Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

AN ASSESSMENT OF PLUME DISPERSION PARAMETERS MEASURED IN FALL AND WINTER AT A TAR-SANDS REFINERY COMPLEX

H. WHALEY AND G.K. LEE

CANADIAN COMBUSTION RESEARCH LABORATORY

MARCH 1977

For presentation at the 70th Annual Meeting of the Air Pollution Control Association, Toronto, Ontario, June 20 - 24, 1977

ENERGY RESEARCH PROGRAM

ENERGY RESEARCH LABORATORIES
ERP/ERL 77-23 (OP) (J)C.2

AN ASSESSMENT OF PLUME DISPERSION PARAMETERS MEASURED IN FALL AND WINTER AT A TAR-SANDS REFINERY COMPLEX

By

H. Whaley* and G.K. Lee*

Abstract

Increased energy processing activity in the north has resulted in a demand for measured data on plume dispersion that is relevant to this particular region. The north was, therefore, selected for study in a comprehensive government/industry research program. The objective of these studies was to assess the behaviour of plumes in various geographic areas in Canada.

The program utilizes airborne and automobile-mounted probes to determine SO_2 and temperature profiles within stack-emitted plumes as well as meteorological data on local atmospheric structure.

The data are then analysed numerically to obtain plume axis elevations and standard deviations of spread and these results are compared to accepted predictive methods.

Good agreement with the analysis of Briggs was observed for predicting the location of the plume axis in neutral conditions; some deviations were noted in stable conditions. Values of the measured product ($\sigma y.\sigma z$) were generally larger than those of Pasquill, particularly for those values close to the source. A difference between the measured values of ($\sigma y.\sigma z$) in fall and winter was observed in stable conditions.

---

*Research Scientists, Canadian Combustion Research Laboratory, Energy Research Laboratories, Canada Centre for Mineral and Energy Technology, Department of Energy, Mines and Resources, Ottawa, Canada.

Nomenclature

C max = concentration on plume centreline, ppm

Cp = specific heat of air at constant pressure, J/kg°C

E = emission rate of SO_2, sm /s

F = buoyancy flux = $gQ/\pi C_p \rho T$, m^4/s^3

g = gravitation constant, m/s^2

h = height of stack above ground, m

L = characteristics length for a buoyant plume = F/U^3, m

Q = heat emission from stack, J/s

S = stability parameter = $g/T\ (\partial\Theta/\partial z)$, s^{-2}

T = absolute temperature of ambient air, K

U = mean wind speed over height of plume, m/s

x = downwind axial distance, km

z = height above reference plane, m

Z = height of plume axis above reference plane, m

ΔZ = elevation of plume axis above stack top, m

Θ = potential temperature of ambient air, K

ρ = density of ambient air, kg/m^3

σy = standard deviation of plume spread in crosswind direction, m

σz = standard deviation of plume spread in vertical direction, m

Introduction

In recent years, the energy shortage has forcussed interest on those fossil-fuel reserves which are relatively inaccessible and difficult to extract. Due to the fragility of the arctic and sub-arctic environment, the Canada Centre for Mineral and Energy Technology (CANMET) of the Department of Energy, Mines and Resources included northern Canada as a geographic region to be studied in its plume dispersion research program. A major objective of this program was to obtain a better understanding of the influence of energy processing activities in the north by studying the dispersion of stack-emitted plumes during the fall and winter. Consequently, two study periods, one in each season, were selected to study the characteristics of plumes from a tar-sands refinery complex located in Northeastern Alberta.

This paper evaluates the changes in plume behaviour that took place during four consecutive days in both fall and winter when atmospheric conditions ranged from neutral to stable. The study periods, October 4 - 7, 1971 and February 14 - 17, 1973, were each characterized by overnight inversions which dissipated at different rates during the because of seasonal differences in solar heating and ground cover. The paper compares measured plume axis elevations and standard deviations with accepted empirical methods.

Emission Source Data

The tar-sands refinery complex is located in the Athabasca River valley, 200 miles northeast of Edmonton, Alberta. The plant site is surrounded by coniferous forests with some large open areas of muskeg.

At normal load the power station consumed 2 x 10^6 kg/day of petroleum coke containing 6% sulphur and the refinery produced 45,000 bbl/day of synthetic crude oil on a yearly basis. During the fall studies, the power station accounted for about 25% of the SO_2 emission, with most of the remainder being emitted from the H_2S flare; only a very small amount of SO_2 was emitted from a refinery flare. In winter, the power station accounted for about 80% of the SO_2 emission, the remainder being from an incinerator stack. Details of the heat and SO_2 emissions during the study periods are given in Table I. The power station stack, H_2S flare and incinerator stack were 106 m, 75.7 m and 106 m in height respectively, and were based at 363 m, 320 m and 363 m above mean sea level.

The Athabasca River which is 238 m above mean sea level was used as the zero altitude baseline for all the studies.

Meteorological Conditions

The synoptic surface maps for October 4 to 7, 1971, are given in Figure 1 and for February 14 - 17, 1973, in Figure 2.

On October 4, 1971, a high pressure area was centred over the northwestern U.S.A. A ridge from this system extended northwestward over central British Columbia and into the Yukon. A warm front from a low pressure area off the Pacific coast extended eastward into the Dakotas just below the Canada - U.S border. During the next 24 hours the Pacific low pressure area moved rapidly northeastward and was centred over the Yukon by noon of October 5. The warm front extended southeast from the low pressure area through central Alberta. By October 6, the low pressure area had moved to the vicinity of Great Slave Lake with the warm front through central Saskatchewan and the cold front extending southwestward, west of Fort McMurray and Edmonton into southwestern British Columbia. As the low pressure area strengthened and began moving southeastward, an area of high pressure from the Pacific had moved into east central British Columbia and western Alberta by October 7.

With the rapid changes occurring in the synoptic pattern during the study period, the surface pressure gradient was initially strong and from the northwest ahead of the ridge backing and becoming lighter as the ridge retreated southward. During the late afternoon and evening of October 5, the surface gradient changed from southerly to westerly and then northwesterly, as the Yukon low pressure area continued east and southeastward. By October 7, the strong northwesterly gradient to the west of this low pressure area decreased with the easterly progression of the Pacific high pressure area.

The maximum surface temperature during this period ranged from 20°C on the 4th to 10°C on the 7th and surface winds varied from 2 to 17 m/s in the same period. During this study period, atmospheric conditions ranged from stable to neutral throughout the dispersion zone as indicated in Table II.

On February 14 and 15, 1973, a large high pressure area which dominated the prairie provinces was centred east of Fort McMurray. By February 16, the centre of the high pressure area had moved into Ontario and a low pressure area, centred off the British Columbia coast, began moving eastward. A warm front from the low pressure area extended eastward across northern British Columbia and then southward through central Alberta, west of Fort McMurray. During the next 14 hours, the Pacific low pressure area moved rapidly southweastward to be centred north of Fort McMurray on the 17th. With passage of the low pressure area, the warm front moved north of Fort McMurray on the 17th.

With the easterly progression of the high pressure area, a strong surface gradient persisted over northern Alberta throughout February 14 and 15 with the winds veering from east to southeast during the afternoon of the 14th. On February 16 and 17, as the Pacific low pressure area moved southeastward, the winds became lighter and southwesterly. This low pressure region which passed northeast of Fort McMurray about noon of the 17th, was accompanied by freezing rain and overcast skies.

During this study period, daytime surface temperatures ranged between -20°C and +7°C with surface winds from 2.7 m/s to 7.4 m/s. Atmospheric conditions in the dispersion zone ranged from stable to neutral. However, the ground-based neutral layer in winter was usually capped by an elevated stable layer which in most cases was well above the top of the plume; it, therefore, had no apparent effect on plume behaviour. Table II gives details of the atmospheric conditions prevailing during this study period.

Plume Dispersion Data

The methodology for obtaining three-dimensional data on plume dispersion together with the determination of local meteorological parameters has been described in detail previously(1). Basically the method, which was developed during five years of field research in Canada, utilizes an instrumented helicopter to measure the spatial distributions of SO_2 and temperature within the plume. Radiosonde and pilot balloon releases near the source provided relevant information on the vertical temperature and wind profiles. In addition, before and after each study the vertical temperature structure of the atmsophere was measured at remote downwind locations and close to the source using the helicopter. Inaccessibility precluded the use of a remote downwind meteorological station or ground-level traversing by instrumented automobile.

During each study, detailed SO_2 distributions across the plume at two or more downwind plume cross-sections were obtained. This information enabled the crosswind sections of the plumes to be constructed and used to derive plan and side-views of the plume. Typical plume profiles are given in Figures 3 and 4. Each crosswind section was then analysed numerically to obtain the spatial location of the plume axis and the standard deviations of plume spread in the horizontal and vertical dimensions σy and σz respectively(2).

Downwind Distance

The downwind distance at each crosswind traverse, against which other dispersion parameters were correlated was obtained by numerical analysis after plotting the plume axis on the derived plan view.

Plume Axis Elevation

Dimensionless plots of the plume axis elevations derived from numerical analysis and emission and meteorological parameters are shown in Figure 5. This analysis, developed by Briggs (3), allows comparisons between the data to be made on a rational basis and any deviations from the Briggs analysis noted.

During neutral conditions which occurred in both autumn and winter, the plume axis elevations were observed to be in good agreement with the limiting value of Briggs as shown in Figure 5a. This commences at an approximate downwind distance of 10 h. In almost all cases, the plume axis elevations at distances greater than 10 h tended to bracket closely this limiting value. The few data points which did not agree with this limiting value were probably influenced by topographic or source geometry effects that are not accounted for by the Briggs formula.

In the case of stable conditions, Briggs predicts a limiting value of dimensionless plume axis elevation of 2.9 at dimensionless downwind distances greater than $x = 2.4US^{-\frac{1}{2}}$. It must be noted that his analysis did not exceed a value of $x/(US^{-\frac{1}{2}}) = 7$. Figure 5b shows that the values reported in these studies range from 10 to >500, well beyond the Briggs' range. A general observation to be made from Figure 5b is that dimensionless plume axis elevations have a tendency to rise to a maximum value and then to fall back to zero, as the concentrations of stack gases approach background levels. This finding was also observed during plume dispersion studies in Ontario and Saskatachewan reported previously (4, 5).

Plume Standard Deviations

The reference works on plume standard deviations used for comparative purposes have been those of Pasquill(6) and more recently Turner(7) and Bowne(8). For convenience, Pasquill has postulated six stability classes ranging from unstable (Class A), to very stable (Class F) which represent progressive stages in atmospheric stability. These stability classes indicate that dispersion behaviour as measured by concentration dilution in the atmosphere is excellent in unstable conditions and poor in stable conditions.

A neutral atmosphere, often used as a basis for simple predictive dispersion models, corresponds to a decrease in temperature of 1°C for every 100 metres of height above ground and is represented by Pasquill Class D.

An examination of the simple gaussian dispersion model reveals that the ability of the atmosphere to dilute plumes is best represented by the decay of maximum or centreline concentration. The maximum concentration is inversely proportional to the product of the plume standard deviations σy and σz according to the relationship:

$$C\ max = \frac{10^6 E}{2\pi U\ \sigma y.\sigma z}$$

A plot of the product ($\sigma y.\sigma z$) against downwind distance as measured in neutral conditions in both fall and winter reveals consistently higher values than would be predicted by Pasquill. This effect is more apparent closer to the source as can be seen in Figure 6a. The implication is, therefore, that plume centreline concentrations will be lower and consequently ground-level concentrations will also be lower than predicted using Pasquill values of σy and σz. The measured values of ($\sigma y.\sigma z$) are almost an order of magnitude higher at a downwind distance of 1 km. There was no apparent difference between the measured data obtained in the winter and fall in neutral conditions. These data confirm that the elevated inversion, present in winter, had little influence on plume behaviour.

In stable conditions, higher values of ($\sigma y.\sigma z$) were measured than were predicted by either of the Pasquill Stability Classes E and F. However, there was a difference between values of ($\sigma y.\sigma z$) measured in the fall compared to values measured in the winter as indicated in Figure 6b. Specifically, measured values of ($\sigma y.\sigma z$) were higher by about one order of magnitude in the fall and two orders of magnitude in the winter than Pasquill Stability Class E at a downwind distance of 1 km. Beyond a downwind distance of 20 km, values were comparable to Pasquill Stability Class E. However, Table II indicated that observed stable atmospheric conditions generally corresponded to a stability class greater than Pasquill Class F. Higher measured values of ($\sigma y.\sigma z$) than Pasquill close to the source have also been reported previously (1, 4, 5, 9). At Fort McMurray, this finding can be attributed to factors such as valley circulation, source configuration and wind shear. It has also been observed that plumes in stable atmospheres tend to follow the terrain rather than impinge on it; this and other studies indicate the existence of a lamellar airflow that carries the plume over gradual changes in terrain elevation without significantly altering the plume profile (4, 9, 10, 11).

Conclusions

The behaviour of plumes from a tar-sands refinery complex located in the Canadian sub-arctic under conditions ranging from neutral to stable and observed during winter and fall indicated that:

1. Plume axis elevations were in good agreement with the limiting value derived by Briggs for neutral conditions. In stable conditions, the plume axis elevations rose to a limiting value and subsequently had a tendency to return to zero at large downwind distances. Briggs analysis does not indicate this, possibly due to the fact that measured dimensionless downwind distances were much larger than those of Briggs.

2. The measured values of plume standard deviations gave values of the product ($\sigma y.\sigma z$) that were consistently higher than the corresponding Pasquill values, especially close to the source. This has also been observed in studies elsewhere in Canada and is believed caused by initial source and terrain effects. Ground-level concentrations of SO_2 were also significantly lower than would be predicted by using Pasquill values.

   In neutral conditions measured values of ($\sigma y.\sigma z$) were greater than the corresponding Pasquill values by about one order of magnitude close to the source (∿1 km) and by half an order of magnitude at 10 km from the source.

   In stable conditions a difference was observed between measured values of ($\sigma y.\sigma z$) in winter and fall. Close to the source (∿1 km) the measured values were two and a half orders of magnitude greater in winter and one and a half orders of magnitude greater in the fall than the corresponding Pasquill value (Class F). All values corresponded to Pasquill Class F at a downwind distance of 20 km.

3. In the tar-sands region of Canada, there were significant differences between measured plume spread parameters and those given in accepted empirical methods such as Pasquill.

It is clear that factual dispersion data will provide a realistic assessment of plume behaviour during different seasons in this region.

Acknowledgements

The plume dispersion studies were undertaken with the active participation and technical assistance of Great Canadian Oil Sands Ltd. Weather forecasting and meteorological support was provided by the Atmospheric Environment Service of Environment Canada.

The cooperation of the Alberta Department of the Environment and the Alberta Energy Resources Conservation Board was greatly appreciated.

This work is part of the conservation program of the CANMET energy R and D program and is sponsored jointly with industry.

List of Figure Captions

Figure 1	Synoptic surface weather maps, 1100 MST, October 4 to 7, 1971
Figure 2	Synoptic surface weather maps, 1100 MST, February 14 to 17, 1973
Figure 3	Typical plume profiles under neutral conditions
Figure 4	Typical plume profiles under stable conditions
Figure 5	Plume axis elevations during neutral and stable conditions; horizontal lines represent limiting values of the Briggs equation
Figure 6	Standard deviations of plume spread for neutral and stable conditions; broken lines indicate closest Pasquill stability classes.

References

1. G.K. Lee and H. Whaley, "Plume Dispersion at Sulphur Plants," Energy Processing - Canada, 24 (November - December 1973).

2. H. Whaley, "The Derivation of Plume Dispersion Parameters from Measured Three-Dimensional Data," Atmospheric Environment, 8, 281 (1974).

3. G.A. Briggs, Plume Rise, U.S.A.E.C. T1D 25075, 38 (1969).

4. H. Whaley and G.K. Lee, "Plume Dispersion from a Thermal Power Station on the Shore of a Large Lake," J. Inst Fuel, 47, 242 (1974).

5. H. Whaley and G.K. Lee, "Plume Dispersion from a Lignite-Fired Power Station in Flat, Rural Terrain," A.S.M.E., Winter Annual Meeting, Paper No. 76-WA/APC-7 (1976).

6. F. Pasquill, Atmospheric Diffusion, D. Van Nostrand Co. Ltd., 1968, pp 179-214.

7. D.B. Turner, Workbook of Atmospheric Dispersion Estimates, U.S.D.H.E.W., P.H.S.P. No 999-AP-26 (1969).

8. N.E. Bowne, "Diffusion Rates," J. Air Pollution Control Association, 24, 832 (1974).

9. H. Whaley and G.K. Lee, "Plume Dispersion in a Mountainous River Valley during Spring," Accepted for Publication, J. Air Pollution Control Association.

10. B.W. Proudfit, Private Communication 1972.

11. D.M. Leahy and R.D. Rowe, "Observational Studies of Atmospheric Diffusion Processes over Irregular Terrain," 67th Annual Meeting, Air Pollution Control Association, Paper 74-67 (1974).

TABLE I. EMISSION SOURCE DATA

Date	Time MST	Heat Emission MJ/s	SO_2 Emission kg/s
4-10-71	1504 - 1618	72.6	6.22
5-10-71	0724 - 0821	69.4	6.12
6-10-71	0710 - 0758	66.5	3.11
7-10-71	1102 - 1200	78.1	6.65
14- 2-73	1448 - 1647	90.6	1.66
15- 2-73	0906 - 1041	107.0	1.86
16- 2-73	0914 - 1158	88.7	1.84
16- 2-73	1402 - 1557	95.8	1.87
17- 2-73	1419 - 1627	93.3	1.78

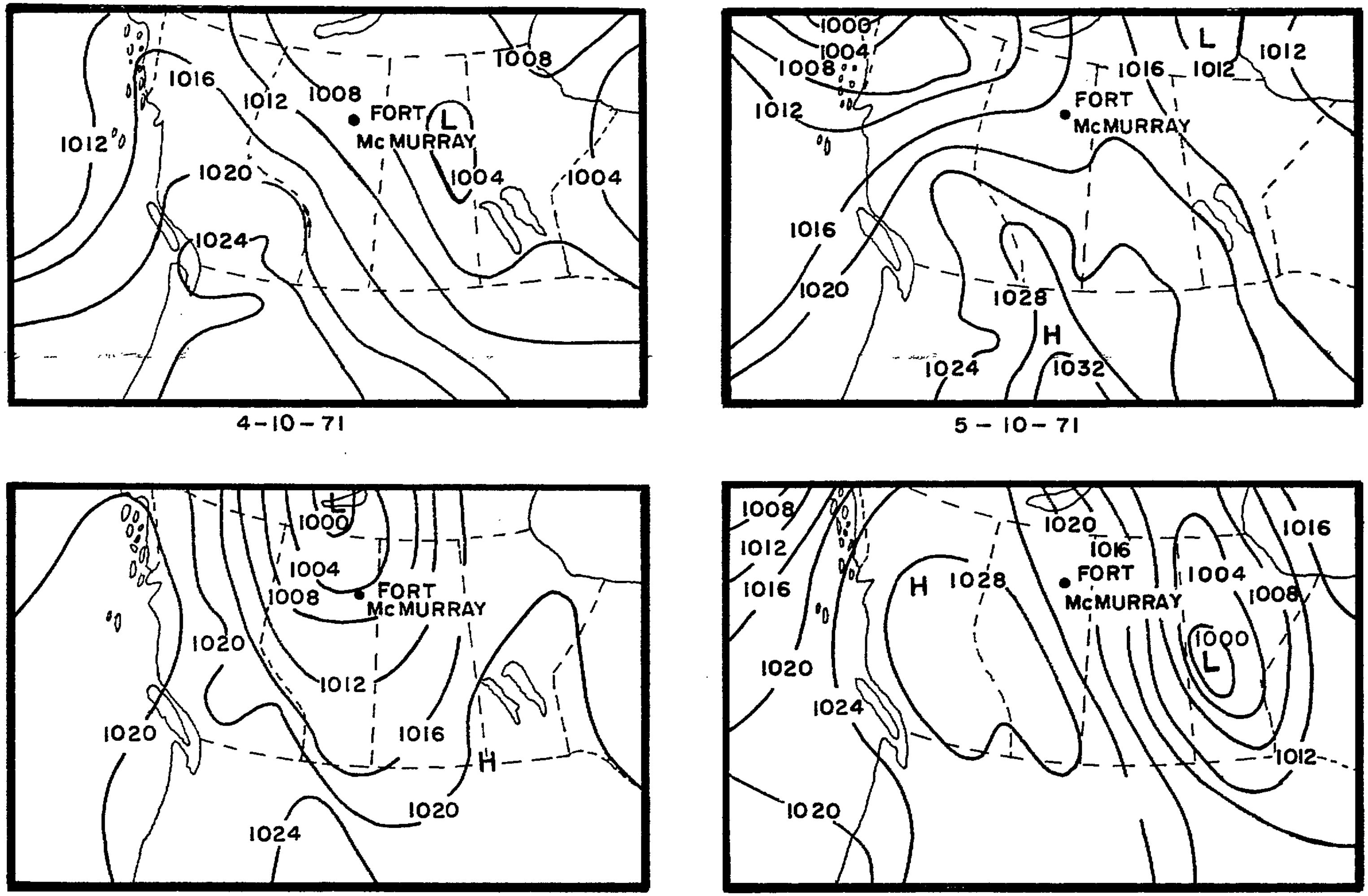
N.B. In 1971, the power station emitted about 25% of the SO_2 and 90% of the heat.

In 1973, the power station emitted about 80% of the SO_2 and 90% of the heat.

TABLE II. ATMOSPHERIC CONDITIONS DURING THE FALL AND WINTER DISPERSION STUDIES

Date	Time MST	Mean Wind		Ambient Temp (Stack Top) °C	$\partial\Theta \vert \partial Z$ °C/100 m	Height Interval m	Atmospheric Stability	
		Speed m/s	Direction deg				Thermal Regime	Pasquill Class
4-10-71	1504-1618	7.0	293.9	16.5	0.04	0-900*	Neutral	D
5-10-71	0724-0821	2.5	236.8	6.6	0.66	0-120	Isothermal	E
					3.81	120-400*	Inversion	F +
6-10-71	0710-0758	6.5	190.6	10.2	4.41	0-300*	Inversion	F +
7-10-71	1102-1200	10.9	312.3	8.6	- 0.37	0-1400*	Neutral	C
14-2-73	1448-1647	5.7	154.7	- 20.9	0.20	0-620*	Neutral	D
					1.31	620-1200*	Isothermal	E
15-2-73	0906-1041	11.1	173.2	- 21.8	0.85	0-660*	Isothermal	E
					3.80	660-1200	Inversion	F +
16-2-73	0914-1158	3.9	263.5	- 2.2	3.26	0-370*	Inversion	F +
					0.64	370-900*	Isothermal	E
16-2-73	1402-1557	4.6	328.3	2.3	0.45	0-1200*	Neutral	D
17-2-73	1419-1627	9.2	278.7	6.1	3.81	0-180*	Inversion	F +
					0.22	180-1200	Neutral	D

* Dispersion Zone



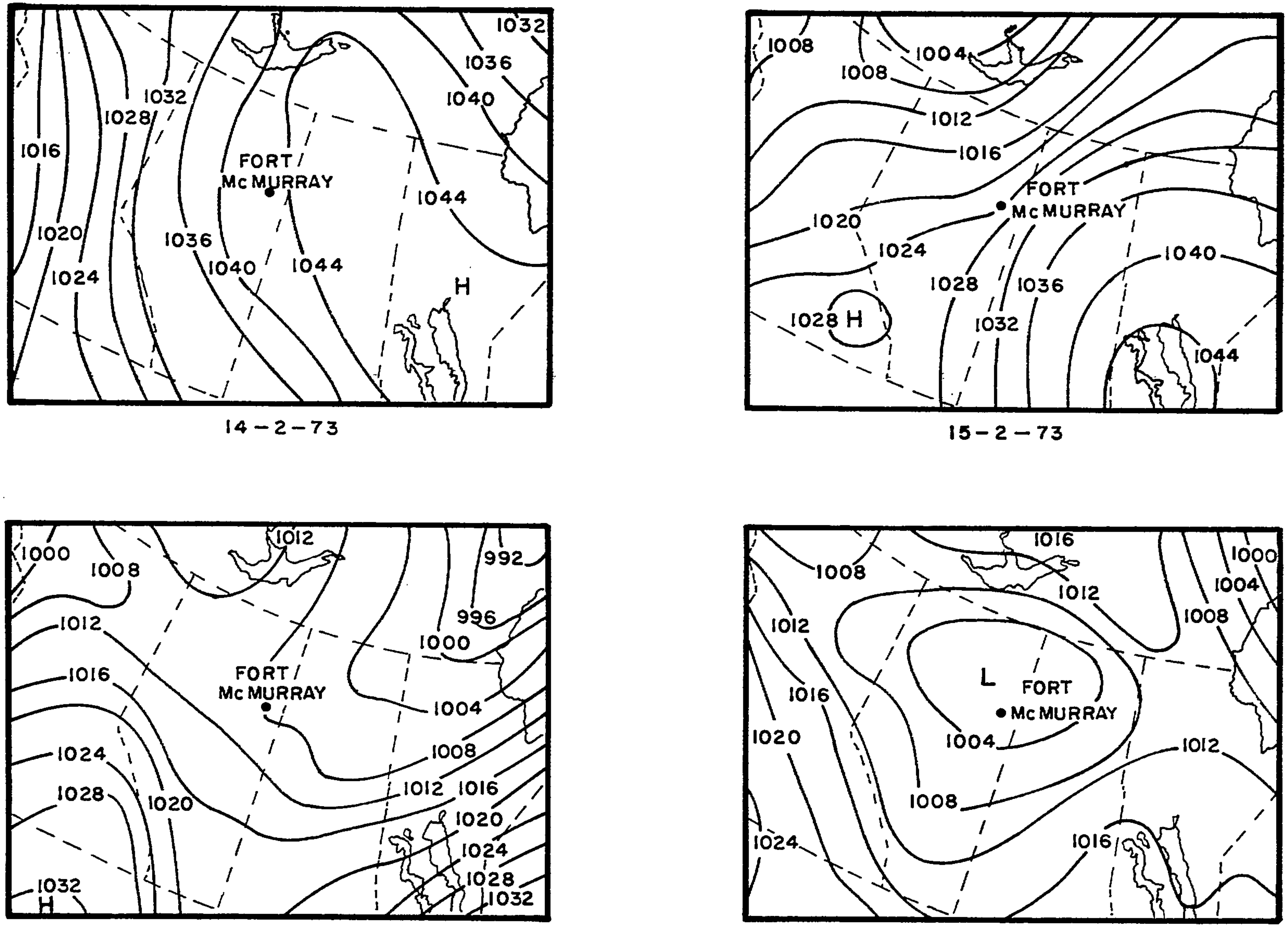
4-10-71

5-10-71

6-10-71

7-10-71

FIGURE 1. Synoptic surface weather maps, 1100 MST, October 4 to 7, 1971.



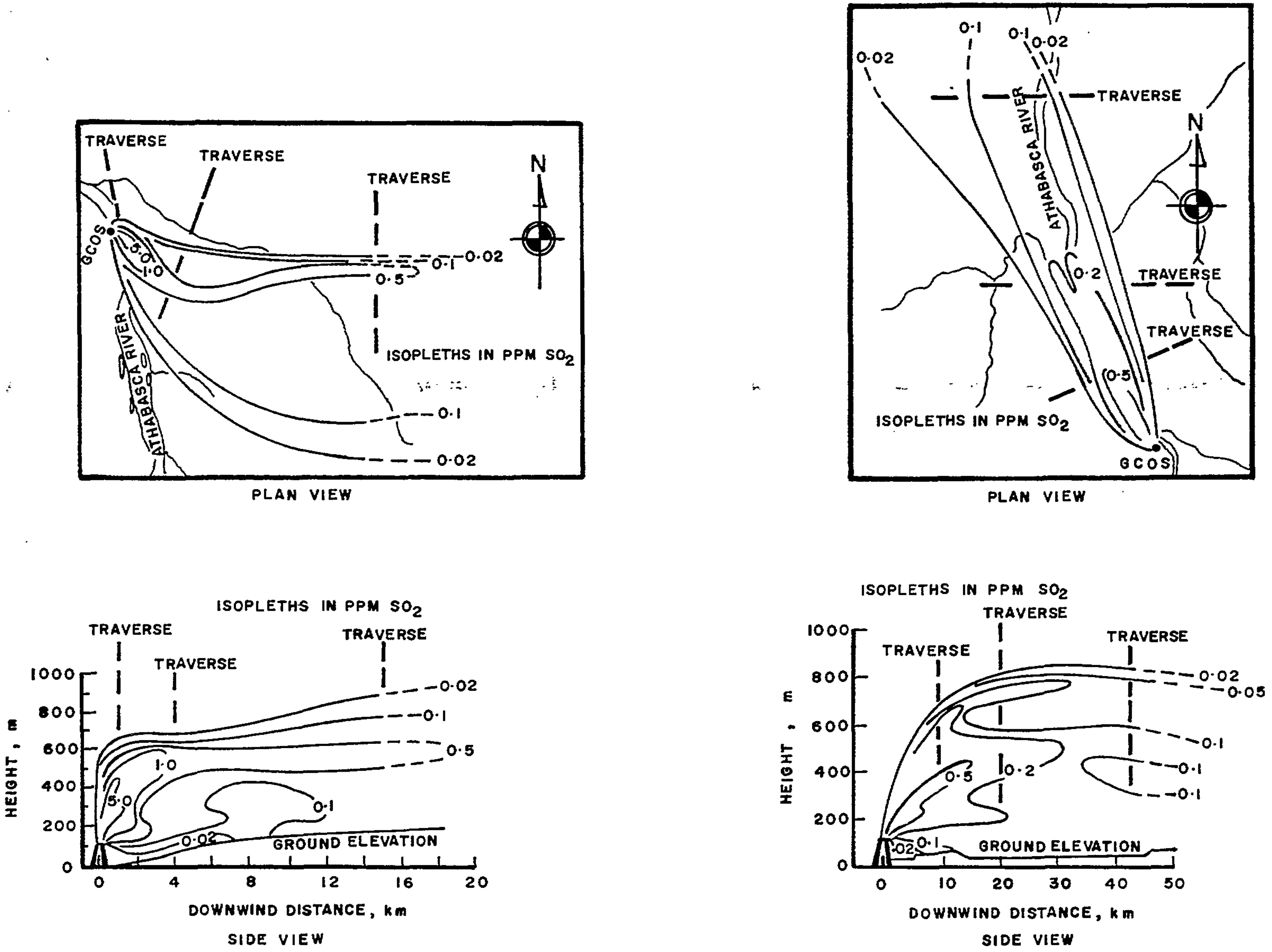
14 – 2 – 73

15 – 2 – 73

16 – 2 – 73

17 – 2 – 73

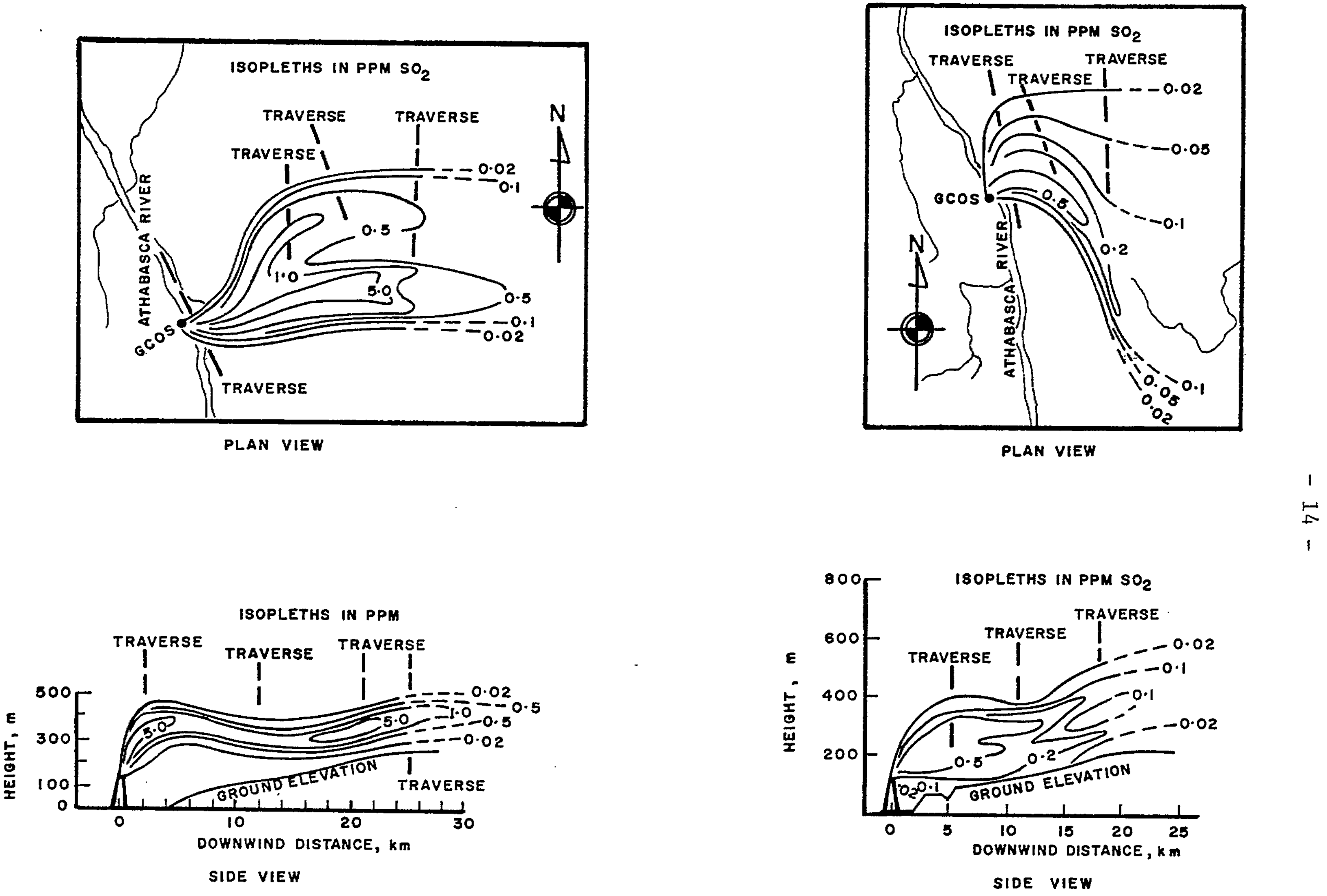
FIGURE 2. Synoptic surface weather maps, 1100 MST, February 14 to 17, 1973.



a) 4-10-71, 1504-1618 MST

b) 14-2-73, 1448-1647 MST

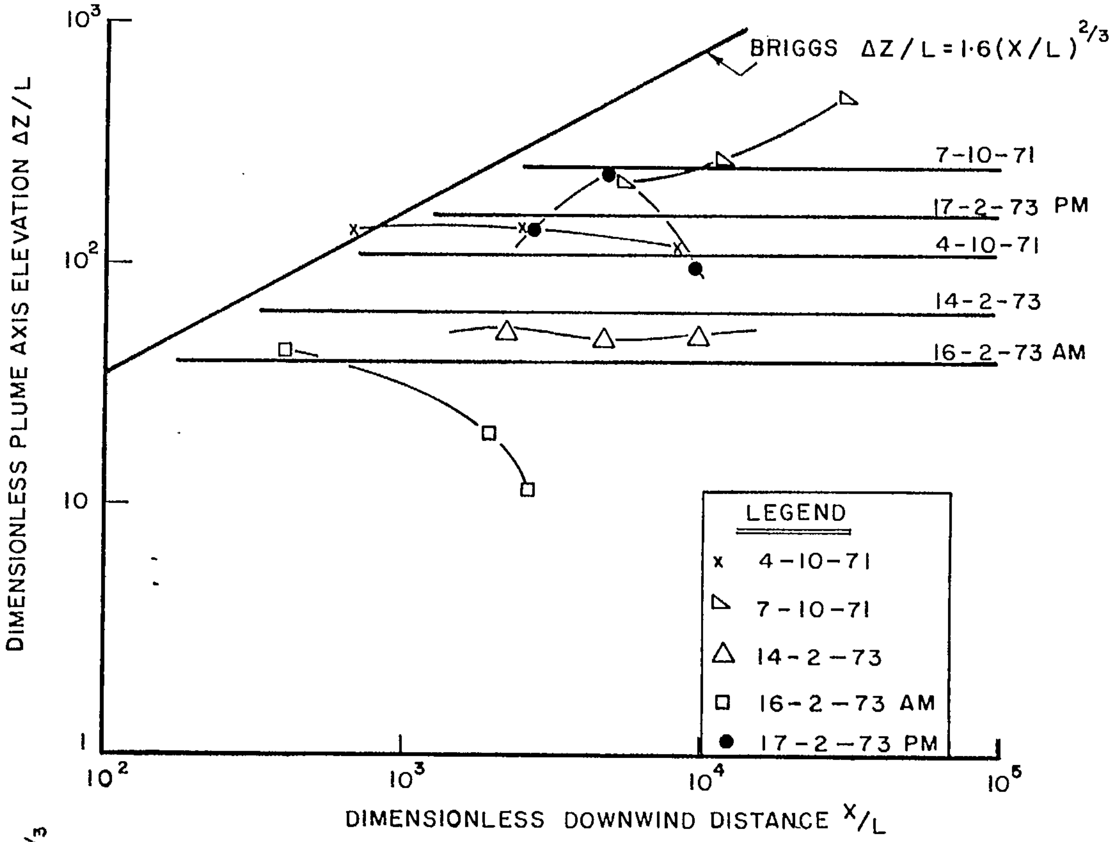
FIGURE 3. Typical plume profiles under neutral conditions.



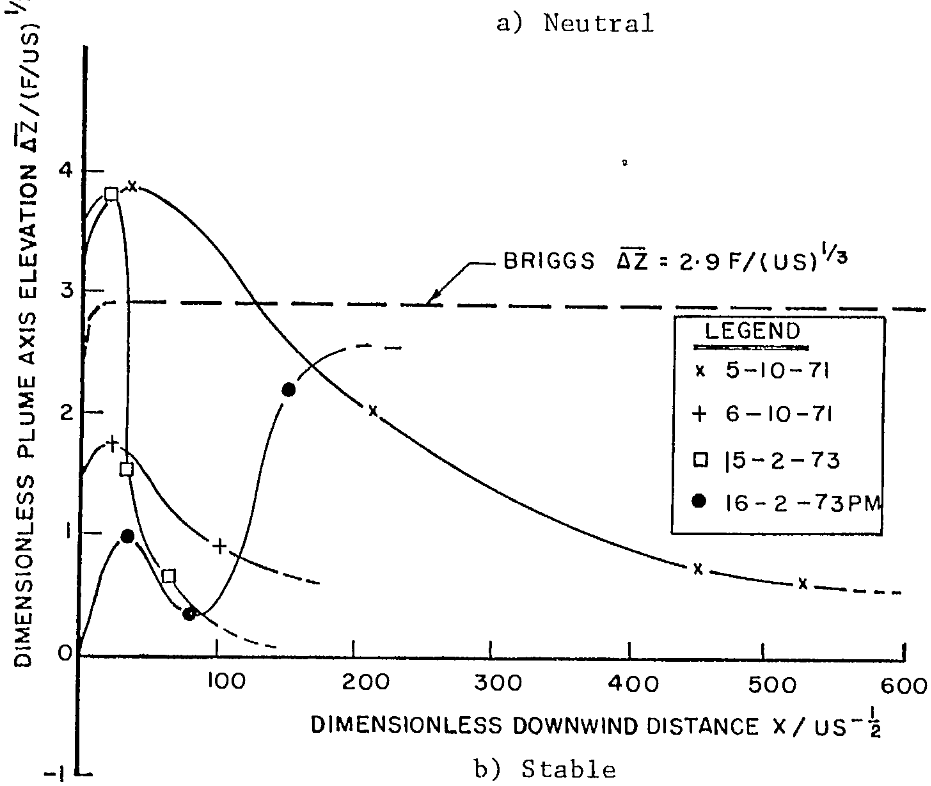
a) 5-10-71, 0724-0821 MST

b) 16-2-73, 0914-1156 MST

FIGURE 4. Typical plume profiles under stable conditions.

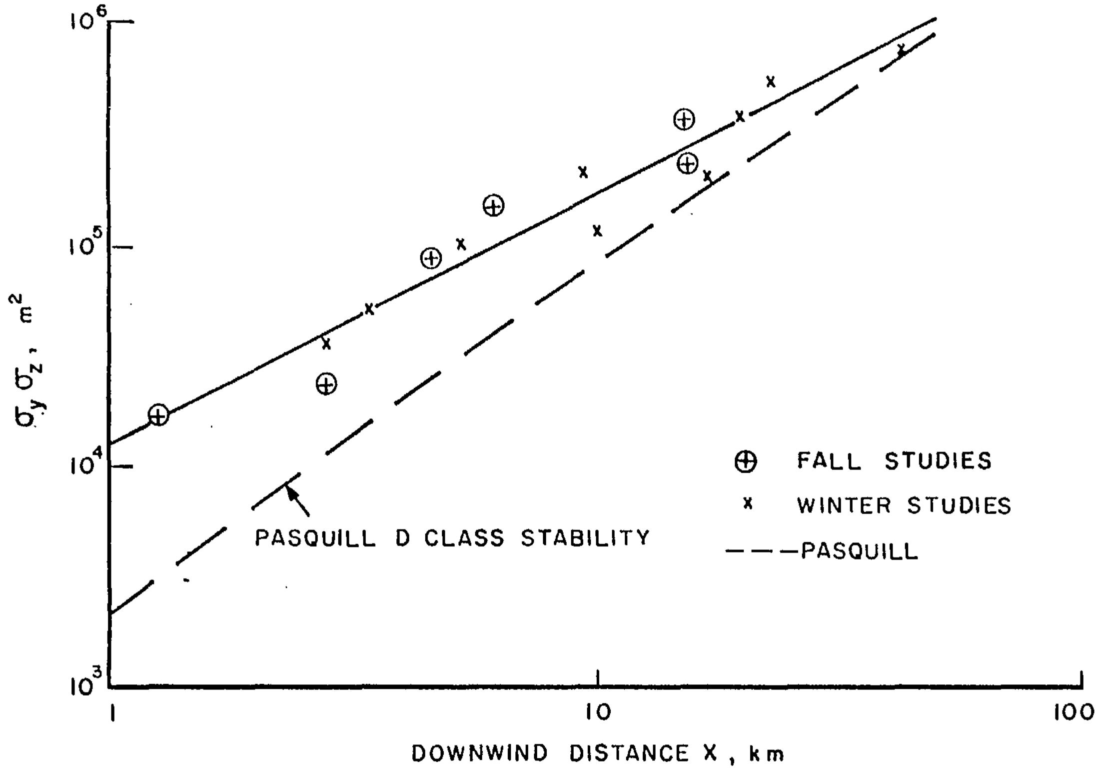


a) Neutral

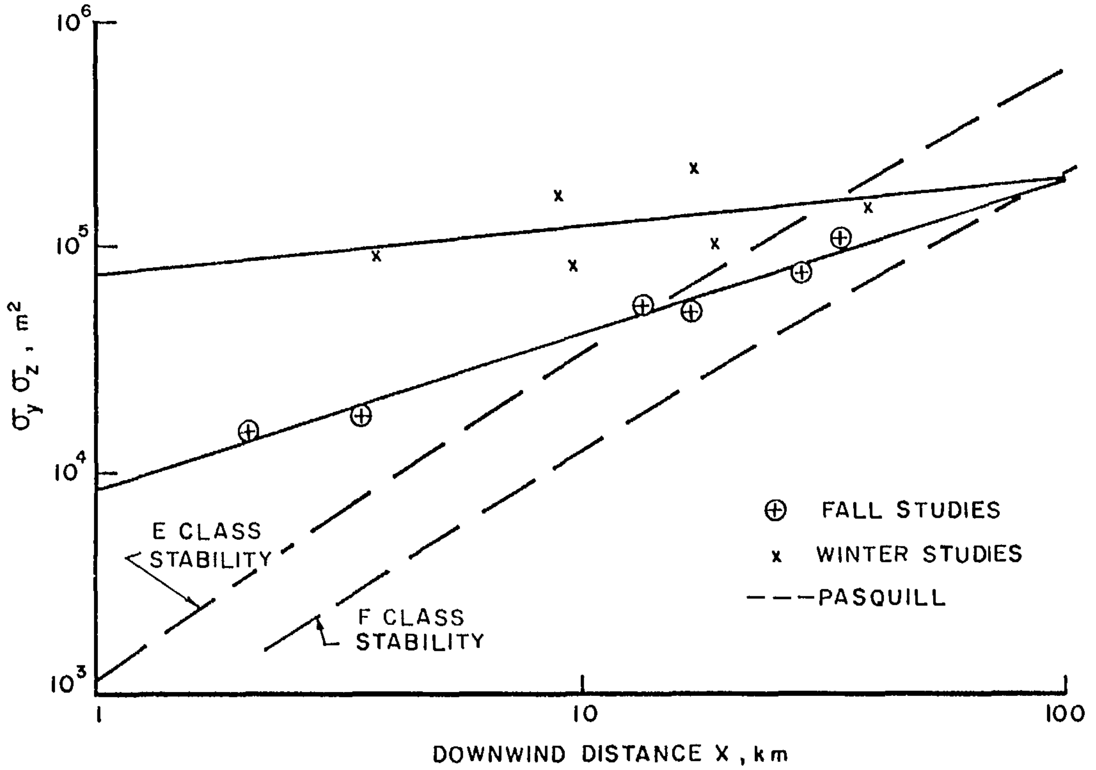


b) Stable

FIGURE 5. Plume axis elevations during neutral and stable conditions; horizontal lines represent limiting values of the Briggs equation.



a) Neutral



b) Stable

FIGURE 6. Standard deviations of plume spread for neutral and stable conditions; broken lines indicate closest Pasquill stability classes.