CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES
MINES BRANCH
OTTAWA

THE DISPERSION OF MULTIPLE PLUMES FROM A LARGE THERMAL GENERATING STATION

H. Whaley, Research Scientist, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada.

L. Shenfeld, Chief, Air Quality and Meteorology Division, Ontario Department of Energy and Resources Management, Toronto, Canada.

G. K. Lee, Research Scientist, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada.

M. S. Hirt, Meteorologist, Canadian Meteorological Service, Toronto, Canada.

S. G. Djurfors, Meteorologist, Ontario Hydro, Toronto, Canada.

FUELS RESEARCH CENTRE

Reprinted from the Proceedings of the Eighth World Energy Conference,

Bucharest, Romania, June 28 - July 2, 1972, Division 2, Paper 2.3-85

Reprint Series RS 119

Price 25 cents

Available by mail from Information Canada, Ottawa,
and at the following Information Canada bookshops:

HALIFAX
1735 Barrington Street

MONTREAL
1182 St. Catherine Street West

OTTAWA
171 Slater Street

TORONTO
221 Yonge Street

WINNIPEG
393 Portage Avenue

VANCOUVER
657 Granville Street

or through your bookseller

Price: 25 cents   Catalogue No. M38-8/119

Price subject to change without notice

Information Canada
Ottawa, 1972

THE EIGHTH WORLD ENERGY CONFERENCE
Bucharest, June 28 — July 2, 1971

LA 8ème CONFERENCE MONDIALE DE L'ENERGIE
Bucarest, 28 juin — 2 juillet 1971

DIVISION	2	PAPER	2.3-85	CANADA
DIVISION		RAPPORT		CANADA

THE DISPERSION OF MULTIPLE PLUMES FROM A LARGE THERMAL GENERATING STATION

by

H. Whaley, Research Scientist, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada.

L. Shenfeld, Chief, Air Quality and Meteorology Division, Ontario Department of Energy and Resources Management, Toronto, Canada.

G.K. Lee, Research Scientist, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada.

M.S. Hirt, Meteorologist, Canadian Meteorological Service, Toronto, Canada.

S.G. Djurfors, Meteorologist, Ontario Hydro, Toronto, Canada.

Introduction

Energy forecasts for the world at large indicate that electric power consumption will at least quintuple by the year 2000. Projections also show that a substantial portion of the increase will be met by large thermal generating stations burning coal and oil, which may contribute heavily to atmospheric pollution. Unfortunately, processes presently available for controlling such pollution at the source have not received widespread acceptance, and until technological breakthroughs occur there is no alternative but to disperse large quantities of combustion products into the atmosphere by properly designed tall stacks. Such stacks effectively utilize the natural dispersion capacity of the atmosphere to assimilate pollution, reducing the ground-level pollutant concentrations. However, detailed information on the effect of atmospheric processes on the dispersion of pollutant plumes is still fragmentary and extensive research in this field is urgently required. One approach is to compare measured data with empirical equations. This is done in this paper for the case of multiple plumes from a 2400 MW(e) thermal generating station. The present data, which were obtained during two helicopter flights, relate emission source data, local meteorological measurements and SO_2 distribution in the plume under the two atmospheric conditions which occurred on August 25, 1969 and May 29, 1970.

Data Acquisition

Emission Source Data

The emission source is a 2400 MW(e) thermal generating station situated on the shore of a large lake, on the outskirts of a large metropolitan area. Combustion gases are discharged into the atmosphere by four 150-metre stacks. During the two flights described, only three stacks were in operation. The total heat efflux rate on August 25, 1969 was 1.92×10^8 J/s (45,900 kcal/s) and on May 29, 1970 was 1.40×10^8 J/s (33,400 kcal/s).

Meteorological Measurements

Radiosondes were released at the plant site before and after each helicopter flight to measure vertical profiles of temperature, humidity, wind speed and wind direction, up to a height of about 1500m. Twice during each flight, pilot balloons were used to measure variations of both wind speed and wind direction with respect to height.

Aerial Monitoring

Aerial probing of the plumes was carried out using a helicopter that was instrumented to provide continuous measurements of SO_2, pressure-height, temperature and wet-bulb depression (1, 2). The sensing probe was mounted on a strut of the helicopter well forward of any downwash at the traversing speed. During each flight, which lasted about two hours, the helicopter was continuously tracked by theodolite and by an electronic navigational system. Airspeed was maintained at 95 km/h during both flights.

Quantitative data on the plume geometry, SO_2 profiles in the plume, and temperature gradients outside and inside the plume were obtained using the following techniques:

(a) Temperature soundings were taken upwind and downwind of the stacks at the beginning and termination of each flight.

(b) Horizontal traverses were flown downwind of the stacks and essentially normal to the plume axis at three selected distances from the stacks. Each traverse consisted of a series of level passes through the plume at vertical intervals of either 30 or 60 m depending on the amount of detail required.

(c) One vertical section of the plume was obtained, essentially along the longitudinal axis, between the farthest downwind horizontal traverse and the stacks. This technique consisted of flying a vertical sawtooth pattern from the top to the bottom of the plume; see Figure 8.

Ground-level Monitoring

Where possible, ground-level measurements were made concurrently with the aerial measurements by traversing the plume along suitable roads, using an automobile equipped with an instrument package similar to that used in the helicopter to monitor SO_2 and temperature continuously.

Analysis of Results

Atmospheric stability is an indication of the physical capacity of the atmosphere to disperse pollutants. Three stability classes are usually defined:

(1) Inversions - this is the most stable atmospheric condition and is characterized by an increase of temperature with height. Under these conditions, vertical atmospheric mixing is inhibited.

(2) Unstable - this results in vigorous overturning of the air, i.e., strong turbulent mixing. This condition is characterized by a decrease of temperature with height greater than the dry adiabatic lapse rate, which corresponds to a decrease of temperature with height of 1°C/100 m.

(3) Neutral - this atmospheric condition is assumed to occur when the temperature decreases with height at a rate of between 0°C and 1°C/100 m.

August 25th, 1969

On this day, the vertical temperature gradient as shown in Figure 1 was approximately -0.88°C/100 m, a neutral atmosphere by definition. The mean wind speed and direction between the top of the stacks and the top of the plume was 11.9 m/s from the northwest. Helicopter measurements at an axial distance of 5.6 km from the stacks gave plume dimensions of 3800 m in width and 740 m in vertical thickness, as shown in Figure 1. These values agree well with theoretical models for neutral atmospheric conditions (3, 4).

The plume centreline as noted in Figure 2 appears to level off at approximately 550 m above the lake giving a plume rise of 400 m. This value is considerably higher than the values calculated from several of the many empirical plume rise formulae available as shown in Table I.

At an axial distance of 3.6 km the temperature on the axis of the plume was observed to be 0.5°C less than ambient suggesting that plume overshooting existed. This plume temperature deficiency was not sufficient to bring the plume down to its equilibrium height.

A plan view of the plume is shown in Figure 3. The curvature of the plume axis over the lake, may be attributed to the change in surface roughness from land to water and to the correolis force.

May 29th, 1970

On this day an elevated inversion existed over the study area. Under the inversion was an isothermal layer, beneath which was a ground-based super-adiabatic layer. This temperature profile occurred as a result of a lake inversion that was destroyed from below by the heat from the warmer ground as the air moved inland. The slope of the base of the inversion, as obtained by helicopter soundings, is shown in Figure 4 as a dashed line.

According to the measured data, the plume was emitted at the base of the inversion layer as shown in Figure 4, and the winds transported the plume into the mixing layer below the inversion. In the lower unstable layer of air, turbulence caused high concentrations of SO_2 down to the ground. Ground-level concentrations as measured by instrumented automobiles are shown in Figure 5. Concentrations of up to 0.9 ppm were measured. At about 7 km downwind the plume became completely trapped beneath the inversion.

Between the top of the stacks and the top of the plume the mean wind speed was 10.3 m/s and the mean direction was easterly with a gradual veer of about 15° within the layer. The height of the plume axis is estimated from Figure 4 to be about 220 m above ground, giving a plume rise of 70 m. A cross-wind section through the plume at 14.1 km downwind is illustrated in Figure 6 where the plume dispersion is shown to be severely restricted in the vertical direction. The directional change of wind with height is reflected in the curvature of the plume axis as shown in Figure 7.

Sawtooth vertical sections, which are more rapidly obtained than those derived from horizontal traversing, are useful for plume rise studies. A comparison between Figures 4 and 8 shows good agreement between the two measuring techniques. However, a vertical section in one plane does not give information on the horizontal spread of the plume.

Comparison of Measured and Empirical Data

Plume behaviour is usually defined in terms of two separate but related stages - plume rise and dispersion. This means that the plume is considered to rise to its final height of emission before diffusion of the plume commences. This ausumption simplifies the theory and enables independent measurements to be made of these two aspects of plume behaviour. Examples of the use of equations to estimate plume rise and subsequent dispersion are discussed in the literature (2, 3, 4, 5, 6, 7).

Plume Rise

Several of the many plume rise equations found in literature are used here to compare the calculated and measured plume rises for the meteorological conditions found during the above two case studies. It must be kept in mind, however, that most of these formulae are recommended for use under neutral atmospheric conditions. Where appropriate equations were recommended for the inversion conditions, they were use in calculating plume rise for the May 29th, 1970 condition.

Table I compares calculated and measured plume rise values. It is interesting to note that the calculations for August 25th, 1970 resulted in plume rises considerably lower than that measured. A factor contributing to this may be that most of the formulae were developed for downwind distances much less than 5.6 km.

TABLE I

Measured Plume-Rise Values Compared with Empirical Values
Valeurs mesurées d'élévation du panache comparées
aux valeurs empiriques

Date	August 25, 1969	May 29, 1970
Mean Heat Flux/stack, J/s	6.4×10^7	4.7×10^7
Plume Rise (m)		
Measured	400	70
Briggs	210	112*
Lucas	138	147
CONCAWE	102	107
Holland	65	44*
CCRL-2	62	66
Moses	54	55

* Value calculated from equation for the prevailing meteorological conditions.

On the other hand, though most of the formulae are not intended for application to inversion conditions some gave good agreement with the value measured on May 29th, 1970.

Dispersion

The standard deviation of the spread of the plume has been calculated for the two atmospheric conditions under consideration. Comparison is made in Figure 9 with the Pasquill-Gifford values (2, 3). It can be seen that values for the Pasquill-Gifford class D for neutral conditions correlated closely with measured data obtained on August 25, 1969. In the case of the inversion breakup, on May 29, 1970, the initial spread of the plume is represented by the Pasquill-Gifford class E for stable conditions which existed below the inversion. However, beyond 6 km axial distance, plume trapping must be considered. With this limited mixing, the computed σ_z curve compares with that measured at

14 km axial distance. However σ_y appears to be unaffected by the plume trapping.

Conclusions

It is apparent from these studies that an instrumented helicopter provides a useful means of obtaining quantitative information on the diffusion of complex plumes in the atmosphere. By using various traversing techniques in conjunction with concurrent meteorological and ground-level measurements, it becomes possible to relate plume characteristics to the meteorological conditions prevailing during the period of the flight.

Although source emissions and wind speeds were similar, higher SO_2 concentrations were measured near the ground during inversion breakup than during neutral conditions.

On August 25, 1969 the calculated plume rise values are all considerably lower than the measured value but on May 29, 1970 most of the calculated values are in reasonable agreement with the measured value.

The standard deviations of the plume spread obtained from measured SO_2 data are in good agreement with Pasquill-Gifford values.

Acknowledgements

The advice and assistance of Dr. F. Frantisak, formerly with the Air Management Branch, Ontario Department of Energy and Resources Management is appreciated.

The permission of the Mines Branch, Department of Energy, Mines and Resources, Ottawa; the Air Management Branch, Ontario Department of Energy and Resources Management, Toronto; the Canadian Meteorological Service, Ministry of Transport, Toronto; and Ontario Hydro, Toronto to publish this paper is acknowledged.

Summary

A description is given of the dispersion of multiple plumes from four 150-metre stacks of a large thermal generating station located on the shore of a large water body, on the outskirts of a large metropolitan area. The operating procedure and flight programming of an instrumented helicopter, equipped to measure pollution and meteorological parameters, together with measurements made by conventional meteorological techniques near the stacks are described.

It was established that the spatial location of the centre lines, boundaries, and SO_2 isopleths of the plumes can be determined with reasonable accuracy. Comparison is made between measured plume parameters and those from the empirical and theoretical equations reported in the literature.

Résumé

On décrit la dispersion de panaches multiples de quatre cheminées de 150 mètres d'une grande centrale thermique, située sur la rivage d'une grande étendue d'eau, au voisinage d'une grande région urbaine. Une description est donnée de la procédure et du programme de vol d'un hélicoptère, muni d'instruments et équipé pour mesurer des paramètres de pollution et météorologie près de cheminées.

On a établi que l'emplacement spatial des lignes centrales, limites et isoplets en SO_2 des panaches peut être déterminé avec une précision raisonnable. On compare les paramètres mesurés des panaches aux paramètres d'équations empiriques et théoriques indiquées dans certains articles.

References

1. Simon, C. and Proudfit, B.W. (1967) Some Observations of Plume Rise and Plume Concentration over New York City, Paper No. 67-83, 60th Annual Meeting A.P.C.A., Cleveland, Ohio, U.S.A.

2. Proudfit, B.W. (1970) Behaviour of Hot Plumes under Stable Conditions, Paper ICFTC-NAFTC-4, North American Fuel Technology Conference, Ottawa, Ontario, Canada.

3. Pasquill, F. (1961) The Estimation of the Dispersion of Windborne Material, Met. Mag. Lond. 90, 33-49.

4. Gifford, F.A. (1961) Uses of Routine Meteorological Observations for Estimating Atmospheric Dispersion, Nuclear Safety. 2, 4, 47-51.

5. Slawson, P.R. and Csanady, G.T. (1967) On the Mean Path of Buoyant, Bent-over Chimney Plumes. J. Fluid. Mech. 28, 311-322.

6. Briggs, G.A. (1969) Plume Rise USAEC TID 25075.

7. Whaley, H. (1969) A Proposed Canadian Standard for Estimating Atmospheric Dispersion of Combustion Source Pollution from Chimneys, Atm. Env., 3, 177-195.

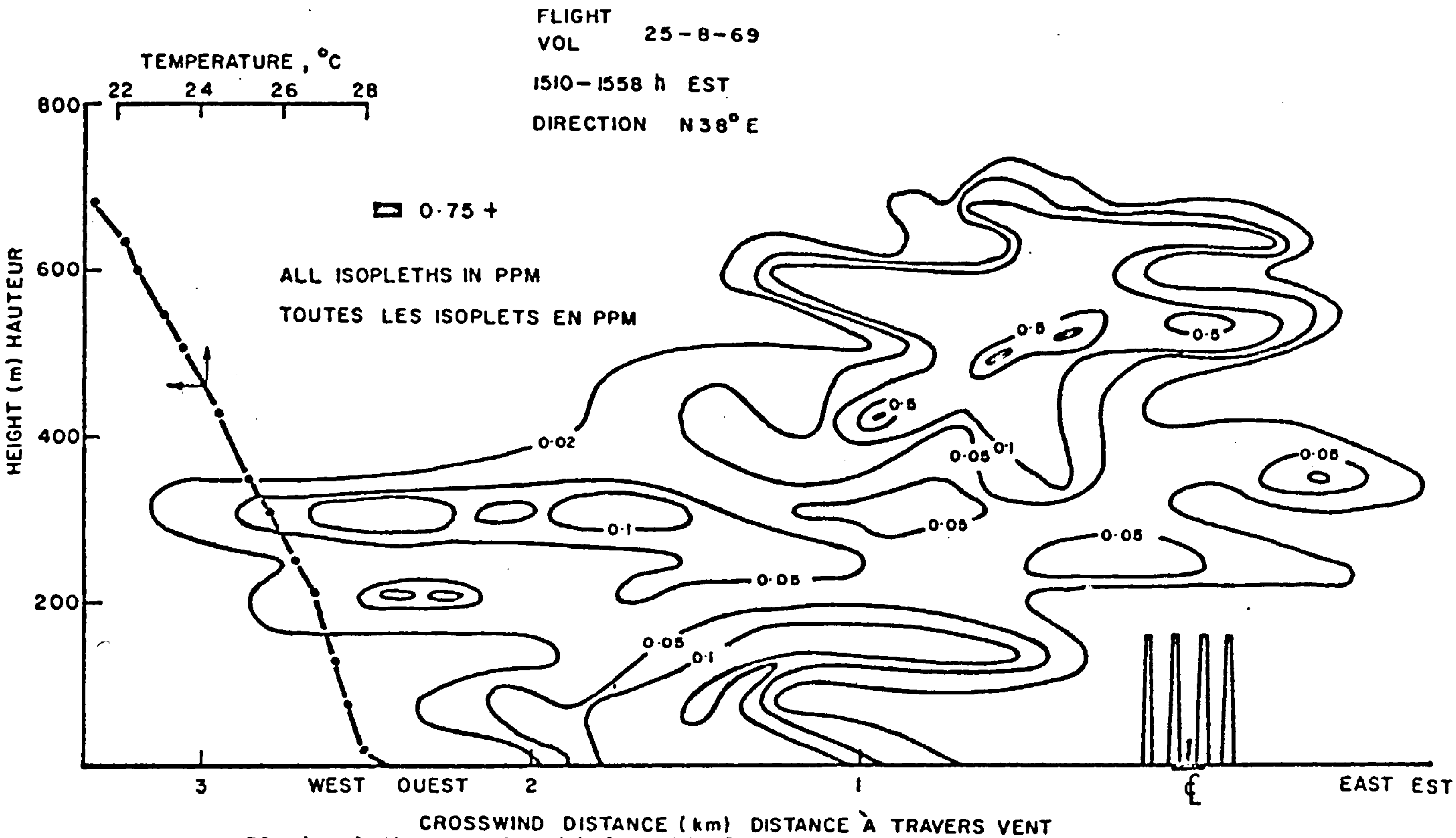

Figure 1. SO_2 isopleths for the third vertical crosswind section of the plume, under neutral conditions, at a mean axial distance of 5.6 km.

Isoplets en SO_2 pour la troisième section verticale à travers vent, dans les conditions neutres, à une distance axial moyenne de 5.6 km.

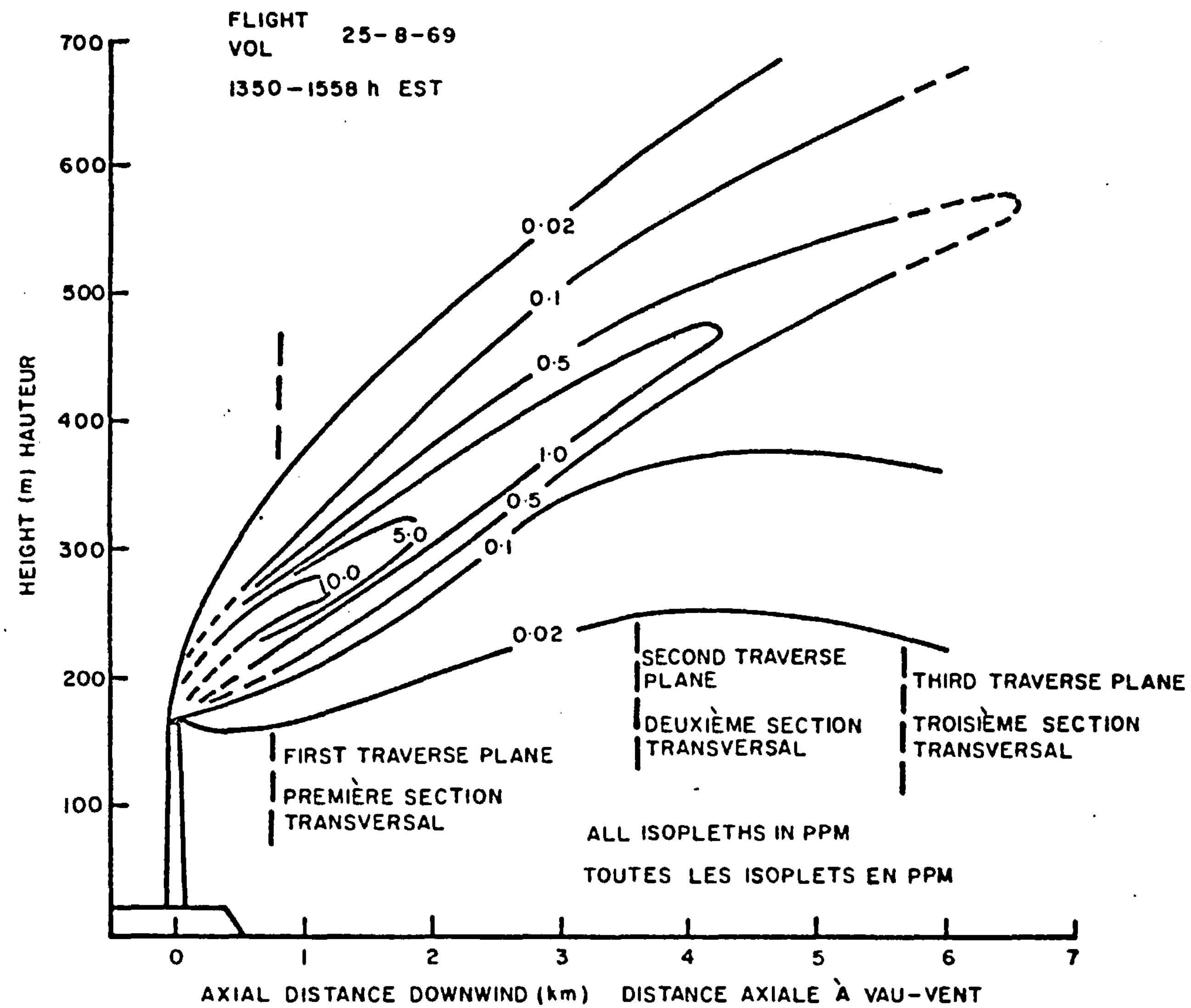

Figure 2. Vertical axial section of the plume, under neutral conditions, derived from horizontal traverses.

Section axiale verticale du panache, dans les conditions neutres, dérivée de traverses horizontales.

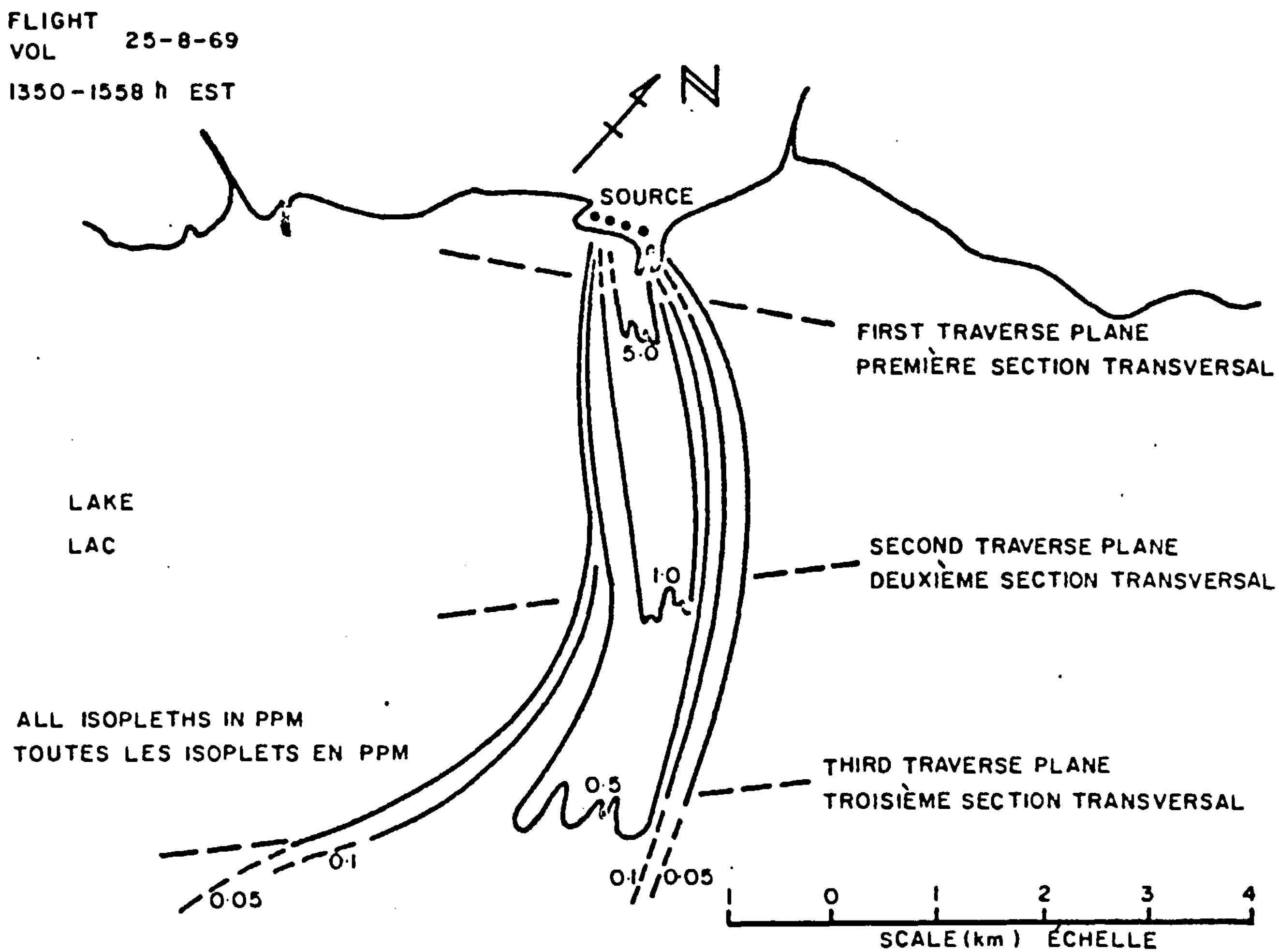

Figure 3. Plan view of the plume under neutral conditions derived from horizontal traverses.
Vue en plan du panache dans les conditions neutres, dérivée de traverses horizontales.

12

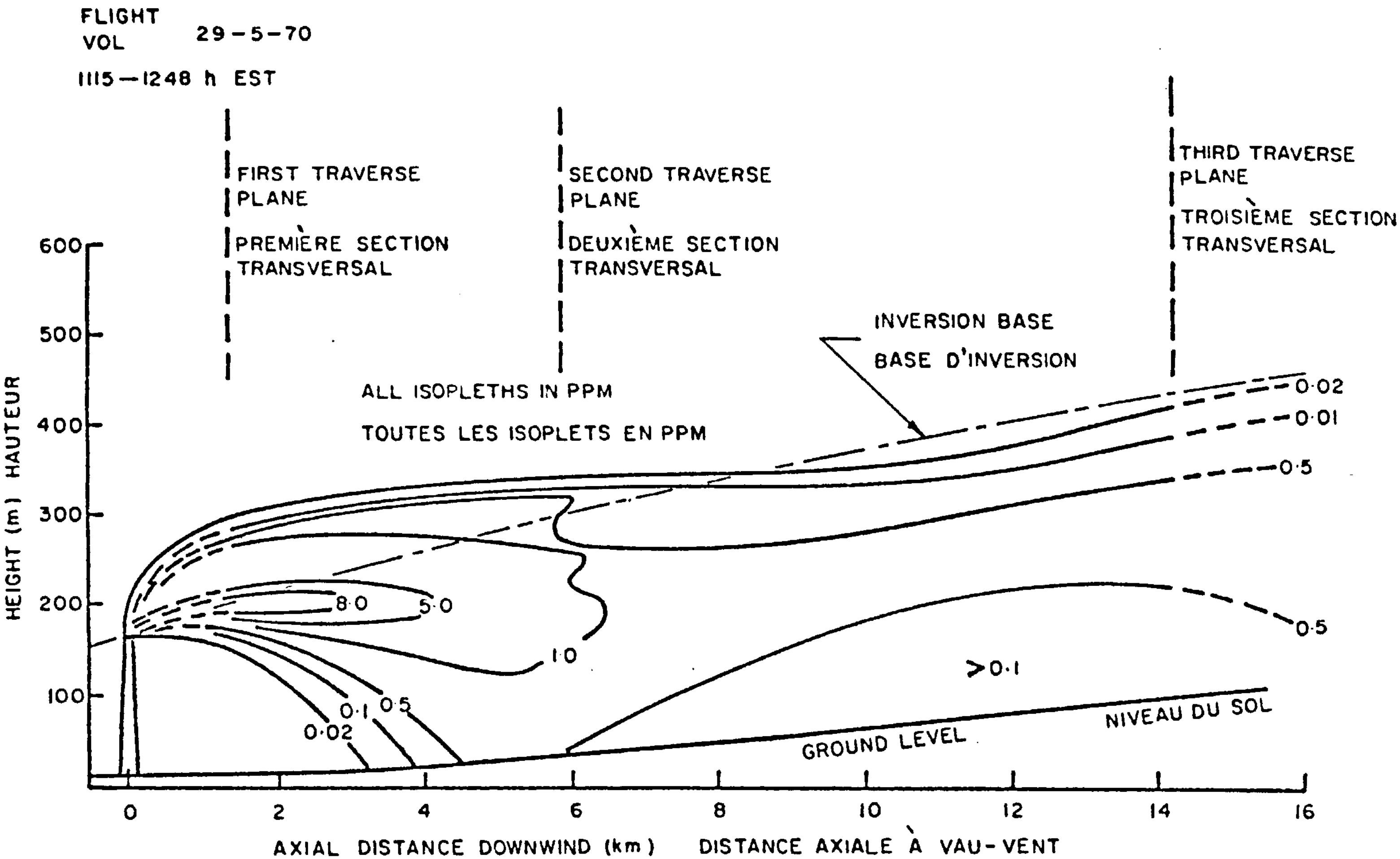

Figure 4. Vertical axial section of the plume, during inversion breakup, derived from horizontal traverses.

Section axiale verticale du panache, pendant une dislocation d'inversion, dérivée de traverses horizontales.

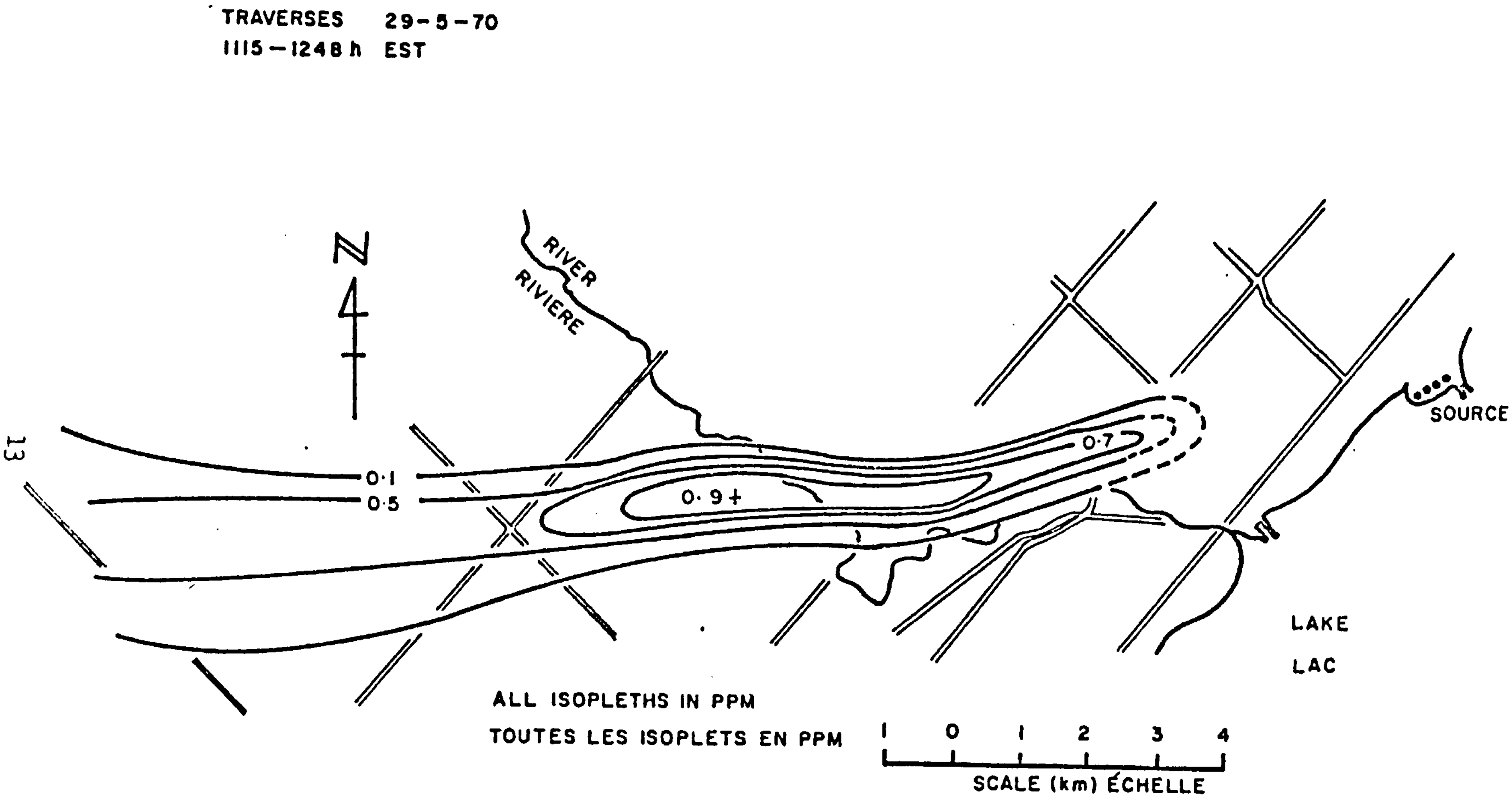

Figure 5. SO_2 isopleths at ground level during inversion breakup.

Isoplets en SO_2 au niveau du sol pendant en dislocation d'inversion.

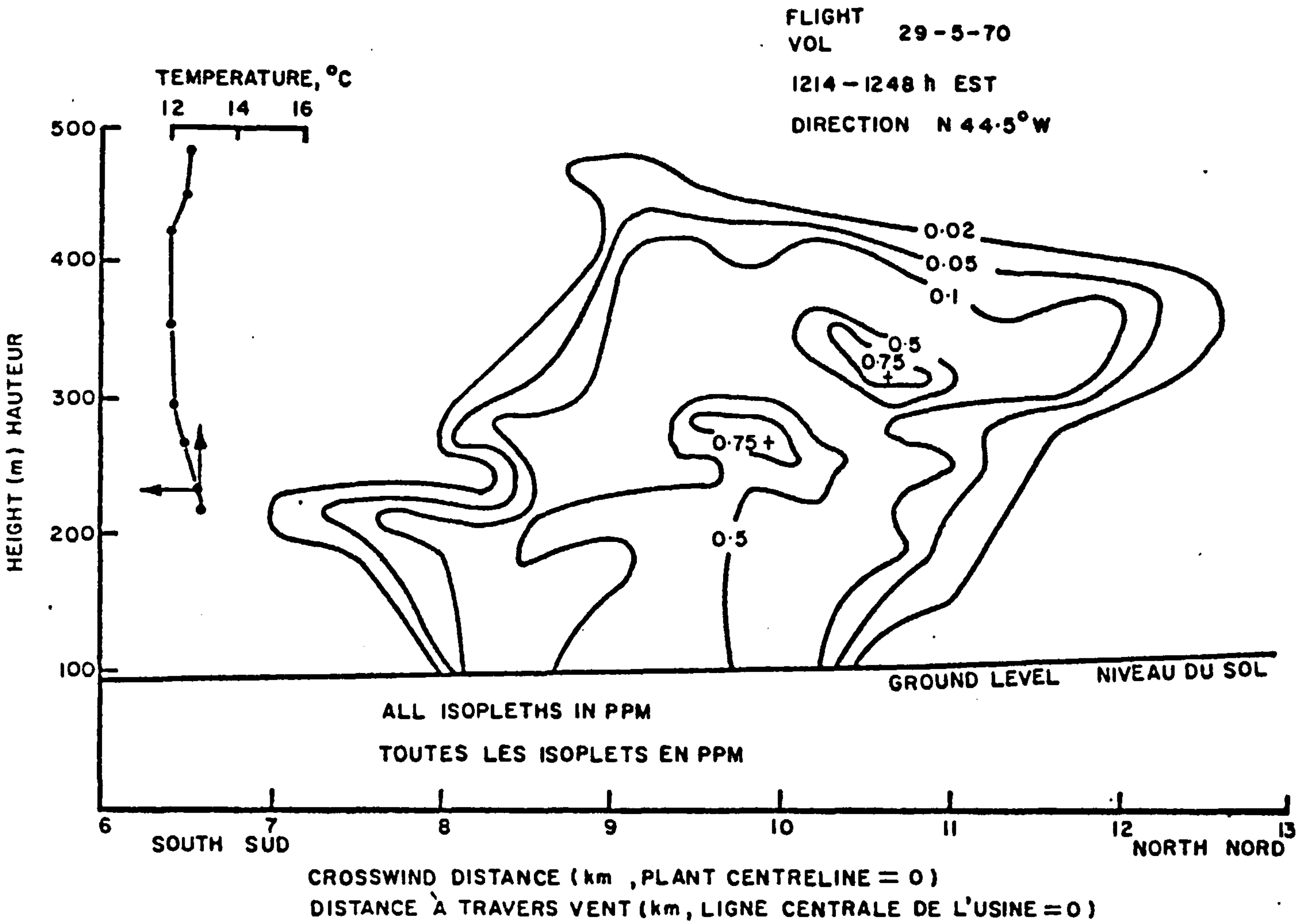

Figure 6. SO_2 isopleths for the third vertical crosswind section of the plume, during inversion breakup, at a mean axial distance of 14.1 km.
Isoplets en SO_2 pour la troisième section verticale à travers vent du panache, pendant une dislocation d'inversion, à une distance axiale moyenne de 14.1 km.

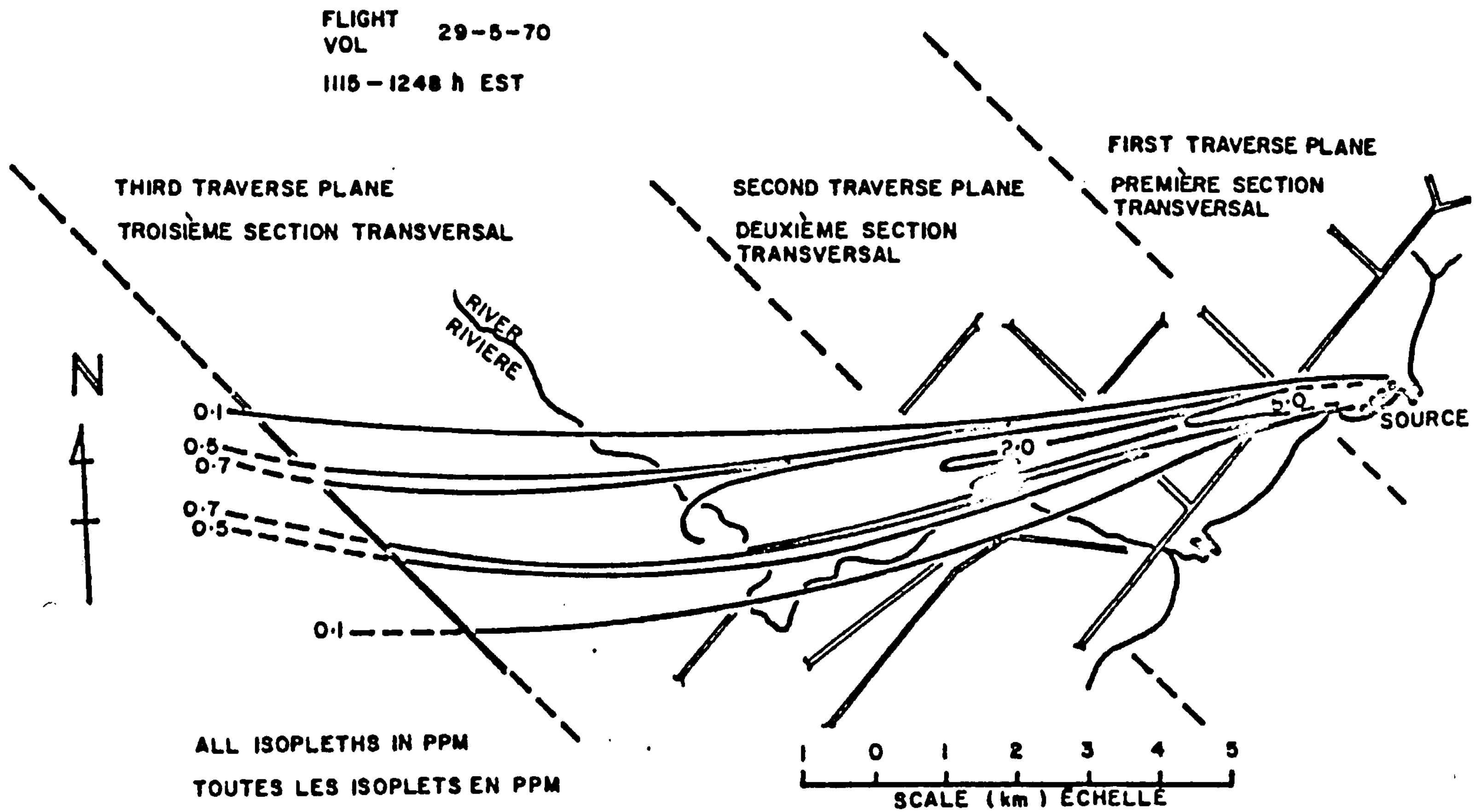

Figure 7. Plan view of the plume during inversion breakup, derived from horizontal traverses.

Vue en plan du panache pendant une dislocation d'inversion, dérivée de traverses horizontales.

2.3-85

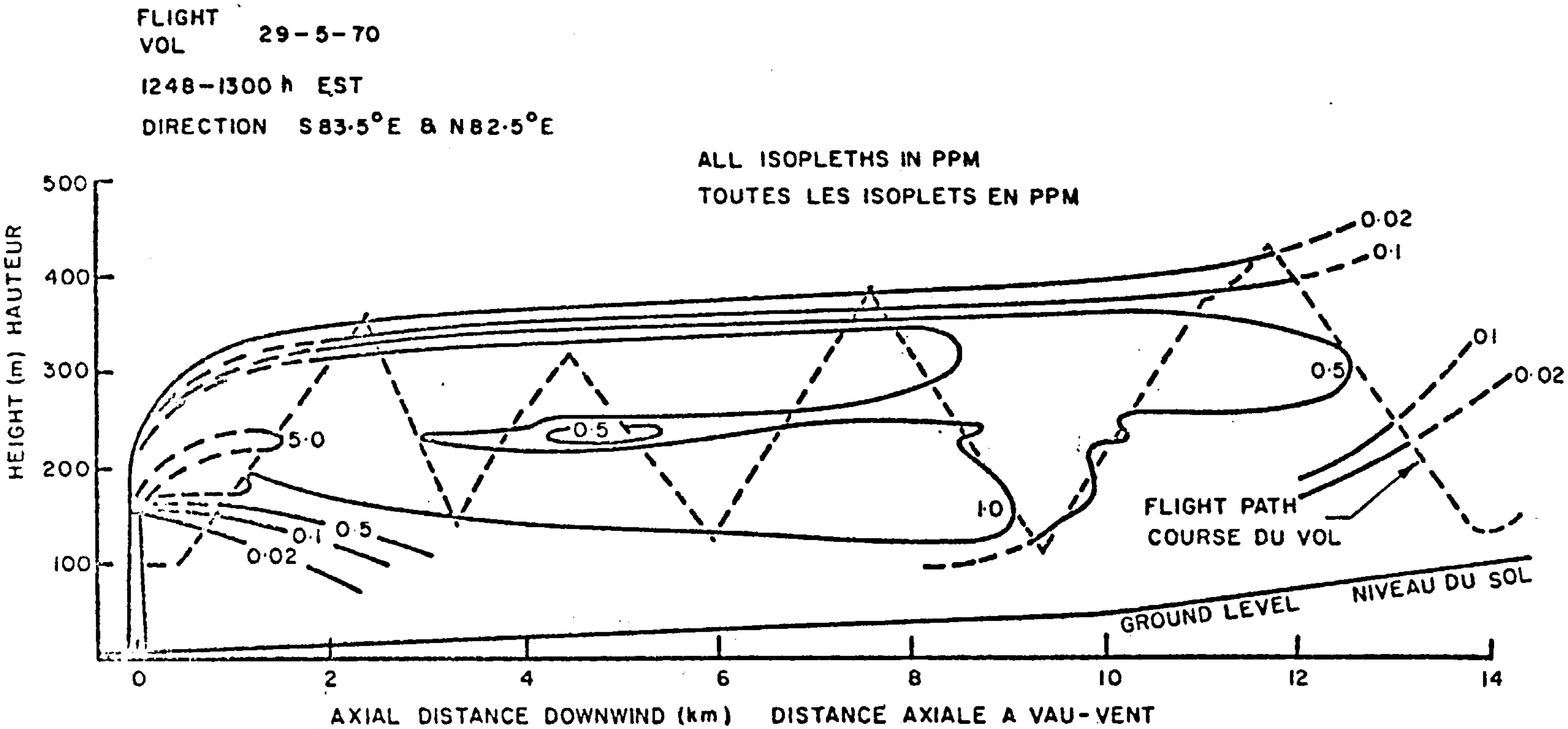

Figure 8.

Vertical axial section of the plume, during inversion breakup, derived from a sawtooth flight.

Section axiale verticale du panache, pendant une dislocation d'inversion dérivée d'un vol en dents de scie.

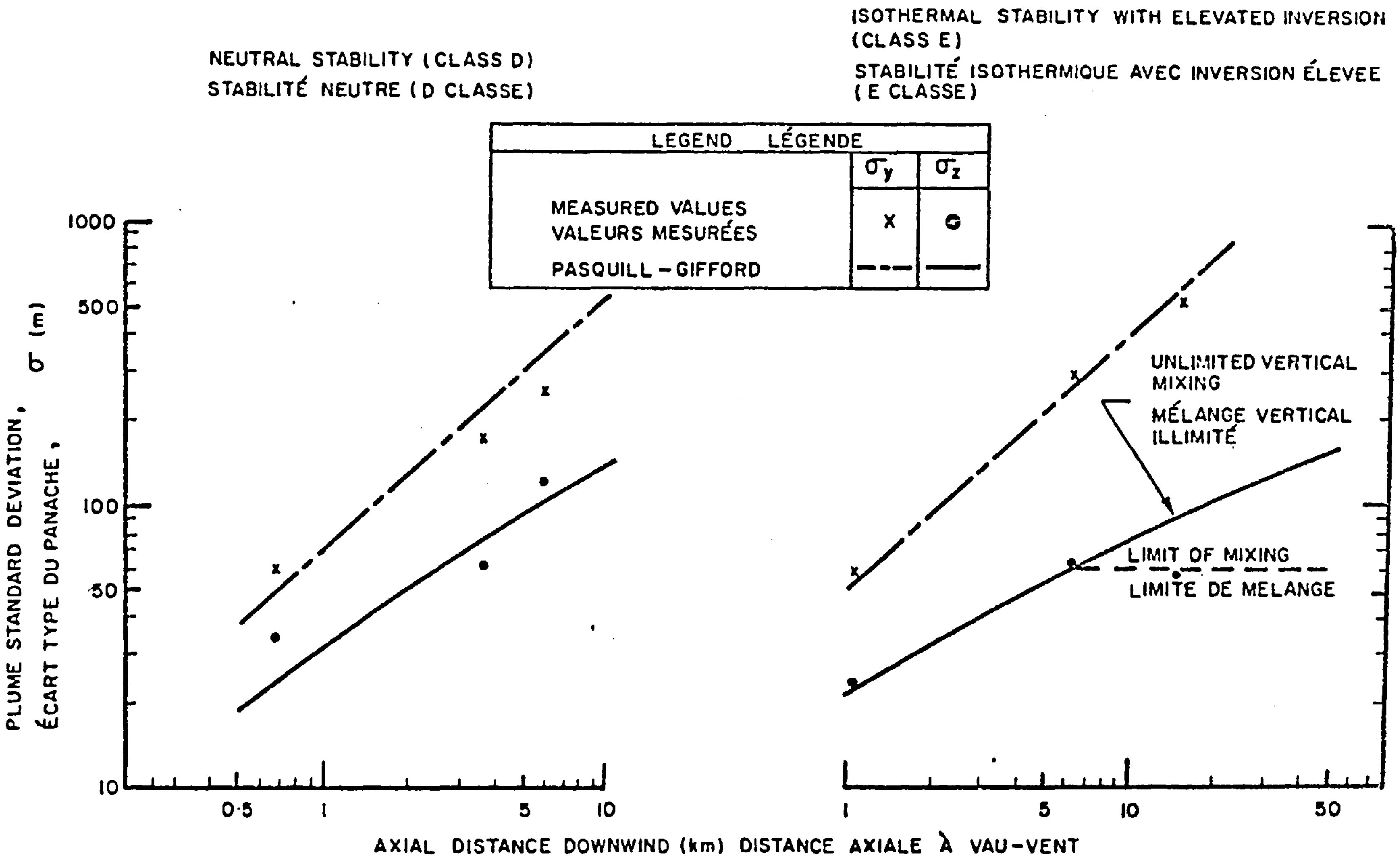

Figure 9. Comparison of measured plume diffusion coefficients with Pasquill-Gifford values.

Comparaison de coefficients de diffusion du panache mesurés avec des valeurs de Pasquill-Gifford.