Study of Atmospheric Dispersion Factors for Radiological Analysis at YONGGWANG (HANBIT) Site in KOREA

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Abstract. In order to estimation the safety of NPPs (Nuclear Power Plants), air pollution models have been studied by the IAEA, NRC, and EPA. The purpose of this study is to develop a more efficient methodology for explaining the atmosphere behavior characteristic and the radiation dose characteristic depending on the atmospheric stability. Generally, Lagrangian, Eulerian or Gaussian models have been used to explain the air pollution behavior in NPPs. These models include various methods to determine the stability of the atmosphere. Furthermore, the models are very important to estimate the radiation dose due to the proportional increase by the atmospheric dispersion factor. In this study, various models and simulations are reviewed. In addition, the respective methodologies are applied to the YONGGWANG site to identify benefits. The key parameters of major atmospheric stability by classification methods are evaluated. Using the meteorological data obtained by the data acquisition system of the YONGGWANG site, various atmospheric stability, dispersion factors, and correlation factors of radiation dose are estimated and confirmed. Pasquill's classification method is the most widely used basic methodology and shows good agreement with a steady state and the reason is due to rapid response condition under timely stability by heating or cooling caused by daily insolation or nocturnal surface radiation. In this study, from a comparison of modeling results, we find that the horizontal and vertical standard deviations of the wind fluctuation method is good response both stable condition and unstable condition. In this study, the classification matrix methodology of Vogt's vertical temperature difference and wind speed is modified for practical use at the YONGGWANG site. From this study, it is also confirmed that the methods using the bulk Richardson number and Vogt's modified graphs are very useful in classifying atmospheric category. Using RG 1.23, modified tables for delta T and wind speed U and the Richardson method were prepared by calculating the reasonable joint frequency distribution from Pasquil's method and other existing results. From the obtained results, the inclusive correlation coefficient (r) was equal to 0.931. The results of radiation dose are proportional to atmospheric dispersion factors. This study carried out various methodology comparisons and establish an optimized methodology.

From this study, the best estimation methodology selected as the delta T and wind speed. In this study, each atmospheric stability method is compared and the key parameters are checked in the case of wind speed, stability, and wind direction. Key parameters are the delta T and the wind speed. In this study, various comparison results of each model are introduced.

KEYWORDS: Atmospheric dispersion factors, Stability, Radiation Dose, ICRP, FGR, NRC.

1 INTRODUCTION

Air pollution models have been studied by the IAEA, NRC, FGR, and EPA [1-8]. These models are useful tools for evaluating emission rates and quantifying adverse pollutant effects in specific regions. The aim of this study is to develop a more efficient methodology of explaining the behavior of the atmosphere using a stability measure. Lagrangian, Eulerian, and Gaussian air pollutions models are available. The Gaussian dispersion models are usually used in estimating atmospheric stability. In the Gaussian model, stability and mixing height are two important dispersion parameters for the calculation. Ideally, hourly input parameters for these models should be calculated from measurements. The atmospheric stability is calculated by determining the turbulence condition using the effect of diffusion and mixing influenced by the methodological phenomena and the air mechanical behavior [9-15]. In particular, a local dimensional Gaussian-type atmospheric diffusion model essentially includes the stability factor. The first study and the improved method were carried out by Cramer in 1957, Pasquil in 1961 and 1967, Vogt's research in 1971, and other groups [16-19]. Notably, a computational method, fitting method, correction graph, and simulation method were respectively studied by Eimutis, Riopelle, and Stubley from 1972 to 1988 [2,16-18]. The methodologies employ wind speed, radiation from the sun, night, and cloud clusters. In detail, the important factors for calculating atmospheric stability are wind speed, standard deviation of wind direction, temperature difference of vertical levels, sunlight, surface radiation, cloud stay time (or cloudiness), cloud height, atmospheric thermal flux, and surface roughness. According to the classification method, these data can be used for calculating stability directly or indirectly.

At present, this concept is generally used for the calculation of atmospheric stability. In this study, Pasquil's method, the wind direction-standard deviation method, vertical temperature difference method, Richardson number method, and wind and vertical temperature method are used and compared with one another. This study is focused on the relation between stability and the atmosphere dispersion factor.

Stability is used for calculating the dispersion factor in most cases. Pasquil stability classes describe the intensity of turbulence by dividing it into seven categories (A, B, C, D, E, F, G)[1-8]. The purpose of this study is to find the best method to determine the atmospheric stability. First, the best estimation and classification method will be selected and the method is completed by modifying and improving the current stability method. In this paper, a new method is introduced.

2 STABILITY METHODS

2.1 Pasquill's Stability

Pasquill's stability class is shown in Tables 1 and 2. The method is dependent on sunlight (cloud stay time at night) and wind velocity. Stability classes describe the impact of atmospheric turbulence in seven categories: A (extremely unstable), B (moderately unstable), C (slightly unstable), D (neutral state), E (slightly stable), F (moderately stable), and G (extremely stable). Because of the advantages to exactly describe seasonal atmospheric stability and to simply collect weather data, this classification method is usually used. However, this method includes some uncertainty. In the case of daytime, Pasquill's stability is controlled by Table 1 and Table 2 for daytime and night time.

Table 1 : Stability based on sunlight

Surface wind speed (m/sec)	Day time		
	Strong	Moderate	Slight
2	A	A-B	B
4<U≤2	A-B	B	C
6<U≤4	B	B-C	C
4<U≤6	C	C-D	D
6<U	C	D	D

Table 2 : Stability based on Cloudiness

Surface wind speed (m/sec)	Night time		
	Thin	Moderate	Heavy
2	E	-	G
4<U≤2	E	-	F
6<U≤4	D	-	E
4<U≤6	D	-	D
6<U	D	-	D

From Tables 1 and 2, the main shortcoming of Pasquill's method is that the stability fluctuation shape is changed into a catastrophic shape close to sunset and at night. For example, before and after sunset and sunrise, stability B is changed into stability E or G. This is due to not considering the effect of the atmosphere-thermal cavity. Therefore, in this study, to address the weakness of Pasquill's method, we applied Turner's calculation method based on cloudiness (cloud stay time at night) and cloud height and level.

2.2 Wind Fluctuation (CF : Combined Fluctuation)

In this study, wind fluctuation is denoted as CF (Combined Fluctuation, considering vertical and horizontal wind direction deviation) in order to simplify the notation of wind fluctuation. If the standard deviation of the wind direction is greater than the typical condition, air pollutants will spread into the atmosphere. This is an unstable atmospheric condition. Also, the standard deviation of the wind direction is very important to calculate the atmospheric dispersion factor and the atmospheric stability. According to Cramer's study in 1957[6], this method is deeply related to the spread distance of air pollutants and is strongly affected by atmospheric stability. Originally, this method entails calculations considering the degree of diffusion of both the vertical direction and horizontal direction, and therefore the vertical standard deviation (δ_E) and the horizontal standard deviation (δ_θ) of the wind direction are usually used. But the vertical standard deviation (δ_E) is very difficult to detect. Generally, in the NRC method, the horizontal standard deviation (δ_θ) is used for determining stability. In this study, the Irwin methodology is applied to calculate the vertical standard deviation of the wind direction. Irwin's method derives the vertical wind deviation from the wind velocity. Using this method, we calculate the vertical wind deviation from the horizontal wind deviation and wind speed between 10m and 60m height. The method is delineated as follows:

$$(\delta_E) = (\delta_\theta) / \triangle U \qquad (1)$$

where $\triangle U$ is the wind velocity difference between 10m and 60m height.

2.3 Vertical Temperature and Wind Speed (△T•U: Delta T U)

Delta T and U (vertical temperature and wind velocity method) uses the temperature difference between two layers of atmosphere and horizontal diffusion by the wind velocity difference between these two layers (height levels 10m and 60m). This method is very useful to estimate and classify the stability exactly using very simple data sampling. In this study, we applied Vogt's research results and modified Vogt's table using a correction graph. Finally, the relation between wind speed (U) and temperature rate ($\triangle T/\triangle Z$) is changed into a new correction graph by using a database of meteorological factors of the YONGGWANG site (see Figure 1 of section 3).

2.4 Richardson Number

The classification method by Richardson number is based on temperature and wind velocity data between two layers of the atmosphere. The method is very similar to the delta T U method. However, it is not dependent on the stability matrix and is dependent on the correction equation. Equation (2) defines the gradient Richardson number (Rx) and a negative value indicates that the diffusion term by convection is greater than the diffusion term by advection. Otherwise, a positive value indicates that any given vertical diffusion term is zero. Generally the Richardson number is expressed as given below:

$$Rx = g(\partial\theta/\partial Z)/[T(\partial u/\partial Z)^2] \qquad (2)$$

where θ is the temperature gradient (K), Z is the layer (height level of atmosphere, m), and g is gravitational acceleration (9.8m/sec). T is the normalized temperature of the atmosphere (K). But the results yielded by this equation are proportional to the square of the wind velocity U difference between two layers of atmosphere and are too sensitive to the behavior of U. The sensitiveness is affected by the accuracy of the detector recording the wind velocity. Also, the state of the atmosphere is not always homogeneous, and the non-homogeneous characteristics may lead to errors in the calculation. These are caused by the surface roughness. In this study, in order to diminish these errors, the Bulk Richardson number method is applied as given below:

$$Rb = [\, g(\partial\theta/\partial Z)/[T(U)^2]]\, Z^2 \qquad (3)$$

2.5 Vertical Temperature (△T/△Z: DeltaT/DeltaZ)

This is known as the NRC method. This has been studied by DeMarrais and Touma from 1958 to 1977. Generally, only the temperature difference between two layers (height levels 10m and 60m) of the atmosphere is used for classifying stability. This method is similar to the delta T U method when the correlation coefficient is more than 0.75 (see Table 3).

2.6 Horizontal Wind Fluctuation (δ_θ : Sigma Theta)

This method is referenced from section 2. 2. Generally, only the horizontal direction is considered for the wind fluctuation standard deviation. This method involves a very simple model and is useful to classify the stability from a simple data set (see Table 3).

In TABLE 3, △T/△Z and δ_θ are reflected to Pasquil stability at both levels of 10m and 60m. The basic categories of stability are selected by the NRC method, referenced from R.G.(Regulatory Guide) 1.23 and R.G. 1.145.

These classification methods have greater conservatism than any other methods of classifying atmospheric stability.

Table 3 : Stability based on △T/△Z and δ_θ

Pasquil Stability	Temperature (△T/△Z,℃/100m)	Wind direction Standard deviation (δ_θ, angle)
	Range	Range
A	△T/△Z≤-1.9	22.5≤δ_θ
B	-1.9<△T/△Z≤-1.7	17.5≤δ_θ<22.5
C	-1.7<△T/△Z≤-1.5	12.5≤δ_θ<17.5
D	-1.5<△T/△Z≤-0.5	7.5≤δ_θ<12.5
E	-0.5<△T/△Z≤1.5	3.8≤δ_θ<7.5
F	1.5<△T/△Z≤4.0	2.1≤δ_θ<3.8
G	4.0<△T/△Z	δ_θ<2.1

3 STUDY STRATEGY

Stability classes describe the impact of atmospheric turbulence in seven categories: A (extremely unstable), B (moderately unstable), C (slightly unstable), D (neutral state), E (slightly stable), F (moderately stable), and G (extremely stable). For the stability calculation, six methods are considered and compared to find the most useful method. Most importantly, we consider the △T·U method to be the best candidate, because it has the characteristic of a dynamical term of wind speed and a statistic term of △T.

3.1 Methodology and Classification Cases

We consider the following cases to determine the best method:
Case01: Pasquill’s methodology

Case02: Wind fluctuation (CF: δ_E, δ_θ)
Case03: Vertical temperature and wind speed (△T•U)
Case04: Richardson number (Rx) and
Bulk Richardson number (Rb)
Case05: Vertical temperature (△T/△Z)
Case06: Horizontal wind fluctuation (δ_θ)

Case 01 determines the stability based on the day time, night time, and cloudiness.
Case 02 determines the stability based on the vertical wind and the horizontal wind.
Case 03 determines the stability based on the vertical temperature gradient and the wind.
Case 04 determines the stability based on the equation derived from Richardson's methodology.
Case 05 determines the stability based solely on the vertical temperature difference rate.
Case 06 determines the stability based solely on the horizontal wind fluctuation.
Cases 01 and Case 05 are specified by low wind speed or zero wind speed.
Case 02 and Case 06 are specified by dynamical behavior of wind or atmosphere.

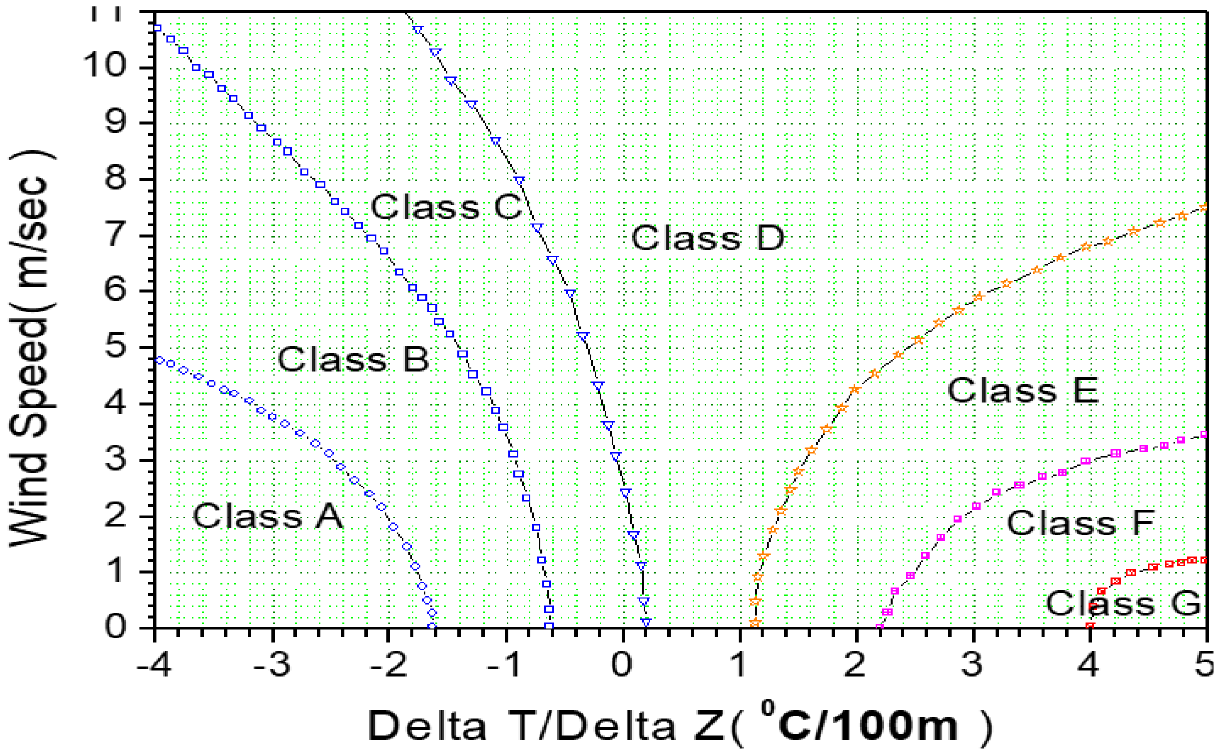
Case 03 and Case 04 are specified by both dynamical and statistic behavior of the atmosphere. Case 03 is focused on the relation between wind speed and vertical temperature gradient. Also, Case 03 is referenced from Vogt's study of FRG report Jul-708-ST. The data set used for the stability methods is introduced in the modified graph in Figure 1.

In case 01~case 06, the Richardson method, wind fluctuation method, vertical temperature method, and Pasquil's method are compared by matching data.

Pasquil's method depends on the cloud and sunlight during a given day. The △T/△Z method is called the vertical temperature method and the wind speed effect is not considered.

Fig.1 shows the relation of wind speed (U) and temperature rate (△T/△Z) based on the meteorological data base of the YONGGWANG site during three years from 2017 to 2019. Figure1 is modified from Vogt's correction graph and is used for calculation using a modified form of Vogt's methodology.

Figure 1 : Wind Speed and Vertical Temperature.



The methodology of Figure 1 is applied to evaluate the atmospheric dispersion factor in an OPR1000 nuclear power plant. The meteorological input data consist of the wind speed, vertical temperature gradient, wind direction standard deviation, and joint frequency at the YONGGWANG site.

3.2 Input Date Base

The data used in this study are from a three-year period. Table 4 provides a summary of the specifications of the data used in this study. The data set is given below:

Table 4 : Input Data in YONGGWANG Site for Atmospheric Stability

Classify	Height	Atmospheric Data			Period
		Wind Direction	Temp.	Other Parameter	
Pasquil	60m	-	-	Cloud, Sunlight	2017 ~ 2019
$\triangle T/\triangle Z$	10m, 60m	-	10m, 60m	-	
$\triangle T \cdot U$	10m, 69m	-	10m, 60m	Wind Speed (10m, 60m)	
(δ_θ), angle	60m	60m	60m	-	
(CF: δ_E,δ_θ)	10m, 60m	60m	60m	Wind Speed (10m, 60m)	
Rb	10m, 60m	-	10m		

The $\triangle T \cdot U$ method was developed by the IAEA (International Atomic Energy Agency) and Vogt's study of FRG report Jul-708-ST [1, 3]. It considers both wind speed and atmospheric temperature effects. The δ_θ method is equivalent to the wind fluctuation method. In this method, atmospheric temperature is not considered. For Rb, Richardson number method or Bulk Richardson number method, all parameters are very similar to those of the $\triangle T \cdot U$ method.

In this study, in order to use the $\triangle T \cdot U$ method, we categorize the vertical atmosphere temperature and the wind speed to estimate the atmospheric stability estimation of YONGGWANG site. In addition, we make the input material from methodological information.

The meteorological input data consist of the wind speed, vertical temperature gradient, wind direction standard deviation, and joint frequency in the YONGGWANG site. As in Table 4, the data used in this study are collected in the three year period from 2017 to 2019.

4 RESULTS AND DISCUSSION

4.1 Comparison with SRP methodology

In this section, the stability classification method and the estimated results are introduced.
Figure 2 indicates that $\triangle T \cdot U$ is more similar to the frequency trend of δ_θ than to the frequency trend of $\triangle T/\triangle Z$. δ_θ is used to explain the dynamical behavior of atmospheric stability. However, $\triangle T/\triangle Z$ is used to explain the statistic behavior. In this case, the only similarity between $\triangle T \cdot U$ and $\triangle T/\triangle Z$ is found in the range of less than 3m/sec of wind velocity because $\triangle T/\triangle Z$ cannot explain the dynamical behavior of the atmosphere.

Table 5 shows that $\triangle T \cdot U$ is in good agreement with $\triangle T/\triangle Z$ in the range of low wind speed of less than 1.5m/sec. However, with strong effects of wind (higher than 1.5m/sec of wind speed), the $\triangle T \cdot U$ method is very similar to the δ_θ method. These results show that the stability of the atmosphere is greatly influenced by the wind condition. In addition, Table 6 shows that $\triangle T \cdot U$, Rb, and CF are in good agreement with one another in the full range of wind speed. These results show the three methods are based on calculations reflecting the dynamical and static behavior of the atmosphere.

From Table 5 and Table 6, $\triangle T/\triangle Z$ method is agreement with only static state. Otherwise, $\triangle T \cdot U$ method and CF method is good agreement with full range wind speed, every category of the atmosphere stability. Thus, $\triangle T \cdot U$ is the good method to replace the $\triangle T/\triangle Z$ method.

Figure 2 : Comparison of stability methods

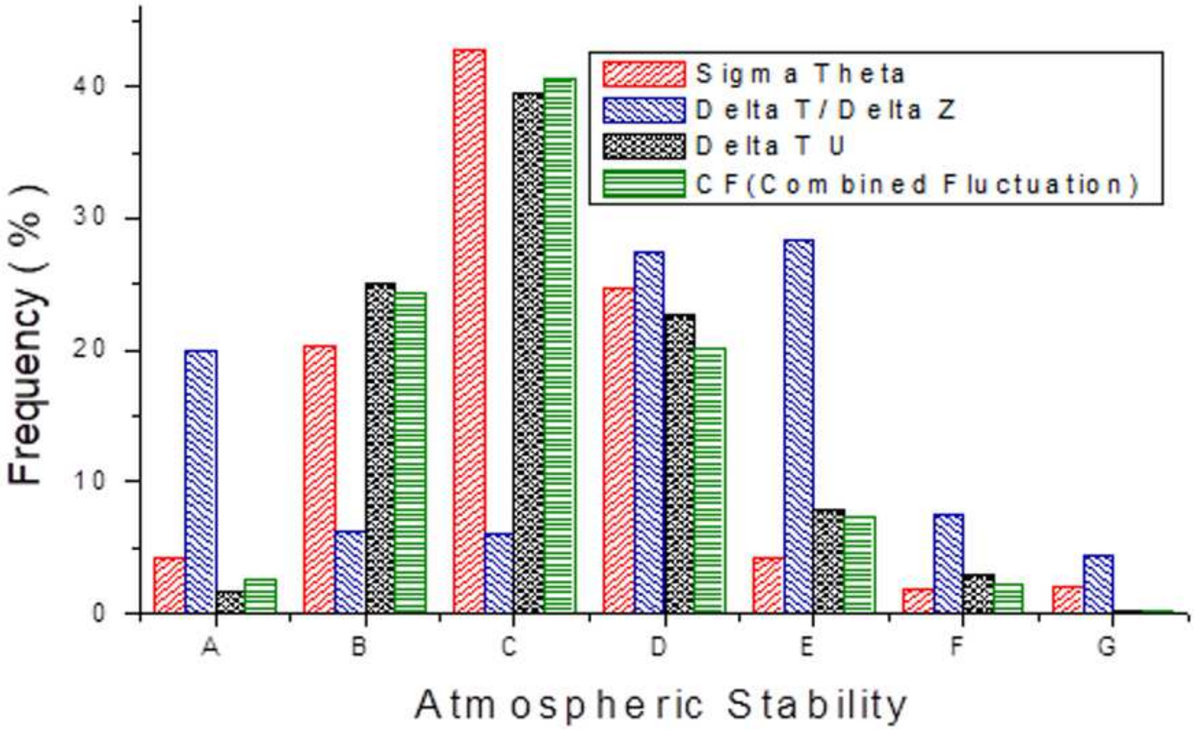


Table 5 : Correction on △T/△Z, δ_θ , and △T·U

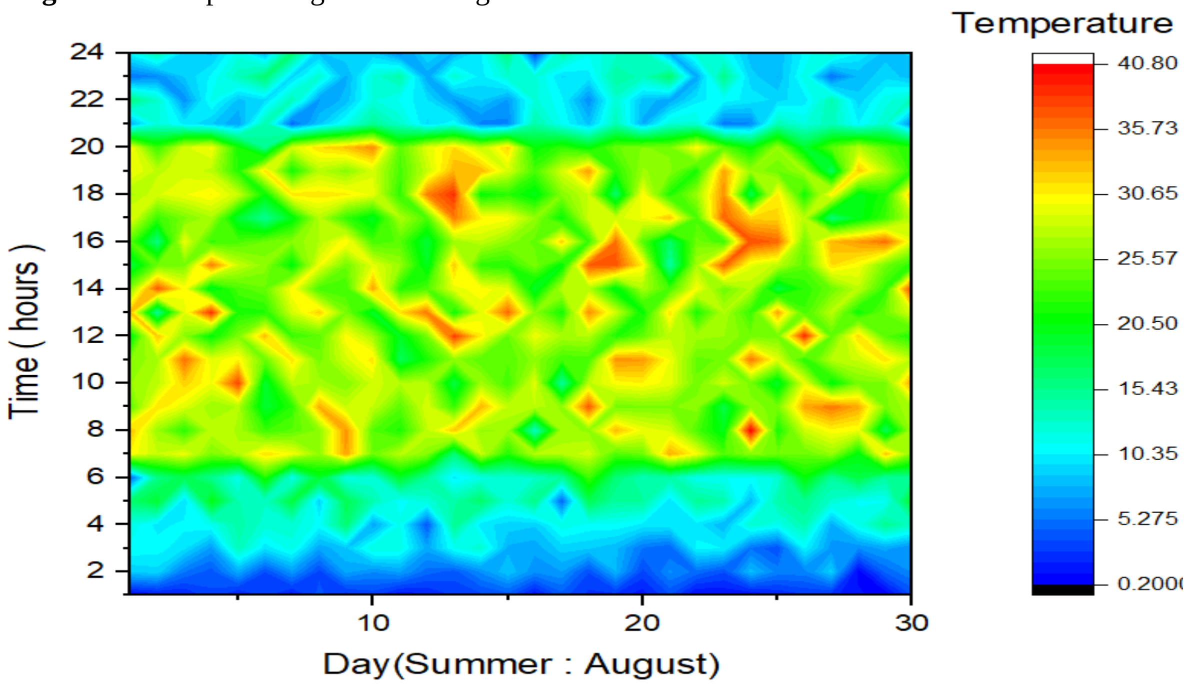
Wind Speed (m/sec)	(△T/△Z) vs (△T·U)	δ_θ vs (△T·U)
	Correlation coefficient	Correlation coefficient
1～1.5	0.95	0.32
1.5～3	0.78	0.46
3～5	0.43	0.87
5～8	0.33	0.96
8～	0.30	0.98

Table 6 : Correction on Rb, CF (δ_θ ,δ_E) and △T·U

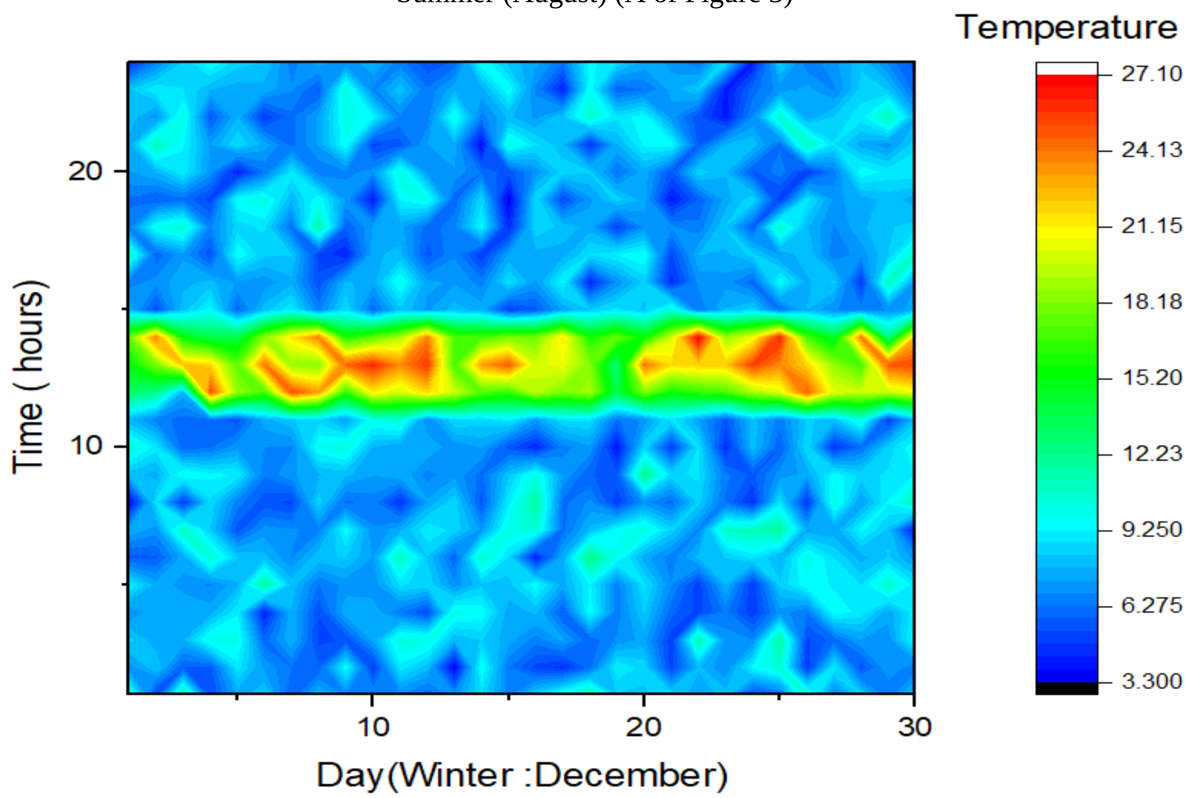
Wind Speed (m/sec)	Rb vs (△T·U)	CF vs (△T·U)
	Correlation coefficient	Correlation coefficient
1～1.5	0.85	0.93
1.5～3	0.79	0.91
3～5	0.84	0.89
5～8	0.82	0.96
8～	0.91	0.97

In order to find the characteristics of the atmospheric behavior, seasonal temperature and wind speed are checked in terms of time vs. day for several months. The results are presented in Figures 3 and 4. These results show that the temperature difference between two layers of atmosphere is proportional to seasonal characteristics. However, wind speed (wind velocity) is independent of seasonal specification, as seen in Figures 3 and 4. This shows that wind speed frequency is homogeneous over 24 hours. A and B of Figures 3 are temperature trends during 24 hours. From Figure 3, the temperature distribution is non-homogeneous in each time area over 24 hours. In addition, B of Figure 3 is colder than A of Figure 3. Their distributions of temperature are remarkably different. But Fig.4 shows that the temperature effect can be neglected when comparing A with B in Figure 4 for the maximum value of wind speed during 24 hours. According to Table 6, the terms of wind speed can explain the stability in seven categories. The results of Figure 4 are equivalent to the results of Table 6. From these results, we infer that wind speed controls the stability of the atmosphere.

Figure 3 : Temperature gradient during annual season

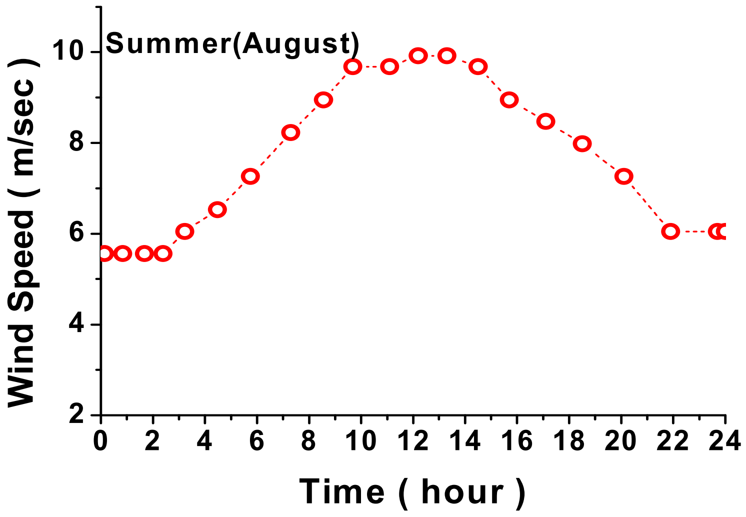


Summer (August) (A of Figure 3)

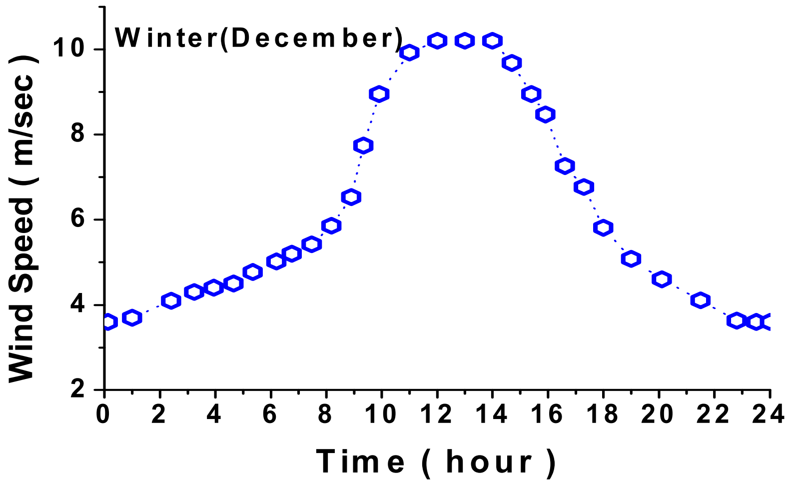


Winter (December) (B of Figure 3)

Figure 4 : Average wind speed (velocity) during 24 hours(Summer, Winter)



(A of Figure 4)



(B of Figure 4)

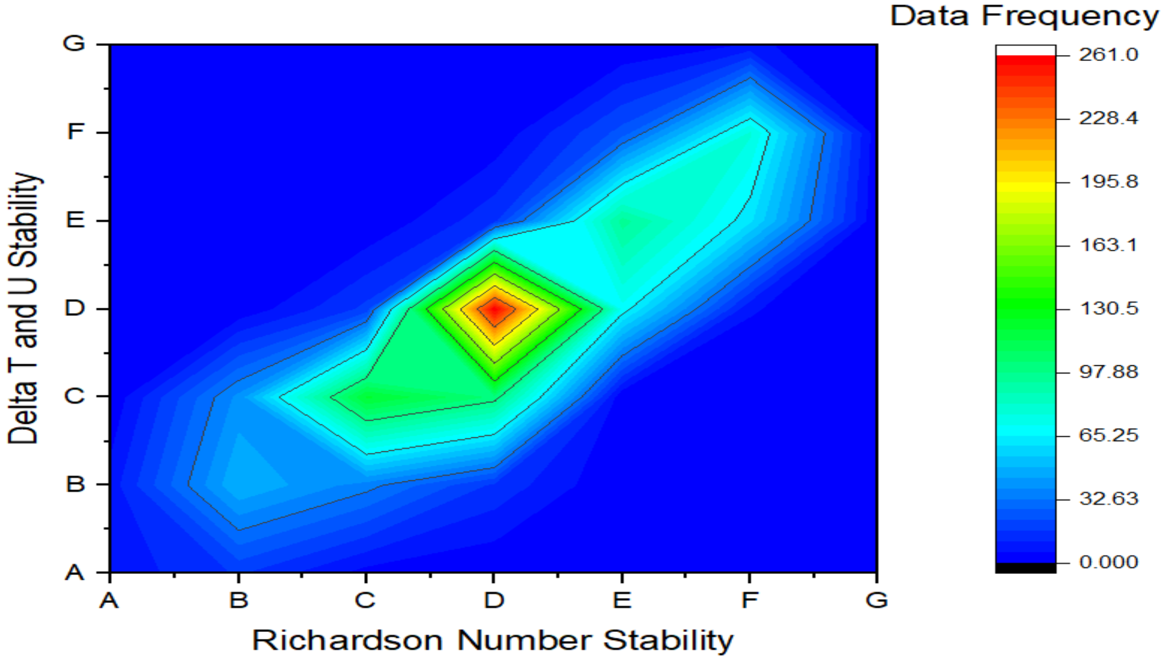
In this section, the stability classification method and estimated results are introduced in Figure 5. Figure 5 is the detailed correlation graph in the seven categories of stability for each stability comparison. Also, the results of Table 5 and 6 are included in Figure 5.
In Figure 5, the equivalent data numbers compared in each category of seven stability (A, B, C, D, E, F, G) are written in each box of the graphs.
$\triangle T \cdot U$ is in good agreement with Rb in seven categories of atmospheric stability. In the same manner, comparing $\triangle T \cdot U$ with CF, both methods are in good agreement in seven categories of atmospheric stability. In comparison between $\triangle T \cdot U$ and vertical temperature, the correlation coefficient of E, F, and G stabilities is 0.90. In the case of horizontal wind fluctuation, the correlation coefficient of A, B, and C is 0.945. In Pasquil's method, the correlation coefficient of D is 0.88.

From these results, in the $\triangle T \cdot U$, Rb, and CF method, the total correlation coefficient (r) is calculated by the root square fitting method. In this study, the inclusive correlation coefficient (r) is 0.931. These results are based on the comparison between $\triangle T \cdot U$ and CF and the comparison between $\triangle T \cdot U$ and Rb presented in Figure 5 (see Figure 5, Comparison of Stability Methods).

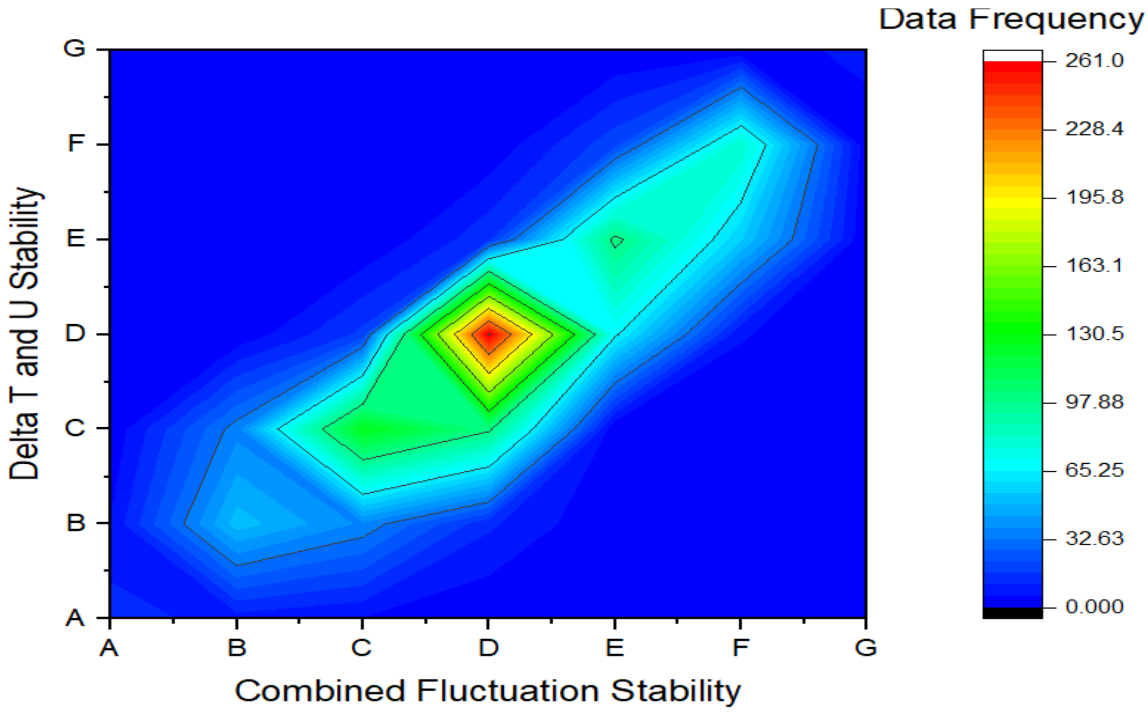
Table 7 presents a comparison of the six methods used in this study. In the cases of the seven categories of atmospheric stability and the frequency of the meteorological data set, all methods are summarized. From these results, we find that the △T·U, Rb, and CF methodologies are well matched in every case. We decide that the △T·U methodology is the best method due to good fitting and good correlation coefficients in every case of Figure 5, Table 6, and Table 7.

Figure 5 and Table 7 summarize the full range of the results obtained in the present study.

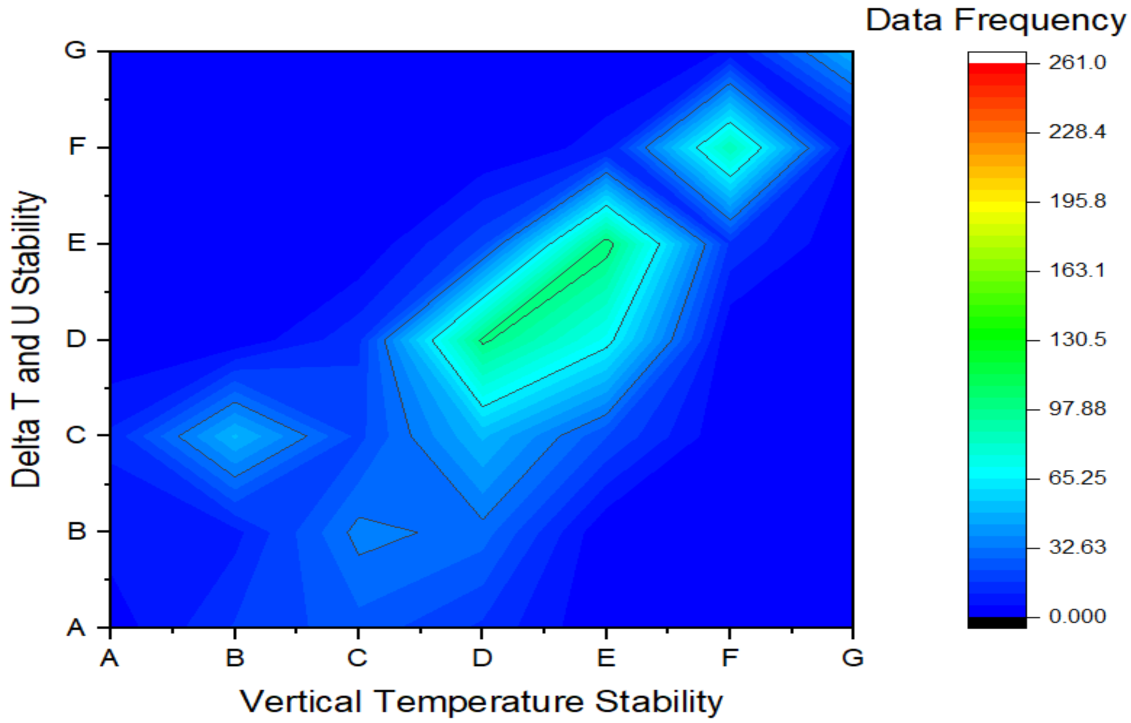
Figure 5 : Comparison of Stability Methods



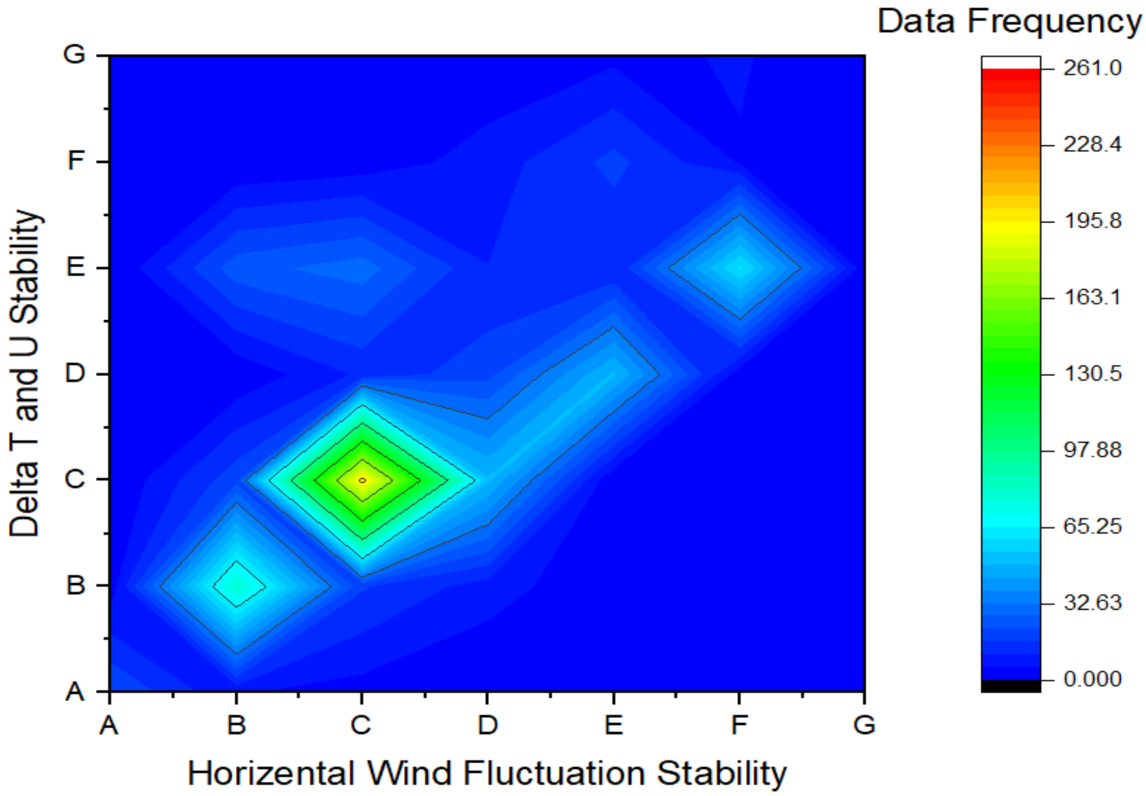
(A of Figure 5)



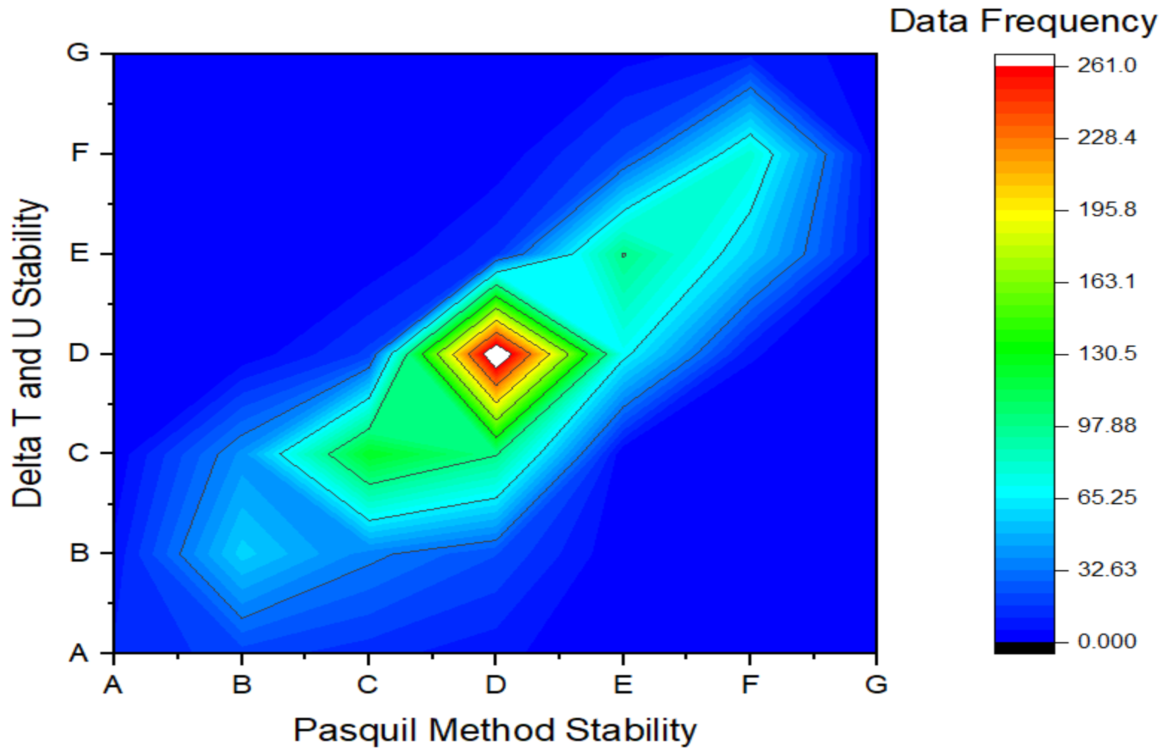
(B of Figure 5)



(C of Figure 5)



(D of Figure 5)



(E of Figure 5)

Table 7 : Results of Classified Stability among Various Methods

Stab.	Pasqu. (%)	CF(δθ,δε) (%)	ΔT·U (%)	Rb (%)	ΔT/ΔZ (%)	δθ (%)
A	240 (0.48)	4575 (9.15)	5480 (10.96)	6000 (12)	205 (0.41)	4770 (9.54)
B	4405 (8.81)	4690 (9.38)	5570 (11.14)	1845 (3.69)	3850 (7.7)	4750 (9.5)
C	8095 (16.19)	10780 (21.56)	3865 (7.73)	7800 (15.6)	5850 (11.7)	10275 (20.55)
D	12910 (25.82)	19665 (39.33)	20120 (40.24)	24195 (48.39)	13400 (26.8)	19300 (38.6)
E	6115 (12.23)	7035 (14.07)	8865 (17.73)	8460 (16.92)	15100 (30.2)	6650 (13.3)
F	15095 (30.19)	3050 (6.1)	3095 (6.19)	1050 (2.1)	6095 (12.19)	2100 (4.2)
G	3140 (6.28)	205 (0.41)	3005 (6.01)	650 (1.3)	5500 (11)	2155 (4.31)
Total (%)	50000 (100)	50000 (100)	50000 (100)	50000 (100)	50000 (100)	50000 (100)

5 CONCLUSIONS

In this study, the various methods of the atmospheric stability determination are reviewed.
In particular, the IAEA methodology (△T·U) (or Vogt's methodology) is discussed and modified. Additionally, the modified methodology is compared with other methods. The modified △T·U methodology of this work provides very reasonable results in terms of both dynamic and static stability. Comparison results and conclusions are as follows:

(1) For wind speed higher than 1.5 m/sec, △T·U is similar to δ_θ.
(2) For wind speed less than 1.5 m/sec, △T·U is in good agreement with △T/△Z.
(3) Stability of the atmosphere is generally impacted by wind speed.
(4) Stability frequency shows similar trends between △T·U and δ_θ.
(5) The △T·U method efficiently explains atmospheric behavior and stability character.
(6) △T·U is in good agreement with Rb.
(7) E, F, G stabilities, D stability, and A, B, C stabilities are equivalent to vertical temperature, Pasquil, and wind fluctuation, respectively.
(8) From this study, the △T·U method is very similar to Rb and CF.
(9) The correlation coefficient of the △T·U method ranged from 0.30 to 0.90.
(10) In the methods of △T·U, Rb, and CF, the total correlation coefficient (r) is calculated by the root square fitting method. In this study, the inclusive correlation coefficient (r) is 0.931.

6 ACKNOWLEDGEMENTS

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