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A COMPARATIVE STUDY OF DIFFUSION CLASSIFICATION BY LAPSE RATE, GUSTINESS AND A MODIFIED PASQUILL METHOD

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Abstract. Nearly all models for calculating atmospheric diffusion include parameters to describe the horizontal and vertical diffusion rates. This study was designed to determine the amount of disagreement among three methods for estimating these parameters and to modify procedures for computing the Pasquill stability classes from surface observations to improve agreement. Two years of hourly surface observations and tower measurements including gustiness classes were used. Lapse rates and stability classes were computed. The degree of agreement between these measures of diffusion was calculated and the conditions under which poor agreement occurred were determined. The method of computing the Pasquill classes was modified and results examined. The modified version gave better agreement between computed stability classes and the other methods and gave a more realistic distribution of unstable, neutral and stable classes.

Introduction

Nearly all models or formulae for calculating dispersion of gases or small particles in the atmosphere contain parameters designed to describe the rate at which the plume or puff spreads and mixes with ambient air in the vertical and horizontal directions. In the commonly used Gaussian plume model, for instance, the horizontal and vertical diffusion rates are specified by the standard deviations of the distribution of material, σ_y in the horizontal and σ_z in the vertical. It was shown by Cramer[1] and confirmed by experience that these parameters are closely related to and can be best estimated from the measured standard deviations of the horizontal and vertical wind direction fluctuations, σ_θ and σ_ϕ. For emissions from an elevated source and short travel distances, $\sigma_y \propto \sigma_\theta x$ and $\sigma_z \propto \sigma_\phi x$ where x is the downwind distance from the source.

In practice it is often necessary to calculate dispersion for locations or times for which no measurements of σ_θ or σ_ϕ are available. In these cases, diffusion parameters are usually estimated from related measurements such as temperature lapse rate or wind gustiness. Lacking these measurements, Pasquill stability classes determined from surface observations by methods described by Turner[2] are widely used. Numerous investigators have recently conducted studies of the differences resulting from use of these various methods.

Luna and Church[3] using data from Augusta, Georgia were among the first to relate calculated Pasquill classes to measured lapse rate and turbulence data. They found that almost any value of σ_θ or σ_ϕ could belong to any stability class. Pendergast and Crawford[4] using Savannah River data showed that large differences in selection of Pasquill stability classes could result from selection of different height intervals over which to calculate lapse rates from temperature measurements. Both Fulle[5] and Portelli[6] found generally poor agreement between lapse rates as measured by radiosondes and Pasquill classes calculated from surface observations

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at several western and Canadian locations respectively. Letizia, et al.[7] conducted a comprehensive comparison of σ_θ and lapse rate as measures of atmospheric stability using two years of data from a tower in western Washington. They found poor agreement between the two methods, poorest during low and best during high wind speeds. They found that σ_θ indicates a much greater frequency of unstable conditions than does lapse rate. None of the above studies compared stability class with actual diffusion measurements but it is judged on the basis of other studies that diffusion would be best described by wind fluctuation measurements. Thus, these reports cast considerable doubt on the practice of estimating diffusion from lapse rate measurements alone.

The Brookhaven wind gustiness classification is a function of both wind speed and lapse rate[8] and has been shown to be a good predictor of measured diffusion at that location[9] and elsewhere. However, it is based on the magnitude and frequency of the horizontal wind fluctuations as measured by a specific wind sensor at a specified height and must be modified for use with other instruments or other elevations.

The Pasquill stability classification, particularly as adapted by Turner[2] for computer use (STAR program) has been widely used but few comparisons of these computations with actual diffusion measurements have been reported. Thus, the system has not been adequately tested but the lack of good agreement with wind fluctuation measurements suggests similar disagreement with diffusion measurements even when the method is confined to those sampling periods and distances for which it was designed.[10]

As part of a study of meteorology and diffusion in coastal zones[11], an investigation of the transport and diffusion climatology of the U.S. east coast is being made.[12] The STAR program was used to calculate stability classes from hourly synoptic data at fifteen coastal stations from Maine to Florida. The results (Figure 1) showed a much larger percentage of neutral cases than expected, a result previously reported[6,13] for other locations.

The purpose of this study is to compare calculated Pasquill stability classes with Brookhaven gustiness and lapse rate measurements, to identify those conditions under which agreement is poor and to determine if better agreement can be obtained by modifying the criteria used for determining the stability classes from surface data. A previous minor modification to the scheme was reported by Ludwig and Dabberdt[14] who achieved improvement by using opaque cloud cover for categorizing daytime solar radiation.

Comparison of Classification Schemes

The Pasquill stability classification scheme as described by Turner[2] is diagrammed in Figure 2 to show the input parameters and the decision-making pathways which lead to the determination of stability classes. Note that all hours with total sky cover less than 7000 feet (2134 m) are automatically classified as neutral (4 or 5) and that the range of pathways is greater during the day than at night. The Brookhaven gustiness classification is diagrammed in Figure 3 as a function of lapse rate and 108-m wind speed. The boxes represent the mean plus and minus one standard deviation in each coordinate direction.[8]

The U. S. Nuclear Regulatory Commission[15] assigned lapse rate ranges to each stability class and these values have been adopted by other users. Using these values for the Pasquill classes, both they and the gustiness classes are related to temperature difference in Figure 4. Note the narrow lapse rate ranges assigned to the unstable and slightly unstable classes and the ranges of physically different lapse rates assigned to the neutral and slightly stable classes. Perhaps a better comparison between the Brookhaven and Pasquill classes is shown in Figure 5 where the classes are referenced to the value of σ_y at 1 km. The values for the Brookhaven classes are taken from Singer and Smith[9] and those for the Pasquill classes from the curves given by Turner.[16]

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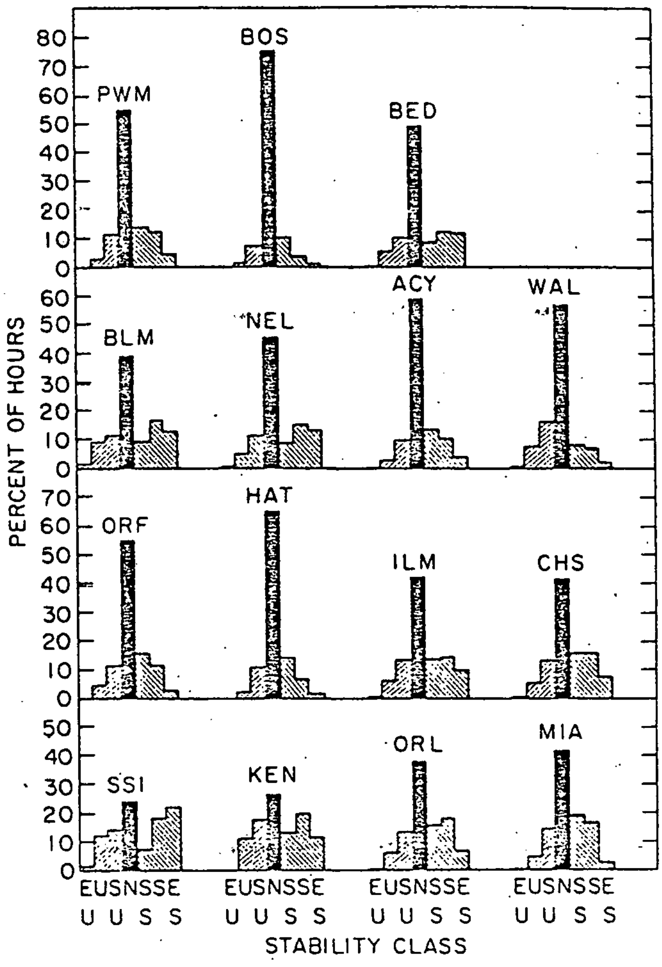

Figure 1. Distribution of stability classes at fifteen coastal stations. Abbreviations refer to classes tabulated in Figure 2.

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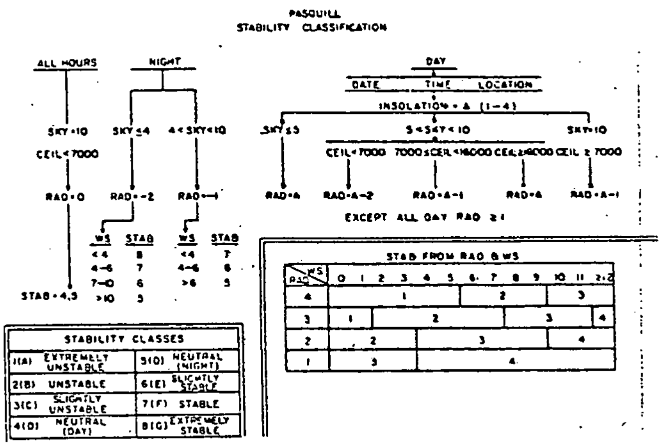

Figure 2. Flow diagram of the STAR program for computing stability class.

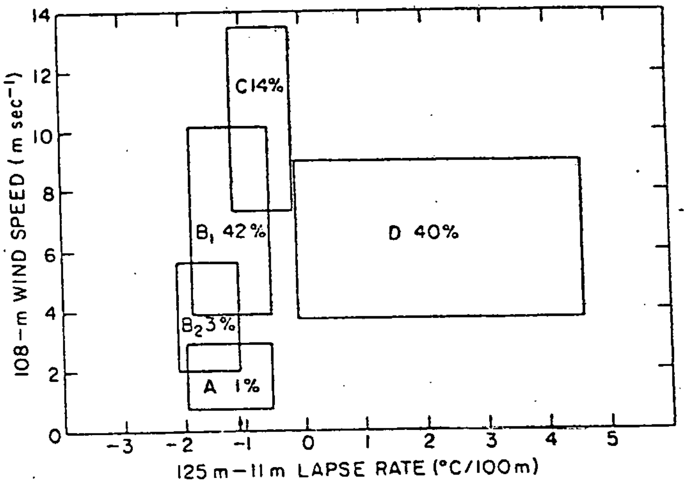

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Figure 3. Diagram showing the relationship of the Brookhaven gustiness classification to lapse rate and wind speed. The boxes represent the mean plus and minus one standard deviation in each direction. The arrow shows the adiabatic lapse rate.

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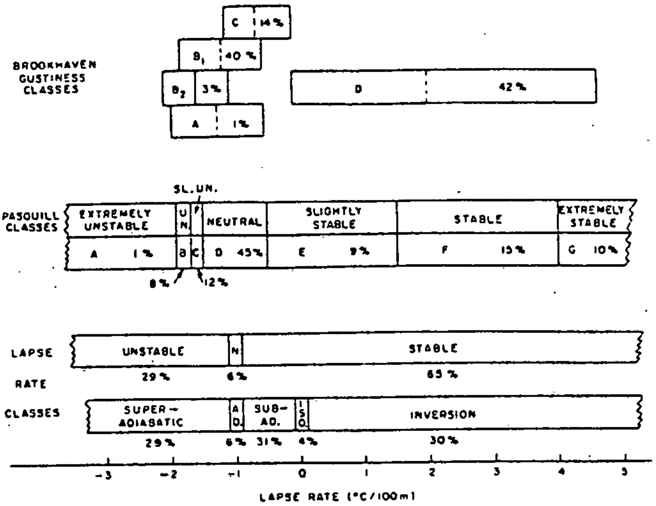

Figure 4. The relationship between the Brookhaven gustiness classification and the Pasquill stability classification as divided by NRC into lapse rate classes and two divisions of lapse rate classes.

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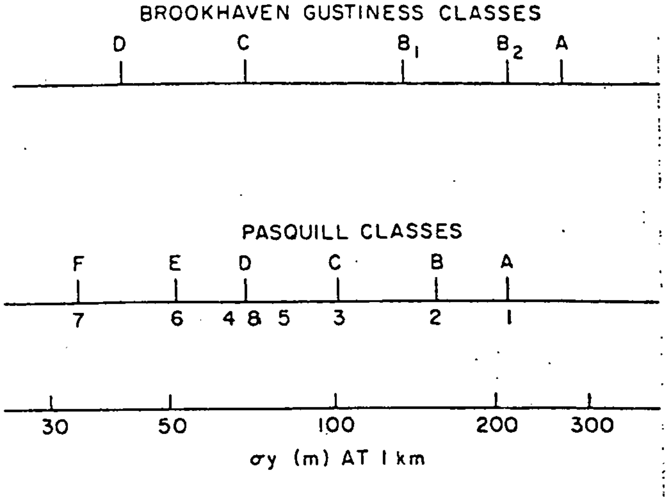

Figure 5. The relationship between the Brookhaven gustiness classes and the Pasquill stability classes and σ_y at 1 km.

Methods

Data taken at Brookhaven National Laboratory over a two-year period from April 1950 to March 1952 were used for this study. The data set includes hourly mean wind and temperature measurements from six levels of the 125-m meteorological tower, hourly wind gustiness at a height of 108 m and hourly surface observations. The latter were used with a selected portion of the STAR program to determine the stability class for each hour. Lapse rates were calculated for four height intervals, 11-125 m, 11-46 m, 46-125 m and 0-11 m. Since the 11-125-m height interval gave the best agreement with the gustiness classes, it was chosen for comparison with the stability classes. These lapse rates were divided into the five classes shown at the bottom of Figure 4.

Although the stability, gustiness and lapse rate classes are not directly comparable, the degree of general agreement between them was determined by joint frequency distributions and other statistical methods. The data were then analyzed to determine the conditions under which poor agreement occurred. The procedures for computing the stability classes were then modified in several physically plausible steps and the changes resulting from each modification or combination of modifications were examined. The modifications found useful were incorporated into a modified STAR program which was then used to recompute stability classes from the Brookhaven data. These results were then related to the gustiness and lapse rate classes to determine the amount of improvement in agreement. The modified program was also applied to the coastal sites shown in Figure 1 and the amount of change in classification documented.

Results

The Brookhaven data were first examined to determine how the hours were distributed among the stability, gustiness and lapse rate classes. As shown in Figure 6, about 45% of all hours were classified as neutral (4 and 5) by the

STAR program with fewer unstable than stable hours. The gustiness classification was dominated by B_1 and D as shown earlier.[8] The hours were nearly evenly divided among three broad lapse rate classes, superadiabatic, subadiabatic and inversion, while the two narrow 0.2°C classes, adiabatic and isothermal, had few hours as expected.

The distribution of the Pasquill classes within the gustiness classes was examined next and is shown in Figure 7. With A and B_2 gustiness, most hours are in the three unstable classes but a substantial number are classed as neutral and a few even stable. With B_1 gustiness, most cases are unstable or neutral but the 58% neutral is not realistic. The C cases cluster around neutral and slightly stable as expected. The majority of the D cases is in the three stable classes but 22% are neutral and about 8% unstable which is not good agreement. In general, the agreement between the two classifications is fair but in need of improvement.

The distribution of the Pasquill classes within the lapse rate classes is shown in Figure 8. With superadiabatic lapse rates, only about 50% of the hours are in the unstable classes, about 45% are neutral and the remainder are stable which indicates poor agreement. The near adiabatic cases are centered on the neutral classes but show a spread across all classes. The subadiabatic cases also are found in all classes but most are neutral and about 24% stable. The near isothermal cases generally range across the neutral and stable classes with about 5% in the unstable classes. The inversion cases peak at the more stable classes as they should but about 15% are classed as neutral and 8% as unstable. The over-all agreement here is similar to that with the gustiness classes.

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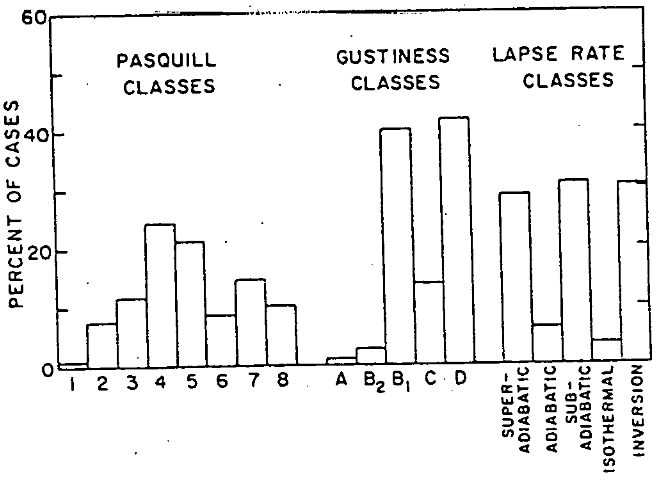

Figure 6. Distribution of Brookhaven data by Pasquill, gustiness and lapse rate classes.

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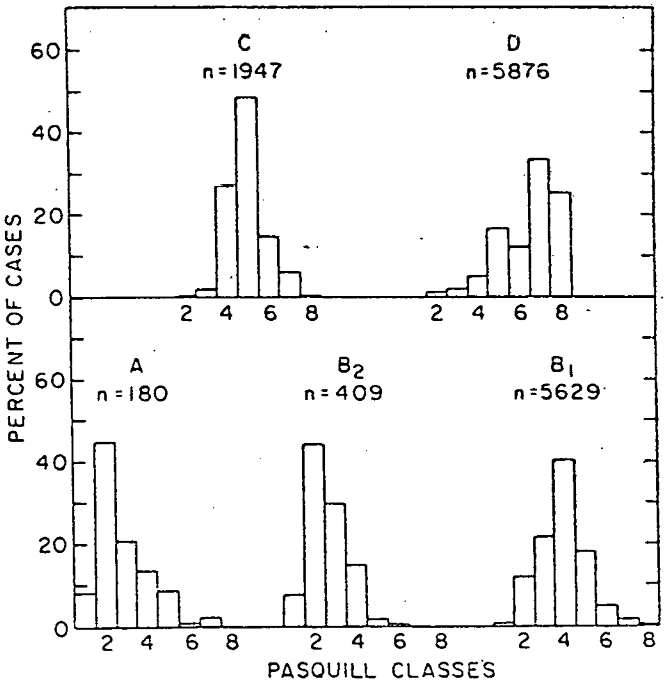

Figure 7. Distribution of Pasquill stability classes by Brookhaven gustiness classes.

Groups of cases which showed poor agreement between the stability class and either or both of the gustiness and lapse rate classes were examined to determine the conditions under which these cases occurred. Variables examined included time of year, time of day, height and amount of cloud and wind speed. It was found that not all low overcast hours had neutral lapse rates or corresponding gustiness classes but could be unstable during the day or stable during the night. Therefore, the mandatory inclusion of all low overcast cases in neutral was eliminated except that precipitation hours were classified neutral. Daytime low overcast cases were assigned the minimum daytime radiation index of 1 and allowed to be either slightly unstable or neutral depending on the wind speed. Night cases were placed by wind speed into either the neutral or the slightly stable class. These changes are diagrammed in Figure 9. These modifications changed the class of 6.2% of all cases or 21.1% of low overcast and precipitation hours. Most daytime cases changed from neutral to slightly unstable and most night cases from neutral to slightly stable.

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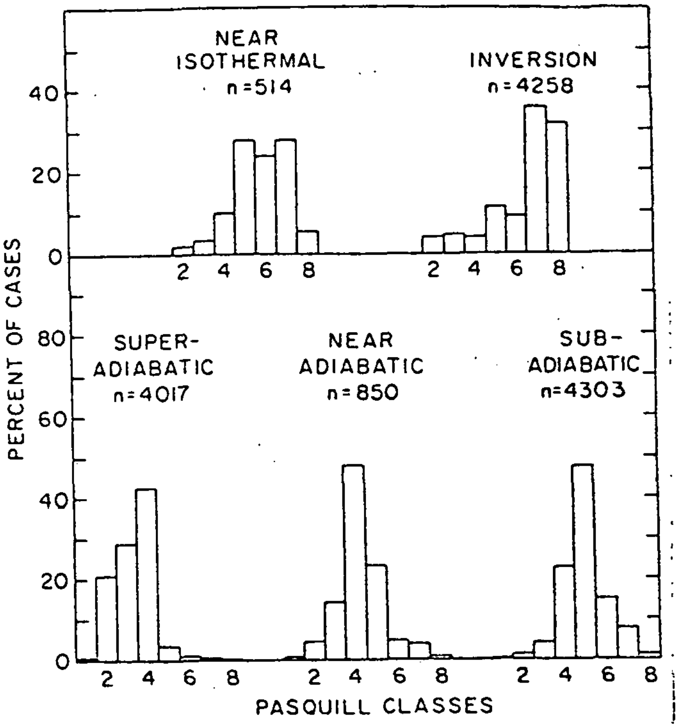

Figure 8. Distribution of Pasquill stability classes by Brookhaven lapse rate classes.

Examination of non-overcast nighttime hours suggested that the original separation of cases into only two groups with no consideration of cloud height was too coarse and did not account for the variability in outgoing long wave radiation and subsequent amount of surface cooling and degree of inversion. Accordingly, the nighttime cases were further subdivided by cloud amount and ceiling height into five rather than two groups with final choice of stability class within each group determined by wind speed (Figure 9). When this change was added to the first modification, 15.9% of all cases or 30.1% of all cases subject to change were reclassified. Some neutral cases became slightly stable, most slightly stable cases became stable and stable cases became either slightly or extremely stable. It was also found that nocturnal stable conditions often persisted longer than the one hour after sunrise considered as night in the original scheme, particularly during the warmer months. Therefore, the program was changed to continue night for two hours after sunrise from May through October. When this modification was added to those described previously, 17.9% of all cases and 39.2% of potentially affected cases were reclassified.

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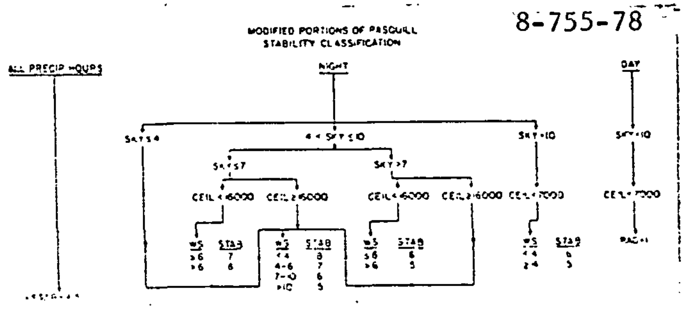

Figure 9. Flow diagram of the modified portions of the STAR program for computing stability class.

This change is appropriate only for sites such as Brookhaven which have prolonged and intense nocturnal inversions.

Other sources of error were examined but the number of cases involved was not great enough to warrant corrective changes. For instance, about 3% of all daytime cases are stable as measured by a positive lapse rate while about 4% of all night cases have superadiabatic lapse rates. These possibilities are excluded from the original scheme but no means were found to correctly classify these cases without wrongly classifying a greater number. It was also found that one hour before sunset was not the best dividing point between day and night in many instances but was for the majority of cases so was retained. The effects of advection and geostrophic wind were also examined but no way was found to use them to improve the classification of cases.

The modified program changed 17.9% of all Brookhaven cases. The actual number of cases changed in the original and new classifications is shown in Table 1 with changed cases underlined. Most cases changed from neutral to slightly stable or within the stable classes. Table 2 summarizes the per cent of cases in the original and modified stability classes for all data and for each gustiness and lapse rate class. The net effect of these changes is to give somewhat better agreement between stability class and both gustiness and lapse rate class although an appreciable percentage of the cases still do not agree. The modified program except for the day-night change after sunrise was applied to data from the 15 coastal stations shown in Figure 1 and changed from 7.8 to 26.0% of the hours at these stations. The per cent of cases in the original and modified stability classes is shown for each station in Table 3. More than 20% of the hours was changed at three stations and more than 10% at seven additional stations. The most frequent change is a reduction in the number of neutral and an increase in the number of stable hours. Unfortunately, no diffusion or wind fluctuation data are available with which to assess the validity of either classification.

Table 1. Distribution of Stability Classes with Original and Modified Program.

Original	Modified Class							
Class	1	2	3	4	5	6	7	8
1	116	0	0	0	0	0	0	0
2	0	1084	0	18	0	0	0	69
3	0	0	1674	28	5	24	26	40
4	0	0	169	3294	77	87	32	0
5	0	0	0	0	2373	854	0	0
6	0	0	0	0	27	895	414	0
7	0	0	0	0	33	405	1383	386
8	0	0	0	0	1	0	0	1531

Table 2. Per cent of Brookhaven Cases in Pasquill Stability Classes with Original (above) and Modified (below) Program.

	Stability Class							
Cases	1	2	3	4	5	6	7	8
All	0.7	7.8	11.9	22.9	21.3	9.2	15.5	10.8
	0.7	7.2	12.1	20.8	16.4	15.6	13.0	14.3
A	8.3	45.0	20.6	13.9	9.4	0.6	2.2	0.0
	9.1	48.5	27.3	7.9	1.2	5.5	0.6	0.0
B_2	7.8	44.3	29.6	14.9	1.7	0.5	1.0	0.2
	7.8	44.3	31.1	13.2	1.0	1.5	0.5	0.7
B_1	0.9	11.6	21.7	40.4	18.3	4.9	1.8	0.5
	0.9	11.4	22.7	38.7	15.5	7.9	2.2	0.7
C	0.0	0.4	2.1	27.9	48.8	14.8	6.0	0.1
	0.0	0.2	2.0	25.6	43.7	19.8	8.4	0.5
D	0.0	2.9	4.3	5.2	16.7	12.3	33.2	25.3
	0.0	1.8	3.6	3.1	9.6	22.6	26.1	33.3
Super-adiabatic	0.7	20.7	28.7	42.5	3.6	1.3	0.5	0.1
	2.5	20.5	29.4	41.7	2.8	2.1	0.7	0.2
Adiabatic	0.5	4.5	14.1	47.9	23.1	4.9	4.4	0.7
	0.5	4.1	15.3	45.3	20.4	8.2	4.9	1.3
Sub-adiabatic	0.1	1.5	4.1	22.7	47.7	14.7	7.8	1.4
	0.1	1.4	5.2	19.1	40.3	22.8	8.6	2.4
Isothermal	0.0	1.8	3.3	9.9	28.0	23.7	27.8	5.7
	0.0	1.6	4.3	6.8	17.5	34.0	28.2	7.6
Inversion	0.0	4.0	4.5	3.8	11.1	8.9	35.6	32.1
	0.0	2.5	3.4	1.6	5.1	18.5	27.0	41.9

Conclusions

In a substantial number of hours, poor agreement was found between calculated stability classes and measured gustiness and lapse rate classes using the original stability classification method. The modified method gives modest improvement with Brookhaven data but should be tested with data from other locations before more general application. Most importantly, both versions need to be tested against actual diffusion data and wind fluctuation measurements. Even if the modified method is shown to give consistently better results than the original, measurements of wind fluctuation should be considered the preferred method for estimating diffusion parameters.

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Table 3. Per cent of Cases at Coastal Stations in Pasquill Stability Classes with Original (above) and Modified (below) Program.

	Stability Class							
Station	1	2	3	4	5	6	7	8
Portland, ME	0.0	2.9	11.3	27.0	28.2	13.9	12.0	4.7
	0.0	2.9	11.7	26.6	23.9	15.1	13.3	6.5
Boston, MA	0.1	1.7	7.6	31.9	43.5	10.3	3.7	1.2
	0.1	1.7	7.6	31.8	39.3	13.5	4.4	1.5
Bedford, MA	0.8	5.9	10.4	25.4	23.9	8.8	12.6	12.3
	0.8	5.9	11.4	24.4	18.8	14.3	8.5	16.0
Belmar, NJ	1.5	9.4	11.2	19.9	19.2	9.3	16.7	12.8
	1.5	9.4	13.6	17.6	14.1	16.1	11.1	16.6
Lakehurst, NJ	0.6	5.3	11.4	24.7	21.1	8.6	15.0	13.2
	0.6	5.3	12.7	23.5	15.8	15.0	9.7	17.5
Atlantic City, NJ	0.3	3.0	9.9	28.6	30.8	13.6	10.2	3.7
	0.3	3.0	10.1	28.4	25.6	16.2	11.5	5.0
Wallops Island, VA	0.5	8.0	16.3	36.1	21.3	8.4	7.1	2.3
	0.5	7.9	17.2	35.3	17.1	11.3	7.5	3.3
Norfolk, VA	0.2	4.5	11.3	26.3	28.8	15.2	11.3	2.5
	0.2	4.4	11.4	26.2	24.3	15.9	14.2	3.3
Cape Hatteras, NC	0.0	2.2	10.6	29.7	35.5	14.2	6.5	1.4
	0.0	2.2	10.5	29.8	30.3	17.4	8.0	1.8
Wilmington, NC	0.5	6.3	13.3	23.4	18.7	13.7	14.3	9.8
	0.5	6.2	13.4	23.5	15.2	13.4	14.5	13.3
Charleston, SC	0.5	5.7	13.7	23.1	18.7	15.7	15.4	7.4
	0.5	5.6	13.5	23.3	14.6	14.6	18.5	9.5
Brunswick, GA	1.7	12.1	14.4	14.0	10.3	7.2	18.2	22.0
	1.7	11.9	14.6	14.1	7.4	10.9	10.6	28.8
Cape Kennedy, FL	0.5	11.0	17.9	13.2	13.1	13.0	19.9	11.6
	0.4	10.6	17.3	14.0	10.0	13.1	17.8	16.6
Orlando, FL	0.8	6.6	13.4	21.4	16.7	15.8	18.1	7.2
	0.8	6.5	13.1	21.7	12.6	15.9	20.2	9.2
Miami, FL	0.1	5.0	14.3	23.0	18.8	19.2	16.7	2.9
	0.1	4.9	13.9	23.5	14.4	17.6	21.6	4.0

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