공학석사 학위논문

Wind Sector Classification Method based on Spatial Similarity of Wind Vector using Spatio-temporal Wind Data

시공간 바람자료를 이용한 바람벡터의 유사성에 따른 바람권역 분류 기법

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Abstract

Measurement of wind is required for wind resource assessment. In region with complex topography, uniformity of wind speed and wind direction significantly decreases and a local wind system is formed. Therefore, clear understanding of local wind system is necessary for accurate wind resource assessment. In this study, wind sector classification method, applying cluster analysis based on spatial similarity of wind vector, was proposed to describe the local wind system more clearly. Wind sectors were classified using wind resource map and the validity of classification method was examined.

Wind sector classification was applied to Jeju island and Busan, where Jeju island has relatively simple terrain and Busan has complex one. Classification result corresponds to the study area's topography and local wind system. Furthermore, wind characteristics of identical wind sector uniformly appeared and wind characteristics of distinct wind sectors appeared differently. The general validity of wind sector classification method was verified.

The proposed wind sector classification method is helpful to describe the local wind system. Moreover, this method can provide a basic information for wind resource assessment.

Keywords: local wind system, wind sector, cluster analysis,
wind resource assessment
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Chapter 1. Introduction

One of the most critical factors of wind generation is variability of wind. This makes the variability and intermittency of wind power, which has negative effect on system operation. The variability of wind power results in uncertainty of wind generation forecast and determines wind project economics. Therefore, understanding and managing the variability of wind is essential for wind project.

Wind speed and direction varies not only in time but also in space. Furthermore, a large group of wind turbines are constructed as a wind farm and several wind farms are geographically spread. Thus, several meteorological masts have to be used to observe the variability of wind in diverse locations for wind resource assessment. Since the local wind system indicates the locations where meteorological masts are needed, understanding the local wind system is necessary.

Until now, classification of wind using clustering analysis was applied to understand the wind flow patterns. By applying principal component analysis (PCA), classification of wind fields was done based on temporal variability (Green *et al.*, 1992; Jimenez *et al.*, 2009). Classification based on spatial similarity, which is more simple and efficient, was also developed (Weber and Kaufmann, 1995; Kaufmann and Weber, 1996; Kaufmann and Whiteman, 1999). Now, classification of wind sectors has to be studied to understand the local wind system exactly. Classification based on temporal variability is done

(Jimenez *et al.*, 2008). However, for more efficient wind sectors classification, classification based on spatial similarity has to be developed and its general validity has to be evaluated.

The main purpose of this study is proposing a wind sector classification method for accurate understanding of the local wind system. A wind sector classification method based on spatial similarity of wind vector using hourly wind data will be developed and this method will be applied to the study areas. Wind characteristics of each wind sectors will be compared by conducting statistical analysis of the wind data. General validity of the classification method will be examined by applying the developed method to relatively simple and complex topography.

Chapter 2. Review on wind classification methods

In order to classify the wind, cluster analysis is applied. Cluster analysis is a process of grouping a set of objects into classes of similar objects. In this process, distance measures are used to compute the dissimilarity of objects. In the research on wind classification, two different distance measures have been applied. One measure depends on the temporal variability, and the other measure depends on the spatial similarity of wind vector. These two distance measures have been used in both classification of wind fields and classification of wind sectors.

2.1 Wind field classification methods

2.1.1 Classification based on temporal variability

Wind fields have been classified according to their temporal variability (Green *et al.*, 1992; Jimenez *et al.*, 2009). Classification based on temporal variability applies principal component analysis (PCA). PCA extracts a group of correlated variables and represents it as a group of new orthogonal variables called principal components. The first principal component has the largest possible variance, and each succeeding component has the next largest possible variance. In PCA, wind data are written as

$$[u(x,t), v(x,t)] = [\bar{u}(x), \bar{v}(x)] + \sum_i^N a_i(t)[u_i(x), v_i(x)] \qquad (2\text{-}1)$$

where $u(x,t)$ and $v(x,t)$ is the zonal and meridional wind data at time t and at each of the N sites ($x = 1, 2, \cdots, N$), $\bar{u}$ and $\bar{v}$ is the time average of the zonal and meridional wind, $a_i(t)$ is the eigenvalue, and $[u_i(x), v_i(x)]$ is the eigenvector for each principal mode i. Eigenvalues describe the variance of principal component, and eigenvectors is the corresponding spatial patterns associated with each principal component. Since eigenvector contains temporal information, it has been used in cluster analysis. Only the significant eigenvectors are used.

Distance measure between two different times A and B is defined by

$$d_{AB} = \frac{1}{M}\sum_{i=1}^{M}[(u_A(x_i) - u_B(x_i))^2 + (v_A(x_i) - v_B(x_i))^2]^{1/2} \qquad (2\text{-}2)$$

where i denotes each sites and M is the total number of sites at each times. u and v are the eigenvectors from PCA. Clustering analysis groups wind fields with similar spatial pattern of principal components.

2.1.2 Classification based on spatial similarity

Classification method based on the spatial similarity for wind fields has been proposed (Weber and Kaufmann, 1995; Kaufmann and Weber, 1996; Kaufmann and Whiteman, 1999). This method relies only on spatial similarity of wind vector and does not require PCA. Distance measure between two different times A and B is defined by

$$d_{AB} = \frac{1}{M}\sum_{i=1}^{M}[(\tilde{u}_{Ai} - \tilde{u}_{Bi})^2 + (\tilde{v}_{Ai} - \tilde{v}_{Bi})^2]^{1/2} \tag{2-3}$$

where i denotes each sites, $\tilde{u}$ and $\tilde{v}$ are the normalized zonal and meridional wind. For normalization, all individual wind vectors at different sites i are divided by the average wind speed of wind field at a given time by

$$\tilde{u}_i = \frac{u_i}{s}\ , \quad \tilde{v}_i = \frac{v_i}{s} \tag{2-4}$$

where

$$\mathrm{s} = \frac{1}{M}\sum_{i=1}^{M}({u_i}^2 + {v_i}^2)^{1/2} \tag{2-5}$$

and M is the total number of sites at each times. Normalization was used to distinguish wind fields by difference in wind directions or by differences in relative wind speed. Wind fields with similar wind direction but different mean wind speed are grouped.

2.2 Wind sector classification methods

2.2.1 Classification based on temporal variability

Classification of wind sectors based on temporal variability also applies

PCA and uses eigenvector for cluster analysis (Jimenez *et al.*, 2008). Distance measure between two different locations A and B is defined by

$$d_{AB} = \frac{1}{N}\sum_{j=1}^{N}[(u_j(x_A) - u_j(x_B))^2 + (v_j(x_A) - v_j(x_B))^2]^{1/2} \qquad (2\text{-}6)$$

where j denotes the principal mode, u and v are the eigenvectors from PCA. Clustering analysis groups wind sectors with similar temporal variability.

2.2.2 Classification based on spatial similarity

Classification based on the spatial similarity has been used for wind sectors (Lee *et al.*, 2006; Jung *et al.*, 2007; Jung *et al.*, 2009). Distance measure between two different locations A and B is defined by

$$d_{AB} = [(\bar{u}_A - \bar{u}_B)^2 + (\bar{v}_A - \bar{v}_B)^2]^{1/2} \qquad (2\text{-}3)$$

where $\bar{u}$ and $\bar{v}$ are annual average of zonal and meridional wind speed. Wind sectors with similar mean vector wind are grouped. However, mean vector wind cannot represent the exact wind system.

Chapter 3. Wind sector classification method

In this study, classification method based on spatial similarity is applied for wind sectors and improved on previous studies. Distance measure is calculated using hourly wind data, which is normalized. Two-step clustering algorithm is used due to its advantage over the single-step algorithms.

3.1 Definition of distance measure

Distance measure between two different locations A and B is defined by

$$d_{AB} = \frac{1}{N}\sum_{j=1}^{N}[(\tilde{u}_{Aj} - \tilde{u}_{Bj})^2 + (\tilde{v}_{Aj} - \tilde{v}_{Bj})^2]^{1/2} \tag{3-1}$$

where i denotes each times, $\tilde{u}$ and $\tilde{v}$ are normalized zonal and meridional wind. All individual wind vectors at different times j are divided by the mean wind speed of each site by

$$\tilde{u}_j = \frac{u_j}{s} , \quad \tilde{v}_i = \frac{v_j}{s} \tag{3-2}$$

where

$$\mathrm{s} = \frac{1}{N}\sum_{j=1}^{N}({u_j}^2 + {v_j}^2)^{1/2} \tag{3-3}$$

and N is the total number of hourly wind data at each site. According to the normalization, wind sectors are classified by difference in wind directions or by differences in relative wind speed. Wind sectors with similar wind direction but different mean wind speed are grouped.

3.2 Clustering Algorithm

In general, major clustering methods can be classified into hierarchical methods and partitioning methods. Hierarchical methods use a hierarchical decomposition of the given set of data objects. Algorithm starts with each object forming a separate group. The groups that are close to on another are merged until all of the groups are merged into one. However, hierarchical methods cannot correct erroneous decisions. Once the merge is done, it can never be undone. Partitioning methods organizes the objects into K clusters based on distance measure. By iterative algorithm, partitioning is improved to satisfy the criterion, however, the result of classification depends on the number of clusters and initial clusters.

Due to the advantages of two-step clustering algorithm over the single step algorithms, two-step clustering algorithm has been applied for synoptic climatological classification (Davis and Kalkstein, 1990; Davis and Walker, 1992). Researches on classification of wind also used two-step clustering algorithm (Kaufmann and Weber, 1996; Kaufmann and Whiteman, 1999; Jimenez *et al.*, 2008; Jimenez *et al.*, 2009). In this study, two-step clustering algorithm is applied.

In the first step of two-step clustering algorithm, hierarchical cluster analysis is done to find appropriate number of clusters and initial clusters, which are used in the second step. Weber and Kaufmann (1995) compared different hierarchical clustering methods for wind field classification and found some advantages of complete linkage algorithm. Complete linkage algorithm defines the distance measure between two groups as the largest value of distance between any possible pair of objects. This method has been used for classification of wind (Weber and Kaufmann, 1995: Kaufmann and Weber, 1996; Kaufmann and Whiteman, 1999; Jimenez *et al.*, 2008; Jimenez *et al.*, 2009). Therefore, complete linkage method was select for the first step.

Appropriate number of clusters is determined from the value of distance measure as the two most similar groups are merged. A large and sudden change in the value of distance measure indicates that two very different groups have been merged. The number of groups before the large and sudden change of distance measure can be used as the appropriate number of clusters and the classified groups can be used as initial clusters in the second step.

In the second step of two-step clustering algorithm, the number of clusters and initial clusters are entered. Then, partitioning cluster analysis is done by *k*-means algorithm, which is the most frequently used partitioning method. *k*-means algorithm determines the centroid of clusters by mean values of the objects in clusters. The wind sectors are classified at the end of the procedure.

Chapter 4. Data and Study areas

In this study, KIER-Windmap^{TM} by Korean Institute of Energy Research was used. Wind sector classification method was applied to Jeju island and Busan (Fig. 4.1). Jeju island and Busan were selected to examine the general validity of the classification method in both simple and complex topography. Jeju island has relatively simple terrain while Busan has complex terrain.

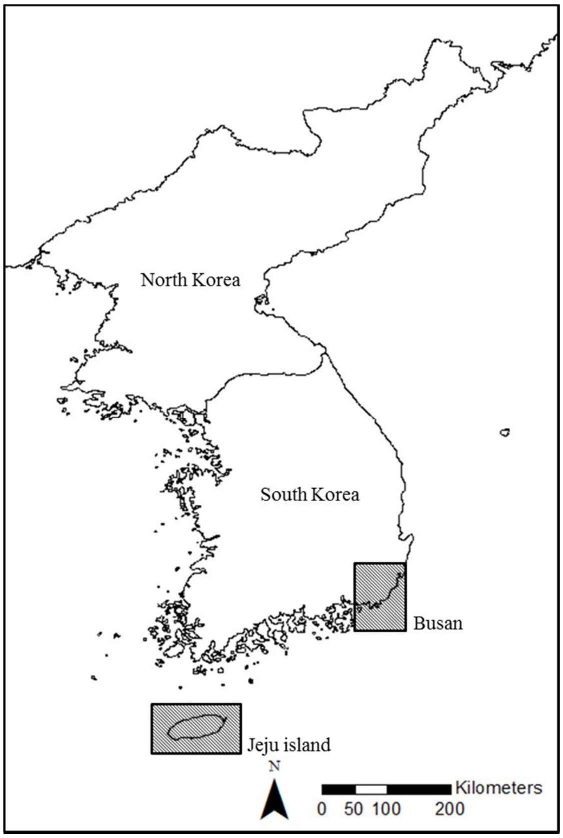


Fig. 4.1 Location of Jeju island and Busan.

4.1 KIER-Windmap^{TM}

KIER-Windmap^{TM} is provided as low spatial resolution of 9 km, medium spatial resolution of 3 km, and high spatial resolution of 1 km. Wind speed, wind direction, temperature, air pressure and air density is included with vertical resolution of 10 m and temporal resolution of 1 hour interval for multiple years (Fig. 4.2).

KIER-Windmap^{TM} was drawn up by Weather Research Forecasting (WRF), a mesoscale numerical weather prediction model. The accuracy was evaluated by comparing KIER-Windmap^{TM} to the wind profiler observation data for onshore and the Synthetic Aperture Radar (SAR) satellite data for offshore (Kim *et al.*, 2014).

In this study, KIER-Windmap^{TM} of Jeju island and Busan was used to classify the wind sectors. Wind data of Jeju island was at 20m above the ground level with spatial resolution of 3 km, temporal resolution of 1 hour interval for 2005-2007. 26 nodes were included from east to west and 22 nodes from north to south. To study the wind sectors in Busan, which has complex terrain, KIER-Windmap^{TM} with high spatial resolution of 1 km was used. Wind data of Busan was also at 20m above the ground level with temporal resolution of 1 hour interval. The period of data was 1 year, in 2007. 46 nodes were included from east to west and 53 nodes from north to south.

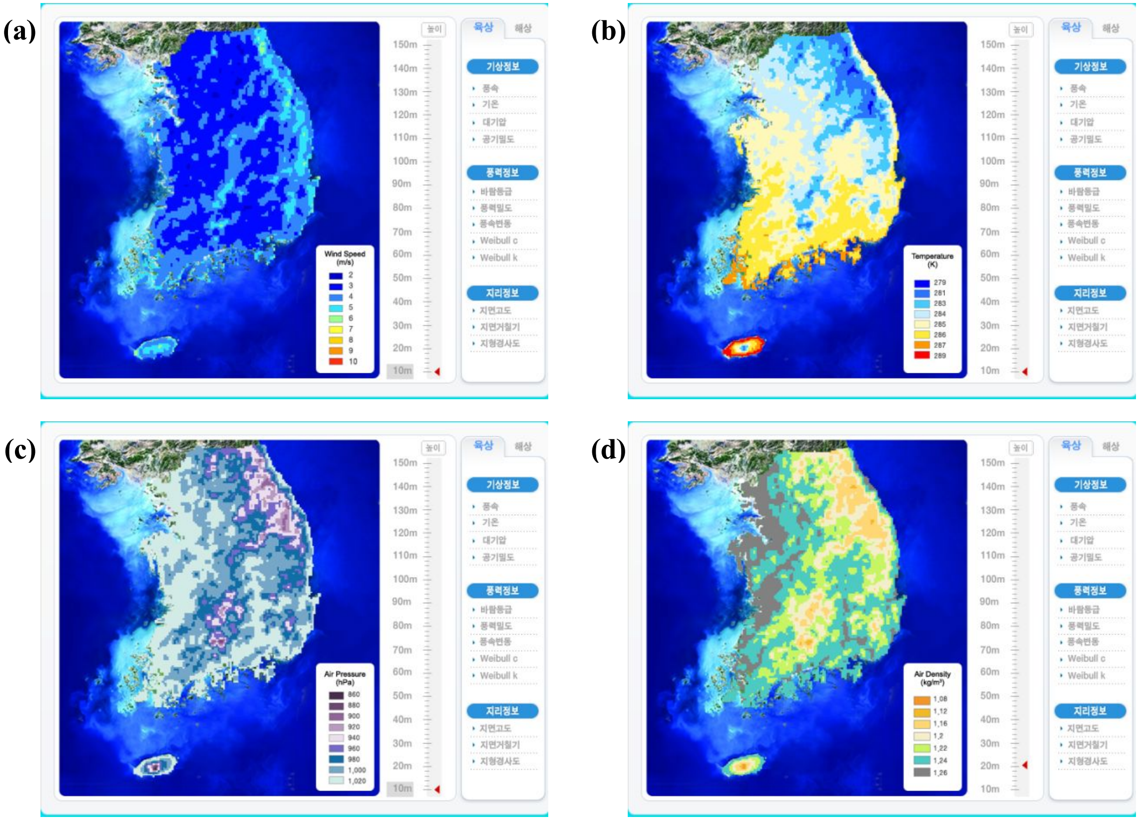


Fig. 4.2 (a) Wind Speed (b) Temperature (c) Air Pressure (d) Air Density of KIER-Windmap™.

4.2 Jeju island

4.2.1 Location, topography of Jeju island

Jeju island is the biggest island in Korea, located in the south of Korean Peninsula, and lies between latitude 33˚11'27''N-33˚33'50''N, longitude 126˚08'27''E-126˚58'20''E. With a total area of 1,849 km^2, it is spanning 73 km east to west and 41 km north to south. Jeju island, formed by volcanic activity, has 2 km high Mt. Halla located at the center of the island. Eastern and western side of Mt. Halla has relative gentle slope (3˚-5˚) while northern and southern side has a steep slope (5˚-10˚). Coastline of Jeju island is relatively simple (Fig. 4.3).

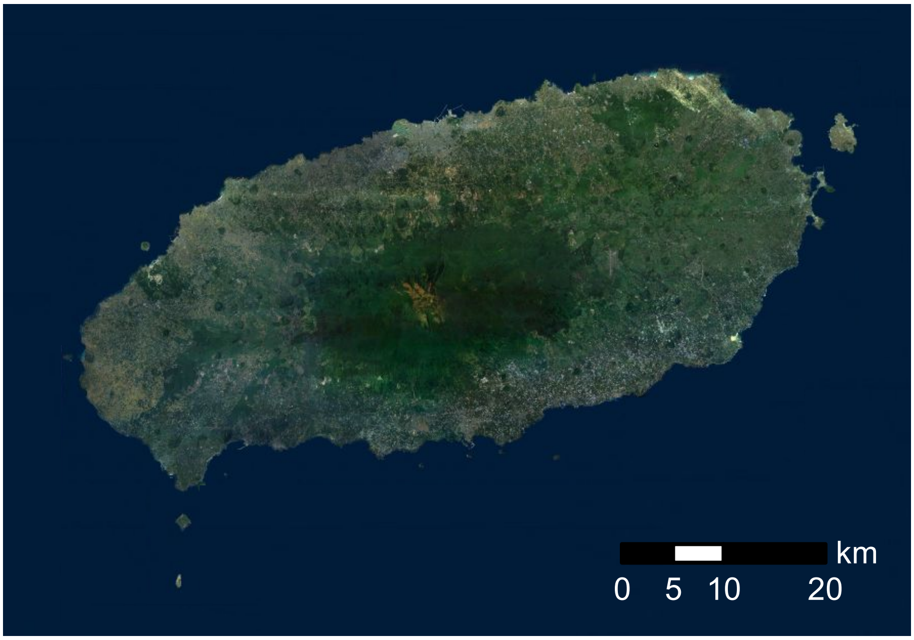


Fig. 4.3 Satellite image of Jeju island (ref: http://www.vworld.kr/).

4.2.2 Wind condition of Jeju island

Jeju island is well-known for its high wind energy potential. Wind speed is very high and high speed wind occurs frequently. Wind speed is higher in offshore than onshore and southern sea of Jeju island is higher than northern sea. In onshore, wind speed is highest at Mt. Halla. In coastal region with low altitude, northwestern and eastern side of Mt. Halla has higher wind speed (Fig. 4.4).

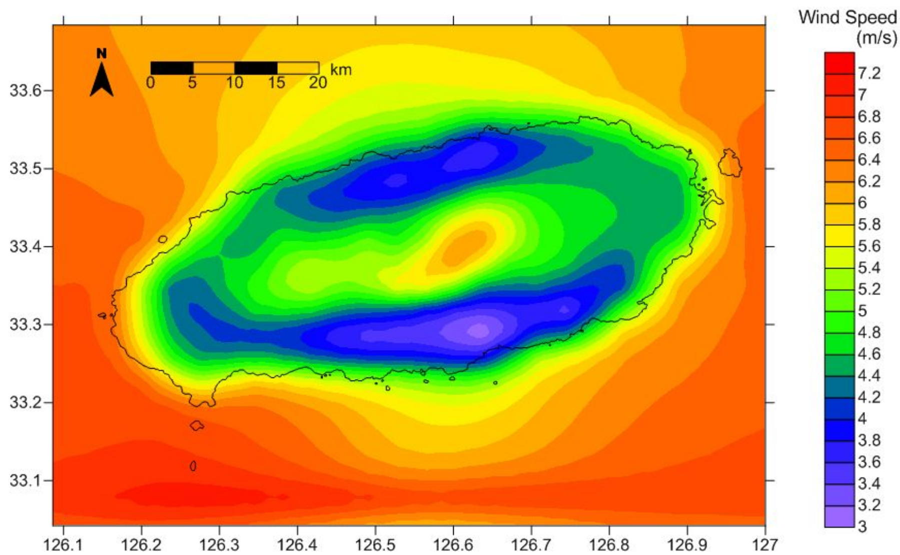


Fig. 4.4 Mean wind speed of Jeju island (KIER-Windmap™)

Jeju island maintains high frequency of northwest winds in winter, and east winds in summer. It is affected by the northwest monsoon in wintertime and southwest, southeast monsoons in summertime. Mean wind speed is higher at wintertime. Fig. 4.5 represents the mean vector winds. Due to the geographical characteristics of Jeju island, different patterns of wind appear according to the direction around Mt. Halla (Kim *et al.*, 2008). Wind vectors expand in all direction, centered on Mt. Halla. In offshore, northern wind series, which is the synoptic wind flow, is dominant.

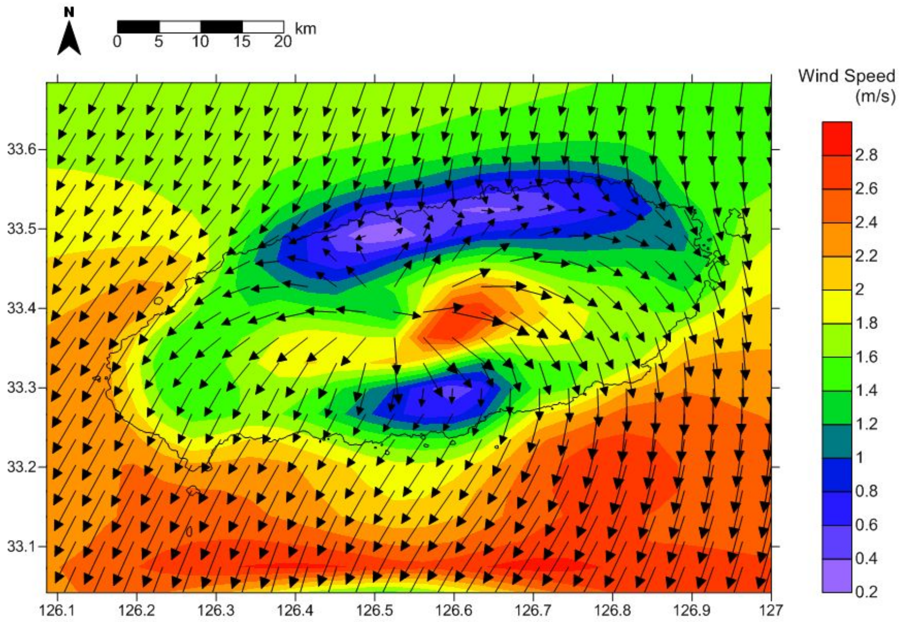


Fig. 4.5 Mean vector wind of Jeju island (KIER-Windmap^{TM})

4.3 Busan

4.3.1 Location, topography of Busan

Busan is the second biggest city in Korea, with a total area of 766 km^2. It is located in the southeastern corner of Korean Peninsula, and lies at latitude

35˚10’46’’N, longitude 129˚04’32’’E. Western side of Busan is flat because of the Gimhae plain which is located at the mouth of Nakdong River. Eastern side includes 300-700 m high hills, since Busan is located in the end of Taebaek mountain range. Coastline of Busan is rias coast which is complex (Fig. 4.6)

Fig. 4.6 Satellite image of Busan (ref: http://maps.google.co.kr/).

4.3.2 Wind condition of Busan

It is very windy in Busan all the year and the wind speed is high. Wind speed is higher in offshore than onshore. In onshore, wind speed is higher at higher altitude and along the coastline (Fig. 4.7). Wind speed is slow at the plains.

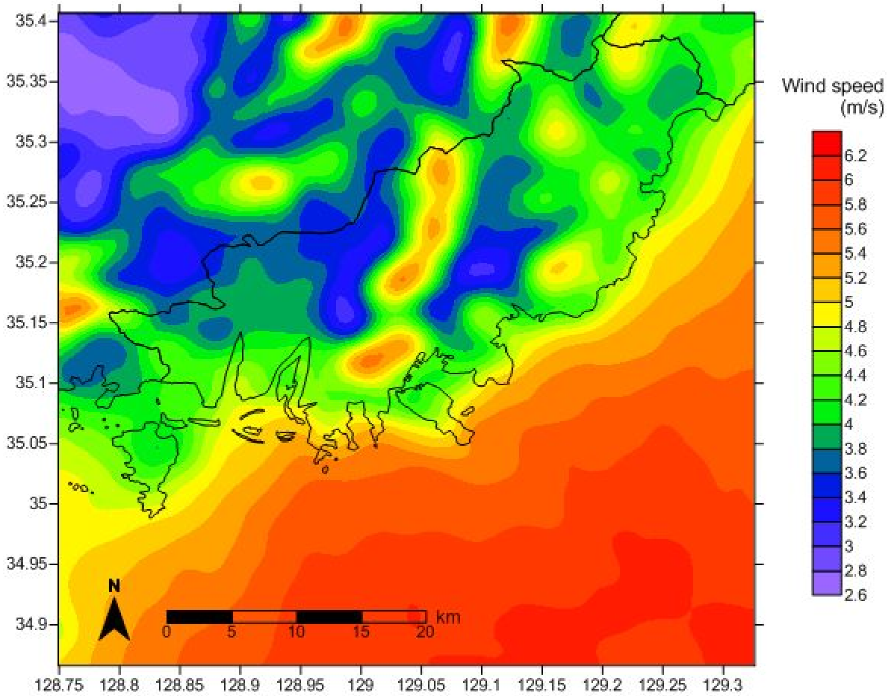


Fig. 4.7 Mean wind speed of Busan(KIER-Windmap^{TM}).

Northwest wind is dominant in winter and southwest wind is dominant in summer. Because of various geographic factors, various local wind flows occurs in Busan. Land-sea breeze appears in the coastal region and complex wind flow pattern appears in the hilly region (Lee *et al.*, 2006). Fig. 4.8, which represents mean vector wind of Busan, shows the wind disturbance and the complexity of wind flow pattern. In offshore, western wind series, which is the synoptic wind flow, is dominant.

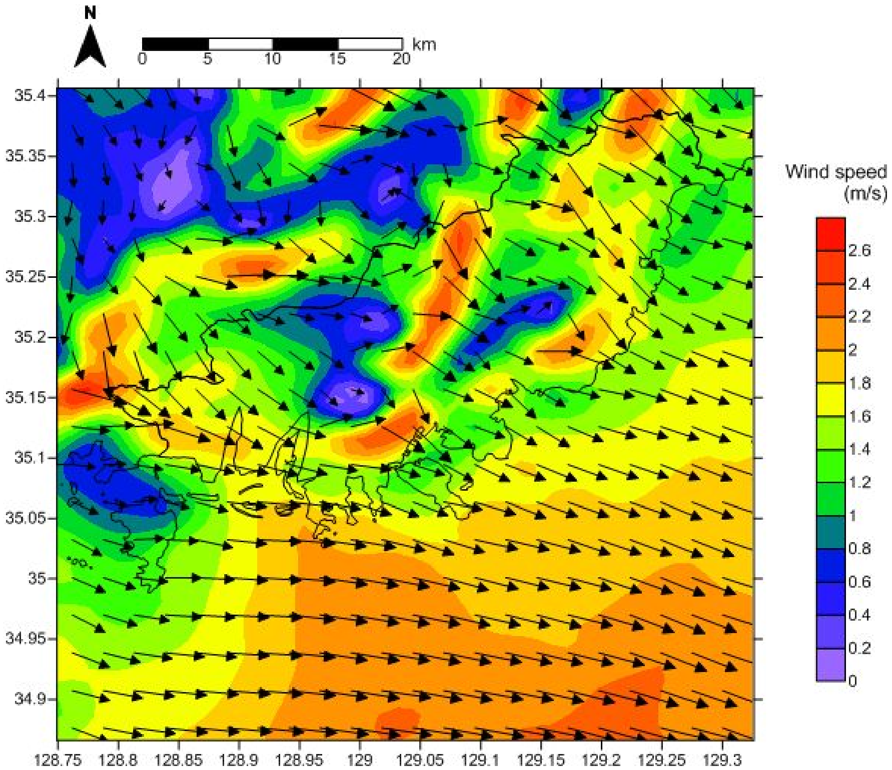


Fig. 4.8 Vector mean wind of Busan (KIER-Windmap™).

Chapter 5. Results and Discussion

5.1 Jeju island

5.1.1 Classification of wind sectors in Jeju island

In the first step of wind sectors classification, appropriate number of clusters was selected. This was done by displaying the value of distance measure as the two most similar groups are merged (Fig. 5.1). A sudden and big change appears when the number of clusters is 3, 8, and 10. In this study, three was selected as the appropriate number of clusters for classification of mesoscale wind sectors.

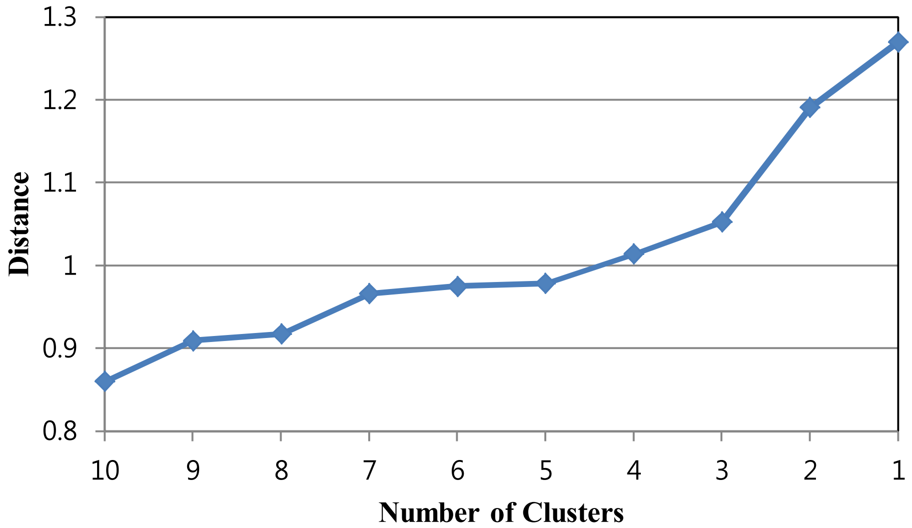


Fig. 5.1 Distance measure for each number of clusters in Jeju island.

Fig. 5.2 represents three wind sectors in Jeju island. Three wind sectors are classified around Mt. Halla at the center. Different wind sectors appear in the south and north of Mt. Halla, and another wind sector appears from the east to west of Mt. Halla. This explains that different patterns of wind appear according to the direction around Mr. Halla (Kim *et al.*, 2008).

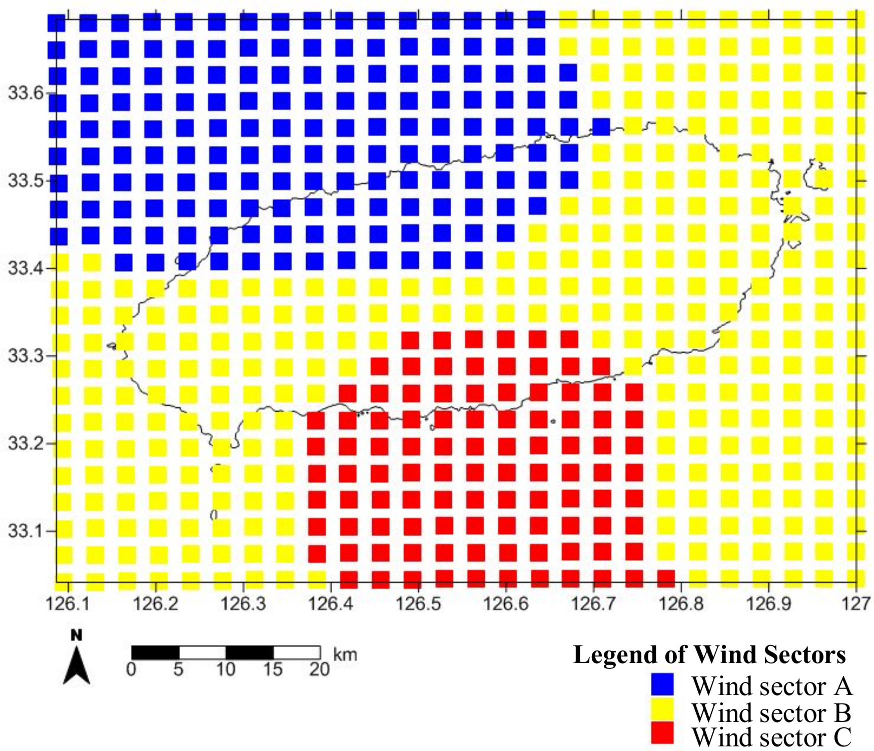
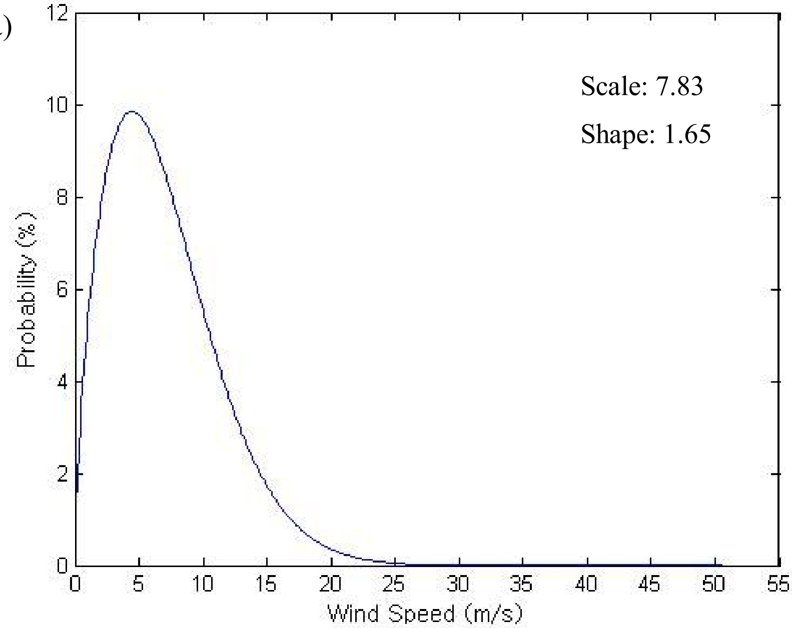


Fig. 5.2 Wind sectors in Jeju island.

5.1.2 Wind characteristics in in Jeju island

Wind characteristics of each wind sectors are analyzed by Weibull distribution and windrose. Mean wind speed and distribution of wind speed is explained at Weibull distribution. Distribution of wind speed is explained at windrose. In wind sector A, wind speed ranged to about 26 m/s and about 5 m/s is the most frequent wind speed (Fig 5.3 (a)). Maximum wind speed of wind sector B is about 25 m/s and the most frequent wind speed is about 6 m/s (Fig 5.4 (a)). Wind speed ranged to about 25 m/s and about 5 m/s is the most frequent wind speed in wind sector C (Fig 5.5 (a)). Distribution of wind speed is similar at wind sector A and C while wind sector B has a distinct characteristic. Scale parameter is biggest at wind sector B (8.48) and similar at A (7.83) and C (7.78). Since scale parameter is proportional to mean wind speed, this means that wind sector B has higher mean wind speed than A and C. Shape parameter is 1.65 at wind sector A, 1.86 at wind sector B, 1.69 at wind sector C. Shape parameter represents the variance of wind speed. This shows that variance of wind speed is highest at wind sector B and then C and A. Northeastern wind is dominant in wind sector A (Fig 5.3 (b)). In sector B, northern and northwestern wind is dominant (Fig 5.4 (b)). Northeastern wind is also dominant is wind sector C (Fig 5.5 (b)), however, northeastern wind is more frequent than wind sector A and wind sector C has second prevailing wind from northwest.

(a)



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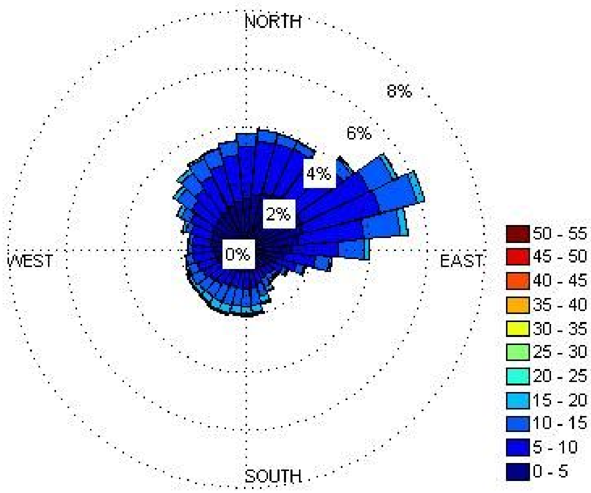
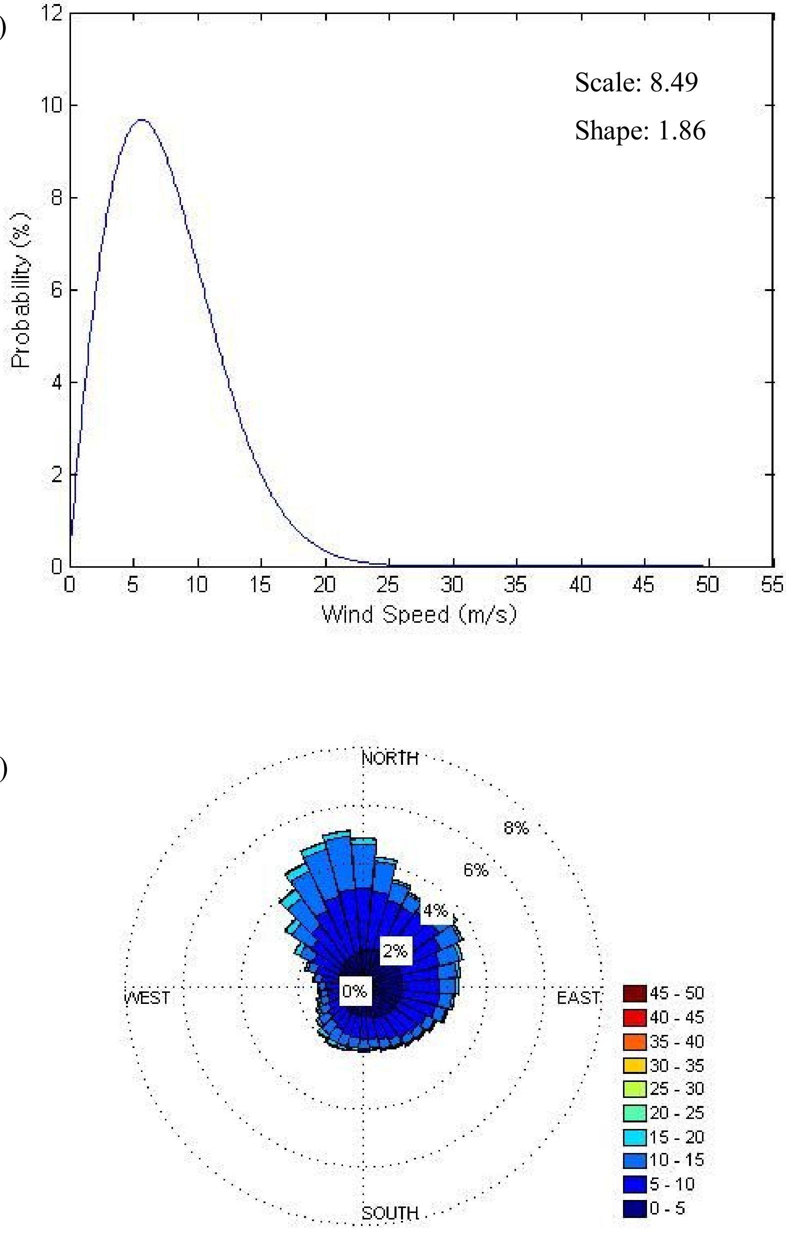


Fig. 5.3 Wind distribution of wind sector A in Jeju island

(a) Weibull distribution of wind speed. (b) Windrose.

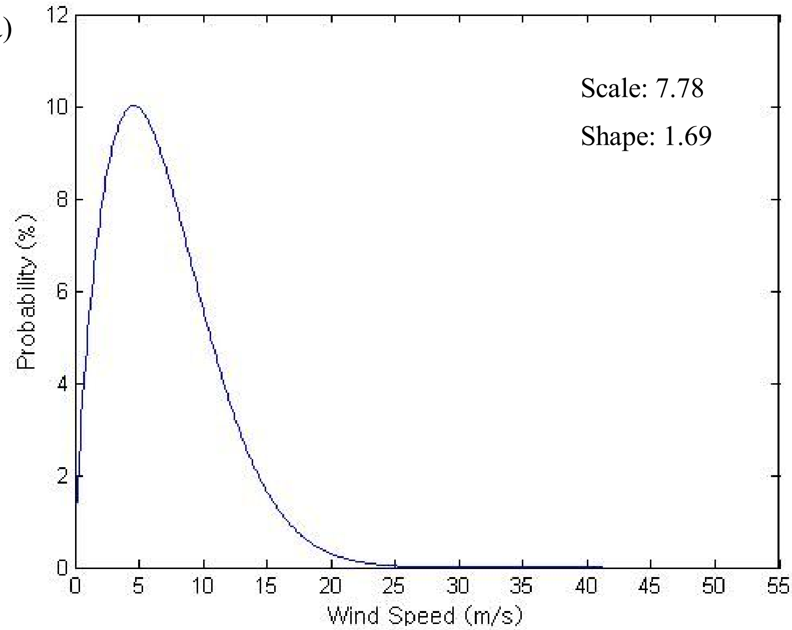
(a)



(b)

Fig. 5.4 Wind distribution of wind sector B in Jeju island
(a) Weibull distribution of wind speed. (b) Windrose.

(a)



(b)

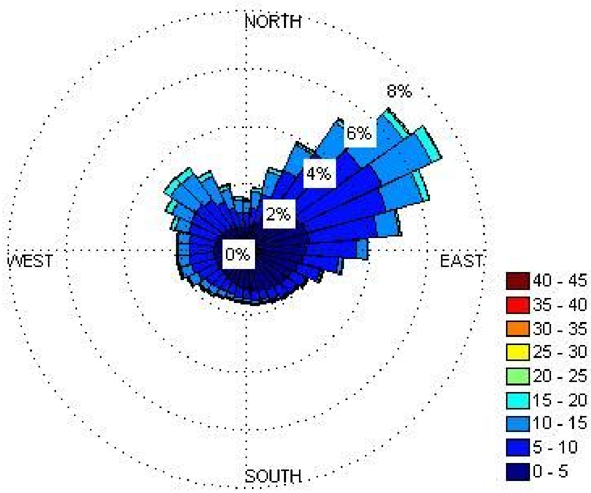


Fig. 5.5 Wind distribution of wind sector C in Jeju island

(a) Weibull distribution of wind speed. (b) Windrose.

5.1.3 Validity of wind sector classification in Jeju island

Mean wind speed, variance of wind speed, prevailing wind direction, and variance of wind direction represents the wind characteristic of each node. Variance is used to interpret the distribution of hourly data. Using representative values of each node, it was checked whether the wind characteristics are similar in the same wind sector and whether there is a difference between wind sectors. Standard error in each wind sector was examined to identify the similarity in the same wind sector. The Kruskal-Wallis one-way analysis of variance (ANOVA) was used to determine the difference between the means of each wind sector. This method was used because it was checked through normality test and equality of variance test that representative values in each wind sectors are not normally distributed and does not have equal variance.

The statistical analysis of wind data in each wind sectors are summarized in Table 5.1 and 5.2. Each wind sectors include 161 nodes, 310 nodes, and 101 nodes. Standard error in each wind sector is low in mean wind speed, variance of wind speed and variance of wind direction. Therefore, these wind characteristics seems similar in the same wind sector. However, since standard error is high, there is a difference in the same wind sector regarding prevailing wind direction.

The result of Kruskal-Wallis ANOVA is presented in Table 5.3 and 5.4. All presentative values have p-value under 0.05. This indicates the rejection of the null hypothesis that all wind sectors has the same median at 5% significance level. At least one pair of wind sectors has different presentative values. To find the pair of wind sectors that has different wind characteristics, pairwise comparison was done by post-hoc analysis. Table 5.5 and 5.6 shows the result of multiple comparisons. Variance of wind speed and prevailing wind direction is different to each other wind sectors. However, wind sector A and C has the same mean wind speed and variance of wind direction while wind sector A and B, B and C are different. Classification of wind sectors are done according to variance of wind speed, prevailing wind direction, and variance of wind direction. By using normalized distance measure to determine the similarity of wind between different nodes, the mean wind speed is not applied. Wind sectors are classified by difference in wind directions or by difference in relative wind speed.

Prevailing wind direction is a significant factor for classification of wind sectors. However, there are three problems in comparing prevailing wind direction of each wind sectors. First, selecting the prevailing wind direction by simple codes has an error. Even though the prevailing wind is not certain, a value is always selected as the prevailing wind direction. Second, if there is several prevailing wind, prevailing wind directions in one wind sector might have various peaks in distribution. This problem gets intensified when the wind system is complex. Third, circularity of wind direction is not applied at pairwise comparison. Therefore, practical limits exist to examine the validity by prevailing wind direction. It would be better if the number of prevailing wind or the direction of second or third prevailing wind is compared.

Table 5.1 Statistics of wind speed in Jeju island.

	Wind sector	N	Mean	Std. deviation	Std. error	Min	Max
Mean wind speed	A	161	7.0	0.5246	0.0413	5.7	7.7
	B	310	7.5	0.3862	0.0219	6.5	8.8
	C	101	6.9	0.6842	0.0681	5.6	8.2
Variance of wind speed	A	161	18.8369	3.3667	0.2653	16.0461	33.1563
	B	310	17.3613	3.7291	0.2118	14.2320	36.8067
	C	101	17.3445	3.9230	0.3904	14.2320	36.8067

Table 5.2 Statistics of wind direction in Jeju island.

	Wind sector	N	Mean	Std. deviation	Std. error	Min	Max
Prevailing wind direction	A	161	70.3	31.2627	2.4638	50	350
	B	310	359.7	37.5883	2.1349	10	360
	C	101	49.7	18.8680	1.8774	10	360
Variance of wind direction	A	161	0.7440	0.0585	0.0046	0.6691	0.9653
	B	310	0.7484	0.0464	0.0026	0.6777	0.8861
	C	101	0.7559	0.0529	0.0053	0.6728	0.9436

Table 5.3 ANOVA table of wind speed in Jeju island.

		Sum of squares	df	Mean square	Chi-sqaure	*p*-value
Mean wind speed	Between Groups	3.66979e+06	2	1834892.6	134.36	6.66827e-30
	Within Groups	1.19259e+07	569	20959.5		
	Total	1.55957e+07	571			
Variance of wind speed	Between Groups	2.45822e+06	2	1229111	90	2.85979e-20
	Within Groups	1.31375e+07	569	23088.8		
	Total	1.55957e+07	571			

Table 5.4 ANOVA table of wind direction in Jeju island.

		Sum of squares	df	Mean square	Chi-sqaure	p-value
Prevailing wind direction	Between Groups	7.42611e+06	2	3713057.07	273.93	3.2928e-60
	Within Groups	8.05361e+06	569	14153.98		
	Total	1.54797e+07	571			
Variance of wind direction	Between Groups	682326	2	341163	24.98	3.96085e-06
	Within Groups	14913397	569	26209.8		
	Total	15595723	571			

Table 5.5 Multiple comparisons of wind speed in Jeju island.

	(I) Cluster	(J) Cluster	Comparison	95% Confidence interval	
				Lower bound	Upper bound
Mean wind speed	A	B	0.0000	-195.0945	-132.1614
	A	C	0.7158	-48.7528	33.4790
	B	C	0.0000	118.8793	193.1029
Variance of wind speed	A	B	0.0000	120.8338	183.7669
	A	C	0.0000	61.0180	143.2498
	B	C	0.0081	-87.2782	-13.0546

Table 5.6 Multiple comparisons of wind direction in Jeju island.

	(I) Cluster	(J) Cluster	Comparison	95% Confidence interval	
				Lower bound	Upper bound
Prevailing wind direction	A	B	0.0000	-136.6675	-73.9688
	A	C	0.0025	58.4122	140.3376
	B	C	0.0000	167.7195	241.6666
Variance of wind direction	A	B	0.0000	-110.3055	-47.3724
	A	C	0.0951	-76.1298	6.1020
	B	C	0.0206	6.7133	80.9369

5.2 Busan

5.2.1 Classification of wind sectors in Busan

The value of distance measure at each number of clusters was examined to determine the number of clusters (Fig. 5.6). A sudden and big change appears when the number of clusters is 5 and 7. By comparing the result of wind sectors classification to topography of Busan, seven was selected as the appropriate number of clusters. 7 clusters well explain the various wind flow pattern in Busan.

Fig. 5.7 represents the wind sectors in Busan when the number of clusters is 5 and 7. Wind sectors in 7 clusters well correspond to the topographic characteristics of Busan. Wind sector A and C are located at valley and basin where the altitude is low, while B is at the hill with high altitude. Wind sector G indicates the Gimhae plain and D, E, and F encounter the coast. Various wind flow patterns appear according to the topography (Lee *et al.*, 2006). If spatially separated, but in same wind sectors, clusters are classified as a different wind sectors, there are 9 wind sectors in Busan.

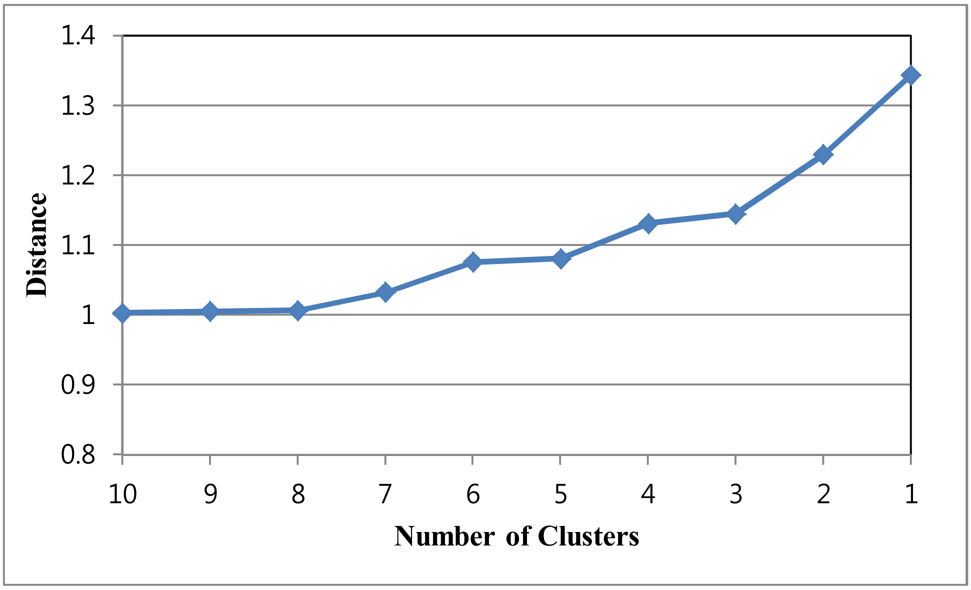


Fig. 5.6 Distance measure for each number of clusters in Busan.

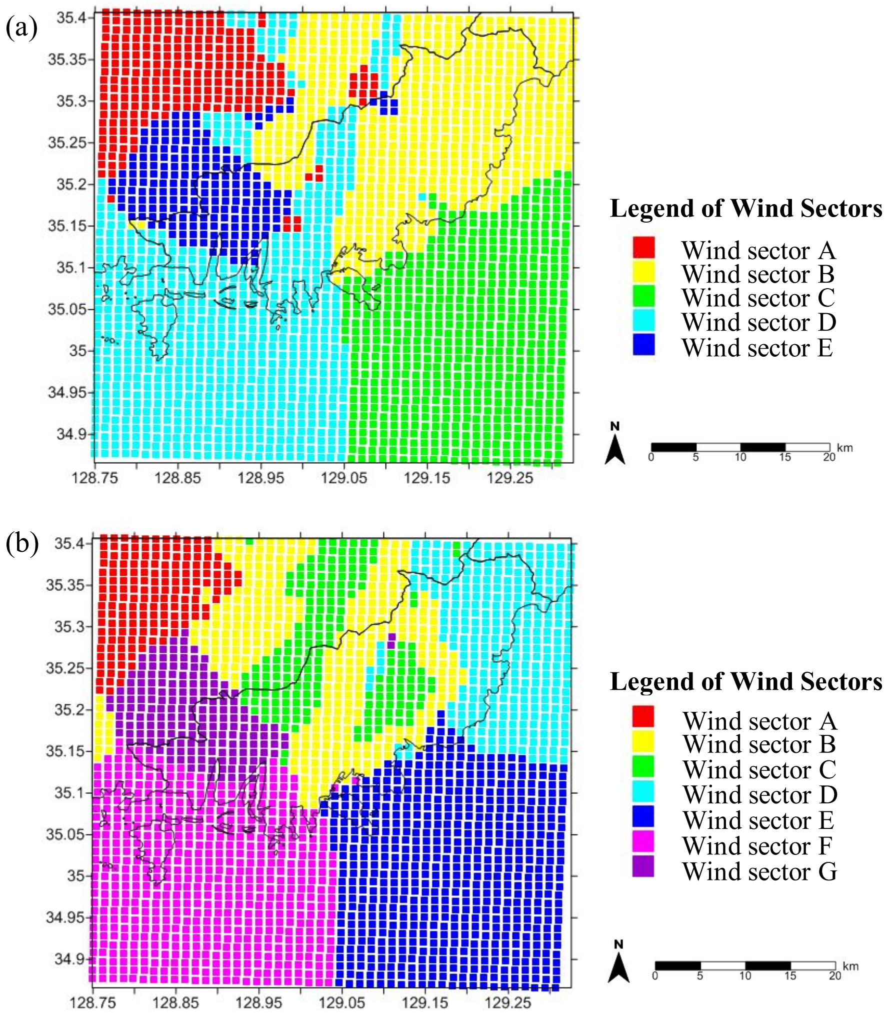


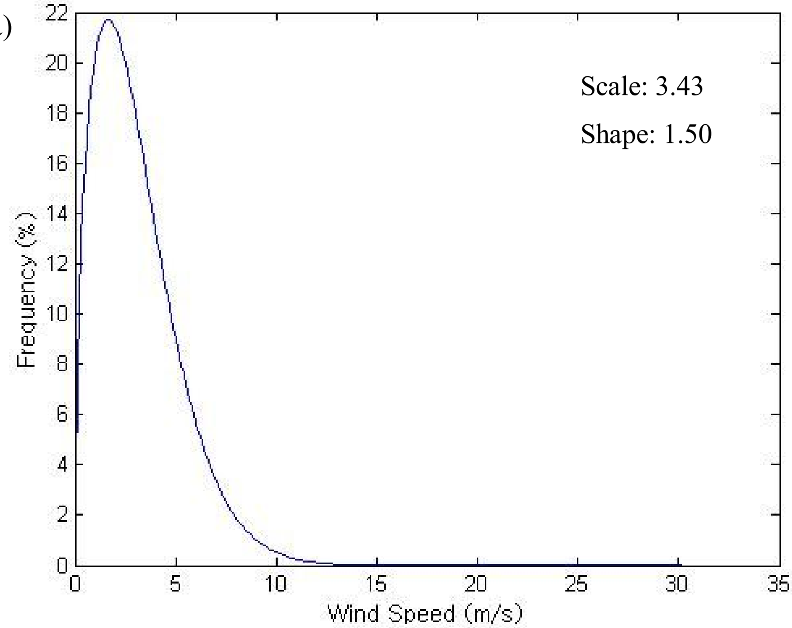
Fig. 5.7 Wind sectors in Busan.

(a) In 5 clusters. (b) In 7 clusters.

5.2.2 Wind characteristics in Busan

Wind sector A, which is located at the basin, has the lowest scale and shape parameter. Mean wind speed is the slowest and the most frequent wind speed appears at the slowest wind speed 1 m/s (Fig. 5.8 (a)). Scale and shape parameter of wind sector C is the next lowest value. Mean wind speed is relatively slow than other wind sectors in Busan. The most frequent wind speed is about 2 m/s (Fig. 5.10 (a)). Wind sector B and G has similar shape parameter. The most frequent wind speed is about 3 m/s. Wind speed ranges to about 15 m/s in wind sector B while it ranges to about 12 m/s in wind sector G. This is because wind sector B includes hills with high altitude which generally has faster wind. Thus mean wind speed is higher at wind sector B than G (Fig. 5.9 (a) and Fig. 5.14 (a)). Wind sector D, E and F includes the offshore region and its wind speed is relatively high. The most frequent wind speed is about 4-5 m/s, slowly rising to the peak. Mean wind speed is highest at wind sector E then F and G (Fig. 5.11 (a), Fig. 5.12 (a) and Fig. 5.13 (a)). Northwestern and northeastern wind is dominant in onshore. In wind sector A, B and G northwestern wind is prevailing (Fig 5.8 (b), Fig 5.9 (b) and Fig 5.14 (b)). In sector B and C, northeastern wind is dominant (Fig 5.9 (b) and Fig 5.10 (b)). Two prevailing wind direction appears in wind sector B. Northern wind is dominant is wind sector D (Fig 5.11 (b)). In wind sector E and F, wind coming from northeast, northwest, southwest is prevailing (Fig 5.12 (b) and Fig 5.13 (b)). Prevailing wind is more certain in wind sector E.

(a)



(b)

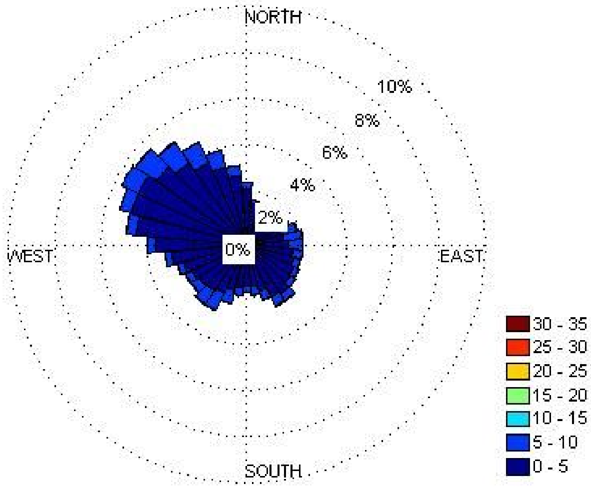
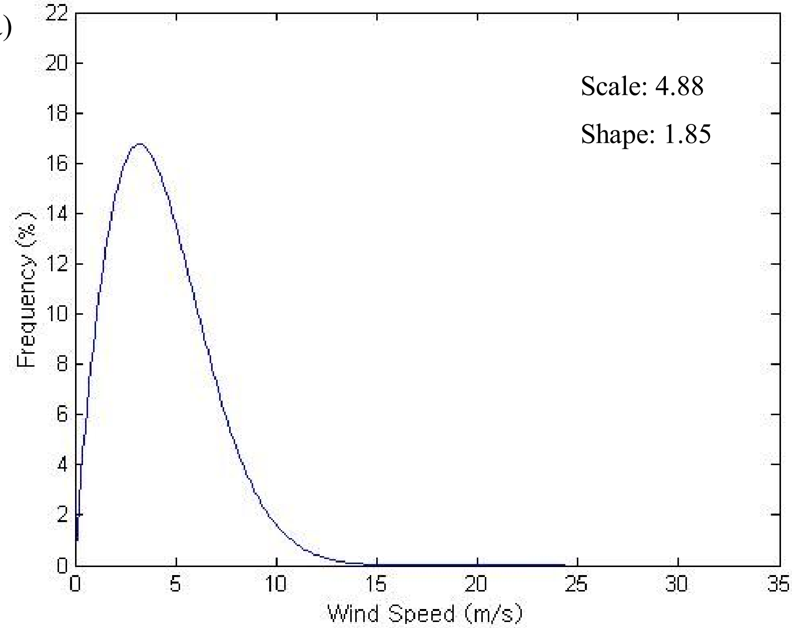


Fig. 5.8 Wind distribution of wind sector A in Busan

(a) Weibull distribution of wind speed. (b) Windrose.

(a)



(b)

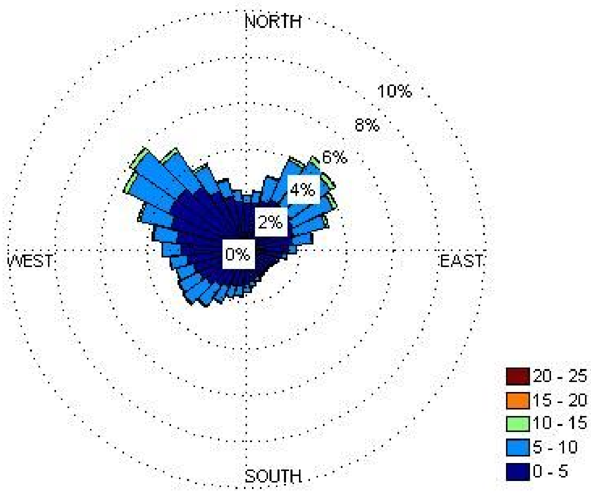
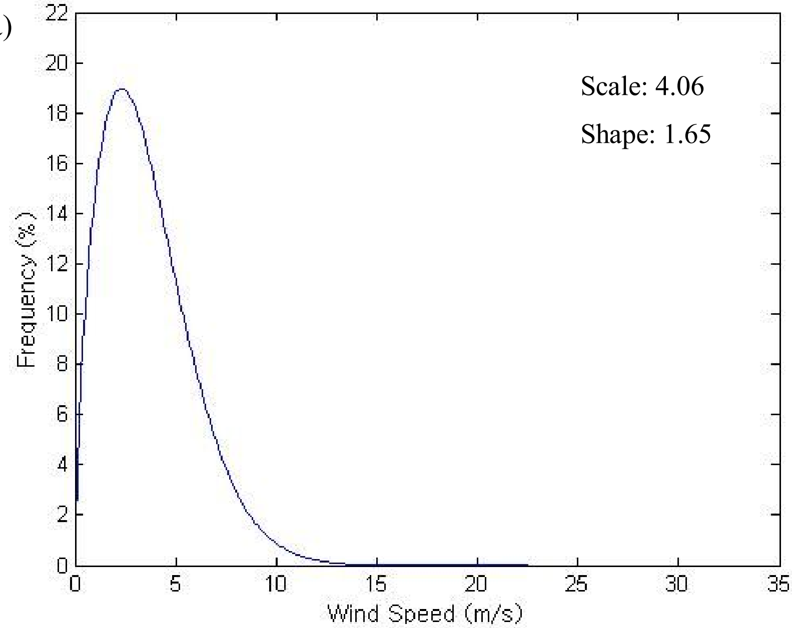


Fig. 5.9 Wind distribution of wind sector B in Busan
(a) Weibull distribution of wind speed. (b) Windrose.

(a)



(b)

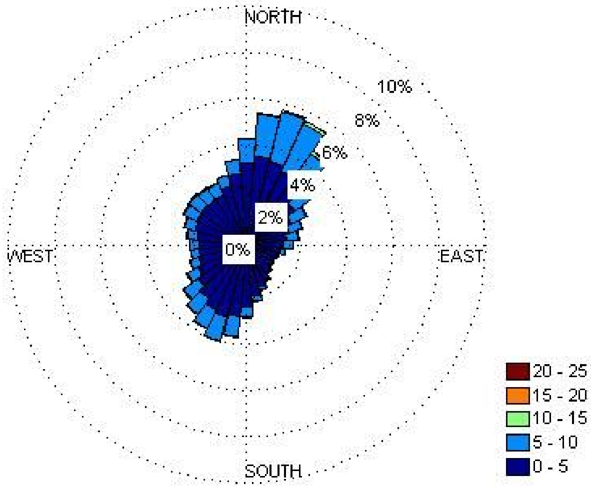
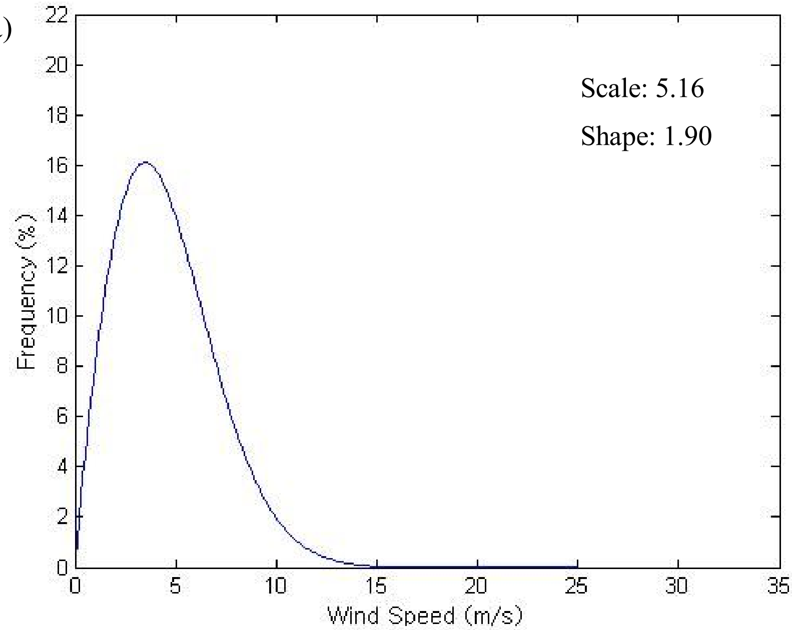


Fig. 5.10 Wind distribution of wind sector C in Busan
(a) Weibull distribution of wind speed. (b) Windrose.

(a)



(b)

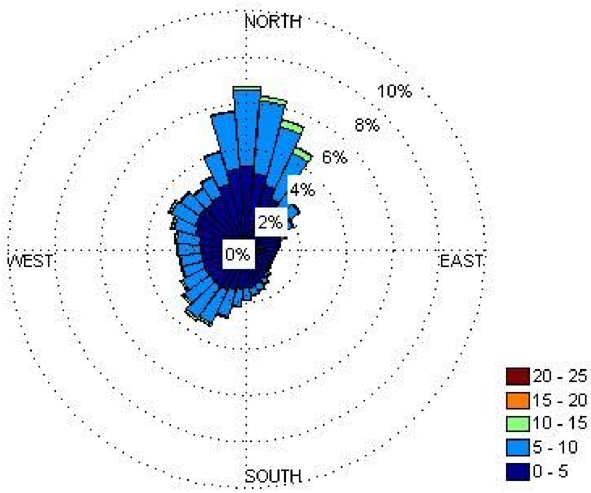
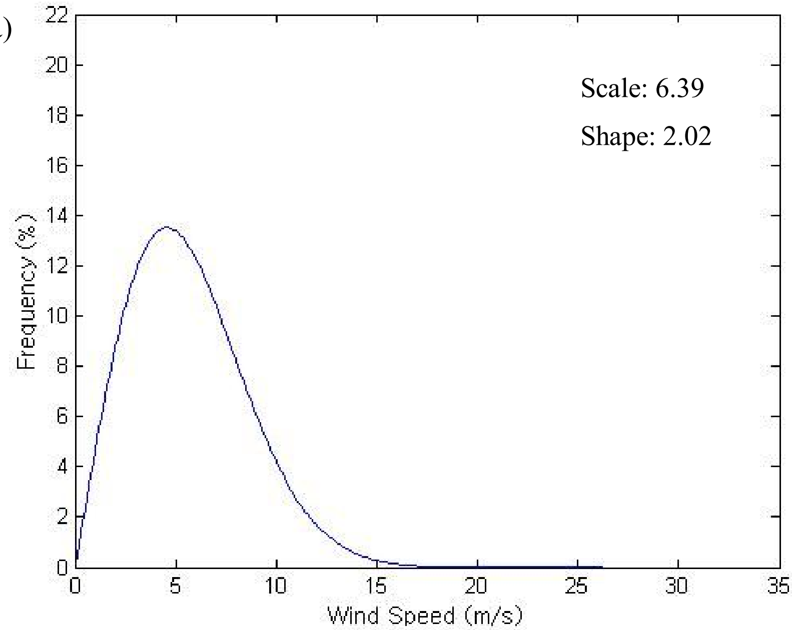


Fig. 5.11 Wind distribution of wind sector D in Busan

(a) Weibull distribution of wind speed. (b) Windrose.

(a)



(b)

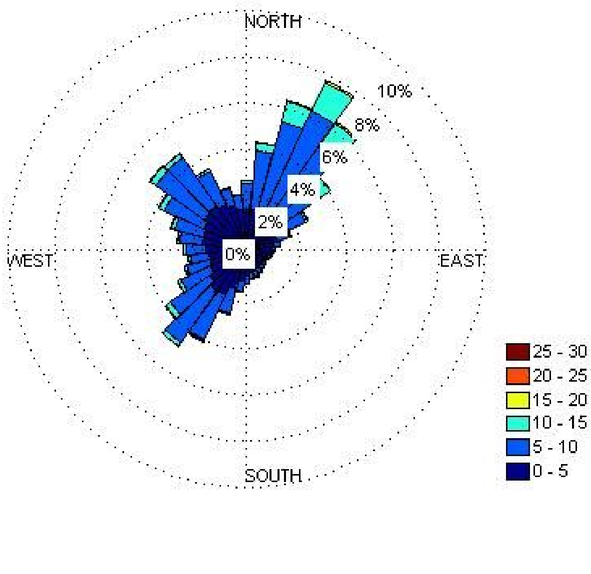
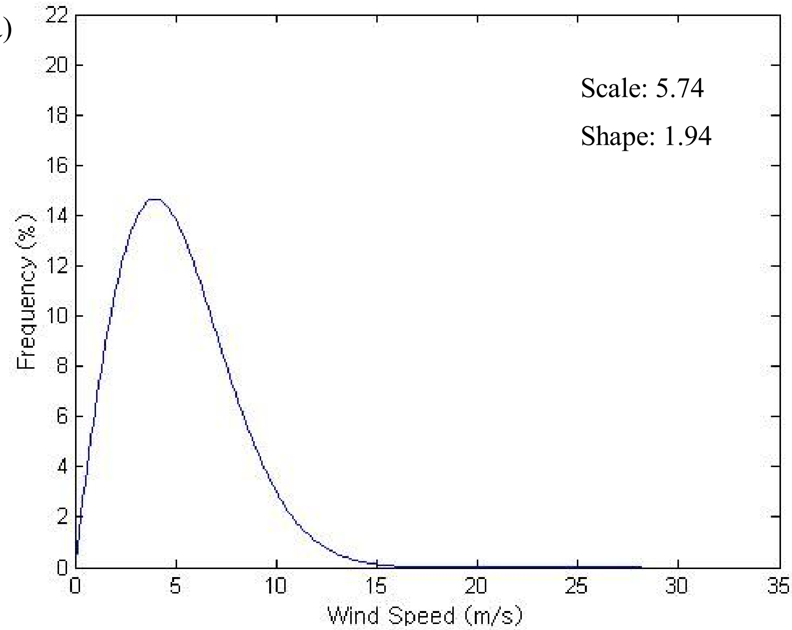


Fig. 5.12 Wind distribution of wind sector E in Busan

(a) Weibull distribution of wind speed. (b) Windrose.

(a)



(b)

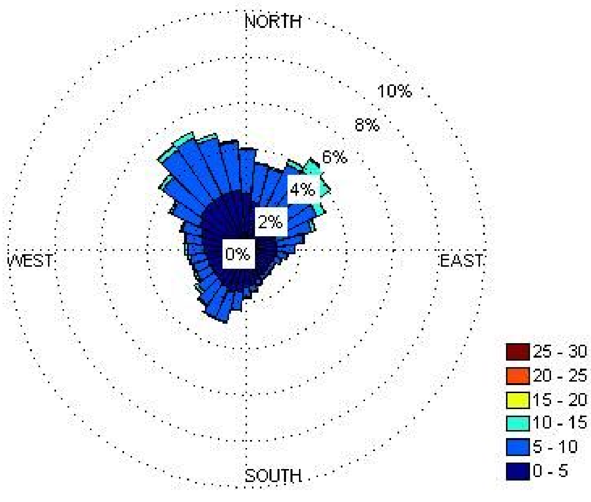
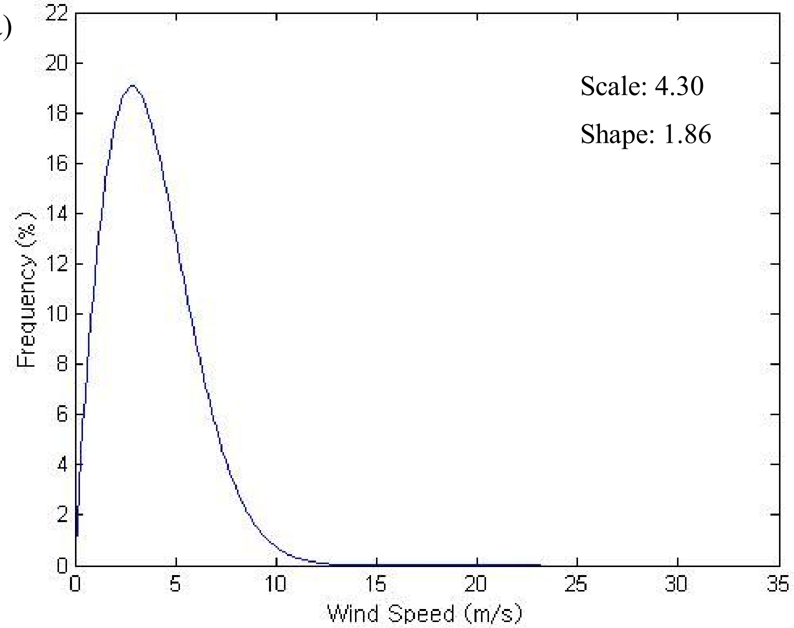


Fig. 5.13 Wind distribution of wind sector F in Busan
(a) Weibull distribution of wind speed. (b) Windrose.

(a)



(b)

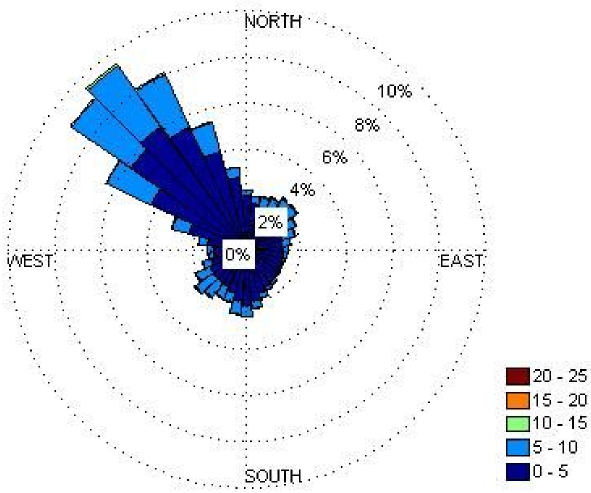


Fig. 5.14 Wind distribution of wind sector G in Busan

(a) Weibull distribution of wind speed. (b) Windrose.

5.2.3 Validity of wind sector classification in Busan

Mean wind speed, variance of wind speed, and variance of wind direction in each wind sectors are summarized in Table 5.7, 5.8, and 5.9. Prevailing wind direction was not analyzed to examine the validity of classification. Nodes classified in the same wind sector seem to have similar wind characteristic. Standard error is low in each wind sectors regarding mean wind speed, variance of wind speed, and variance of wind direction.

The result of Kruskal-Wallis ANOVA is presented in Table 5.10. The null hypothesis that all wind sectors has the same median at 5% significance level is rejected. At least one pair of wind sectors has different presentative values. *p*-values from post-hoc analysis are summarized in Table 5.11, 5.12, and 5.13. Even though wind sectors are classified by difference in wind directions or by difference in relative wind speed, mean wind speed is distinct in each wind sectors. Only wind sector C and G has similar mean wind speed. Variance of wind speed and wind direction is also different in each wind sectors. Wind sector A and G, wind sector B and D has equal wind speed variance. Wind sector B and D, wind sector D and E has equal wind speed variance. Considering wind speed variance and wind direction variance together, wind sector A and G, wind sector D and E can be distinguished. However, wind sector B and D is still not distinguished. Wind sector B and D has different mean wind speed and prevailing wind direction (Fig. 5.9 and Fig. 5.11). By considering mean wind speed and prevailing wind direction, wind sector B and D is distinguished. Classified wind sectors in Busan have different wind characteristics considering variance of wind speed, prevailing wind direction, and variance of wind direction.

Table 5.7 Statistics of mean wind speed in Busan.

	Wind sector	N	Mean	Std. deviation	Std. error	Min	Max
Mean wind speed	A	165	3.1	0.3228	0.0251	2.6	3.9
	B	350	4.3	0.5535	0.0296	3.2	5.6
	C	196	3.6	0.2363	0.0169	3.1	4.4
	D	330	4.6	0.4878	0.0269	3.7	5.5
	E	619	5.7	0.4307	0.0173	4.0	6.1
	F	598	5.1	0.6180	0.0253	3.6	6.0
	G	180	3.8	0.2966	0.0221	3.1	4.8

Table 5.8 Statistics of wind speed variance in Busan.

	Wind sector	N	Mean	Std. deviation	Std. error	Min	Max
Variance of wind speed	A	165	7.4435	1.9575	0.1524	3.4643	9.4457
	B	350	6.9969	1.8866	0.1008	2.7888	10.0182
	C	196	5.0566	0.9285	0.0663	3.2037	7.9327
	D	330	7.1725	1.7989	0.0990	3.8859	9.5665
	E	619	8.3723	1.0604	0.0426	3.9527	9.4593
	F	598	7.0762	1.3769	0.0563	3.8859	9.2270
	G	180	6.3577	1.8191	0.1356	3.8542	9.2270

Table 5.9 Statistics of wind direction variance in Busan.

	Wind sector	N	Mean	Std. deviation	Std. error	Min	Max
Variance of wind direction	A	165	0.7267	0.0293	0.0023	0.6454	0.9133
	B	350	0.7136	0.0473	0.0025	0.5640	0.9090
	C	196	0.7990	0.0815	0.0085	0.5837	0.9732
	D	330	0.7150	0.0407	0.0022	0.5521	0.8119
	E	619	0.7171	0.0166	6.6873e-04	0.6454	0.7709
	F	598	0.7362	0.0480	0.0020	0.6239	0.9428
	G	180	0.7033	0.0380	0.0028	0.5815	0.8675

Table 5.10 ANOVA table in Busan.

		Sum of squares	df	Mean square	Chi-sqaure	p-value
Mean wind speed	Between Groups	8.67557e+08	6	144592814.6	1750.79	0
	Within Groups	3.40034e+08	2431	139874.1		
	Total	1.20759e+09	2437			
Variance of wind speed	Between Groups	6.89615e+08	6	114935870.8	1391.69	1.52597e-297
	Within Groups	5.17976e+08	2431	213071		
	Total	1.20759e+09	2437			
Variance of wind direction	Between Groups	2.54269e+08	6	42378160.5	513.13	1.24611e-107
	Within Groups	9.53322e+08	2431	392152.1		
	Total	1.20759e+09	2437			

Table 5.11 *p*-values of mean wind speed comparison in Busan.

	A	B	C	D	E	F	G
A	0.0000						
B	0.0000	0.0000					
C	0.0280	0.0000	0.0000				
D	0.0000	0.0080	0.0000	0.0000			
E	0.0000	0.0000	0.0000	0.0000	0.0000		
F	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
G	0.0000	0.0000	0.3204	0.0000	0.0000	0.0000	0.0000

Table 5.12 p-values of wind speed variance comparison in Busan.

	A	B	C	D	E	F	G
A	0.0000						
B	0.0000	0.0000					
C	0.0000	0.0095	0.0000				
D	0.0000	0.3707	0.0000	0.0000			
E	0.0000	0.0000	0.0000	0.0000	0.0000		
F	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
G	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 5.13 *p*-values of wind direction variance comparison in Busan.

	A	B	C	D	E	F	G
A	0.0000						
B	0.0000	0.0000					
C	0.0000	0.0000	0.0000				
D	0.0000	0.0581	0.0000	0.0000			
E	0.0000	0.0386	0.0000	1.0000	0.0000		
F	0.0296	0.0000	0.0000	0.0000	0.0000	0.0000	
G	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Chapter 6. Conclusion

In this study, a wind sector classification method was proposed to more clearly describe the local wind system. The key point of this study is summarized in the following.

(1) Wind sector classification method based on spatial similarity of wind vector using hourly wind data was developed. Wind sectors are classified by the similarity of wind directions and by the similarity of relative wind speed.

(2) Appropriate number of clusters is determined from the change of distance measure. However, this decision refers to the classification result. It has to be confirmed whether the classification result corresponds well to the topographic characteristic.

(3) Nodes in the same wind sector have similar wind characteristics regarding mean wind speed, variance of wind speed, and variance of wind direction. Prevailing wind direction was not compared because of the difficulties in selecting prevailing wind direction by simple codes.

(4) All wind sectors have distinct wind characteristics, considering mean wind speed, variance of wind speed, prevailing wind direction and variance of wind direction together. However, wind sectors are not different when only one wind characteristic is compared.

(5) The classification method was applied to study area with relatively simple and another study area with complex topography. Similarity in the same wind sector and distinct wind characteristics of each wind sectors were confirmed. From these results, the general validity of wind sector classification method was verified.

(6) Wind sector classification results from the developed classification method can be used to understand the local wind system and to conduct an accurate wind resource assessment.

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초 록

풍력자원평가를 위해서는 바람 관측이 수행된다. 복잡한 지형에서는 풍속과 풍향의 일률성이 현저하게 낮아지며 국지적인 풍계가 형성된다. 따라서 정확한 풍력자원평가를 위해서는 국지 풍계에 대한 정확한 파악이 선행되어야 한다. 본 연구에서는 매시간 바람벡터의 유사성을 이용한 군집분석을 적용하여 국지 풍계에 대한 정보를 획득하는 바람권역 분류 기법을 제시하였다. 풍력자원지도 자료를 이용하여 바람권역 분류를 수행하고 바람권역 분류 기법의 타당성을 평가하였다.

비교적 지형이 단순한 제주도와 복잡한 부산에 대해 바람권역 분류를 수행하였다. 그 결과, 연구지역의 지형 및 국지 풍계와 일치하는 바람권역을 얻을 수 있었다. 또한, 같은 바람권역으로 분류된 지점들의 바람 특성이 일률적 나타났으며, 서로 다른 바람권역은 바람 특성에 차이가 있는 것으로 나타났다. 따라서 바람권역 분류 기법의 타당성을 확인할 수 있었다.

본 연구에서 제시한 바람권역 분류 기법은 국지 풍계를 파악하는데 도움이 될 것이며, 풍력자원평가를 위한 기초자료로 사용될 수 있을 것으로 기대한다.

주요어: 풍계, 바람권역, 군집분석, 풍력자원평가
학 번: 2013-21010