, Katia Luis-García, Javier Ballote-Álvarez and Vivian Beatriz Elena-Parnás

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Methodology for obtaining a new map of basic wind speeds
Metodología para la obtención de un nuevo mapa de velocidades básicas del viento

Camila Aldereguía Sánchez[1] https://orcid.org/0000-0002-8102-5300, **Ingrid Fernández Lorenzo** [1] https://orcid.org/0000-0002-1223-0968, **Katia Luis García**[1*] https://orcid.org/0000-0003-1861-6017, **Javier Ballote Álvarez**[1] https://orcid.irg/0000-0003-3824-6009, **Vivian Beatriz Elena Parnás**[1] https://orcid.org/0000-0001-7912-7570

[1]Facultad de Ingeniería, Universidad Tecnológica de la Havana, José Antonio Echeverría CUJAE. Calle 114 entre Ciclovía y Rotonda. C. P. 19390, Cuba. Marianao, La Habana, Cuba.

***Corresponding author:** Katia Luis García
email: katialuisg@gmail.com

KEYWORDS: Exposure Correction; Extreme Winds; Method of Independent Storms; Teledetection.

PALABRAS CLAVES: Corrección por Exposición; Método de Tormentas Independientes; Teledetección; Vientos Extremos.

ABSTRACT: Within the methods for obtaining extreme wind speeds for the development of structures, conditioning techniques have emerged, such as the differentiation of winds according to their generating mechanisms. This has proven to be effective in places with mixed climates, such as Cuba. Another way to reduce the uncertainties in calculating the wind load is by verifying the conditions of the meteorological stations and their speed records. The World Meteorological Organization establishes specific criteria to guarantee that the records of a station are reliable, among which are the characteristics of the surrounding terrain. The present work contributes to the improvement of the current Cuban wind standard where these techniques were not considered, and aims to obtain a new wind speed map that applies the method of independent storms. In addition, the wind speed values were corrected from the terrain roughness data of the stations studied by using two methods. The results showed concordance between both methods of obtaining the roughness of the terrain and differences with the values of wind speeds of the current Cuban standard.

RESUMEN: Dentro de los métodos en la obtención de velocidades extremas de viento para el cálculo de estructuras han surgido técnicas de acondicionamiento tales como la diferenciación de los vientos según los mecanismos generadores de estos, la cual ha demostrado ser efectiva en lugares con climas mixtos como Cuba. Otra vía para disminuir las incertidumbres que existen en el cálculo de la carga de viento es la verificación de las condiciones de las estaciones meteorológicas y sus registros de velocidades. La organización mundial de meteorología establece ciertos criterios para garantizar que los registros de una estación sean fiables, entre los que se encuentra las características del terreno que rodea a la misma. El presente trabajo contribuye al perfeccionamiento de la norma cubana de viento vigente donde no se tuvieron en cuenta estas técnicas y tiene como objetivo obtener un nuevo mapa de velocidades de viento aplicando el método de tormentas independientes. Además, se corrigieron los valores de velocidad de viento a partir de los datos de rugosidad del terreno de las estaciones estudiadas aplicando dos métodos. Los resultados mostraron concordancia entre ambos métodos de obtención de las rugosidades del terreno y diferencias con los valores de velocidades de viento de la norma cubana actual.

1. Introduction

The speed related to the geographical location of a structure and used in its design is known as basic design speed. There are two main methods for probabilistic obtaining these speeds: the maximum series and the exceedance series [1]. A significant drawback of using the series of maximums is the loss of secondary events in a year that can present even higher velocities than the maximums of other years that were considered. It is also added that in climates where the maximum wind values come from more than one type of atmospheric phenomenon, wind data must be partitioned according to the type of meteorological mechanism that originates them. It is widely accepted that extreme wind speeds are modeled by the Gumbel probability density function (Type I) [2]. However, the current Cuban standard for wind actions on structures [3] used the Frechet distribution to obtain the basic pressures, which may give rise to incorrect results.

In addition to variations in the extreme event analysis methods, some alternatives for conditioning the series are recognized. The generation of synthetic values is one of the most recent. Based on a hurricane simulation model, Vickery [4] developed wind speed maps for return periods of 50, 100, 700, and 1700 years for the Caribbean area, which included Cuba. The model was validated by comparing the results obtained in the simulation and historical records in the area, which allowed him to conclude that the simulation showed excellent approximations of the actual wind behavior in the region. In previous works of analysis of extremes on Cuban stations from existing records [5, 6] the Method of Independent Storms (MIS) [7] was applied with differentiation in the origins of the extremes. Values of basic speeds were obtained for a return period of 50 years in adequate correspondence with the studies of Vickery [4]. In some stations, while in others, it was possible to detect that the quality and quantity of recorded hurricane wind data were not sufficient to allow for the development of an adequate analysis through the MIS [6]. More advanced methods have been developed [2, 8]; however, considering the limited number of acquired data, their use may provide distorted results or be endowed with a false level of accuracy [9]. Another problem detected in the stations consisted of non-compliance with the requirements established by the World Meteorological Organization [10] regarding the characteristics of the surrounding terrain, mainly. In most cases observed in Cuba, the ideal ground conditions are not satisfactory; consequently, it is necessary to make corrections for exposure [11], which fundamentally depend on the determination of the roughness length (z_0). There are various methods for determining this parameter, and the selection of either one or the other is based on the availability of data, simplicity of use, and precision of the needed results. Among the most used are the morphometric method [12, 13] and the classifications method [14, 15], which use techniques such as remote sensing and geographic information systems for the characterization of the surface, which, in addition to constituting the most up-to-date technology, allows carrying out both methods with better accuracy and ease, which is why it was selected for this work.

Considering the data obtained from the Cuba meteorological stations, this work aims to propose a methodology based on the Independent Storms Method to obtain the basic velocities that will serve as the basis for establishing a new map for the calculation of structures in Cuba.

2. Materials and methods

2.1. Description of weather stations and the extreme wind method

As a starting point for the investigation and based on the definition of the MIS as a method of analysis of extreme winds, the reference database was established based on the characterization and selection of the surface weather stations to be used in the study to guarantee the representativeness, reliability, and homogeneity of the data as recommended [9]. The primary data was provided by the Cuban Institute of Meteorology. The analysis period consisted of 20 years, and the recorded speeds corresponded to the averages in 10 minutes, stored every three hours in 16 meteorological stations.

After the creation of the database, the events were separated according to the types of meteorological mechanisms (hurricanes, cold fronts, and other events (local storms. or other unidentified ones that exceed the set threshold); the threshold value was set at the average speed of 35 km/h in 10 min and a time gap of four days was established between the events considered to guarantee statistical independence between the selected values. The data from each event separately were adjusted to a Gumbel distribution using the Least Squares Method. The procedure to establish each of these parameters is detailed in previous works [6].

Considering the events identified, hurricanes have the strongest wind records in Cuba. Still, at the same time, they are the least frequent to register in the stations, making the quality of the processing difficult. During the analysis of the particular data, it was possible to detect that in some stations, there was not enough data Table 1 (3, 4, 5 events). For these stations, an inverse analysis was decided based on the maps of wind speeds [4].

Table 1 Number of processed events per origin and station.

Station	Hurricane related events	Station	Hurricane related events
Cabo de San Antonio	13	Caibarién	5
Paso Real de San Diego	8	Sancti Spíritus	4
Güira de Melena	6	Camagüey	3
Punta del Este	8	Puerto Padre	5
Melena del Sur	9	Cabo Cruz	12
Casa Blanca	13	Punta Lucrecia	5
Playa Girón	10	Santiago de Cuba	13
Cienfuegos	4	Maisí	7

The process consisted of adjusting the values extracted from the hurricane wind maps to a Gumbel-type distribution (the same to which the other winds from other sources are adjusted in order to apply the MIS method) and then combining with the distributions of the winds from other source origins of each station [16]. Studies prior to this article compared three methods: Generalized Extreme Values (GEV), Peaks over the threshold (POT), and the Method of Independent Storm (MIS) in several meteorological stations [6]. In the case of the GEV, the values showed, according to the value of the form factor, an adjustment to a Frechet distribution. For high return periods, the basic pressure values showed a pronounced growth; in addition, in some stations, basic pressure values greater than any recorded meteorological event were obtained. This behavior is evidence that the Frechet distribution does not offer, for Cuba, an adequate adjustment model for high return periods. For the analysis, records of 20 years were used, which limits the application of methods that work with annual maximums, such as the GEV. If there had been a greater data record, perhaps the results would be different. Furthermore, in international research, it has been shown that adjusting to a Type II or Frechet distribution leads to making errors in the calculation of the basic pressure since it indicates that the data come from a mixed climate, which is why methods have emerged in which recent years that pre-condition the adjustment to a Type I or Gumbel distribution and the separation of events according to the extreme generating mechanism is recommended, which is not possible if the GEV is used.

The Gumbel distribution is based on two parameters (dispersion and scale), which were obtained using the classical Least Square methodology. In the literature review, it was found that using the wind speed squared instead of the wind speed provides better accuracy of the method because it makes the distribution converge rapidly to a Type I distribution. Therefore, the data are first squared so that values of $q = V^2$ are used rather than values of V, following the Cook approach [7]. The square of the velocity from the extreme sample was plotted in the y-axis against the plotting position that makes the Gumbel distribution linear, then the data was fit, and the slope and intercept corresponded to the dispersion and scale parameters, respectively. The theoretical probability used for obtaining the plotting position was the one provided by Gringorten. Once the parameters of the Gumbel distribution were obtained, they were used to obtain the velocity for different return periods by the cumulative distribution of Gumbel, considering that the return period is the non-exceedance probability. For this, the zones on the Vickery map where the stations were located were first identified, and the speed values corresponding to their location for two return periods were taken in order to have two equations and to be able to solve the two unknown characteristic parameters of the Gumbel distribution. To obtain the speeds from the Vickery map, the speeds were converted from mph to m/s and transformed from an averaging interval of 3 s to 10 min, allowing for the location characteristics of the stations involved. For this, Equation (1) [17] was used, and the gust factor that allows converting between averaging intervals was determined.

$$G = 1 + \frac{I}{2}\ln\left(T/t\right) \tag{1}$$

In Equation (1), I is the turbulence intensity (Equation 2), T is the average wind speed period (10 min), and t is the gust duration period (3 s).

$$I = \frac{1}{ln\left(\frac{z_s}{z_0}\right)} \tag{2}$$

Where z_s is the height of the anemometers, 10 meters for both stations, and z_0 is the roughness length. The z_0 considered are obtained from the roughness analyses of each station that were carried out. Parameter determination is one of the most difficult aspects of the process. Therefore, two methods were used, to establish comparisons between the results. The methods were Classifications, specifically, the classifications determined by Davenport [18] with the addition of two new classes, updated by Wieringa [19], and the Morphometric method from the calculation of the Normalized Difference Vegetation Index (NDVI).

After the separate analysis of each event in the stations, the distributions of independent events obtained were combined to obtain the basic speeds for the different return periods using Equation 3.

$$1 - \frac{1}{R} = exp\left\{-exp\left[-U - \left(\frac{u_i}{a_i}\right)\right]\right\} \ldots \cdot exp\left\{-exp\left[-U - \left(\frac{u_n}{a_n}\right)\right]\right\} \tag{3}$$

Where R corresponds to the return period analyzed, U is the basic speed squared, u and a are the parameters of the Gumbel distribution, *n* is the quantity of identified mechanism in each station that formed an independent distribution.

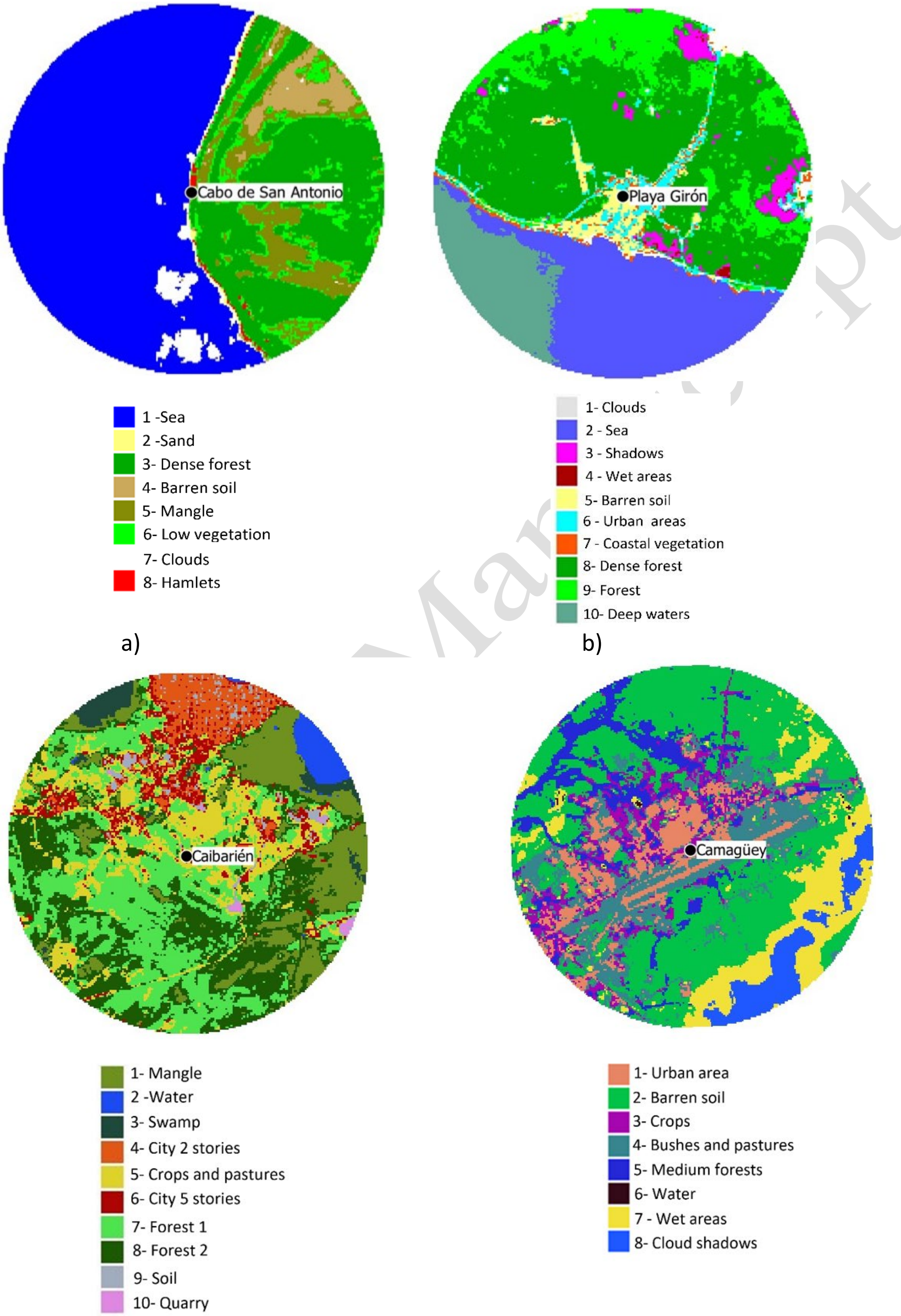
2.2 Roughness correction of the estimated wind speed values

To eliminate the effect of the roughness of the terrain on the speeds recorded at each station, the correction factor (ECF) was established based on Equation (4) [10, 14]:

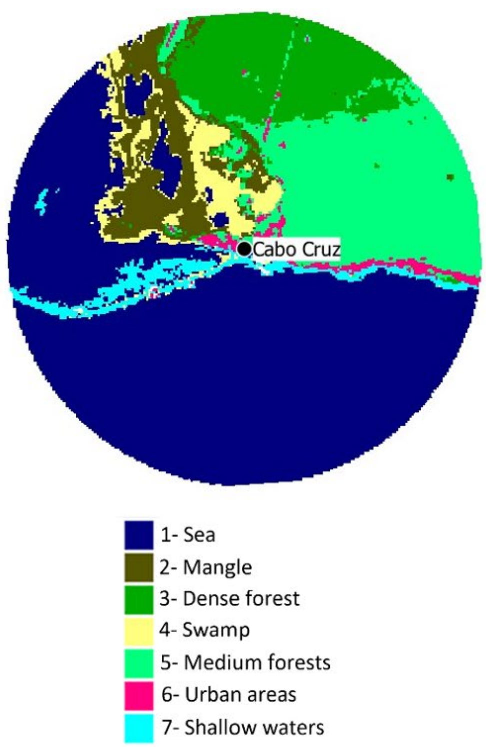
$$ECF = \frac{U_p}{U_s} = \frac{\ln\left({}^{z_b}/_{z_0}\right)\ln\left({}^{z_r}/_{z_{0r}}\right)}{\ln\left({}^{z_s}/_{z_0}\right)\ln\left({}^{z_b}/_{z_{0r}}\right)} \tag{4}$$

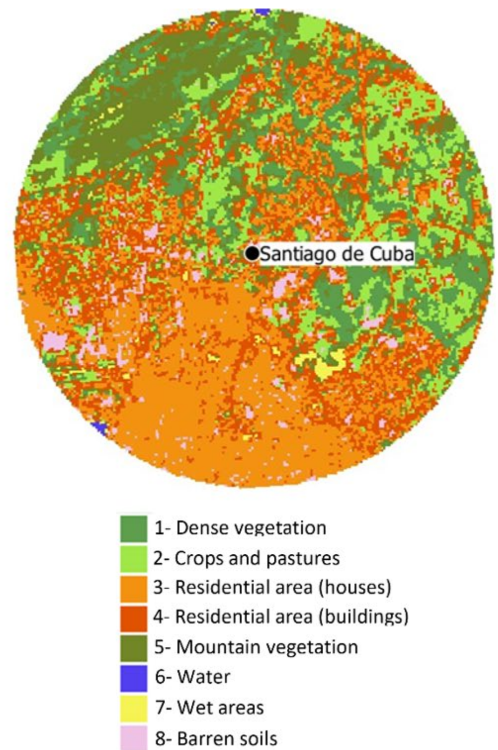
Where z_b is the mixing height, 60 m for maximum roughness element heights between 20 and 30 meters, z_s anemometer height, z_r reference height, 10 m, z_{0r} reference roughness length equal to 3 cm for ground stations, and z0 roughness length of the station [10].

An area of 3 km around each station was analyzed. For the determination of roughness, images corresponding to the OLI/TIRS sensor of the Landsat 8 satellite were used and taken in 2018 and 2020. The official site of the United States Geological Service (www.earthexplorer.usdh.gov) offers images with different correction levels; in this case, those from collection 2, level 1 (C2L1) were selected because it already contains radiometric and geometric corrections, so it was only necessary the atmospheric correction. The image processing was carried out through the Semi-Automatic Classification Plugin (SCP) of the QGIS v3.10 software. Supervised classification was performed in each of the study areas based on prior analysis of false-color compositions and high-resolution images from Google Earth. To show the results in this work, representative stations of each of the regions into which the island is divided were selected to form a new map of basic speeds. The division by zones was based on similarities in terms of values of extreme speeds obtained from the processing. Figure 1 shows the analysis of these aforementioned stations.


Cabo de San Antonio
1 -Sea
2 -Sand
3- Dense forest
4- Barren soil
5- Mangle
6- Low vegetation
7- Clouds
8- Hamlets
a)
Playa Girón
1- Clouds
2 - Sea
3 - Shadows
4 - Wet areas
5- Barren soil
6 - Urban areas
7 - Coastal vegetation
8- Dense forest
9- Forest
10- Deep waters
b)
Caibarién
1- Mangle
2 -Water
3- Swamp
4- City 2 stories
5- Crops and pastures
6- City 5 stories
7- Forest 1
8- Forest 2
9- Soil
10- Quarry
Camagüey
1- Urban area
2- Barren soil
3- Crops
4- Bushes and pastures
5- Medium forests
6- Water
7 - Wet areas
8- Cloud shadows

c) d)





e) f)

Figure 1 Supervised classification a) Cabo de San Antonio, b) Playa Girón, c) Caibarién, d) Camagüey, e) Cabo Cruz, f) Santiago de Cuba.

For the Classification method, the data on the type of land cover were obtained, and from the supervised classification, the z_o values were assigned to each class as appropriate.

To determine the representative roughness length of the station area, the drag coefficients Cd were obtained for each classification, based on Equation (5):

$$C_d(z_r) = [0.41/\ln(z_r/z_0)]^2 \quad (5)$$

Where Cd is the drag coefficient, z_o is the roughness length (of each individual classification), and z_r is the reference height (10 m). Subsequently, the values of the individual drag coefficients were averaged using Equation (6):

$$C_{d\,prom} = \frac{\sum(C_{di} \cdot A_i)}{\sum A_i} \quad (6)$$

C_{di} is the drag coefficient obtained for each sector and A_i is the area of each sector.

Classes with an area less than 1% of the total area analyzed were neglected. With $C_{d\,prom}$ the representative $z_o$value of the station was obtained, solving Equation (5).

In the case of analysis by the NDVI method, the image corresponding to the value of this index in each pixel was obtained from the combination of the red and near-infrared spectral bands. To obtain the relationship between the value of z_o and the NDVI index, expressions have been developed, such as the one used in this work, Equation (7) [20]:

$$z_o = \exp(\, a + b \cdot NDVI) \tag{7}$$

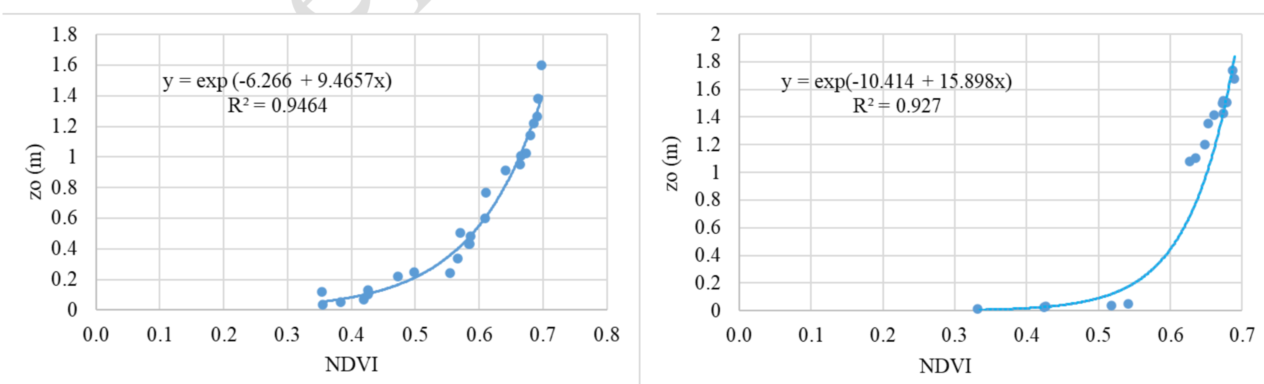
Parameters a and b are coefficients that depend on the type of vegetation in the study area and are obtained mathematically by fitting the curve produced between the ratios of the z_o observed at certain control points taken from the local vegetation against their values. of NDVI obtained by remote sensing. The observed roughness length was determined from the Simple Rule Method (Equation 8):

$$z_o = f_o \cdot Z_H \tag{8}$$

Z_H is the average height of the roughness elements, in this case, the average height of the surrounding vegetation, and $f_o = 0.13$ for crops and grasslands and $f_o = 0.06$ for forests, empirical coefficients are recommended [21].

It was verified that the R2 parameter was greater than 60% at each station, which guarantees a good fit [20]. Figure 2 shows the fit curves that allow z_o, to be obtained in vegetation zones, from the same stations as Figure 1, where x is the mean value of the NDVI image.

One of the main disadvantages of the NDVI-based morphometric method lies in its exclusive application in vegetation areas, therefore, in areas close to the stations where bodies of water and urban areas were identified. Therefore, it was necessary to exclude these classes from the image of NDVI to prevent them from influencing its mean value. A hybrid methodology was used to apply it in the stations located on the coastline. First, the water area was subtracted from the 3km ratio analyzed, the remaining (green area) was studied using the NDVI method, and a roughness length for vegetation was calculated. In the case of the water area, a $z_o$value from the Wieringa classification table was assigned. Finally, a hybrid methodology was used to obtain an effective roughness in the surrounding area for the analyzed station, considering the surface area for each class [22].



a) b)

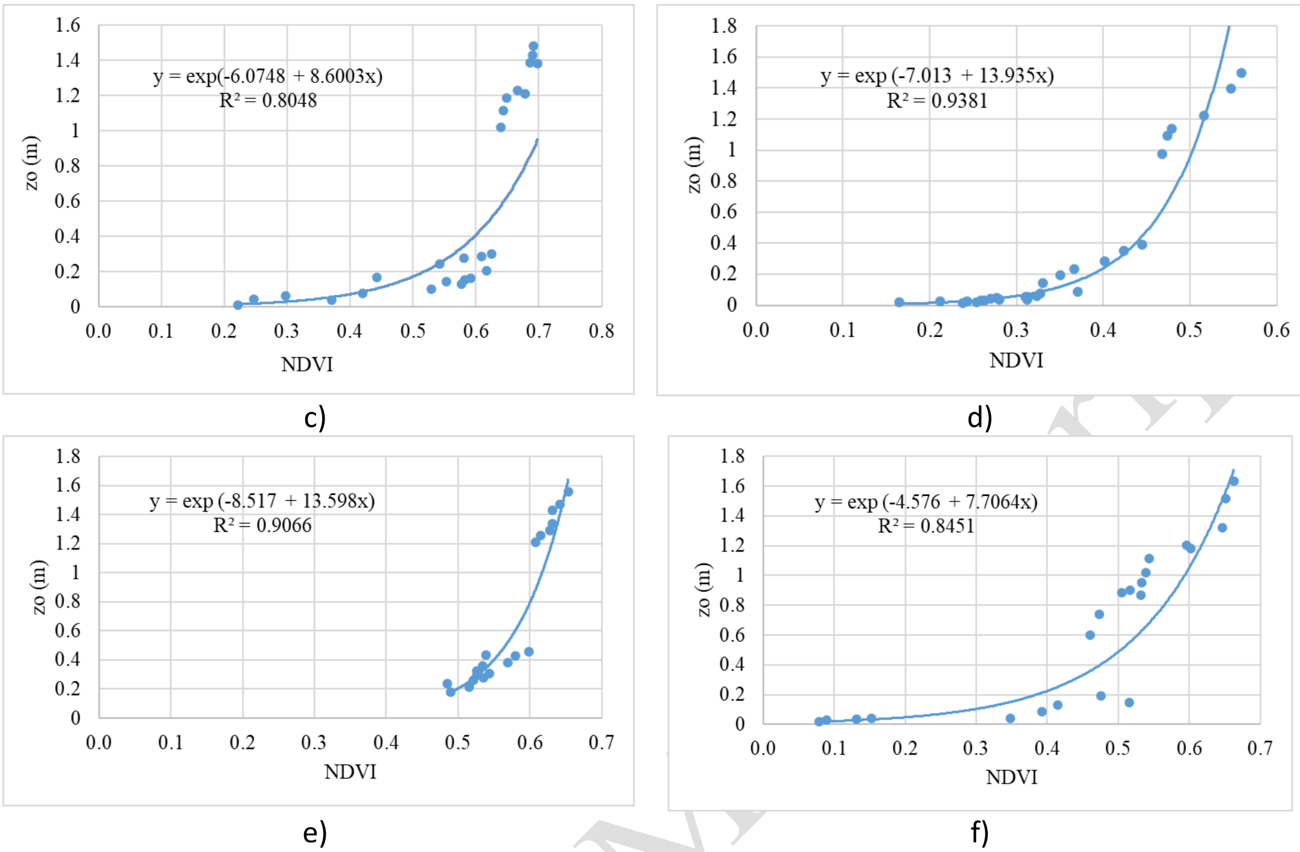


Figure 2 Exponential curve of z_0 (determined by the Simple Rule Method) vs. NDVI, a) Cabo de San Antonio, b) Playa Girón, c) Caibarién, d) Camagüey, e) Cabo Cruz, f) Santiago de Cuba

3. Experimental results and analysis

The analysis shown is carried out for the same stations in Figure 2. The results that stand out in the analysis are the roughness length values of those stations (z_o), speed correction factors (ECF) derived from the z_0, as well as the speeds obtained by the MIS, with the procedure described in the previous section, both uncorrected and corrected, for a return period of 50 years.

All the stations analyzed after carrying out the processing to determine the roughness turned out to have z_0 greater than 3 cm; thus, this requirement was not met, and it was necessary to correct the speed values obtained. Table 2 shows the z_0 obtained for each station by both described methods, as well as the correction factor derived from them.

Table 2 Values of z_o and ECF obtained for each station.

Stations	Classifications Method		Morphometric Method (NDVI)	
	z_0	ECF	z_0	ECF
Cabo de San Antonio	0.217	1.122	0.216	1.121
Playa Girón	0.416	1.195	0.425	1.198
Caibarién	0.330	1.166	0.355	1.174
Camagüey	0.064	1.035	0.067	1.038

Cabo Cruz	0.178	1.104	0.186	1.108
Santiago de Cuba	0.607	1.253	0.593	1.249

As shown in Table 2, the correlation of the values of roughness length, z_o is good by both methods, and even slight differences do not have a major impact on the values of the ECF correction factor. The application of two methods validates the value of the roughness length obtained since it is a very influential factor in correctly estimating the final basic wind speed. Of these stations, only the one in Camagüey, which is close to an airport, presents favorable roughness conditions for wind measurement without almost having to apply a correction; that is why the ECF value is practically 1, as the data shows.

Figure 3 shows the comparative results of the basic speeds obtained without correcting and corrected with the factors given in Table 2. The corrections for exposure increased the speed values because the roughness around the stations is higher than that indicated by the World Meteorological Organization (WMO), which confirms the influence of roughness on wind speeds and the importance of their consideration to determine basic speeds from data from weather stations with non-ideal surrounding terrain.

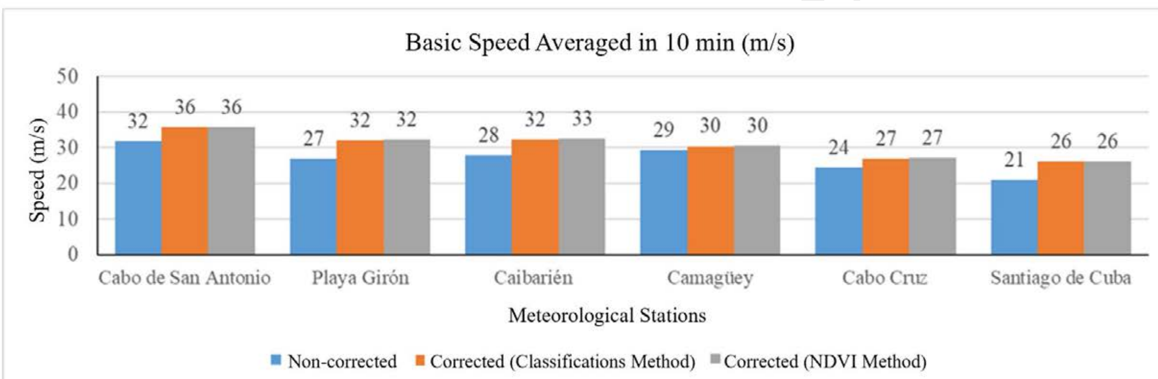


Figure 3 Comparative graph of basic speeds averaged in 10 min.

These values, when compared with those of the current Cuban standard [3] for a return period of 50 years, show that the established basic pressure value of Zone I (where the stations of Cabo de San Antonio, Playa Girón, and Caibarién) is 1.3 kN/m^2, which responds to an approximate basic speed of 45m/s, and that is more than 20% higher than the value of the largest station in this group, which is Cabo de San Antonio. For Zone II (where Camagüey would be), the basic pressure of the standard is 1.1 kN/m^2, for an approximate basic speed of 38 m/s, which is 21% higher than the one calculated in this investigation. Furthermore, for the eastern region (Cabo Cruz and Santiago de Cuba stations), the basic pressure is 0.9 kN/m^2 (approximate speed of 31 m/s), 13% higher than the values of the stations considered for the present investigation.

The values of the basic speeds calculated using the methodology proposed in this research concur with those obtained by Vickery [4]. For example, the Cabo de San Antonio station, according to the Vickery map, is in an area that corresponds to a value of 37 m/s (averaged in 10 min) equivalent to 120 mph (averaged in 3 s) on the map of 50-year return period in Figure 1. The difference between the value proposed by Vickery and the one calculated in this paper is less than 3%.

Based on the proposed methodology, a new map of basic wind speeds for Cuba was proposed, which is shown in Figure 4.

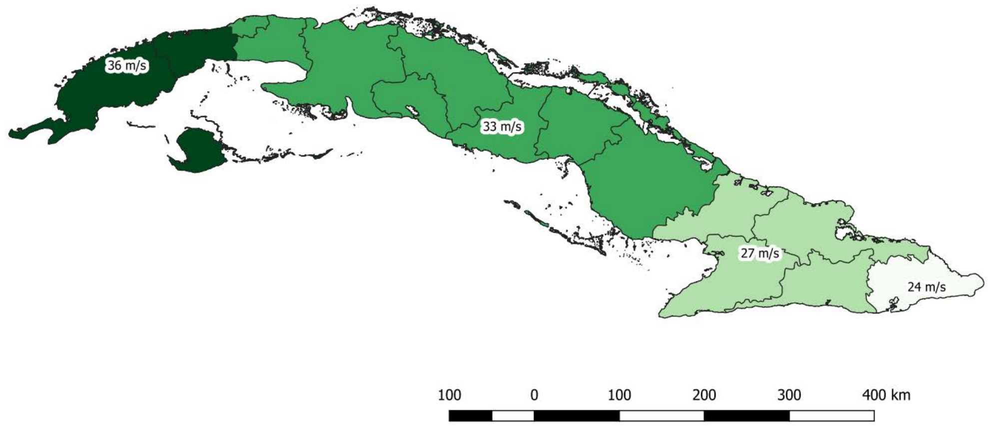


Figure 4 Proposal of the New Basic Wind Speed Map for Cuba.

4. Conclusions

In the present work, a procedure was established to obtain the basic wind speeds that will be the basis for updating the Cuban standard NC-285 [3]. In the procedure, the method is used for obtaining updated extreme speeds, for which the MIS is proposed, and the correction for roughness of the speeds obtained from the stations is incorporated, since the results confirm its marked influence on the final outcome. Consequently, an adequate correspondence was evidenced between the results of roughness length z_0, estimated by the classification method and the NDVI morphometric method in the analyzed stations. The potential of using the NDVI to obtain the roughness length with the assistance of satellite images in areas where vegetation predominates was revealed, and once again, the obtaining of reasonable values by the Classification Method was confirmed.

In relationship to the comparative results between the values obtained in the stations and those of the present NC-285 [3] standard, there is a marked divergence between them (13-21%), as demonstrated by previous works [6, 11]. However, an adequate correspondence with the Vickery values was observed, which differ from those proposed in this research by less than 3%.

5. Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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7. Author contributions

Camila Aldereguía Sánchez: Formal analysis performed related to the correction of the basic wind speeds, realization of the proposed map, prepared figures. Ingrid Fernández Lorenzo: Statistical analysis of the data and prepared the manuscript. Katia Luis García: Analysis of the data for obtaining the basic wind speed. Javier Ballote Álvarez: Analysis of satellite images. Vivian Elena Parnás: Statistical analysis of the data and prepared the manuscript.

8. Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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