LACUNARITY AS INDEX OF EVALUATION OF WIND DIRECTION IN PERNAMBUCO

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- ABSTRACT: Wind direction data were recorded from January 2008 to February 2011, at nine weather stations (Recife, Caruaru, Arcoverde, Garanhuns, Surubim, Floresta, Ibimirim, Serra Talhada and, Cabrobó), in the state of Pernambuco, Brazil, operated by the Instituto Nacional de Meteorology (INMET). Lacunarity analysis was performed in order to evaluate wind direction on those weather stations. In Recife the predominance of the wind was in the east (E)-southeast (SE) direction. In the agreste of the state of Pernambuco the predominant direction of the wind is the same one of Recife. In the Sertão of Pernambuco the wind predominates in the east (E)-sul (S) direction. Small values of lacunarity are caused by the presence of local winds, while large values of lacunarity are caused by lack of wind in a certain direction.

- KEYWORDS: Series temporal; invariance; Climatological stations; fractals

1 Introduction

The winds are formed by atmospheric pressure gradients thus generating displacement masses of air in relation to the earth's surface, also suffering influences of movement and Earth-rotation, according (MUNHOZ and GARCIA, 2008; BUENO et al., 2011). The wind is very important for the dynamics of the planet, facilitating exchanges of heat, carbon dioxide and water vapour between the atmosphere and vegetation. In the agriculture, it is fundamental for its influence in studies of the spread of disease control, pollination of flowers and practical windbreak, another positive aspect is the generation of energy source (SANTANA *et al*., 2008; MUNHOZ and GARCIA, 2008).

The wind direction is a very sensitive variable the change in time and space, this occurs due to location, surface roughness, topography, vegetation and climate of season (MUNHOZ and GARCIA, 2008). Research about the prevailing wind direction contributes to numerous activities such as installation of windbreaks; installation of industries; thermal comfort and the harnessing of wind energy (GALVANI *et al*., 1999).

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MUNHOZ and GARCIA (2008) found in their study that in most parts of the year there is predominance of winds from the southeast (SE), except for the period from December to February where the wind blows in the northwest (NW). According GALVANI *et al*. (1999) observed in their study that the predominant direction of winds in Maringa was northeast (NE) during the night period, in the southeast position (SW) in the period from January to May and from October to December and winds toward the east (E) in the months from July to September.

SANTANA *et al*. (2008) study conducted in Cuiabá, MT noted that the prevailing wind direction in spring and summer is located in the north - northeast (N and NE), in the fall and winter are predominant in the south - southwest (S-SO).

BUENO *et al*. (2011) in a study conducted in Lavras region, Minas Gerais, observed that the prevailing wind direction east (E) followed west (W) from February to November, already in January and December the predominant direction is inverted west (W) then east (E).

SILVA *et al*. (1997) concluded in their study that the wind direction in Pelotas is east (E) for the period between spring and summer, in the fall is Southeast (SE) and in winter the prevailing direction is northeast (NE). SILVA *et al*. (2002) in their study of wind potential at 77 locations in Northeast Brazil observed that the wind predominates in the east (E).

LUCENA *et al*. (2017) evaluated the direction of wind in the island of Fernando de Noronha through the analysis of lacunarity and concluded that greater the presence of wind smaller will be the lacunarity in a sector, the same number was verified by Lucena (2016) that evaluated the direction of wind through lacunarity in municipality of Serra Talhada.

Given the importance of wind energy, this study aims to characterize the wind direction in Pernambuco state using lacunarity analysis.

2 Material and methods

2.1 Data

Data of wind direction and speed observed from January 2008 to February 2011. Data are from nine stations (Recife, Caruaru, Arcoverde, Garanhuns, Surubim, Floresta, Ibimirim, Serra Talhada and Cabrobó) the climatological network in the state of Pernambuco operated by the National Institute of Meteorology (INMET).

Data were collected by the National Institute of Meteorology and measured through universal anemographs installed at 10 meters above the soil surface. The values of wind direction and speed were registered by anemograms hourly according to the following period's 0 to 1a.m., 1a.m. to 2a.m. and so on up to 24 hours.

The predominant wind directions were characterized by a frequency analysis of the daily observations, using the following expression

$$f(x)=(n/N)\times 100,$$

where, $f(x)$ is the frequency of occurrence of wind in a given direction, n is the number of occurrences of a given wind direction and N is the total number of observations. For better visualization of the frequency of wind directions was used to the compass rose.

The wind direction was registered hourly according to the following period's 0 to 1a.m., 1a.m. to 2a.m. and so on up to 24 hours. Each sector received the hourly record according to the following criteria described in Table 1.

Table 1 - Hourly wind direction record in each sector

Sector	Wind Direction (DW)	Sector	Wind Direction (DW)
N	$337.5º \leq DW < 22.5º$	S	$157.5º \leq DW < 202.5º$
NE	$22.5º \leq DW < 67.5º$	SW	$202.5º \leq DW < 247.5º$
E	$67.5º \leq DW < 112.5º$	W	$247.5º \leq DW < 292.5º$
SE	$112.5º \leq DW < 157.5º$	NW	$292.5º \leq DW < 337.5º$

Thus for each sector of wind direction a time series of 0's and 1's was created, where 0 is represented by the absence of wind at a given hourly and 1 is represented by the presence of wind at a certain hourly.

2.2 Lacunarity

The concept of lacunarity was introduced by Mandelbrot (1982) as a measure of the distribution of gap sizes in the fractal object. Geometric objects with gap sizes distributed over a wide range have greater lacunarity than those with smaller and more uniform gaps. The lacunarity is a measure is very explored in climatic and ecological phenomena (MARTINEZ *et al.*, 2007; MARTINEZ *et al.*, 2010; LUCENA *et al.*, 2017; LUCENA, 2016; LUCENA *et al.*, 2015; LUCENA, 2015; LUCENA *et al.*, 2014; LANA *et al.*, 2014; LUCENA and CAMPOS, 2014; LUCENA and STOSIC, 2013).

Lacunarity is related to the deviation of a geometric object from translational invariance (GEFEN *et al.*, 1983). Homogeneous and translationally invariant geometric objects have low lacunarity, while heterogeneous and not translationally invariant geometric objects have high lacunarity. Translational invariance (and lacunarity) is also scale dependent: the objects that are heterogeneous at small scale can appear homogeneous at higher scale and vice versa. Lacunarity was originally developed to describe properties of fractal objects, but it can be extended on general spatial patterns including those with fractal and multifractal properties and can be used with both binary and quantitative data in one, two and three dimensions (PLOTNICK *et al.*, 1996).

Various methods for calculating lacunarity have been developed with advances in computation (MANDELBROT, 1982; GEFEN *et al.*, 1983), as gliding box algorithm (ALLAIN and CLOITRE, 1991). This algorithm was extensively used in studies in medicine (DOUGHERTY and HENEBRY, 2001; LUCENA, 2015; LUCENA and STOSIC, 2014), ecology (SAUNDERS *et al.*, 2005), climatology (MARTINEZ *et al.*, 2010; MARTINEZ *et al.*, 2007; LANA *et al.*, 2014; LANA *et al.*, 2010; LUCENA *et al.*, 2016; LUCENA *et al.*, 2015; LUCENA, 2015; LUCENA *et al.*, 2014; LUCENA and CAMPOS, 2014, LUCENA and STOSIC, 2013).

Wind direction study using lacunarity analysis were reported by Lucena *et al.* (2017) where they found that the greatest lack of water was in the N direction (less presence of wind in the island) and smaller in direction SE (greater presence of wind in the island) by evaluating the wind in the island of Fernando de Noronha. In the municipality of Serra

Talhada, Lucena (2016) found that the lowest lacunarity occurred in sector S and the largest in sector W.

To characterize the wind direction, the lacunarity is a measure of the distribution of segments, defined as a sequence of consecutive hours that the wind is found in a certain direction, and the gaps defined as sequence of consecutive hours that the wind is not in particular direction. Lacunarity analysis has been used in eight different wind directions. Quantitatively, we have $n(s, r)$ is the number of windows mobile size r(2, 4, 8, 16, 32, 64 and 128 hours) containing s segments (hours is not found in a particular direction). The probability $p(s, r)$ is define as

$$p(s, r)=n(s, r)/N(r),$$

where, $N(r)=L-r+1$ is the total number of windows of size r, and L is the total length of record, including segments of occupied sites and gaps.

Lacunarity is now defined by

$$L(r) = \frac{M2(r)}{[M1\,(r)]^2},$$

where $M1(r) = \sum_{s=1}^{r} s * p(s,r)$ and $M2(r) = \sum_{s=1}^{r} s^2 \times p(s,r)$ are the first and second moment of $p(s,r)$.

For scale free process lacunarity decreases with window size as power law given by

$$L(r) = \alpha r^{\beta},$$

where scaling exponent β can be determined as the slope of linear regression of $log[L(r)]$ versus $log(r)$ using least squares method and $\varepsilon \sim N(0, \delta^2)$ (MARTINEZ *et al.*, 2007). If Y is values of $log\ L(r)$ and X the values r and n is total of observations, soon $\hat{\alpha} = \bar{Y} - \hat{\beta}\bar{X}$ and $\hat{\beta} = \frac{\sum_{i=1}^{n} X_i Y_i - n\bar{X}\bar{Y}}{\sum_{i=1}^{n} X_i^2 - n\bar{X}^2}$.

3 Results and discussion

The wind in the city of Recife is very predominant in the eastern (E) regions with 21.0% and southeast (SE) reaching 34.2% of the winds in this region already in the northwest (NW) sector the frequency of winds does not reach 5.0%, Figure 1 and Table 2. Similar results were found in LUCENA et al. (2017) evaluating the direction of wind in the Island of Fernando de Noronha, Pernambuco, Brazil.

Table 2 - Frequency distribution of wind direction in relation to the cities

| Station	Wind direction (n - %)							
	N	NE	E	SE	S	SW	W	NW
Recife	1062-5.0	1256-6.0	4434-21.0	7204-34.2	2076-9.8	1696-8.1	2492-11.8	874-4.1
Caruaru	423-1.5	1294-4.6	4534-16.2	8630-30.8	10158-36.3	2140-7.6	587-2.1	249-0.9
Garanhuns	407-1.4	4439-15.1	10887-37.0	11219-38.1	2065-7.0	259-0.9	85-0.3	62-0.2
Arcoverde	516-2.0	1237-4.7	6375-24.1	14223-53.7	3255-12.3	274-1.0	231-0.9	345-1.3
Surubim	281-1.0	1262-4.5	10552-38.0	9971-36.0	3538-12.7	1551-5.6	390-1.4	220-0.8
Ibimirim	1039-4.6	3218-14.3	1587-7.0	8005-35.6	7586-33.7	514-2.4	282-1.2	281-1.2
Floresta	965-4.8	1792-8.9	3119-15.5	9534-47.3	3690-18.3	446-2.2	260-1.3	352-1.7
S. Talhada	2448-11.8	1668-8.1	640-3.1	3193-15.4	9288-44.8	1953-9.5	524-2.5	1001-4.8
Cabrobó	609-2.2	1283-4.7	2088-7.6	10243-37.4	11277-41.2	1073-3.9	371-1.4	425-1.6
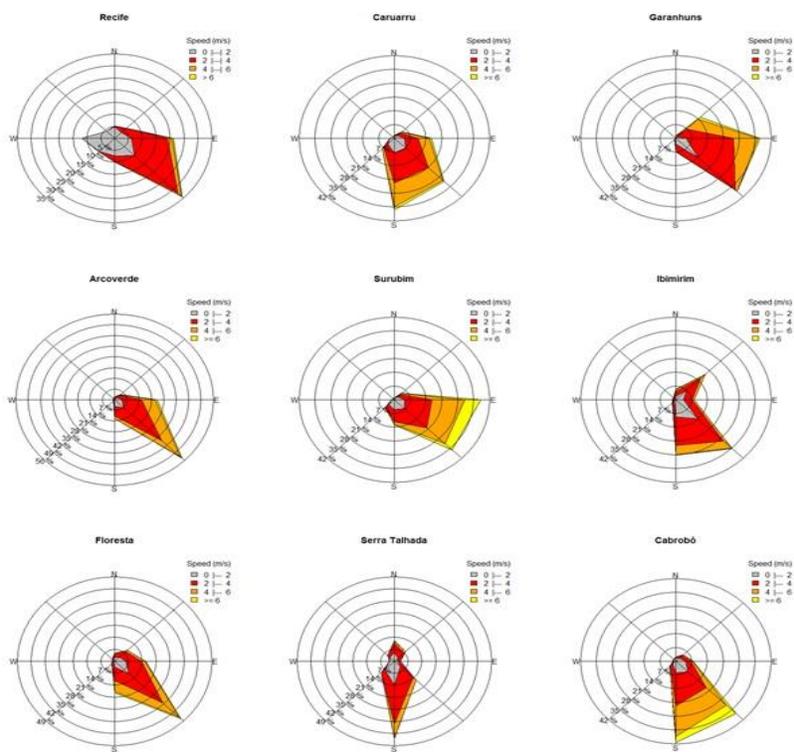
Figure 1 - Frequency distribution of the wind in relation to the areas of Recife, Caruaru Garanhuns Arcoverde Surubim, Ibimirim Floresta, Serra Talhada and Cabrobó from January 2008 to February 2011.

Assessing the harsh region of Pernambuco is noted that in Caruaru the predominance of wind directions is in southeast (SE) with 30.8% of the winds and south (S) exceeding the 35.0% frequency, Figure 1 and Table 2. Investigation of the behavior of the wind in the city of Garanhuns we note that the wind is predominant in the eastward (E) with 37.0% and southeast (SE) with a frequency of 38.1% Figure 1 and Table 2. In Arcoverde noticed the predominance of air mass toward the southeast (SE) where 53.7% of the frequencies of the wind in this region, Figure 1 and Table 2. In the city of Surubim the predominant wind direction is from the east (E) with 38.0% and southeast (SE) reaching 36.0% of the frequencies, Figure 1 and Table 2.

Starting to evaluate the backcountry region of Pernambuco is observed that in the region of Ibimirim the predominance of wind reaches 35.6% frequency toward the southeast (SE) and 33.7% in the south (S), Figure 1 and Table 2. In the region of Floresta predominant wind is toward the southeast (SE) exceeding 47.0% frequency, Figure 1 and Table 2. In the city of Serra Talhada wind is predominant in the south (S) with 44.8% frequency, Figure 1 and Table 2. In the region of Cabrobó is observed that the predominant wind direction is located between the Southeast (SE) with 37.4% and South (S) exceeding the 40.0% frequency, Figure 1 and Table 2. Similar patterns of wind direction were found by LUCENA (2016), corroborating these findings.

In the analysis of lacunarity, it is observed through the scatterplot of the logarithm of lacunarity versus the logarithm of the size of the window to the city of Recife the smallest values of lacunarity are the eastward (E) and Southeast (SE) and higher values in north (N), Figure 2.
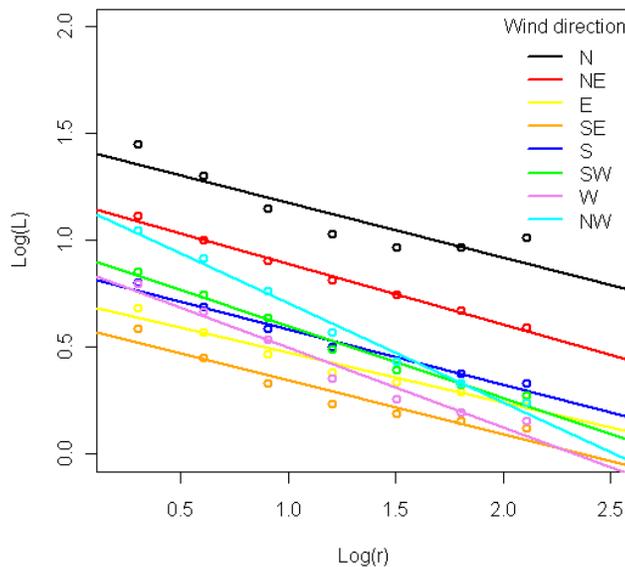

Figure 2 - Dispersion of the logarithm of lacunarity and the logarithm of the window size for different wind directions in Recife station.

In relation to harsh Pernambuco it is observed that lower values of lacunarity are found in the regions between the east (E) to the south (S) and higher values of lacunarity in the directions from the west (W) to north (N), Figure 3. In the backwoods of state of Pernambuco minors lacunarity values are found in the directions of Southeast (SE) and south (S) and larger from the southwest (SW) to the northwest (NW), Figure 4.
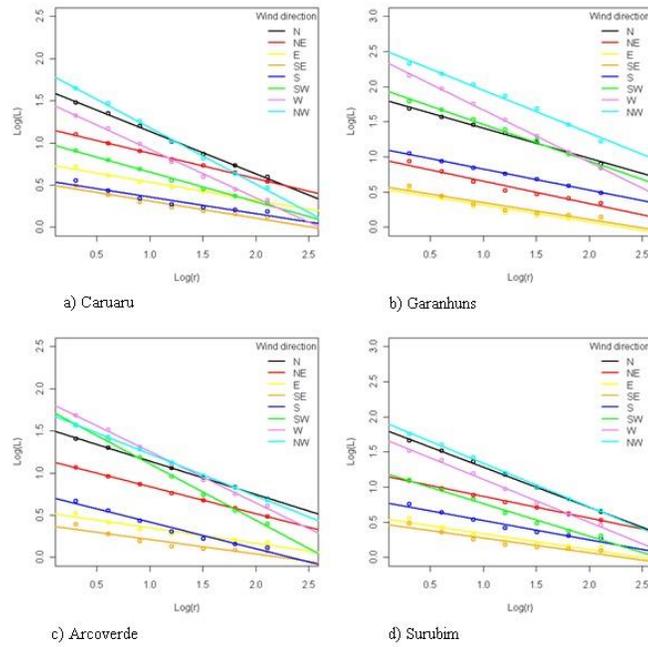

Figure 3- Dispersion of the logarithm of lacunarity and the logarithm of the window size for different wind directions in Caruaru, Garanhuns, Arcoverde and Surubim stations.
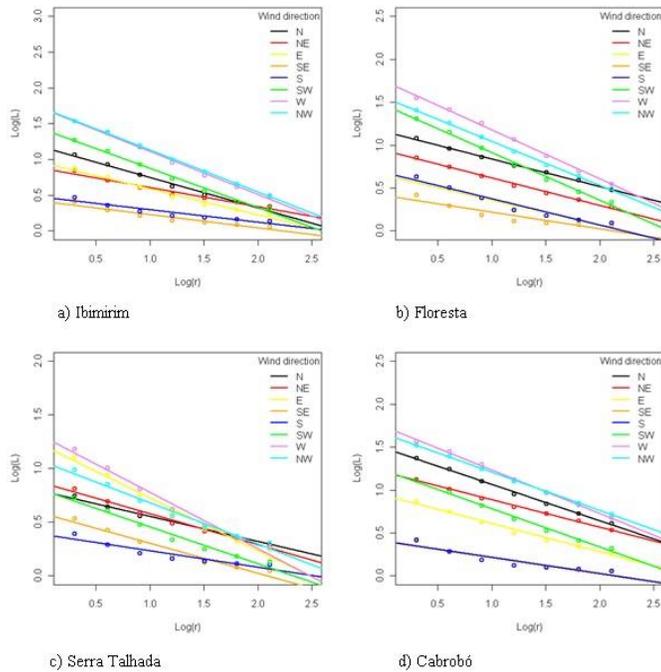
Figure 4- Dispersion of the logarithm of lacunarity and the logarithm of the window size for different wind directions in Ibimirim, Floresta, Serra Talhada and Cabrobó stations.

It is observed in Table 3 that there are very significant differences for the estimates of alpha and beta parameters for each set, in different wind directions, in relation to municipalities. In directions where it has little wind presence, the values of the exponent beta lacunarity are studied independently of the smaller stations, while where the wind is more prevalent, have lower values of beta lacunarity exponent for all stations in the study, similar results are found such as those by Lucena (2016).

It is observed in Table 3 that there are quite significant differences between the estimates of alpha and beta parameters for each models fitted in different wind directions in relation to meteorological stations. In directions where wind predominance is small, the values of exponent beta of lacunarity are higher independent to the station. Where wind is more prevalent, the value exponent beta of lacunarity is small for all stations in the study as shown in Table 3 and Figure 5 (ratio between the beta exponent and wind frequency for all directions and stations).

Table 3 - Estimates of model parameters for the different directions and cities

| Recife	$\hat{\alpha}$	$\hat{\beta}$	R²	Caruaru	$\hat{\alpha}$	$\hat{\beta}$	R²	Garanhuns	$\hat{\alpha}$	$\hat{\beta}$	R²
L(N)	4.2	-0.26	80.1	L(N)	5.2	-0.50	99.8	L(N)	6.3	-0.43	99.6
L(NE)	3.2	-0.28	99.3	L(NE)	3.3	-0.30	99.8	L(NE)	2.7	-0.32	95.7
L(E)	2.0	-0.23	95.5	L(E)	2.1	-0.21	98.1	L(E)	1.7	-0.24	90.6
L(SE)	1.8	-0.25	92.6	L(SE)	1.7	-0.20	94.5	L(SE)	1.8	-0.24	90.4
L(S)	2.3	-0.26	97.2	L(S)	1.7	-0.20	91.5	L(S)	3.1	-0.30	99.8
L(SW)	2.6	-0.34	98.0	L(SW)	2.7	-0.35	99.4	L(SW)	7.3	-0.52	99.2
L(W)	2.4	-0.37	96.2	L(W)	4.5	-0.57	99.5	L(W)	11.1	-0.74	99.9
L(NW)	3.2	-0.47	98.9	L(NW)	6.4	-0.67	99.7	L(NW)	12.9	-0.61	98.9
Arcoverde	$\hat{\alpha}$	$\hat{\beta}$	R²	Surubim	$\hat{\alpha}$	$\hat{\beta}$	R²	Ibimirim	$\hat{\alpha}$	$\hat{\beta}$	R²
L(N)	4.7	-0.40	99.9	L(N)	6.4	-0.57	99.9	L(N)	3.2	-0.43	99.1
L(NE)	3.2	-0.32	99.9	L(NE)	3.2	-0.31	99.7	L(NE)	2.4	-0.27	96.8
L(E)	1.7	-0.18	92.6	L(E)	1.8	-0.22	89.5	L(E)	2.6	-0.37	97.9
L(SE)	1.5	-0.17	87.2	L(SE)	1.6	-0.21	90.6	L(SE)	1.5	-0.18	91.6
L(S)	2.1	-0.31	97.6	L(S)	2.2	-0.27	96.5	L(S)	1.6	-0.18	90.6
L(SW)	5.9	-0.67	99.8	L(SW)	3.4	-0.46	98.7	L(SW)	4.2	-0.55	99.2
L(W)	6.4	-0.61	99.7	L(W)	5.6	-0.61	99.6	L(W)	5.5	-0.60	99.6
L(NW)	5.6	-0.50	99.9	L(NW)	7.1	-0.62	99.8	L(NW)	5.6	-0.59	99.9
Floresta	$\hat{\alpha}$	$\hat{\beta}$	R²	Serra Talhada	$\hat{\alpha}$	$\hat{\beta}$	R²	Cabrobó	$\hat{\alpha}$	$\hat{\beta}$	R²
L(N)	3.2	-0.32	99.8	L(N)	4.2	-0.23	98.9	L(N)	4.3	-0.42	99.7
L(NE)	2.6	-0.32	99.5	L(NE)	2.4	-0.29	98.3	L(NE)	3.3	-0.32	99.7
L(E)	1.9	-0.29	97.0	L(E)	3.4	-0.49	98.3	L(E)	2.6	-0.33	98.2
L(SE)	1.5	-0.19	86.7	L(SE)	1.8	-0.28	95.5	L(SE)	1.5	-0.19	89.0
L(S)	2.0	-0.31	94.9	L(S)	1.5	-0.15	88.9	L(S)	1.5	-0.19	86.2
L(SW)	4.3	-0.56	99.5	L(SW)	2.2	-0.34	97.5	L(SW)	3.4	-0.45	99.3
L(W)	5.7	-0.57	99.8	L(W)	3.7	-0.52	98.5	L(W)	5.7	-0.51	99.9
L(NW)	4.7	-0.51	99.9	L(NW)	2.9	-0.38	97.8	L(NW)	5.2	-0.45	99.9
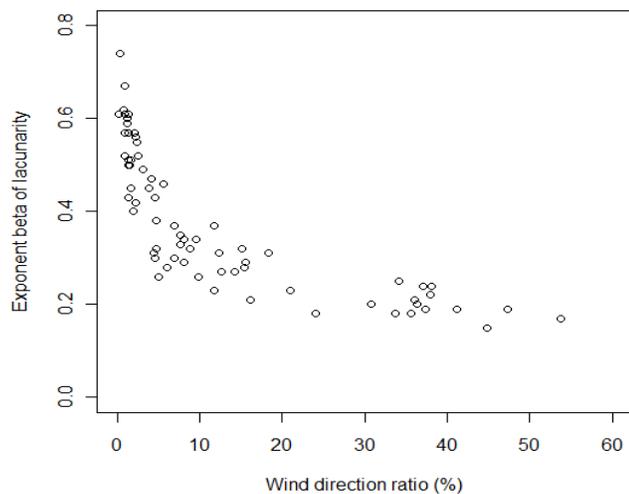
Figure 5 - Dispersion between exponent beta and wind direction ratio in region and direction.

Finally, we would like to point out that one may understand that there is a misconception when angular coefficient is used for the estimation of fractal dimension, once lacunarity computation does not involve the computation of an angular coefficient. Actually, there is a difference between the calculation of lacunarity and an estimate of the lacunarity. Lacunarity is calculated through a quotient taking into account the size of the boxes. Lacunarity can be estimated taking into account box sizes through a power model, where the variable response is the observed lacunarity itself, and box size as explanatory variable, as described by Martinez *et al*. (2007). The estimated angular coefficient was not calculated for lacunarity but for beta exponent of lacunarity.

Conclusions

In Recife the predominance of wind in the eastward (E) and Southeast (SE), to the harsh region of Pernambuco in which direction the wind is predominantly the same as Recife and in the backwoods of Pernambuco of the wind predominates in the east direction (E) to the south (S).

The lacunarity is reliable for evaluating wind direction measurement. Small values of lacunarity are caused by the presence of wind in the locality and large values of lacunarity are caused by lack of wind in a certain direction.

Acknowledgements

LUCENA, L. R. R.; FILHO, M. C. Lacunaridade como índice de avaliação da direção do vento em Pernambuco. *Rev. Bras. Biom*. Lavras, v.37, n.1, p.95-106, 2019.

- *RESUMO: Dados de direção do vento foram observados no período de janeiro de 2008 a fevereiro de 2011 em nove estações climatológicas do estado de Pernambuco (Recife, Caruaru, Arcoverde, Garanhuns, Surubim, Floresta, Ibimirim, Serra Talhada e Cabrobó) operadas pelo Instituto Nacional de Meteorologia (INMET). Análise de lacunaridade foi realizada para avaliar a direção do vento nessas localidades. No Recife a predominância do vento foi nas direções leste (E) e sudeste (SE). No agreste de Pernambuco a direção predominante do vento é a mesma do Recife. No sertão de Pernambuco o vento predomina nas direções leste (E)-sul (S). Pequenos valores de lacunaridade são ocasionados pela presença de ventos locais, enquanto grandes valores de lacunaridade são ocasionados por falta de vento em uma determinada direção.*

- *PALAVRAS-CHAVE: Série temporal; invariância; estações climatológicas; fractal.*

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