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# DEPARTMENT OF ENERGY, MINES AND RESOURCES MINES BRANCH OTTAWA

*Mines Branch Program on Environmental Improvement*

# *A STUDY OF THE METEOROLOGICAL CONDITIONS WHICH DEVELOPED A CLASSIC "FUMIGATION" INLAND FROM A LARGE LAKE SHORELINE SOURCE*



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## ABSTRACT

A Study of the Meteorological Conditions which developed a Classic "Fumigation" Inland from a Large Lake Shoreline Source

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The study describes the change in meteorological conditions and associated air quality both at ground level and aloft from just prior to sunrise, at which time a stable atmosphere and low ground level pollutant concentrations existed, to the early afternoon of the same day when solar heating resulted in the development of a classic inversion fumigation condition for a period of a few hours.

Profiles of temperatures and winds were obtained using specifically designed battery operated radiosonde receivers with slow rise balloons. The spatial distribution of sulphur dioxide concentrations was obtained utilising two automobiles and a helicopter each instrumented with a continuous rapid response analyser.

The plume was measured to rise to a level at which an intensification of an inversion was noted. Average ground level concentrations as high as 0.90 ppm. were measured at a distance of 6 km. from the source during the inversion fumigation. The measured concentrations compared well with predictions using established formulae.

# A STUDY OF THE METEOROLOGICAL CONDITIONS WHICH DEVELOPED A CLASSIC "FUMIGATION" INLAND FROM A LARGE LAKE SHORELINE SOURCE

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## I. Introduction

The requirement of great amounts of water for cooling purposes or in manufacturing processes makes it desirable for industries to locate over lands adjacent to large bodies of water such as the Great Lakes. Such bodies of water have a major influence on the meteorological parameters which affect the dispersion of pollutants into the atmosphere. This influence was described in general terms by Hewson and Ollson (1967). A report by Ollson and Brock (1969) discussed the effects in more detail giving experimental data and a comprehensive review of the subject. Lyons (1970) described lake effects on emissions along the south shore of Lake Michigan. He suggested that during a lake-breeze situation, a convergence zone forms inland and that high concentrations of pollutants occurred along this zone. The mechanics of an advective inversion was described. The high concentrations of pollutants occurring inland were indicated by visual observations of a dense cloud of particulates and by their odour. No actual measurements of the concentrations of pollutants were included in Lyons report.

This study gives the results of co-ordinated meteorological and air quality measurements taken during a lake induced limited mixing condition. The plume from a large thermal generating station located on the shore of Lake Ontario was studied during a day in spring when gradient winds from the southeast direction occurred across the Lake. (See Figure 1). The air temperature was much warmer than that of the water. As a result of the warm gradient flow, an advective inversion persisted throughout the afternoon on the lee shore of the Lake. The breakdown of the inversion at elevations from the surface to above the plume centre line caused a classic "fumigation" condition resulting in sustained ground level concentrations of sulphur dioxide averaging up to 0.90 ppm. and instantaneous measurements of over 1.0 ppm.

## 2. Sources of Data

### (a) Meteorological

Two mobile, meteorological stations equipped with radiosonde and pilot balloon instrumentation were utilised to obtain vertical profiles of temperature and wind. One station was located on the lakeshore near the thermal power generating station; the second station was located 4 km. inland. The modification of both the temperature and wind profiles as the air moved inland off the Lake could thus be determined.

The helicopter which was instrumented to measure the sulphur dioxide concentrations was also equipped to record ambient temperatures.

Soundings were carried out simultaneously at the two meteorological stations just prior to the beginning of the helicopter survey and again towards the end. The 100-gram radiosonde balloons were filled to give a slow ascent rate of approximately 140 meters/minute. The response time of the temperature sensor is approximately 5 seconds. Wind speed and direction data were obtained by following the radiosonde balloons optically. In addition, supplementary wind data was obtained by releasing ceiling balloons to determine whether any wind shifts occurred during the course of the aerial survey.

(b) Sulphur Dioxide

The plume under study was emitted from a 2400 mw. thermal generating station located on the shore of Lake Ontario just west of Metropolitan Toronto. The station has four 155-meter stacks, each serving two 300 mw. units. During this study only three of the stacks were in service. During the morning survey the total heat flux was $2.6 \times 10^7$ cal./sec. and the sulphur dioxide emission rate was $2.3 \times 10^3$ g/sec. During the afternoon survey the heat flux was increased to $3.3 \times 10^7$ cal/sec and $SO_2$ emission rate was $5.6 \times 10^3$ g/sec.

A fast response Sign X sulphur dioxide sampler was used in a helicopter to provide continuous measurements of sulphur dioxide. The sensing probe was mounted on a strut of the helicopter, positioned so that the propeller downwash would not influence the measurements. Sulphur dioxide concentration, pressure height, temperature and dew point depression measurements were recorded simultaneously. The helicopter was continuously tracked by an electronic, navigational system, which gave helicopter positions to within ± 10 feet accuracy. The air speed was maintained at 95 km/hr during each survey.

Two automobiles were instrumented with similar Sign X sulphur dioxide samplers. These vehicles obtained ground level sulphur dioxide readings in conjunction with the helicopter surveys. The helicopter obtained data downwind by flying horizontal traverses at three selected distances from the source nearly normal to the plume axis. Each traverse consisted of a series of level passes through the plume at intervals in height of 30 or 60 meters as found necessary to obtain the detail required. The early morning survey under stable conditions had a duration time of 57 minutes while the afternoon survey lasted for one hour and thirty-three minutes.

3. Synoptic Conditions - May 29, 1970

The synoptic weather pattern was dominated by a slow moving high pressure system which, on May 29, was centred just east of the lower Great Lakes. This high was a westward extension of the semi-permanent Bermuda anti-cyclone. Radiosonde data from Buffalo indicated warming aloft had taken place due to subsidence within the air mass.

Southeasterly winds prevailed over the lower Great Lakes as a result of a pressure gradient west of the high.

During the daytime the ambient temperatures just south of Lake Ontario ranged from 24 to 27° C. The surface water temperature of Lake Ontario ranged from 3° C at the middle of the Lake to about 7° C within a mile of the shore. The air-water temperature contrast was thus between 13 and 20° C, producing a situation for a low level advection inversion to develop over lands adjacent to the north shores.

4. Vertical Profiles of Temperatures and Winds

Figures 2(a) and (b) show the potential temperature and wind profiles obtained during the morning at the lakeshore site and at the inland location. Results of the soundings obtained during the afternoon at these locations are shown in Figures 3(a) and (b). In both figures the results obtained just prior to the helicopter survey are shown as dashed lines and the thin solid lines indicate the results obtained towards the end of the survey. The thick solid lines indicate the mean potential temperature profile averaged over the period during which the aerial survey was conducted.

During the morning, the soundings at the inland and lakeshore stations were very similar with only a slight variation in the wind profile below 150 meters. At the inland location, the surface temperature was 1° C higher than at the lakeshore. The surface winds at both locations were light easterly at the surface and backed with height by about 30° in the first 150 meters while at the lakeshore location, the winds veered by about the same amount up to this elevation. Above this, the winds were similar at both locations. The atmosphere was stable in the lower levels with the potential temperature gradient ($\partial\theta/\partial z$) of + 1.5° C/100 meters at both loactions from the surface to 1200 meters.

By the afternoon, solar heating warmed the lower layers of the air resulting in an increase in potential temperature of 2° C at the lakeshore location and 5° C at the inland site. The potential temperature gradient at the shoreline location, (Figure 3(a)), shows a gradient of -1° C/100 meters from the surface up to 150 meters. Between the 150-meter and 700-meter heights, the gradient was + 1.8° C/100 meters and above this + 0.8° C/100 meters. The mixing height was 185 meters.

At the inland location, (Figure 3(b)), the potential temperature gradient up to 200 meters was -1.9° C/100 meters, almost twice the rate of that at the lakeshore. Above 200 meters, the gradient at both locations became similar. The mixing height at the inland site was 270 meters.

Temperature soundings obtained by the instrumented helicopter indicated a mixing height of 220 meters over a semi-rural inland location to the west of the meteorological station site.

A vertical section of temperature from 2 km. off-shore to 14 km. inland is shown in Figure 4. This section was constructed using data from both the morning radiosonde observations and helicopter measurements. A stable, almost isothermal layer, extended from the surface to 200 meters at the lakeshore, sloping upward to 350 meters at a location 14 km. inland. There was a gradual increase in temperature with height above the isothermal layer. Some surface heating is evident over the inland station.

Figure 5 shows a vertical section of temperature constructed from data obtained during the afternoon from about 1 km. offshore to 14 km. inland. In contrast to the morning cross section, a well defined temperature pattern is evident. The coldest air is near the shore at a height of 120 meters extending inland and sloping upward parallel to the terrain. Surface heating is evidently increasing in intensity with distance from the lakeshore. At 14 km. inland the axis of the cold air is at a height of about 300 meters above the lake surface.

## 5. The Behaviour of the Plume

### (a) Morning Survey

A vertical axial section of the plume at a point of 1 km. downwind of the source during the morning stable conditions is shown in Figure 6. The plume (centre line) rose to about 250 meters above the surface at this point but at 4 km. downwind the centre line of the plume was found to be at 220 meters in height. Beyond this location the plume gradually rose upward increasing gradually in elevation with the terrain.

There was little vertical spread of the plume consistent with the stable stratification of theair. Cross sections taken nearly perpendicular to the plume axis at three locations are shown in Figures 7(a), (b) and (c). These sections are at distances from the source of 1.4, 4.0 and 10.8 km. respectively. The marked skew, evident in the figures, is in part due to the variable plume temperatures of each of the three stacks which were in operation. This resulted in a variation of the plume rise from each stack. The levels of the maximum concentrations could be detected for each plume. There was also a wind directional shear of about 25 to 30$^{\circ}$ between the height of the top of the stack and the height of the top of the plume. The relationship between wind shear and plume skew has been discussed in more detail by Pooler and Neimeyer (1970).

The maximum centre line concentration measured was just over 5 ppm. With the limited vertical mixing, this was somewhat lower than expected. It is possible that, as a result of the step-profiling technique used, the actual centre line maximum concentration was missed since this would be within a very thin layer.

A plan view of the plume at the level of maximum concentration as derived from the horizontal cross sections is shown in Figure 8. At 4 km. downwind from the source, the horizontal spread of the plume was about 2.2 km. and the vertical thickness was about 40 meters. Automobile traverses detected no significant ground level concentration of sulphur dioxide anywhere beneath the plume.

(b) Afternoon Survey

The vertical, axial section of the plume drawn from data obtained during the afternoon survey is shown in Figure 9. The top of the plume was found to be at 350 meters at a location of 4 km. downwind and at 450 meters at 14 km. The height of the centre line of the plume is shown to be at about 225 meters at 3 km. from the source. At greater distances from the source, vigorous mixing in the downward direction resulted in a classic "fumigation" condition. High ground level concentrations of sulphur dioxide were measured by a series of automobile traverses approximately perpendicular to the plume axis. Ground level concentrations, averaging as high as 0.90 ppm., were measured at a number of points from 6 to 10 km. along the length of the plume downwind from the source. The isopleths of sulphur dioxide concentrations at ground level are shown in Figure 10.

Vertical crosswind sections of the plume at distances of 1.2, 6.3 and 14.1 km. downwind from the source are shown in Figures 11(a), (b) and (c) respectively. At a point where the plume first reaches the ground at a detectable concentration (3.5 km. downwind), the plume was about 350 meters in thickness and had a horizontal spread of 1.2 km. Figure 12 shows a plan view of the plume through the centre of maximum concentration.

## 6. Discussion of Results

During the morning when conditions were stable, the plume rose about 65 meters and stratified in a thin layer. The crosswind spread of the plume was great when compared with the vertical spread. The plume did not reach the ground within the distance from the source that measurements were taken (15 km.). For purposes of comparison, Briggs formula for stable conditions was utilised to calculate the plume rise:

$$\Delta H = 2.4 \left(F/\bar{u}s\right)^{1/3}$$

where $F = 3.7 \times 10^{-5}\, Q_H$

$Q_H$ = Heat emission due to efflux of stack gases

$\bar{u}$ = Mean wind speed

$S$ = Stability parameter = $g/T \dfrac{\partial \theta}{\partial z}$

$g$ = Gravitational acceleration

$T$ = Average absolute temperature of ambient air

The formula gives a predicted rise of 147 meters as compared with the measured rise of 65 meters. The lower than predicted rise is likely due to an intensification of the inversion aloft at the low height above the stacks.

During the afternoon an internal boundary layer became pronounced due to effects of solar heating taking place inland from the lake. The top of the superadiabatic layer of air was quite well defined. The sulphur dioxide measurements indicated fumigation conditions which accompanied the break-up of low level temperature inversions.

Detectable concentrations nearest to the source were found to occur at the distance of 3.5 km. downwind. Concentrations averaging about 0.90 ppm. occurred from 6 km. to 10 km. from the source, affecting an area of about 1 1/2 $km^2$. Concentrations averaging between 0.5 and 0.9 ppm. occurred over an area covering more than 14 $km^2$.

Concentrations were calculated utilising a formula for estimating inversion fumigation concentrations given in the "Recommended Guide for the Prediction of the Dispersion of Airborne Effluents", edited by Maynard Smith and published by the American Society of Mechanical Engineers. The formula: $C_{IF} = \frac{0.4Q}{H \sigma_y \bar{u}}$

$Q$ = Emission rate of the pollutant

$H$ = Effective stack height

$\sigma_y$ = Horizontal standard deviation of the plume

$\bar{u}$ = Mean wind speed

estimates a concentration of 0.87 ppm. at 6 km. from the source, comparing very well with measured values. A concentration of 0.65 ppm. was computed at the distance of 10 km.

7. Summary

The behaviour of a plume emitted by a multiple stack source was described for stable and inversion fumigation conditions using simultaneous measurements of the concentrations of sulphur dioxide

and the meteorological parameters which affect dispersion.

Computed ground level concentrations for inversion fumigations compared well with the measured values.

8. References

1. ASME Committee on Air Pollution Controls. "Recommended Guide for the Prediction of the Dispersion of Airborne Effluents", Maynard Smith, Editor, Brookhaven National Laboratory, 1968.

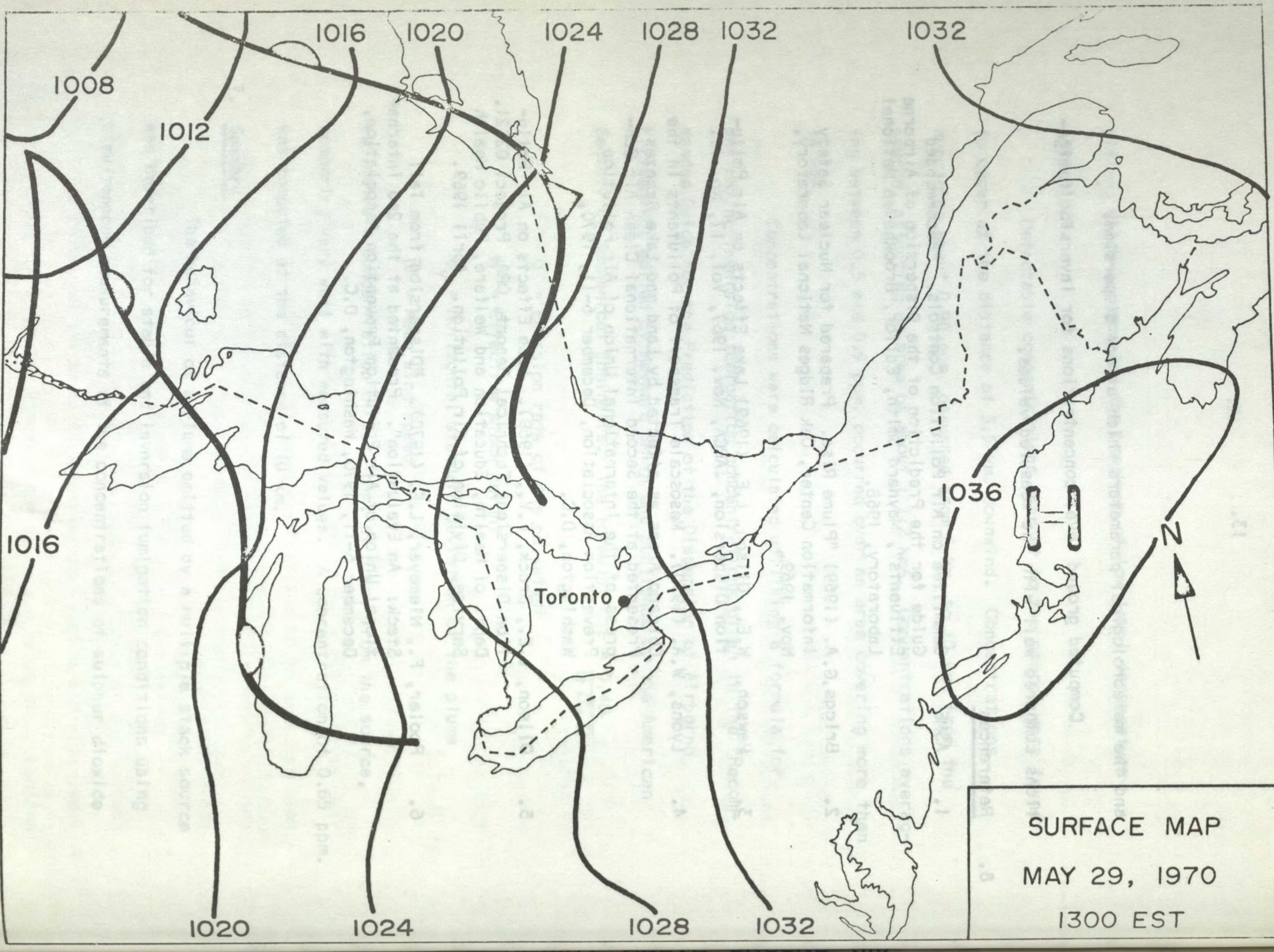
2. Briggs,G.A. (1969) "Plume Rise. Prepared for Nuclear Safety Information Center, Oak Ridges National Laboratory, Nov. 1969.

3. Hewson, W.E., Ollson, L.E. (1969) Lake Effects on Air Pollution Dispersion, JAPCA, Nov. 1967, Vol. 17, No. 11.

4. Lyons, W.A. (1970). Mesoscale Transport of Pollutants in the Chicago Areas as affected by Land and Lake Breezes. Presented at the Second International Clean Air Congress of the International Union of Air Pollution Prevention Association, December 6-11, 1970, Washington, D.C.

5. Ollson, L.E., Brock, F.V., (1969). Lake Effects on Air Pollution Dispersion, Technical Report, ORA, Project 02621. Dept. of Health, Education and Welfare, Public Health Service, Division of Air Pollution. April 1969.

6. Pooler, F., Niemeyer, L.E. (1970). "Dispersion from Tall Stack: An Evaluation". Presented at the 2nd International Union of Air Pollution Prevention Association, December 6-11, 1970, Washington, D.C.




SURFACE MAP
MAY 29, 1970
1300 EST

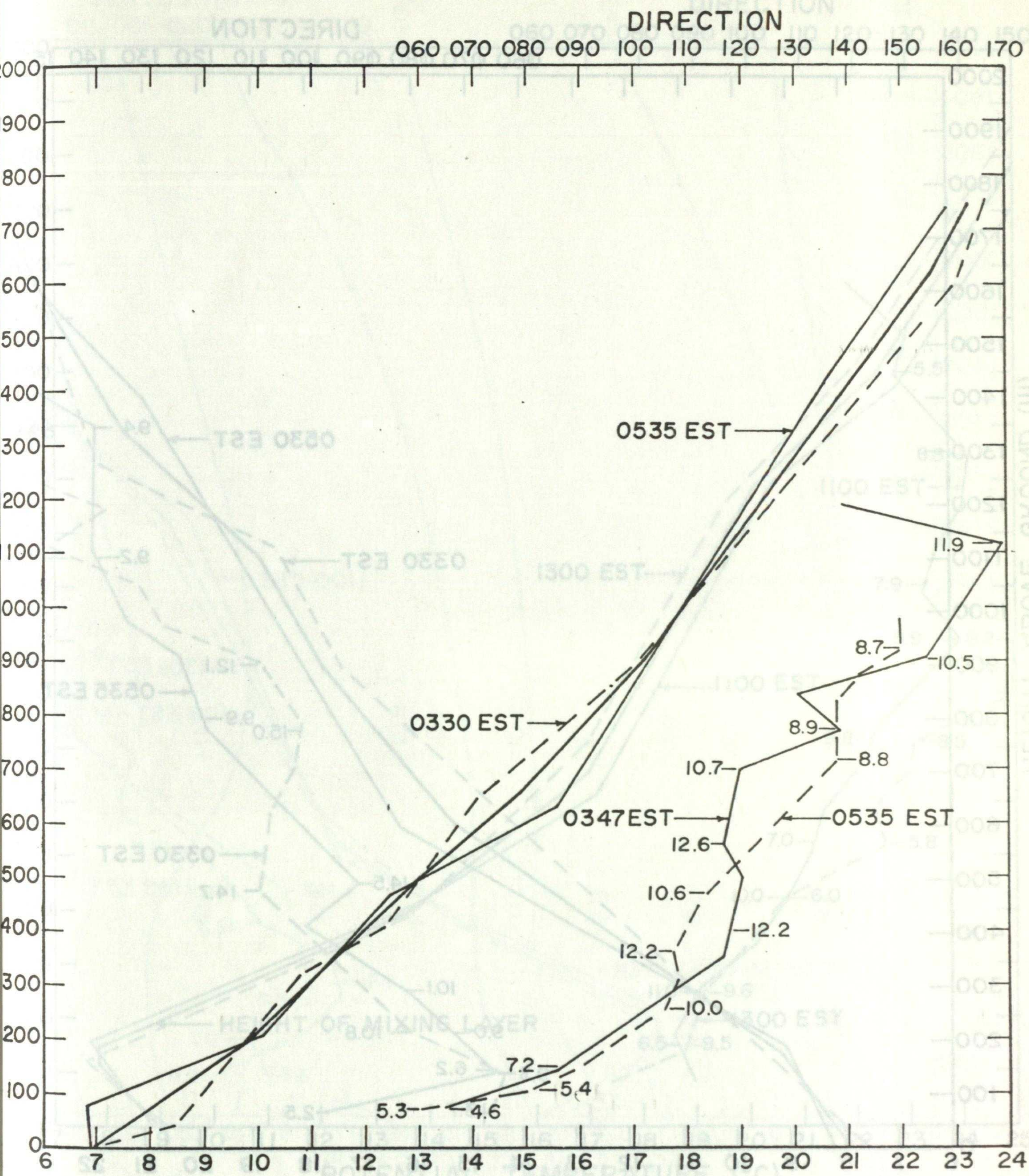



Fig. 2 (a): Potential temperature and wind profiles at the lakeshore site during the morning. Wind speed in m/sec.

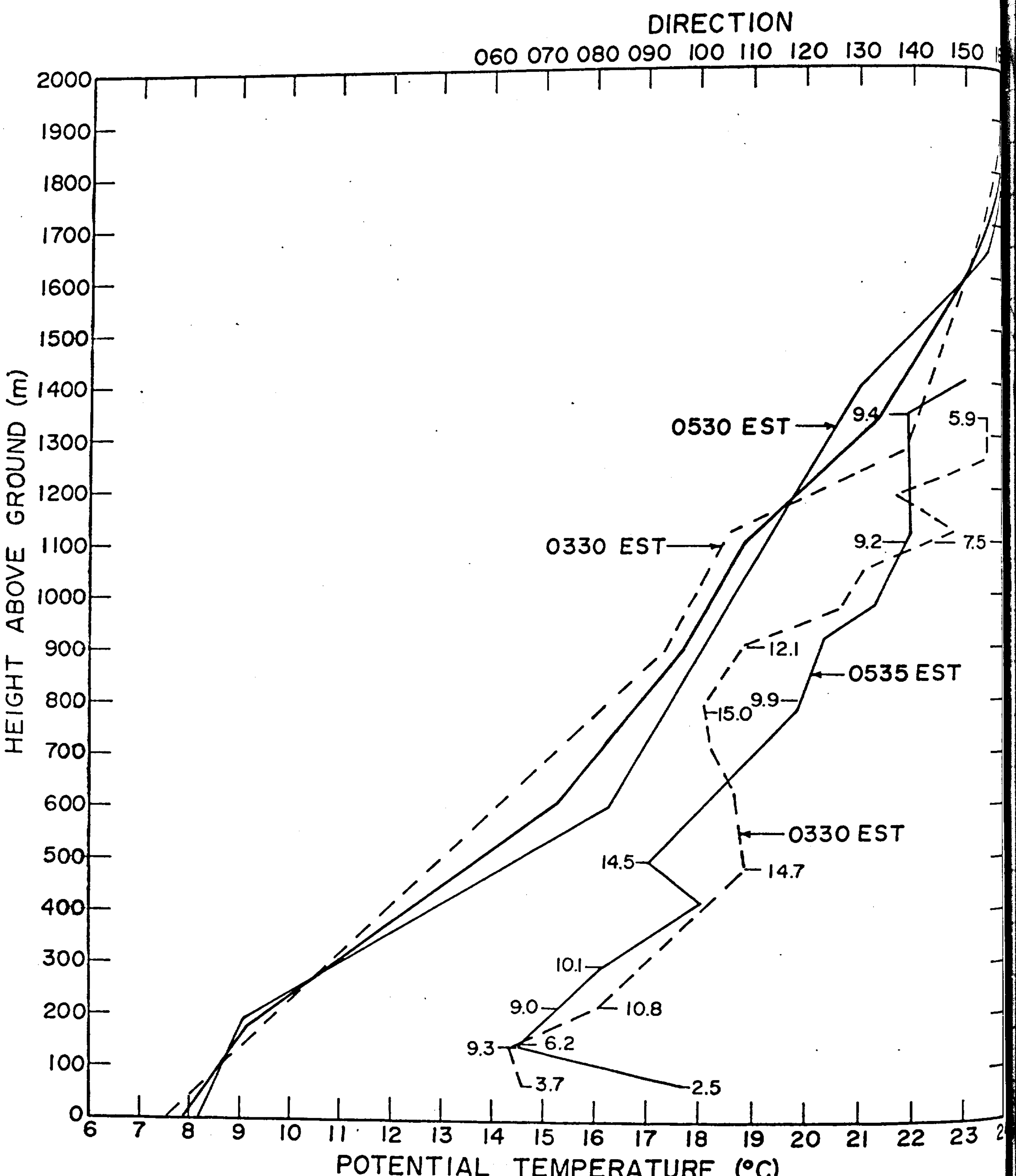



Fig. 2 (b): Potential temperature and wind profiles at the 4 km inland site during the morning. Wind speed in m/sec.

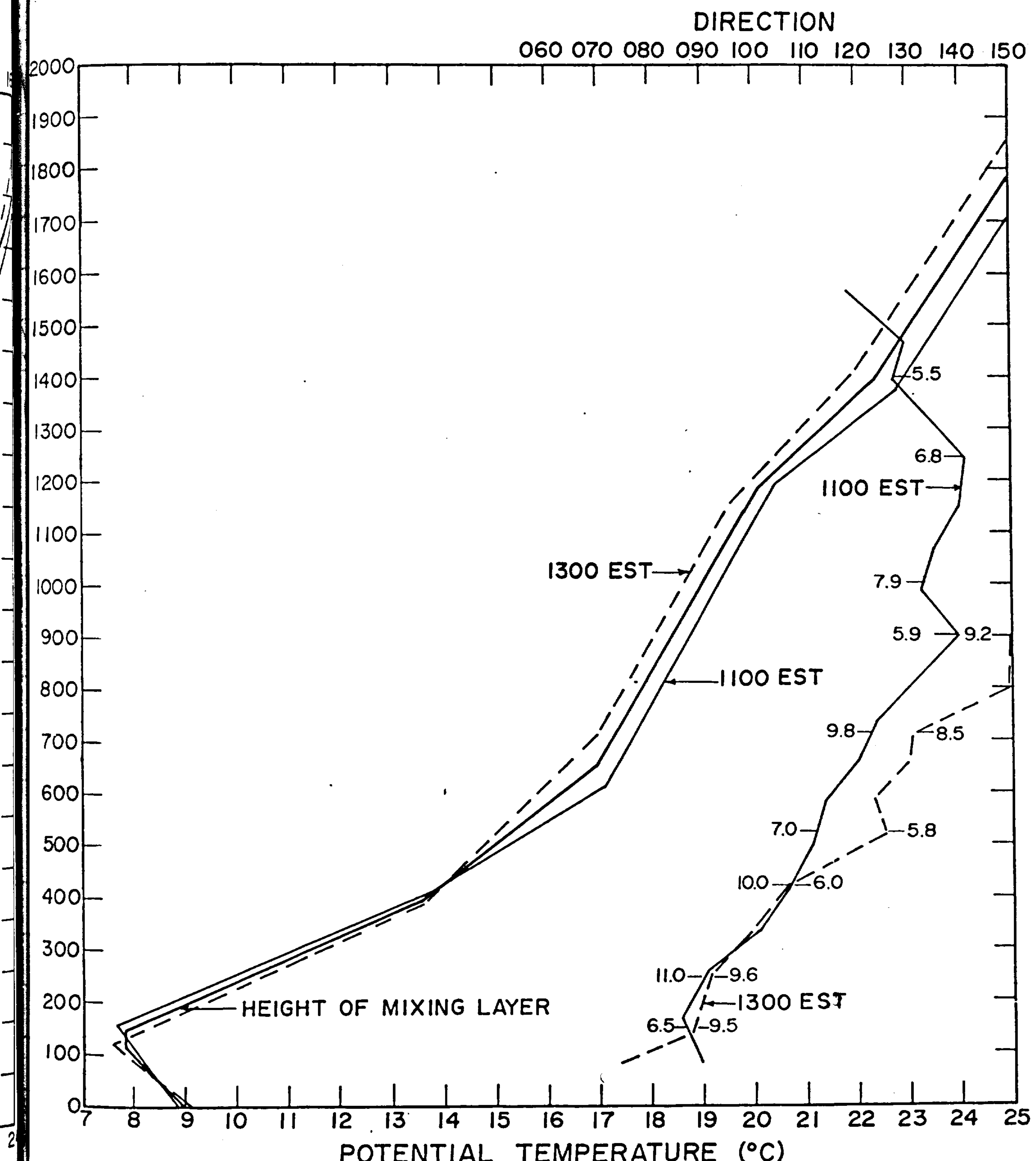



Fig. 3 (a): Potential temperature and wind profiles at the lakeshore site during the afternoon. Wind speed in m/sec.

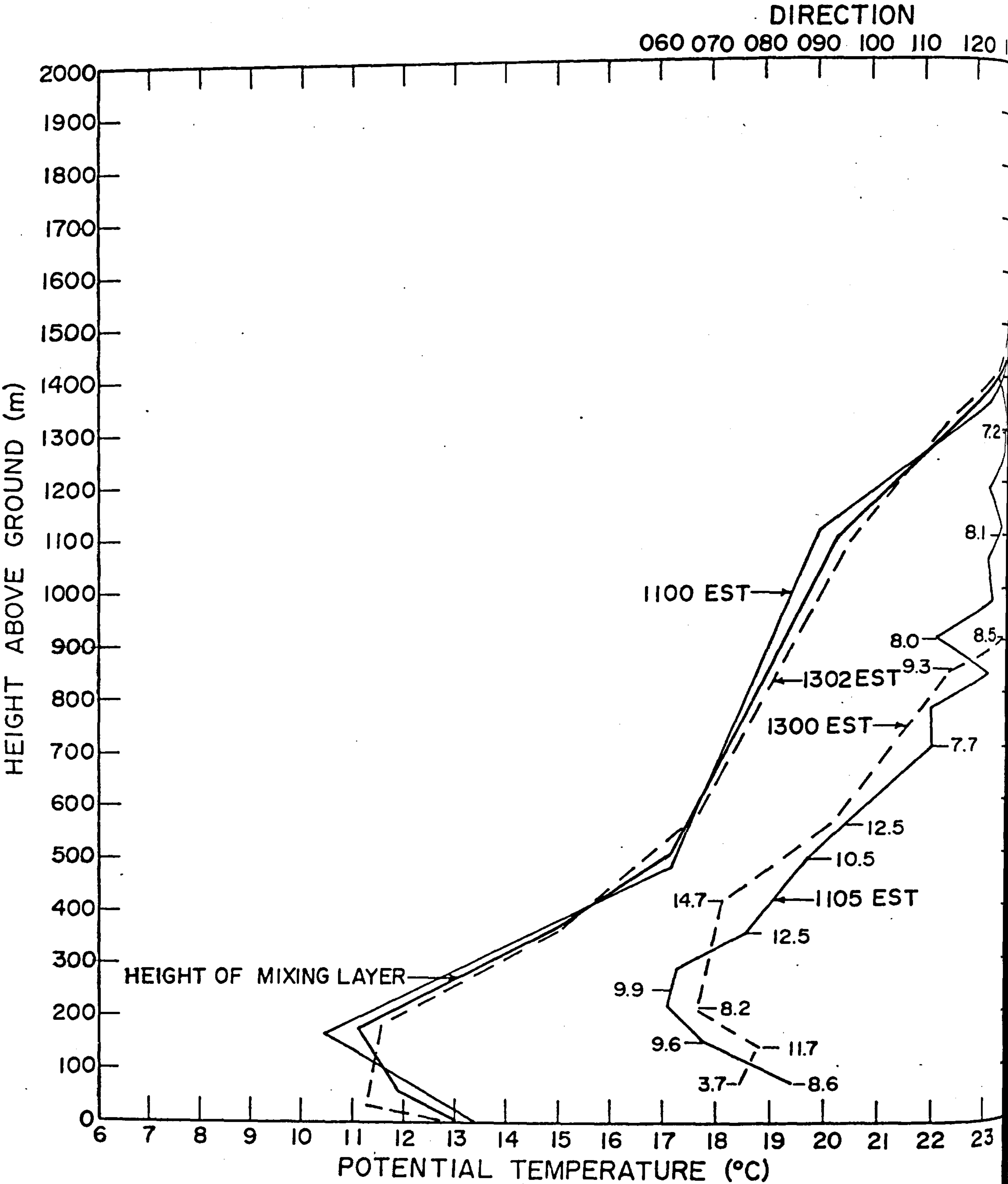



Fig. 3 (b): Potential temperature and wind profiles at 4 km inland during the afternoon. Wind speed in m/sec.

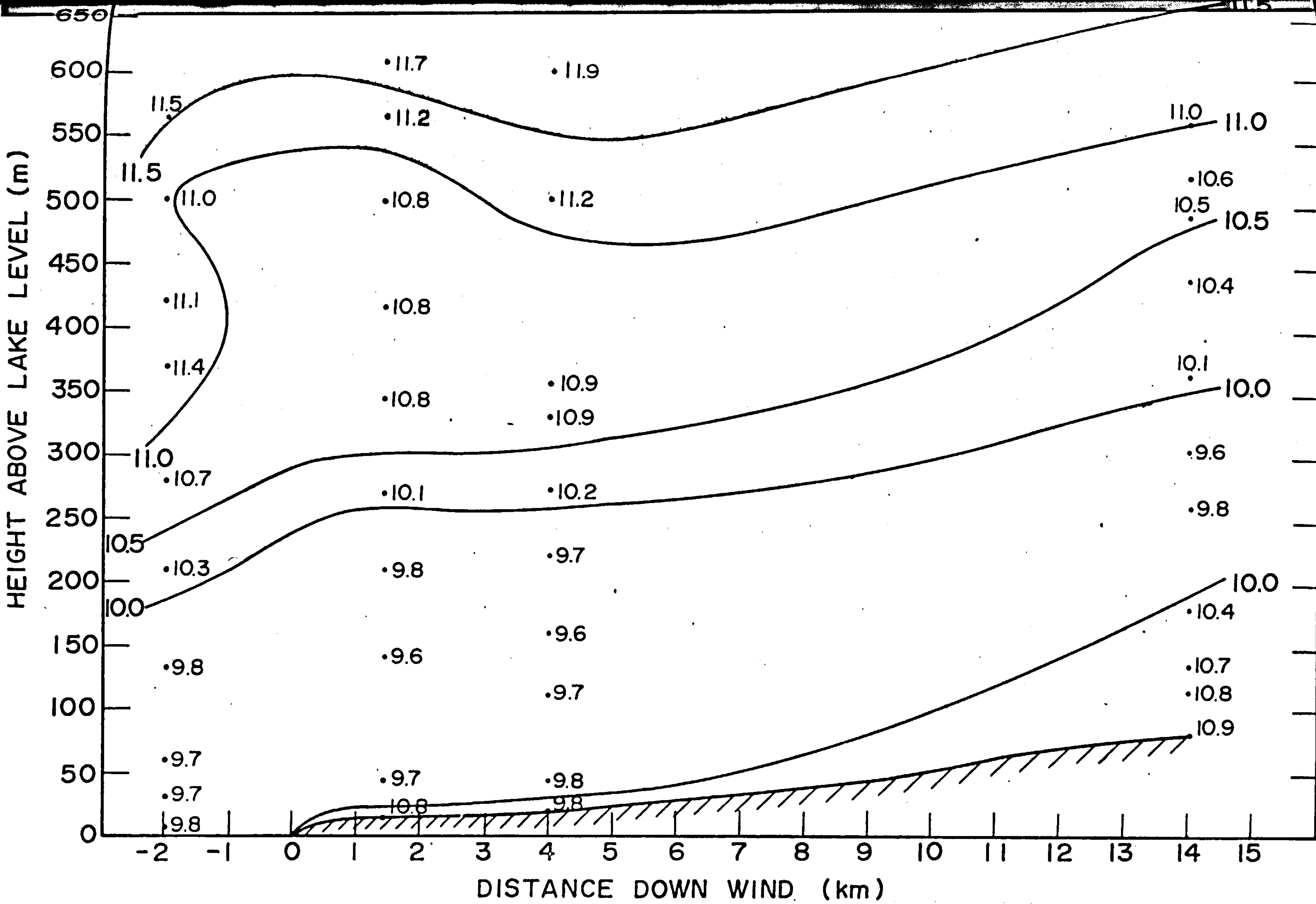



Fig. 4: A vertical section of temperature during the morning of May 29, 1970.

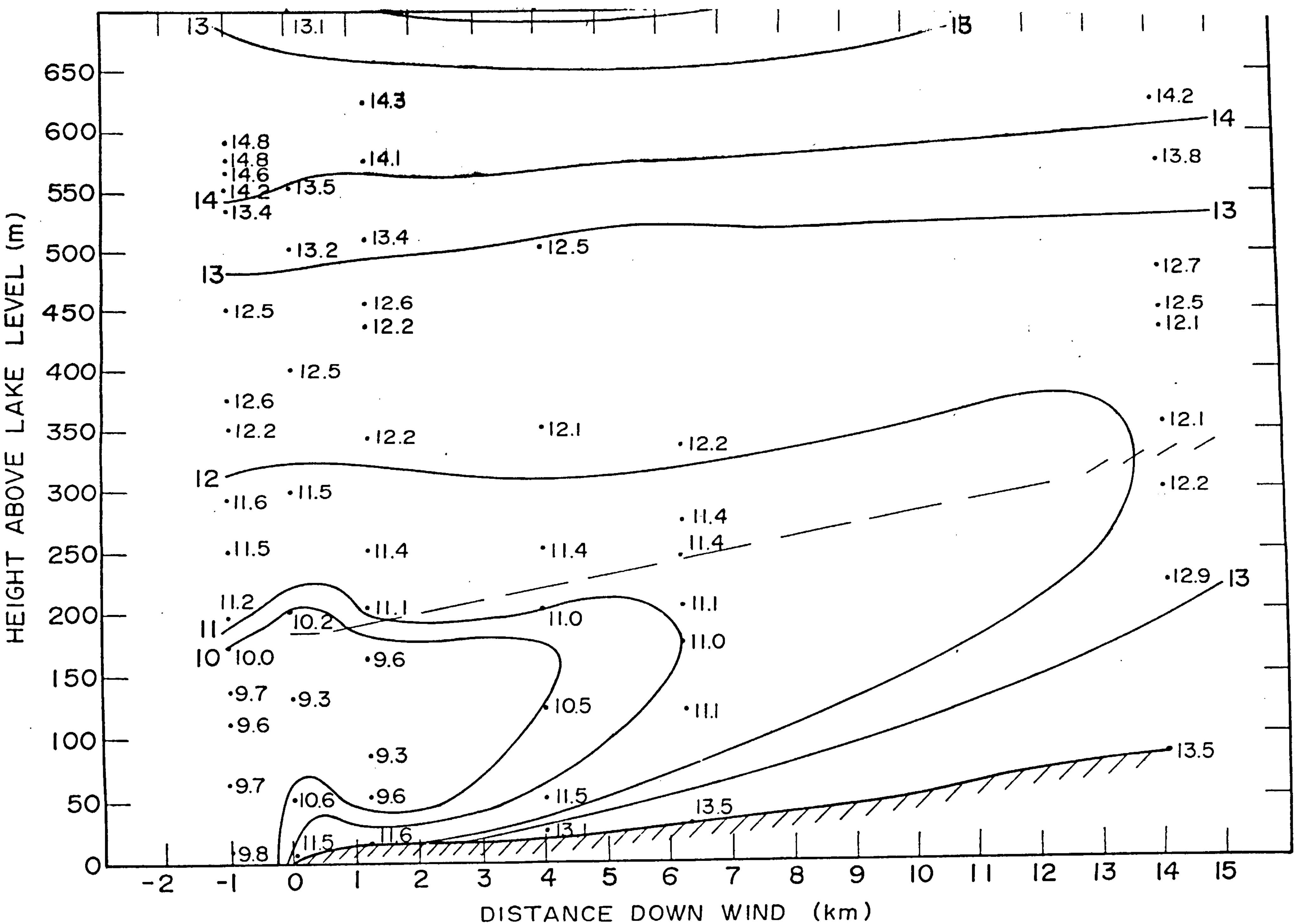



Fig. 5: A vertical section of temperature during the after-

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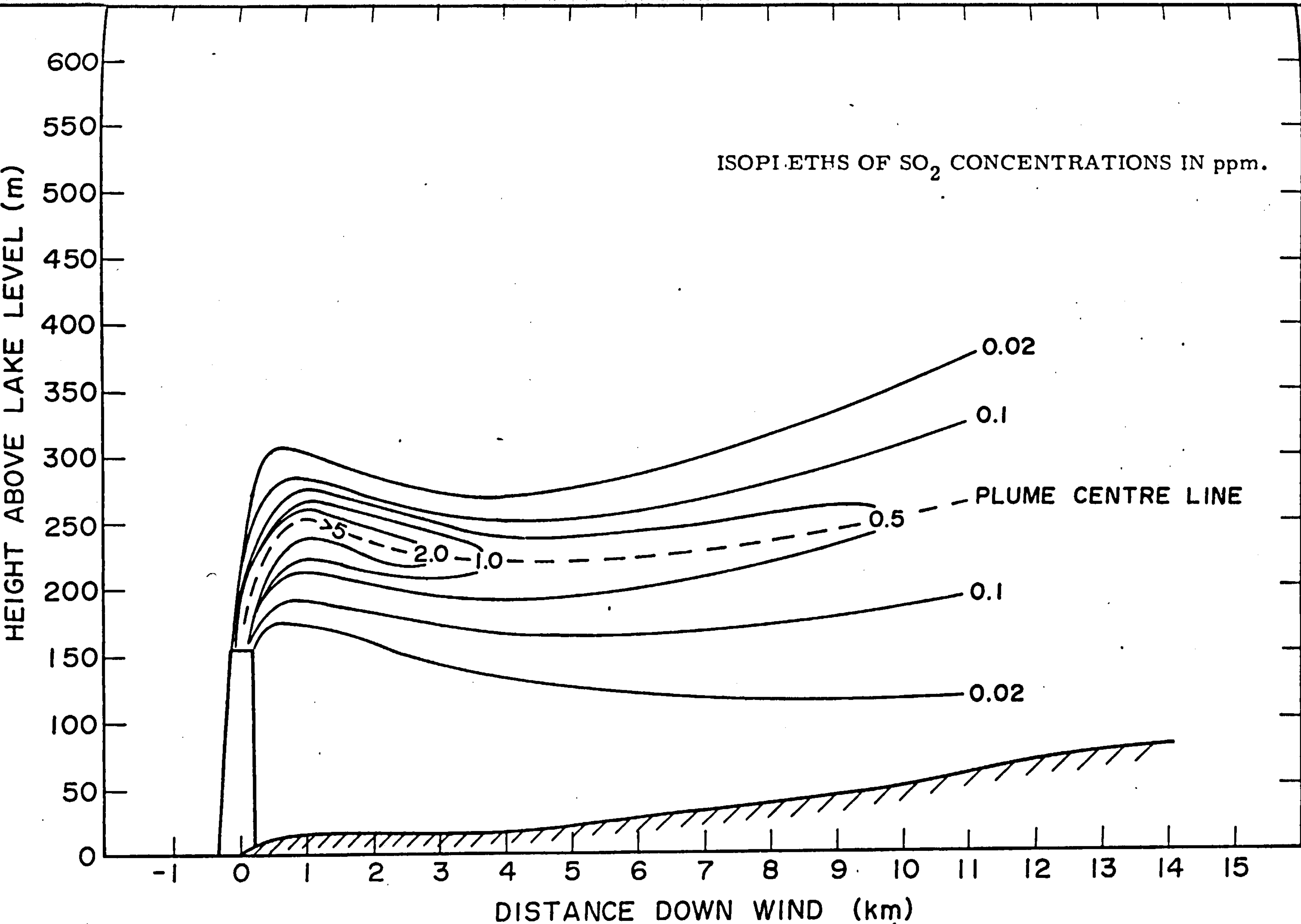


Fig. 6: A vertical axial section of the plume during the morning stable conditions of May 29, 1970.

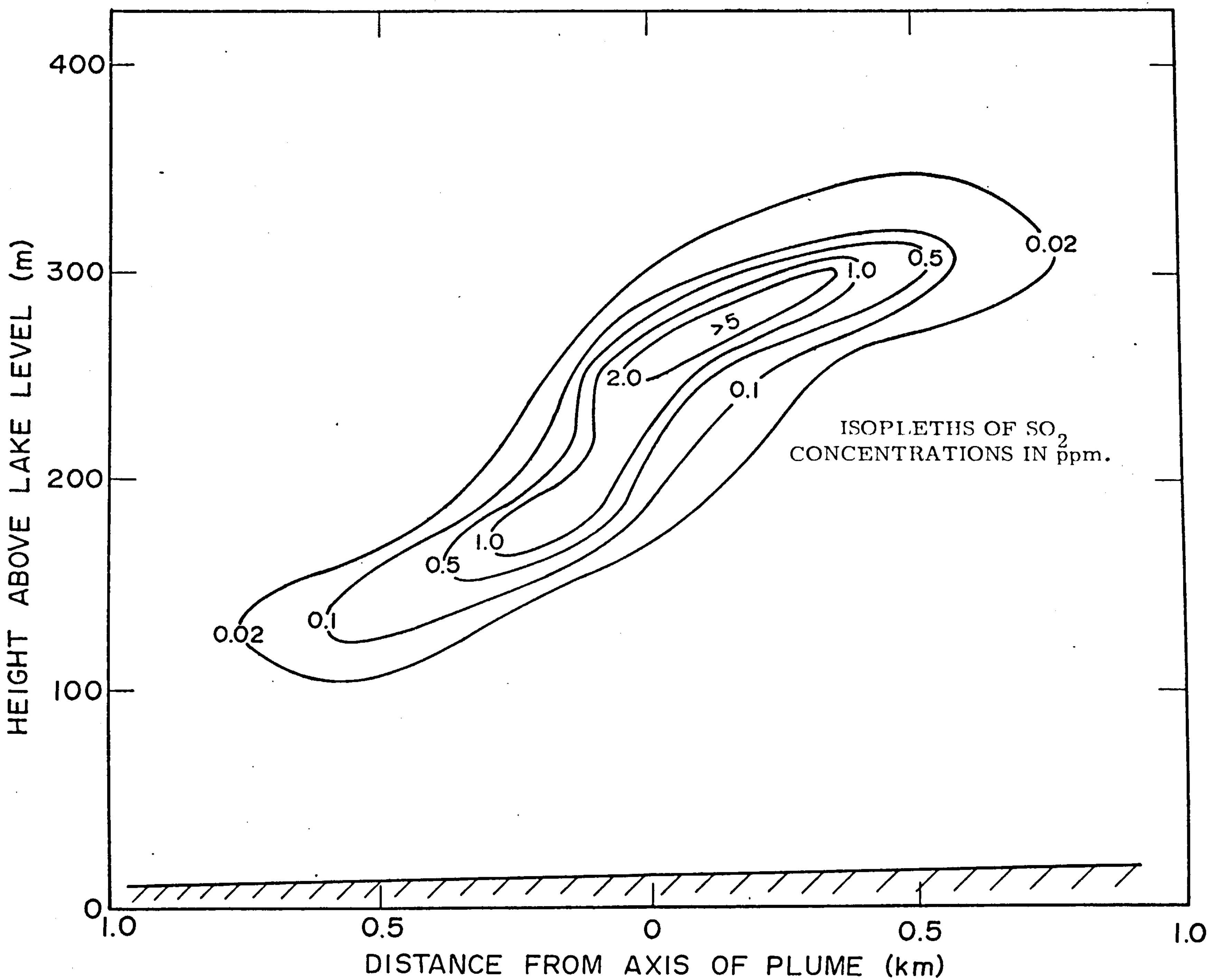


Fig. 7 (a): Cross-section of plume during the morning at 1.4 km

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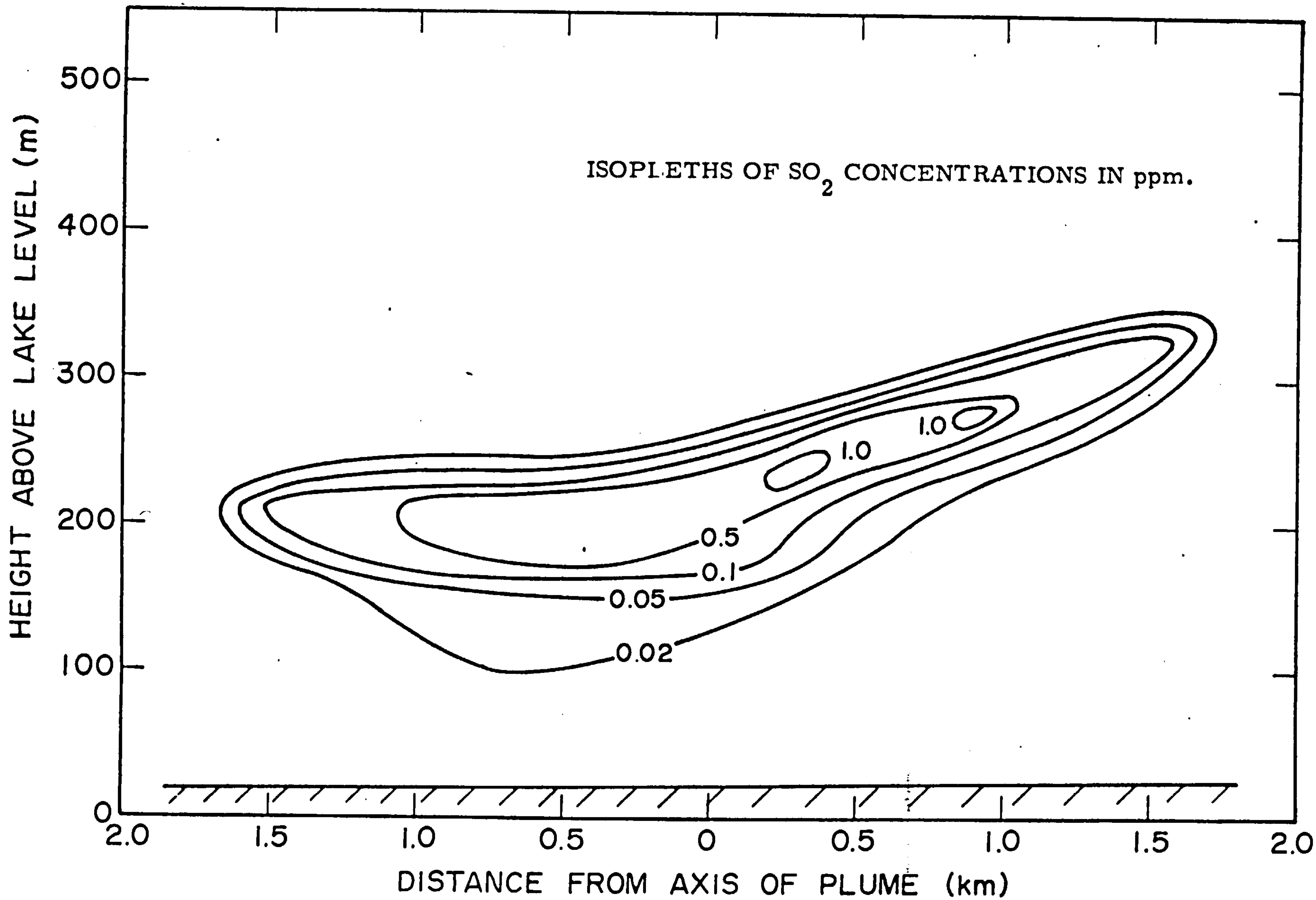



Fig. 7 (b): Cross-section of plume during the morning at 4.0 km downwind of the source.

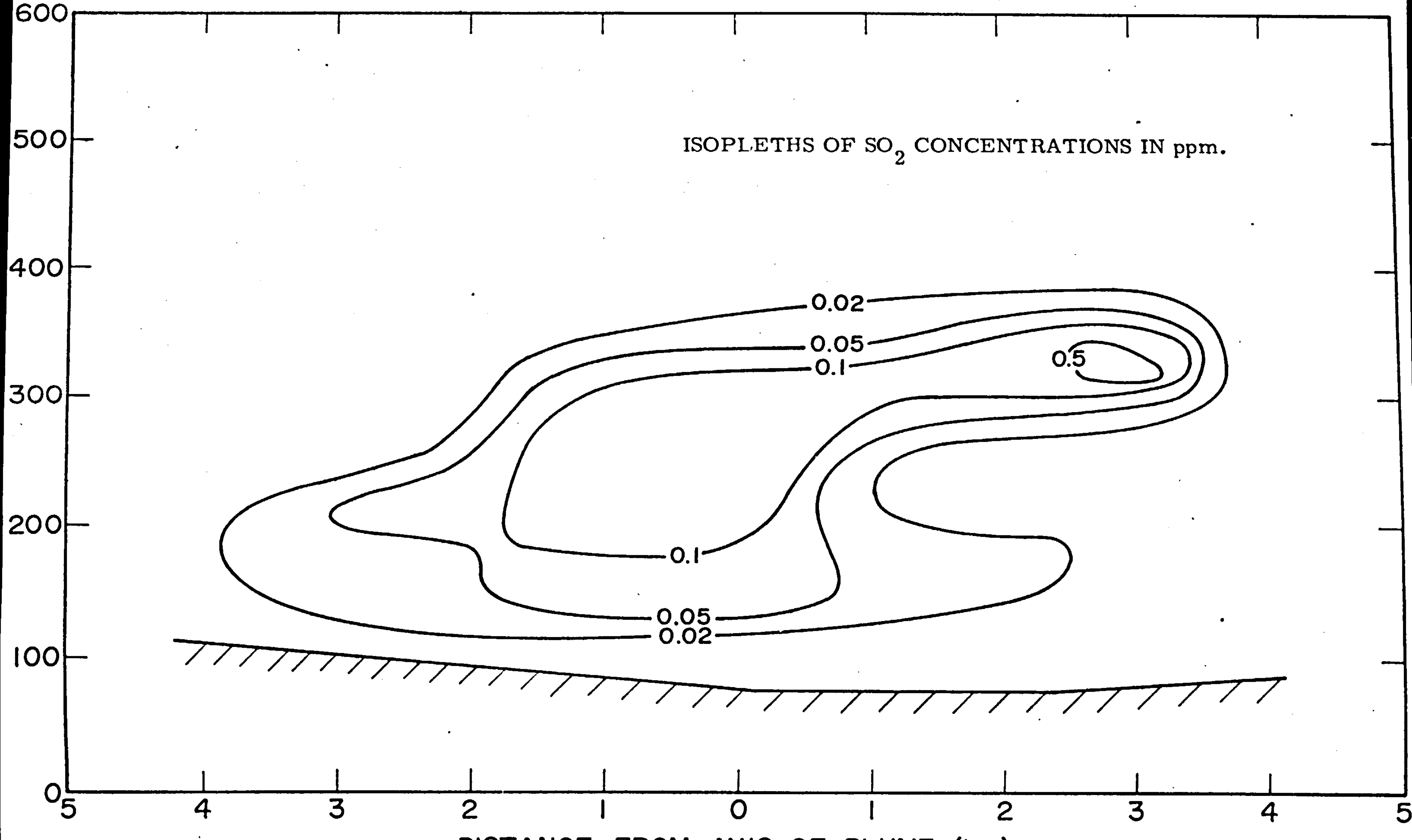



Fig. 7 (c): Cross-section of the plume during the morning at 10.8 km downwind of the source.

downwind of the source.

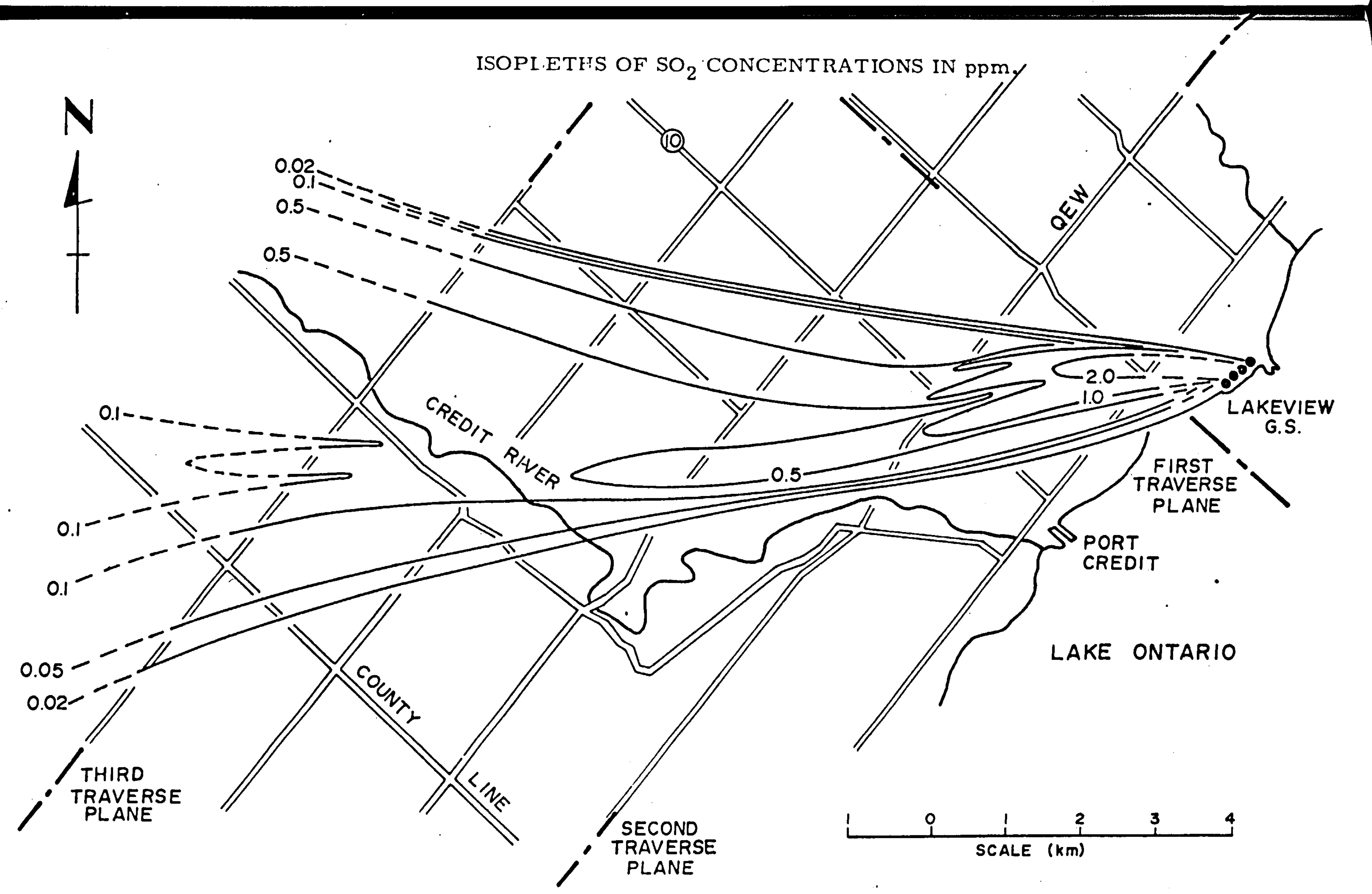
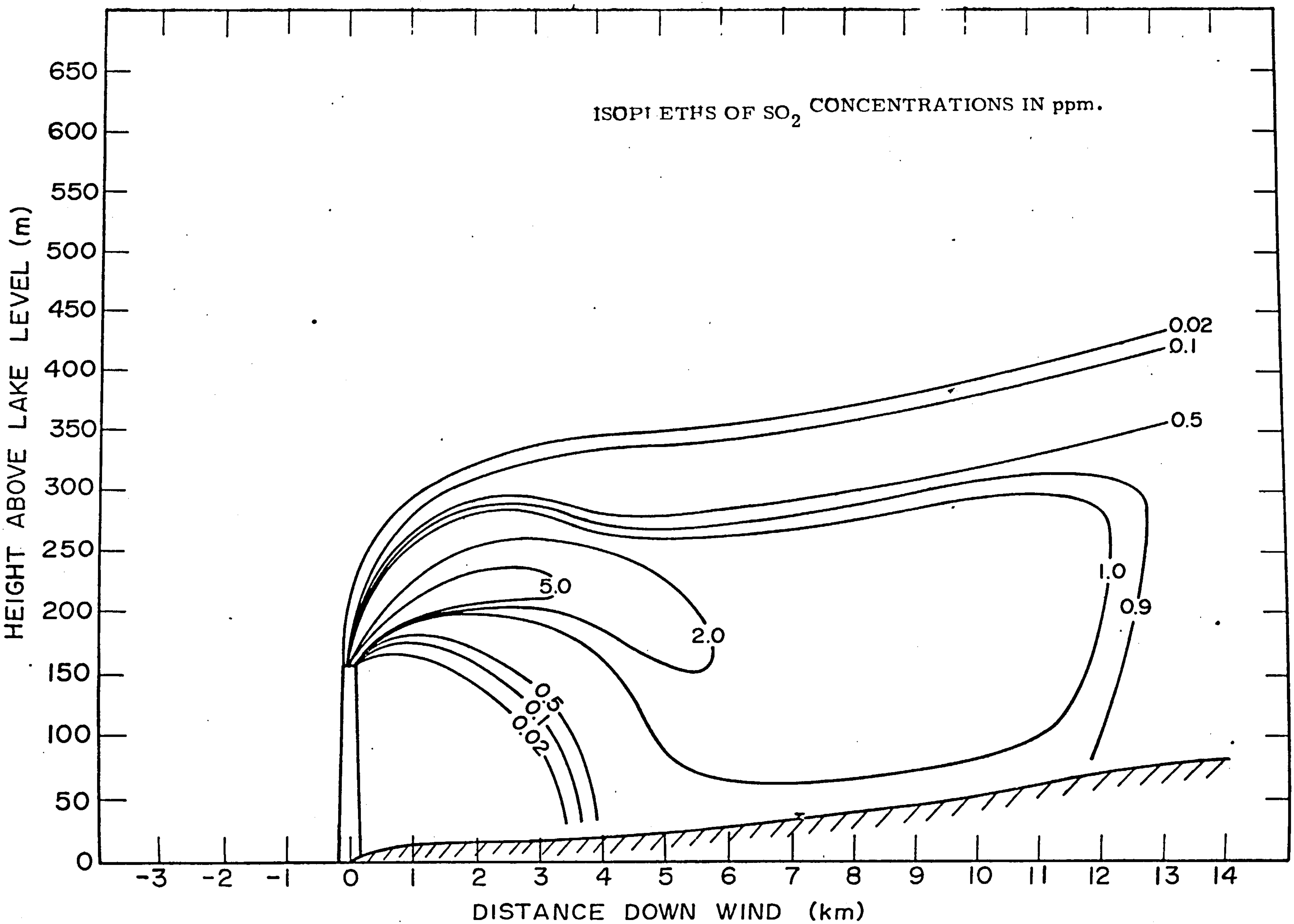



Fig. 8: A plan view of the plume through the level of maximum concentration during the morning of May 29, 1970.


ISOPLETHS OF $SO_2$ CONCENTRATIONS IN ppm.
HEIGHT ABOVE LAKE LEVEL (m)
DISTANCE DOWN WIND (km)
0.02
0.1
0.5
1.0
0.9
5.0
2.0
0.5
0.1
0.02
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-3
-2
-1
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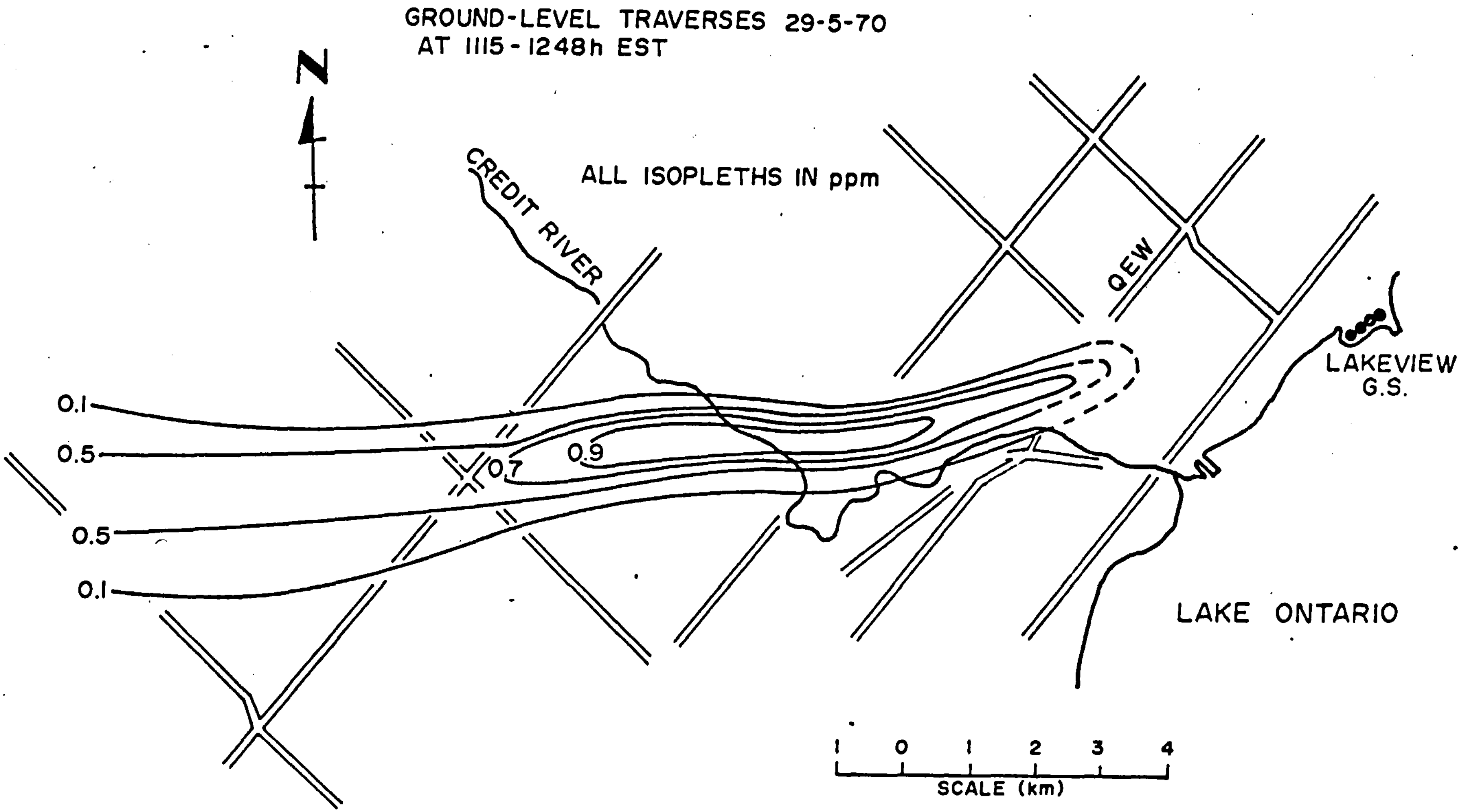


Fig. 10: Mean ground level concentrations of sulfur dioxide during the afternoon of May 29, 1970.

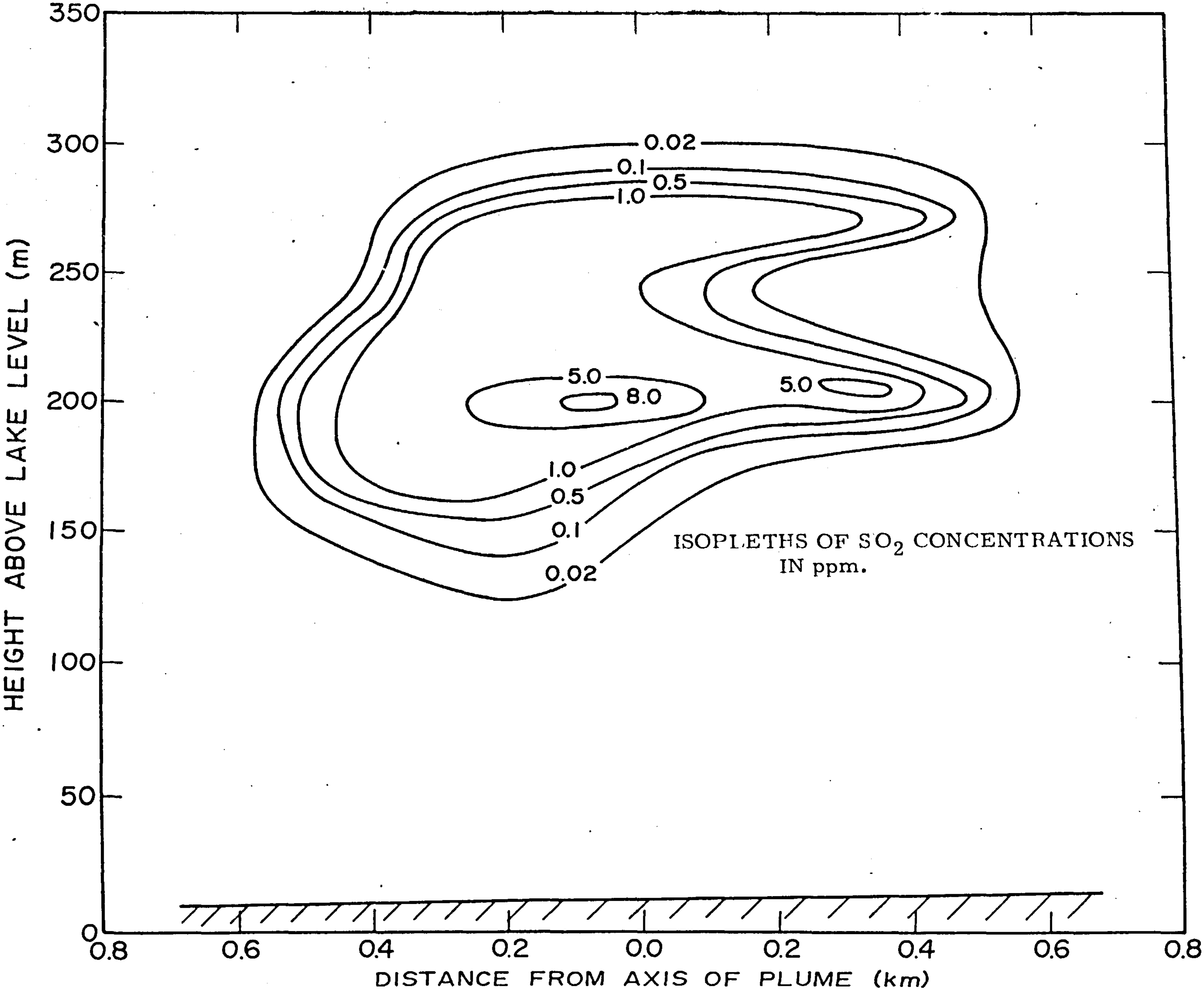


Fig. 11 (a): Cross-section of plume during the afternoon at 1.2 km

400

Fig. 11 (a): Cross-section of plume during the afternoon at 1.3 km

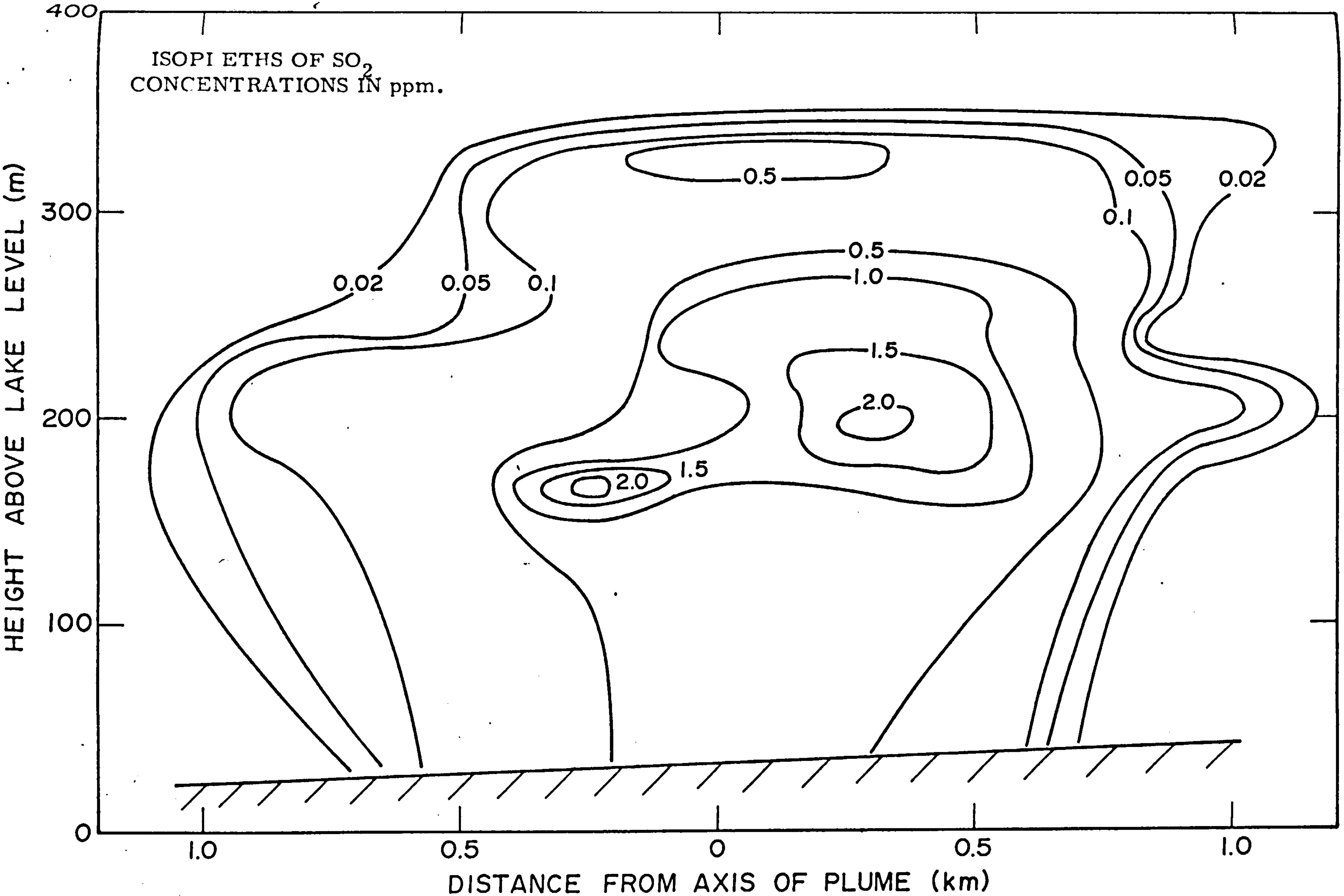


Fig. 11 (b): Cross-section of plume during the afternoon at 6.3 Km downwind of the source.

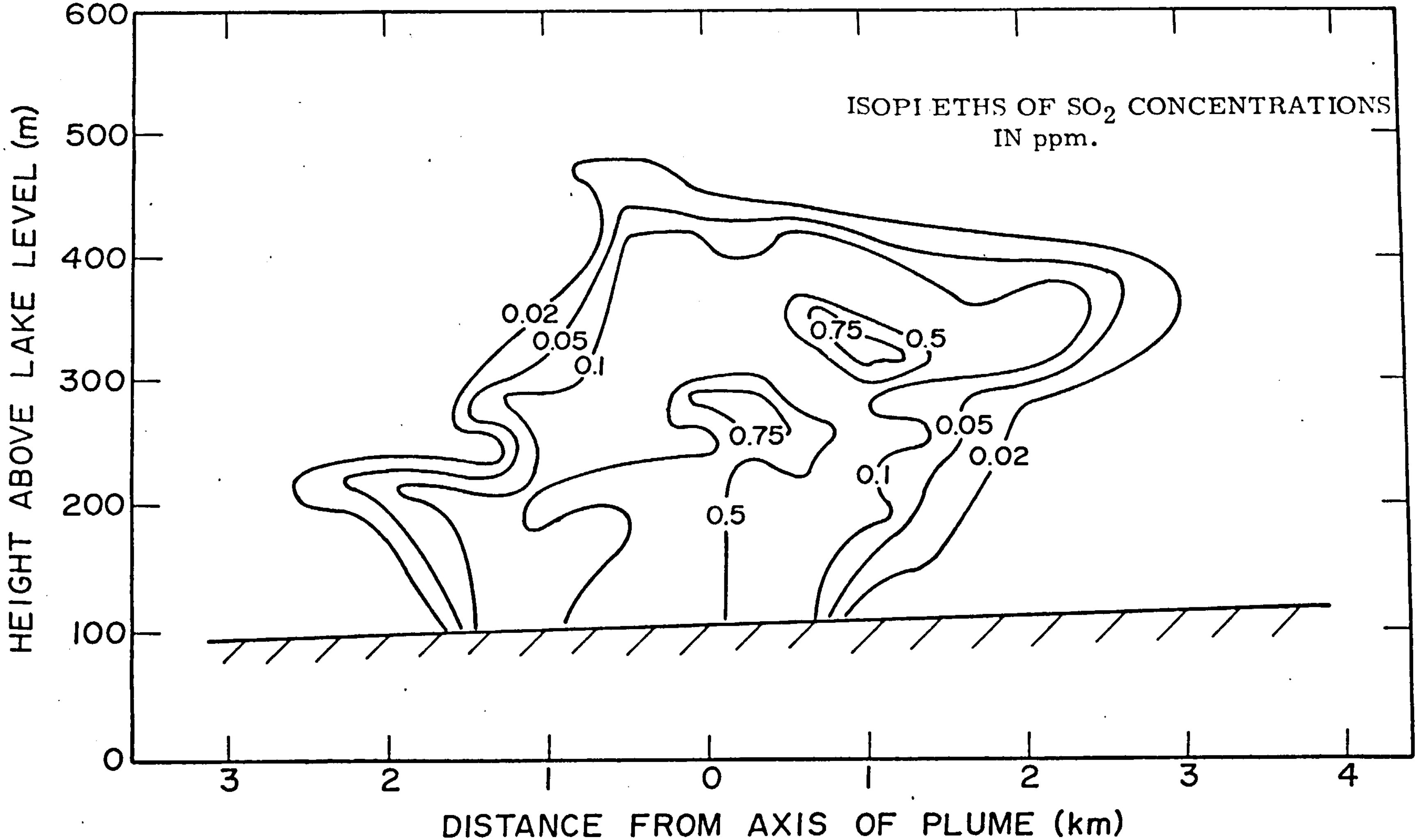


Fig. 11 (c): Cross-section of plume during the afternoon at 14.1 km downwind of the source.

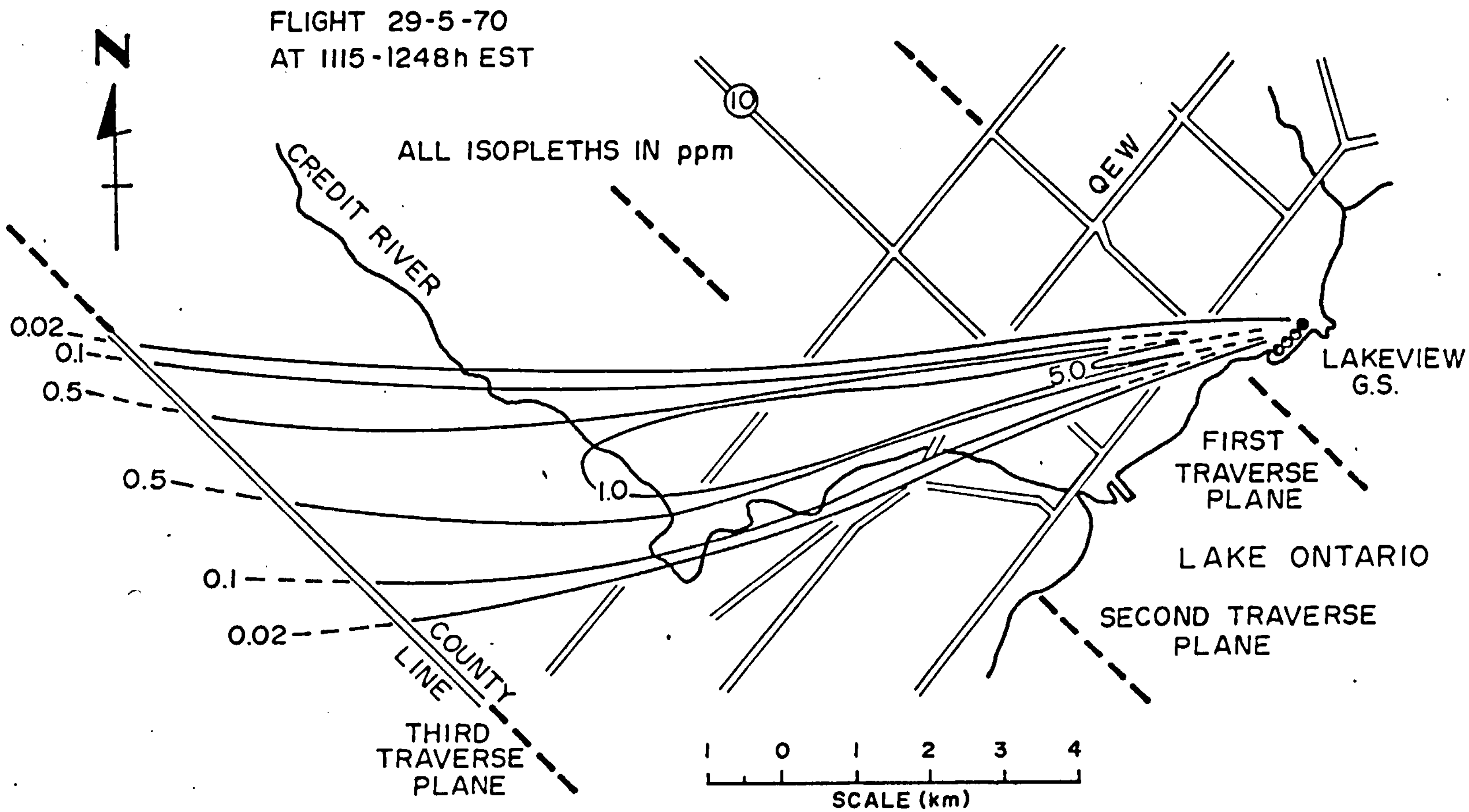


Fig. 12: A plan view of the plume through the level of maximum concentration during the afternoon of May 29, 1970.