CALCULATIONS OF ANNUAL AVERAGED SULPHUR DIOXIDE CONCENTRATIONS AT GROUND LEVEL IN THE AOSERP STUDY AREA

by

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ALBERTA OIL SANDS ENVIRONMENTAL RESEARCH PROGRAM

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

The Climatological Dispersion Model and the input data required for calculation of annual averaged values of sulphur dioxide concentrations at ground level are described. The most important meteorological input to the model is the long-term joint frequency distribution of winds in the vicinity of the sources of atmospheric pollution. These data are computed with the help of statistics of wind correlation between Fort McMurray and Mildred Lake, Alberta.

Numerical experiments are performed with and without parameterized pollutant removal processes. The effect of incorporating terrain in the model is examined. Experiments comparing concentrations due to existing sources with those due to existing and future sources are performed. Results are also compared with observational data from pollution monitors and snowpack sampling. Estimates are made of sulphur loading due to dry deposition.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based upon numerical experiments performed with the Climatogical Dispersion Model (CDM). The CDM calculations were reasonably well correlated with available observational data, leading to the conclusion that the model is adequate for computing seasonal- or annual-average concentrations of sulphur dioxide at ground level. The maximum annual-average concentration at present is calculated to be below the Federal Maximum Desirable Level, National Air Quality Objective. According to model results, when the Syncrude Canada Ltd. plant becomes operational, annual-average concentrations will not be significantly higher provided the emission rates and stack characteristics prove to be according to design and provided there is no flaring by Syncrude. The CDM, however, was never intended for evaluation of shorter-term concentrations. Consequently, no conclusion can be drawn from the calculations regarding hourly- or daily-average concentrations. Estimates of sulphur loading due to dry deposition can be made from the CDM sulphur dioxide concentration results. Otherwise, no conclusions can be reached regarding possible severity of problems related to medium and long-range transport of air pollution. The CDM assumption of flat terrain appears to be valid for most of the area considered. The model, however, makes no attempt to simulate channelling of the flow due to terrain, impingement or fumigation. These effects will be most noticeable in the vicinity of the walls of the Athabasca River valley, where the calculated results will underestimate true values.

RECOMMENDATIONS

1. In order to determine whether the conclusions reached regarding Syncrude's contribution to the annual average sulphur dioxide concentration will be valid, it will be necessary to monitor emission rates and stack characteristics of the new stack. If these prove to be different from values assumed in the present study, it is recommended that the model results be updated with observed values of stack input data for Syncrude.

2. In order to properly verify model calculations of annual-average concentrations a good number of monitor locations, each with at least three years of data, is desirable. It is therefore recommended that the number of monitoring stations be increased as soon as possible from the present five to at least ten and that the new stations be located as close as possible to the positions of the maximum sulphur dioxide concentrations determined by the CDM.

3. Since Fort McMurray STAR data are available on a monthly basis for the period 1963-75, the calculations done in the present study could be repeated on a seasonal basis by grouping data from three or more of the individual months. The groupings could be done according to snowpack season (e.g., November to March or longer) or growing season (e.g., May to August) depending on "user" requirements. It is therefore recommended that computer programs be established to handle user requirements for CDM seasonal-average sulphur dioxide concentrations at ground-level and that a specific AOSERP Project be assigned to this work.

4. The CDM uses stability-wind rose data as meteorological input. The validity of this approach should be examined by a method which calculates individual concentration patterns a large number of times over several years. It is therefore recommended that average values of sulphur dioxide concentration for the period 1974-75 be determined from hourly calculations using Mildred Lake wind data and Fort McMurray stability classification and at least one of the following modelling techniques:

a. Gaussian dispersion without cross-wind averaging,

b. Trajectory-dispersion (e.g., see Heffter and Ferber, 1975).

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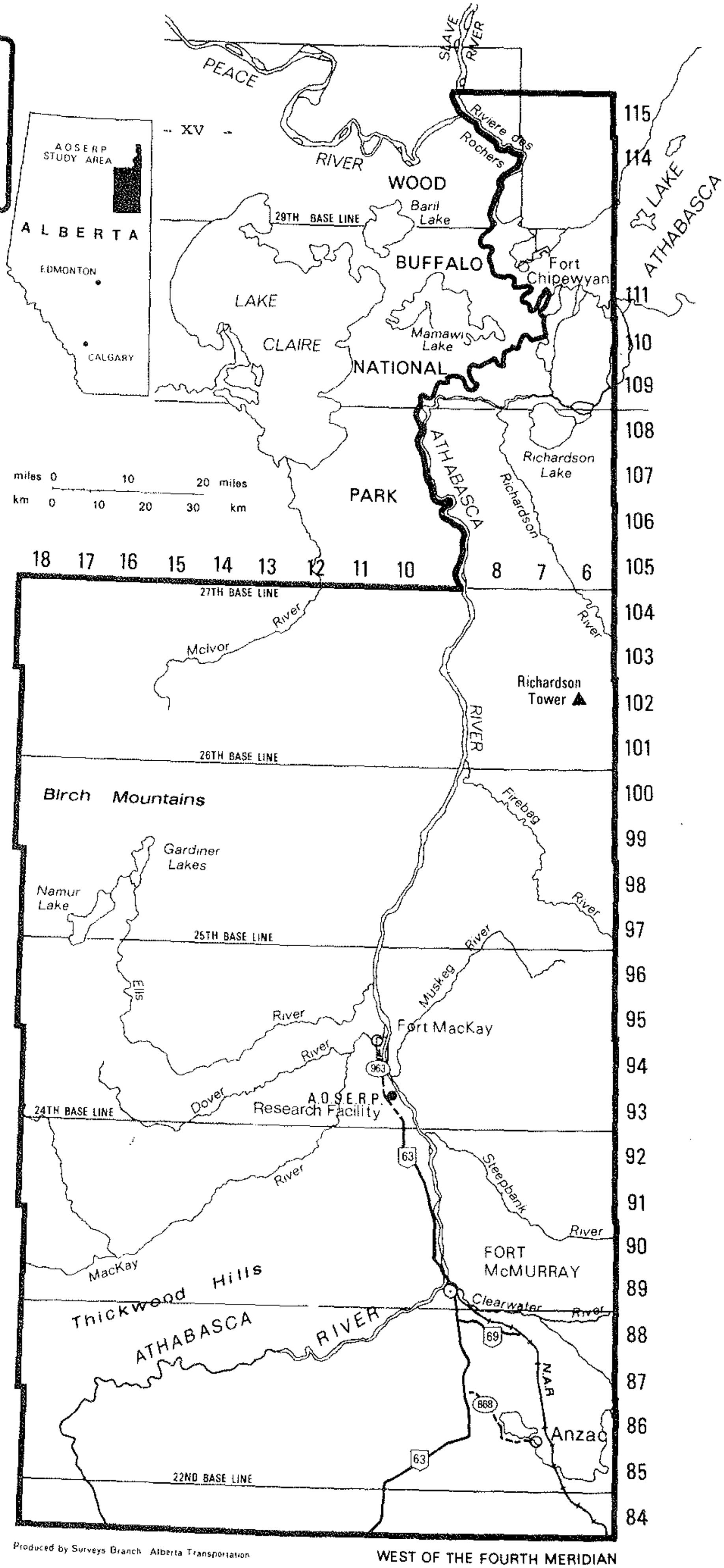

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WEST OF THE FOURTH MERIDIAN

Figure 1. Location of the AOSERP Study Area.

1. CLIMATOLOGICAL DISPERSION MODEL AND DATA INPUT

1.1 DESCRIPTION OF THE MODEL

1.1.1 The Basic Model

The Climatological Dispersion Model (CDM) is described by Busse and Zimmerman (1973). Only a brief outline of the model will be included in the present report.

The CDM determines long-term (seasonal or, as in the present study, annual) pollutant concentrations at any ground-level receptor point. Pollution is assumed to be dispersed with a Gaussian distribution in the vertical and cross-wind averaging through each wind direction sector. Limited mixing calculations are included where applicable, i.e., for receptors sufficiently far from the source. At each receptor point contributions from all emission sources are accumulated, the calculations being performed using the appropriate wind direction from the source to the receptor. Thus, for every receptor-source combination, 36 separate calculations (for 6 wind speed classes in combination with 6 atmospheric stability categories) are done, the results being weighted according to the relative frequency of occurrence of the wind direction- wind speed-stability category concerned.

The CDM uses a power law to parameterize increase of wind speed with height, the exponent in the relationship depending on atmospheric stability. Plume rise is computed by the Briggs' formulae in this study. Fumigation situations are not simulated.

Input data consist of information pertaining to the receptor grid, source emission rates, stack characteristics and meteorological information, all of which will be described in this section of the report.

1.1.2 Modification to Incorporate Terrain

The CDM assumes flat terrain. In this study it was decided to investigate the consequences of that assumption. Methods of incorporating topography within constraints imposed by the model were examined. One method that was considered was to assume the ground-level concentration would be the concentration computed in the atmosphere at the appropriate height above (or below) a flat reference level. The model, however, assumes reflection at the reference level and modifications to simulate reflection at the actual elevation of the ground would have been very complicated. This method, therefore, was rejected. Instead it was assumed that there was no terrain slope in the cross-wind direction but that in the downwind direction, the flow (and pollutants carried with it) followed a path governed by the mean terrain slope between the source and the receptor. Thus, effective source heights, downwind distances and dispersion coefficients were adjusted for the slope but no channelling of the flow was implied.[1] This could cause inaccuracies in the immediate vicinity of the Athabasca River. The larger-scale flow over the broad upland plain is implicitly incorporated, however, in the wind direction frequency data which are input to the model. With this method of including terrain effects it is also not possible to simulate impingement[2] of pollution at the ground. This would not likely be a problem except in the relatively small areas where terrain slopes are steep, such as along the Athabasca River valley walls.

1.1.3 Receptor Grid for Calculations

A model grid of grid size 2 km was defined with respect to the Universal Transverse Mercator (UTM) grid. The domain could be as large as 100 km x 100 km centered near the oil sands plants. For most experiments, however, calculations were only required over a 26 km x 26 km region as concentrations became quite small (e.g., less than 5 $\mu g \cdot m^{-3}$) beyond this area. The elevation of each grid point above the Athabasca River was extracted from topographic maps for use in calculations which incorporated terrain. The origin of the grid was at 12VVT2070 in the UTM reference convention.

1.2 "STAR" METEOROLOGICAL DATA

The Climatological Dispersion Model accepts data obtained from the DAY/NIGHT version of the STAR program developed by the National Climatic Center at Asheville, North Carolina. The STAR data are essentially a joint frequency distribution of occurrences

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[1] Further details are given in Appendix, Section 4.1.

[2] Impingement here and elsewhere in this report means contact of the plume centerline with the ground.

of wind direction, wind speed class and atmospheric stability classification. The data thus consist of 16x6x6 = 576 frequencies, the sum of which is 1.00. The 6 stability classifications are similar to the Pasquill-Gifford categories (Pasquill, 1961) except that the neutral category (Pasquill-Gifford D stability) is split into two (one for daylight hours, the other for nighttime) and the two most stable categories (E and F) are combined. These DAY/NIGHT STAR data are readily available for first-order Canadian weather stations, such as Fort McMurray,[3] from Central Services Directorate of Atmospheric Environment Service, Downsview, Ontario. Unfortunately, however, an examination of wind roses for Fort McMurray and Mildred Lake (Figure 1) reveals that the STAR data for Fort McMurray will not be representative of the true situation in the vicinity of the GCOS and Syncrude plants. Moreover, the Mildred Lake weather station does not perform all the meteorological observations required for the STAR program and the period of record is relatively short (since 1973). It was decided, therefore, to generate synthetic STAR data for Mildred Lake for use as input to the CDM. Before this could be done it was necessary to investigate the correlation between winds at Fort McMurray and Mildred Lake.

1.3 CORRELATION OF WIND AT FORT MCMURRAY AND MILDRED LAKE

1.3.1 Introduction

The only first-order station in the Alberta Oil Sands is located at Fort McMurray Airport. A long-term record is available at this site, only 50 km SSE of the GCOS and Syncrude plants. The airport is located on relatively flat land about 13 km SE of the town of Fort McMurray, 3 km S and 120 m above the floor of the Clearwater River valley. Airport winds, however, seem to be mainly influenced by the broader-scale topographic features of the Muskeg and Stony Mountains situated about 100 km apart and lying to the NNE and SSW of the station, respectively. Thus the winds tend to have a pronounced east-west orientation (Figure 1).

The plant locations, however, are located close to the Athabasca River, GCOS being on the valley floor and Syncrude about 60 m higher, 6 km W of the river on the upland plain. In the valley

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[3] See Appendix, Section 4.2.

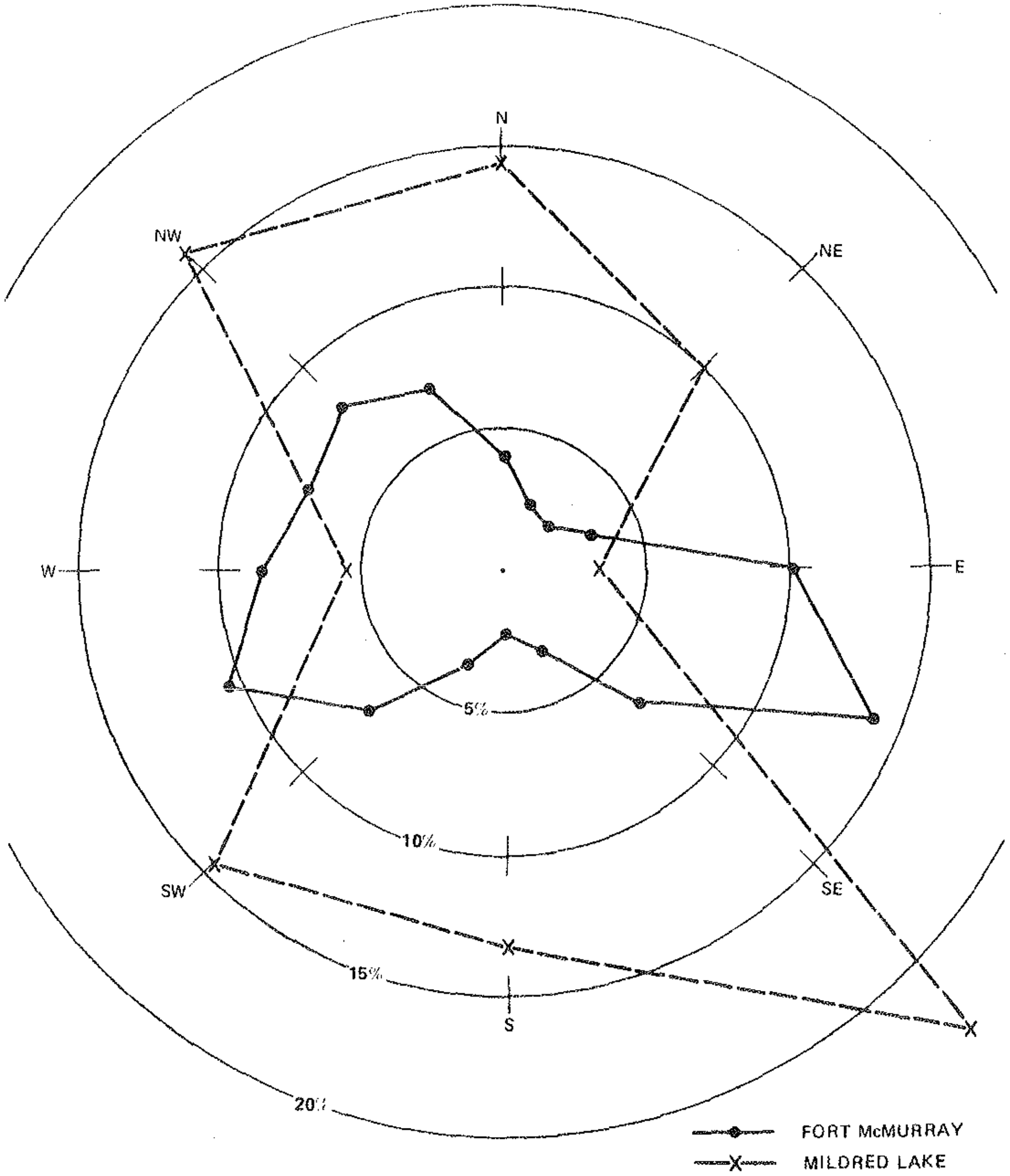

Figure 1. Fort McMurray and Mildred Lake Wind Roses, 1974-75.
Fort McMurray: U2A anemometer, 16 point compass.
Mildred Lake: 45B anemometer, 8 point compass.
The percentage of calms distributed in the above wind roses is 17.4% and 2.6%, respectively.

the flow is strongly influenced by the fairly steep valley walls, an effect which extends at least to 60 m above the river level (Mickle et al. 1977).

On the upland plain adjacent to the Athabasca River Valley, the winds are influenced by higher land to the west (ranging from the Birch Mountains in the northwest to the Thickwood Hills in the southwest) and Muskeg Mountain to the east. The upland plain, 50-100 km wide, experiences winds which have a pronounced north-south or northwest-southeast orientation (Figure 1).

A weather station located on the adjacent upland plain at Mildred Lake within 10 km of GCOS and 1 km E of the Syncrude plant would give much more representative data on winds near the plants than would Fort McMurray. Even the major plumes at GCOS often rise above the valley walls and would come under the influence of winds similar to those observed at Mildred Lake. The disadvantages with Mildred Lake, however, are that the station has only been in operation since 1973, it is not a first-order station (hence all the data necessary to run the "STAR" program are not available) and wind directions are only observed to 8 compass points.

Wind roses for Mildred Lake and Fort McMurray are shown in Figure 1. The values for the latter average half those of the former due to the fact that directions are given to 16 compass points at Fort McMurray. The wind roses confirm what was stated earlier about topographic influences on wind direction.

It is interesting to note the large percentage of calms reported at Fort McMurray (17.4%) compared with the much smaller incidence at Mildred Lake (2.6%). A possible physical explanation was gleaned from station inspection reports for Fort McMurray which indicate that the U2A anemometer cupwheel was raised about 3 m in September 1976 to position it at a level higher than the tops of trees located about 60 m to the south. A more plausible explanation lies in the different anemometer types used at Fort McMurray and Mildred Lake (U2A and 45B, respectively). Starting speeds are approximately 3 knots and 2 knots, respectively. (Ed Wheeler, Atmospheric Instruments Branch, AES, personal communication). This factor would account for 45B anemometer response for low wind speeds that would be indicated as calms by the U2A.

Another factor which is different from one site to the other is the averaging time. A one-minute interval close to the hour is used at Fort McMurray whereas Mildred Lake records information on a wind run basis throughout the hour. Thus a certain amount of sampling error is inherent in any attempt to correlate the data. It is difficult to say *a priori*, however, that these sampling discrepancies would lead to a systematic overestimate of calms at Fort McMurray and/or underestimate at Mildred Lake.

In this report calms are included in the lowest wind speed class, 0-3 knots, weighted by the frequency of occurrence of directions during low wind speed (1-6 knots) cases. This is in agreement with the STAR program and with a procedure recommended by Munn (1970). Consequently, possible errors in the number of calms reported is of no concern in our calculations.

A computer program to compute correlation coefficients for simultaneous occurrence of wind velocities at Fort McMurray and Mildred Lake for the two-year period 1974-75 was devised. This program involved tabulation of hourly simultaneous occurrences of wind velocity at the two stations, distribution of calms, and calculation of the relative frequency of simultaneous occurrences.

1.3.2 Correlation of Simultaneous Occurrences

The 1974-75 wind data for Fort McMurray and Mildred Lake were processed as follows. At each station the observations were classified according to wind direction (sixteen compass points) and wind speed (six classes excluding calm). This made a total of 96 categories. It should be noted that every second category at Mildred Lake had zero occurrences since the station only reported direction to eight compass points. The 96 categories were retained, nevertheless, for convenience. Calm conditions and missing observations accounted for two additional categories at both stations. A 98x98 correlation matrix was constructed, each element of the matrix containing the number of simultaneous occurrences of the appropriate categories at the two stations. Such a table is obviously too large to present here.

1.3.3 Distribution of Calms

The correct method of distributing calms in this combined direction and speed correlation program proved to be quite complex, the object being to distribute the calms into the lowest wind speed classes and, further, to distribute them amongst the wind directions in such a manner as to be consistent with the STAR program. This means that summation over the Mildred Lake observations should give a summary table for Fort McMurray that is identical to the Fort McMurray STAR results for 1974-75. A further, obvious constraint is that the calms must be distributed in such a way that the total number of simultaneous observations remains the same. The proper method of achieving these objectives is illustrated by the formula:

$$b_{ij} = a_{ij} + \nabla_i \; a_{97,j} p_i + \nabla_j \; a_{i,97} q_j + \nabla_i \; \nabla_j \; a_{97,97} \; r_{ij} \quad ,$$

$$i = 1,2,3,\ldots.,96 \qquad\qquad (1)$$
$$j = 1,2,3,\ldots.,96$$

where b_{ij} = number of simultaneous occurrences of category i at Fort McMurray and category j at Mildred Lake, with calms distributed,

a_{ij} = as above, without calms distributed (i = 97, j = 97 for calm at Fort McMurray, Mildred Lake, respectively; i = 98, j = 98 for missing observations),

$$i = k+16\ (\ell - 1) \quad , \quad k = 1,2,3,\ldots.,16, \quad \ell = 1,2,3,\ldots., 6, \qquad (2)$$

where k = wind direction at Fort McMurray,

ℓ = wind speed class at Fort McMurray,

$$j = m+16\ (n-1) \quad , \quad m = 1,2,3,\ldots.,16, \quad n = 1,2,3,\ldots., 6 \qquad (3)$$

where m = wind direction at Mildred Lake,

n = wind speed class at Mildred Lake,

$$\nabla_{\alpha} = \begin{cases} 1 & , \ \alpha = 1,2,3,\ldots.,16, \\ 0 & , \ \alpha = 17,18,19,\ldots.,96, \end{cases} \tag{4}$$

$$p_i = \frac{F_{1,i} + F_{2,i}}{\sum_{k=1}^{16} (F_{1,k} + F_{2,k})} \quad , \quad i = 1,2,3,\ldots.,16, \tag{5}$$

$$q_j = \frac{M_{1,j} + M_{2,j}}{\sum_{m=1}^{16} (M_{1,m} + M_{2,m})} \quad , \quad j = 1,2,3,\ldots.,16, \tag{6}$$

$$r_{ij} = p_i \, q_j \quad , \quad i = 1,2,3,\ldots, 16; \ j = 1,2,3,\ldots,16, \tag{7}$$

where $F_{\ell,k} = \sum_{j=1}^{98} a_{ij}$, (8)

is the number of simultaneous occurrences of wind direction k and wind speed class ℓ at Fort McMurray,

$$M_{n,m} = \sum_{i=1}^{98} a_{ij} \tag{9}$$

is the number of simultaneous occurrences, similar to $F_{\ell,k}$ but for Mildred Lake.

From Equations (5) to (9) it is readily verified that :

$$\sum_{i=1}^{16} p_i = 1 \tag{10}$$

$$\sum_{j=1}^{16} q_j = 1 \tag{11}$$

$$\sum_{i=1}^{16} \sum_{j=1}^{16} r_{ij} = \sum_{i=1}^{16} \left[p_i \sum_{j=1}^{16} q_j \right]$$

$$= \sum_{i=1}^{16} p_i = 1 \ . \qquad (12)$$

Thus it may be shown that :

$$\sum_{i=1}^{96} \sum_{j=1}^{96} b_{ij} = \sum_{i=1}^{96} \sum_{j=1}^{96} a_{ij} + \sum_{j=1}^{96} a_{97,\, j} + \sum_{i=1}^{96} a_{i,97} + a_{97,\, 97}$$

$$= \sum_{i=1}^{97} \sum_{j=1}^{97} a_{ij}$$

or that the total number of simultaneous observations remains unchanged when the calms are distributed.

Furthermore it may be shown using Equation (1)

$$\sum_{j=1}^{96} b_{ij} + a_{i,98} + \nabla_i \, a_{97,98} \, p_i$$

$$= \sum_{j=1}^{96} a_{ij} + \nabla_i \, p_i \sum_{j=1}^{96} a_{97,\, j} + a_{i,97} \sum_{j=1}^{16} q_j$$

$$+ \nabla_i \, a_{97,97} \sum_{j=1}^{16} r_{ij} + a_{i,98} + \nabla_i \, a_{97,98} \, p_i$$

$$= \sum_{j=1}^{98} a_{ij} + \nabla_i \, p_i \left[\sum_{j=1}^{98} a_{97,j} \right] \ . \qquad (13)$$

Equation (13) verifies that the distribution of calms is consistent with the STAR program. The Fort McMurray STAR results for 1974-75, for i = 1 (wind speed class = 1, direction = 1 or North), for example, give

$$F_{1,1} \equiv \sum_{j=1}^{98} a_{1,j} = 206,$$

$$\text{Number of calms} \equiv \sum_{j=1}^{98} a_{97,j} = 3041,$$

$$p_1 = \frac{206 + 189}{4782 + 5215} \quad .$$

Thus, from Equation (13) is calculated:

$$\sum_{j=1}^{96} b_{1,j} = 326.16 \; .$$

When this number is divided by 17520, the total number of observations at Fort McMurray, the relative frequency that results is 0.018616, the same number given by the STAR program.

1.3.4 Relative Frequency of Simultaneous Occurrences

Once the calms have been properly distributed using Equation (1) it is a simple matter to obtain the relative frequencies:

$$c_{ij} = \frac{b_{ij}}{\sum_{\alpha=1}^{96} \sum_{\beta=1}^{96} b_{\alpha\beta}} \quad . \tag{14}$$

It will be noted that $c_{ij} = 0$ whenever j is even because of the 8 point compass winds at Mildred Lake.

Again it is impossible to display the resulting 96x96 table of relative frequencies. By summing over the wind speed classes, however, a 16x16 table of wind direction correlation is obtained (Table 1). Similarly, by summing over wind direction, a 6x6 table of wind speed correlation results (Table 2). These tables reveal a fair degree of correlation in the data. This would be expected due to synoptic-scale influences on two locations which are only 50 km apart. The wind speeds are particularly well

TABLE 1. RELATIVE FREQUENCY OF SIMULTANEOUS OCCURRENCE OF WIND DIRECTION AT FORT McMURRAY AND MILDRED LAKE, 1974-75.

MILDRED LAKE

FORT McMURRAY

		j 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	i	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	TOTAL
N	1	.012495	0	.010657	0	.000534	0	.002526	0	.002508	0	.002801	0	.000793	0	.007888	0	.040203
NNE	2	.006477	0	.007645	0	.000526	0	.002360	0	.001345	0	.001784	0	.000514	0	.003090	0	.024840
NE	3	.004956	0	.009881	0	.000520	0	.003937	0	.001322	0	.001207	0	.000533	0	.002073	0	.021029
ENE	4	.006385	0	.008423	0	.001935	0	.006542	0	.003420	0	.001760	0	.000492	0	.002464	0	.031512
E	5	.017479	0	.013598	0	.009183	0	.034398	0	.018225	0	.004606	0	.003002	0	.005575	0	.101056
ESE	6	.011434	0	.007447	0	.009559	0	.074425	0	.022226	0	.005169	0	.002788	0	.005428	0	.137476
SE	7	.003773	0	.003117	0	.002727	0	.037344	0	.011351	0	.002337	0	.001405	0	.002523	0	.064578
SSE	8	.001571	0	.001730	0	.000958	0	.016309	0	.006028	0	.001971	0	.000708	0	.001284	0	.030559
S	9	.000973	0	.001015	0	.000340	0	.008577	0	.007234	0	.003673	0	.000706	0	.001096	0	.023716
SSW	10	.001826	0	.000810	0	.001199	0	.007260	0	.011455	0	.008952	0	.001526	0	.002956	0	.035984
SW	11	.003922	0	.001658	0	.001578	0	.009746	0	.013739	0	.025256	0	.005526	0	.007095	0	.068520
WSW	12	.007012	0	.007436	0	.002122	0	.008864	0	.013899	0	.044575	0	.011150	0	.016232	0	.107270
W	13	.007201	0	.003277	0	.001439	0	.004826	0	.006651	0	.024835	0	.014392	0	.024515	0	.087135
WNW	14	.017512	0	.006805	0	.001286	0	.003892	0	.004463	0	.008801	0	.009275	0	.031845	0	.075879
NW	15	.025143	0	.011617	0	.001160	0	.004295	0	.004655	0	.004348	0	.003413	0	.027224	0	.081855
NNW	16	.024126	0	.013273	0	.000775	0	.004307	0	.004325	0	.002956	0	.002332	0	.016235	0	.068388
TOTAL	17	.144285	0	.100391	0	.033871	0	.230336	0	.133849	0	.145032	0	.054713	0	.157523	0	1.000000

Summation on Main and Main Plus Adjacent Pairs of Diagonals:

MAIN = 0.138 MAIN + 1 = 0.421 MAIN + 2 = 0.617 MAIN + 3 = 0.743 MAIN + 4 = 0.845

TABLE 2. RELATIVE FREQUENCY OF SIMULTANEOUS OCCURRENCE OF WIND SPEED CLASSES AT FORT McMURRAY AND MILDRED LAKE, 1974-75.

			MILDRED LAKE						
		j 1	2	3	4	5	6	7	
	KNOTS i	0-3	4-6	7-10	11-16	17-21	>21	TOTAL	
FORT McMURRAY	0-3 1	.273416	.129503	.040163	.002068	0	.000063	.445210	1
	4-6 2	.114529	.110958	.064595	.007706	.000198	.000063	.298039	2
	7-10 3	.036652	.055949	.081574	.026001	.001128	0	.201303	3
	11-16 4	.002068	.004887	.021678	.023119	.001880	.000125	.053756	4
	17-21 5	.000125	.000063	.000439	.000752	.000251	.000063	.001692	5
	>21 6	0	0	0	0	0	0	0	6
	TOTAL 7	.426790	.301360	.208446	.059645	.003446	.000313	1.000000	7

Summation on Main and Main Plus Adjacent Pair of Diagonals:

MAIN = 0.489 MAIN + 1 = 0.904

correlated, the same or next adjacent speed class occurring simultaneously with a frequency of 90%. Wind directions are also well correlated, although local topography (or, possibly in some cases frontal passages or other phenomena) is responsible for wind shifts of up to 90° in 71% of the cases during 1974-75. Such wind direction deviations are quite easily understood from an examination of topographic maps of the area. The same or next adjacent wind direction on the 16-point compass occurs simultaneously only 42% of the time.

1.4 SYNTHETIC MILDRED LAKE "STAR" DATA

Mildred Lake synthetic STAR data[4] are calculated using an 8-point compass, initially, and then are interpolated to obtain the 16-point distribution.

In the first step, the synthetic STAR data for Mildred Lake over an 8-point compass are computed using the relative frequency correlation coefficient c_{ij} as follows:

$$g_{mn\gamma} = \sum_{i=1}^{96} \left[\frac{c_{ij}}{\sum_{\beta=1}^{96} c_{i\beta}} f_{k\ell\gamma} \right] , \qquad (15)$$

where j = $m + 16\ (n-1)$,

i = $k + 16\ (\ell-1)$,

γ = stability class ,

c_{ij} = correlation coefficient defined in Equation (14),

$f_{k\ell\gamma}$ = Fort McMurray STAR relative frequency of occurrence of wind direction k, wind speed class ℓ, and stability class γ, for the period 1963-75,

$g_{mn\gamma}$ = Mildred Lake synthetic STAR relative frequency of occurrence of wind direction m, wind speed class n, and stability class γ.

Verification that the above relative frequency distribution sums to 1.0 is shown via the following equation:

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[4] See Appendix, Section 4.3.

$$\sum_{m=1}^{16}\sum_{n=1}^{6}\sum_{\gamma=1}^{6} g_{mn\gamma} = \sum_{\gamma=1}^{6}\sum_{j=1}^{96}\sum_{i=1}^{96}\left[\frac{c_{ij}}{\sum_{\beta=1}^{96} c_{i\beta}} f_{k\ell\gamma}\right] \qquad (16)$$

$$= \sum_{\gamma=1}^{6}\sum_{i=1}^{96} f_{k\ell\gamma}\frac{\sum_{j=1}^{96} c_{ij}}{\sum_{\beta=1}^{96} c_{i\beta}} = \sum_{k=1}^{16}\sum_{\ell=1}^{6}\sum_{\gamma=1}^{6} f_{k\ell\gamma} = 1.0 \text{ by definition.}$$

At this point, since $c_{ij} = 0$ for even values of j, therefore $g_{mn\gamma} = 0$ for even values of m.

In the second step, simple linear interpolation was used to obtain the 16-point wind rose Mildred Lake synthetic STAR data for even-numbered m elements. This was achieved via the following equation:

$$g_{mn\gamma} = \begin{cases} \frac{1}{2}\left[g_{m-1,\ n\gamma} + g_{m+1,\ n\gamma}\right], & m = 2,4,6,\ldots,14 \\ \frac{1}{2}\left[g_{15,\ n\gamma} + g_{1,n\gamma}\right], & m = 16 \quad . \end{cases} \qquad (17)$$

Since the above operation revised the summation defined in Equation (16) to 2.0, all $g_{mn\gamma}$ values were halved.

1.5 OTHER METEOROLOGICAL INPUT DATA

A value of 1020 m was assumed for the annual average maximum mixing height based on the work of Portelli (1977). The nocturnal minimum mixing height was assumed to be zero. The annual average air temperature was assumed to be 0°C as determined from climatological data for Fort McMurray.

1.6 SULPHUR DIOXIDE SOURCE EMISSION DATA

The CDM input data consisted of stack locations, SO_2 emission rates, stack heights, stack diameters, gas exit velocities, gas temperatures and elevations of stack bases above the Athabasca River. The data for the four existing stacks and one future stack are given in Table 3 . Stack locations are given to the nearest

TABLE 3. SOURCE EMISSION RATES AND STACK CHARACTERISTICS.[1]

Plant Stack	GCOS Powerhouse	GCOS Incinerator	GCOS Main Flare	GCOS Acid Gas Flare	Syncrude Main[5]
UTM Location[2], Block 12VVU:					
East (km)	71.010	70.976	71.131	71.166	62.450
North (km)	17.736	17.991	18.130	18.076	22.000
Model Grid Coordinates:					
x	25.505	25.488	25.566	25.583	21.225
y	23.868	23.996	24.065	24.038	26.000
Elevation[3] of Base (m)	22	22	8	8	73
Stack Height (m)	107	107	99	76	183
Stack Diameter (m)	5.8	1.8	1.1	0.52	7.9
Exit Velocity ($m.s^{-1}$)	17.5	17.0	5.0[4]	5.0[4]	23.7
Gas Temperature (°C)	272[7]	610[7]	600[4]	600[4]	246
SO_2 Emission Rate ($kg.s^{-1}$)	2.60	0.27	0.10	0.27	3.30[6]

[1] All data derived from information supplied by M. Strosher of AOSERP, except where otherwise noted.

[2] UTM locations from topographic maps and air photographs.

[3] Elevations above the Athabasca River (775 ft above sea level) from topographic maps of scale 1:50,000.

[4] Data not available. Assumed values are shown.

[5] Syncrude data from design characteristics.

[6] Emission rate for the ultimate plant design, assuming no breakdowns.

[7] Data from GCOS measurements, March 1976. Use of recent AOSERP estimates of 232 and 538°C cause an increase in calculated SO_2 concentration of about 1 μg m^{-3} (see Table 6, footnote 2).

metre in the table, though the accuracy is probably of the order of 10 m for the GCOS stacks and of the order of 100 m for the Syncrude stack. For the flare stacks at GCOS, emission rates were calculated from monthly reports prepared by GCOS for the period January 1975 - July 1976 inclusive. Total emissions for the 19 month period were assumed to be emitted at a uniform rate in order to determine representative annual emission rates. No flaring was assumed for the Syncrude operation since it is impossible to estimate at the present time how often flaring will take place and which of several options would be used when flaring is necessary. Other Syncrude data are from the design characteristics for the stack. It still remains to be seen how close the actual operations come to these design data.

1.7 TOPOGRAPHIC DATA

Elevations of all receptor grid points used by the model were extracted at intervals of 2 km from topographic maps of scale 1:50,000. Heights were estimated to the nearest 5 ft; then the elevation of the Athabasca River in the vicinity of GCOS, 775 ft, was substracted and the results converted to metres. Elevations of the bases of all stacks and of the five pollution monitor locations were obtained in a similar manner.

The grid point elevation data were contoured by a computer program and the resulting map is shown in Figure 2. The Athabasca River valley shows up clearly as a trench about 80-100 m deep traversing the upland plain from the north central portion of the map to the southeast corner. The valleys of the Poplar and Steepbank Rivers are in the vicinity of Monitor #1 and Monitor #5 respectively. It appears from this map as if the tributary rivers must flow uphill into the Athabasca; this is merely due to the digitizing and objective contouring processes.

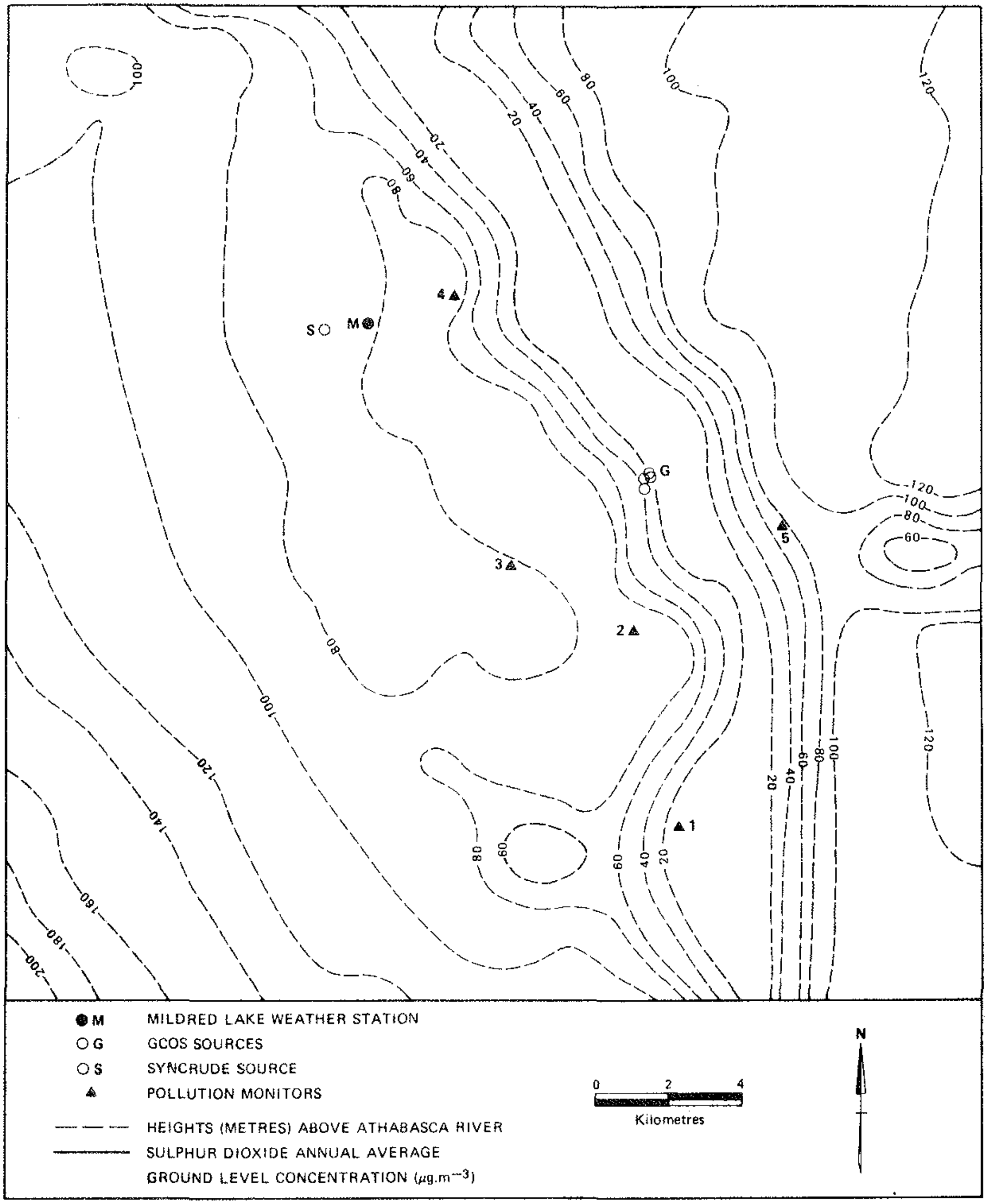

Figure 2. Topographic Data Used in the Model

2. NUMERICAL EXPERIMENTS

In the following sections are described the results of experiments which were conducted to determine annual average ground-level concentrations of sulphur dioxide that could be expected in different situations. The experiments were performed to investigate the effect of incorporating terrain in the model and to determine the decrease in sulphur dioxide concentration due to parameterized pollutant removal processes of deposition and transformation to sulphates. By adding the Syncrude stack to the existing GCOS sources a projection of concentration calculations into the near future was attempted.

2.1 EXISTING SOURCES

2.1.1 Effect of Terrain

In Figure 3, CDM calculations are shown for an experiment with the four GCOS Sources (Table 3), without incorporating terrain and with a 20 h half-life for sulphur dioxide employed to simulate removal processes. (A discussion of the appropriateness of this half-life is found in Section 2.4). Maxima of 21 and 22 $\mu g{\cdot}m^{-3}$ are located, respectively, 2.3 km south southeast and 2.3 km north northwest of the GCOS plant site. These values are somewhat less than the Federal Government Maximum Desirable Level of 30 $\mu g{\cdot}m^{-3}$ for an annual average. They are considerably less than the corresponding Maximum Acceptable Level of 60 $\mu g{\cdot}m^{-3}$. Calculations were done on a 2 km grid. At every grid point 36 separate contributions (representing 6 wind speed classes and 6 stability categories) were accumulated, each given a weight according to the relative frequency of occurrence for the appropriate wind direction. The final grid-point results were then contoured using a computer subroutine which was appended to the CDM. Low values to the east and west of the plant site reflect the low frequency of occurrence of west and east wind directions, respectively. Waves in the patterns at large distances are merely a result of the fact that a finite number of wind directions, sixteen, were employed. Close to the pollutant sources the wind direction sectors are close enough that differences in results

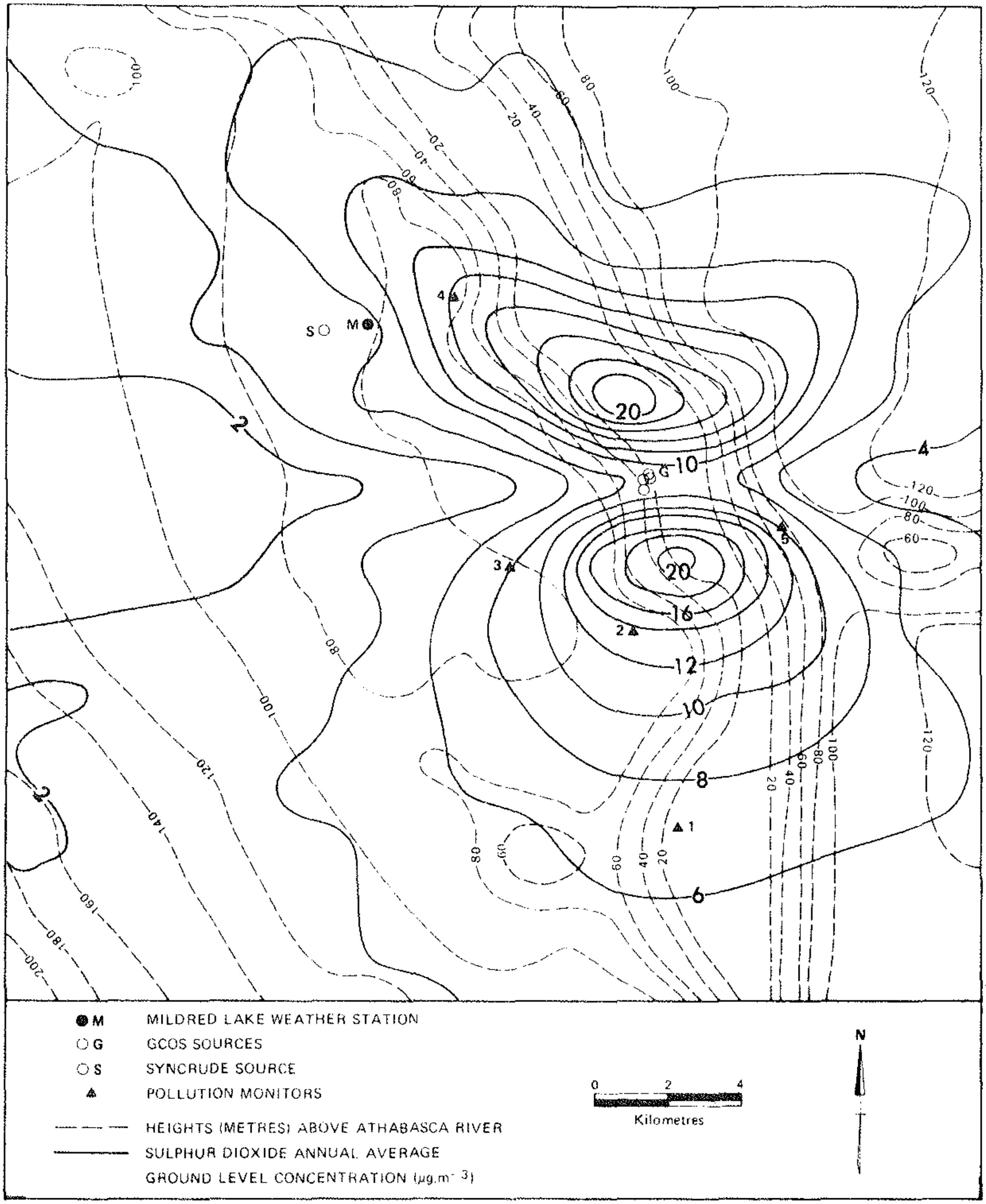

Figure 3. Annual Averaged Sulphur Dioxide Concentrations at Ground Level: Four Sources, 20 Hour Half-Life

from one sector to the next are not apparent to the contouring routine.

The same experiment was repeated with the grid-point terrain values (see map, Figure 2) and stack base elevations (Table 3) used in the modified version of the model. Results indicated that attempting to incorporate terrain in the manner described earlier had a negligible effect on results for this particular case. In fact, only at one grid point, in the southwest part of the region, was a difference of more than 0.05 $\mu g \cdot m^{-3}$ noted. That particular value changed from 1.9 to 2.1 $\mu g \cdot m^{-3}$ affecting slightly the position of the 2 $\mu g \cdot m^{-3}$ countour in that area. Otherwise grid point values and the contours were identical to those shown in Figure 3.

Test of individual grid-point calculations indicated that slopes were always very small. An examination of Figure 2 reveals that the steepest slopes are only of the order of a 80 m elevation change in 2 km (or 1:25 or 2.3°). Thus the slope factors introduced changes that were typically less than 1 m for effective source height and less than 10 m for downwind distance with correspondingly small changes of the order of 1 m or less in dispersion coefficient. In some cases these changes compensated one another in the concentration calculation.

These experiments revealed that for the area shown in Figure 2 and for any area of similar slopes, the modification to the CDM to incorporate terrain is not required. Furthermore the results are probably as good as may be expected for the CDM except possibly along the Athabasca River valley where channelling and impingement effects may be significant.

2.1.2 Effect of Pollutant Removal

In order to evaluate the effects of removal of pollutant using a half-life of 20 h, two comparison experiments were performed with a 10 h and infinite half-life, respectively. The patterns which resulted were quite similar to those of Figure 3. Magnitudes were within a 2 $\mu g \cdot m^{-3}$ and more typically within 0.5 $\mu g \cdot m^{-3}$ at all points, higher values being calculated for the infinite half-life (no removal) and lower values for the 10 h half-life. Because these results are not significantly different from those of Figure 3 they are not presented in contoured form in this report. Calculated values are shown, however, for the five monitor locations in Table 6 (see Section 2.3.2).

2.2 EXISTING AND FUTURE SOURCES

In order to estimate future pollution levels, an additional numerical experiment was performed with the Syncrude Main Stack (Table 3) as the only source of pollution. Results showed that the maximum concentrations due to Syncrude alone are calculated to be less than 1 $\mu g \cdot m^{-3}$ at all points within the area shown in Figure 2 and beyond into the larger 100 km x 100 km domain. Typical values fell in the range 0.3 to 0.7 $\mu g \cdot m^{-3}$. These results are based on the assumptions that the actual operating stack characteristics will be according to design values (Table 3) and that the plant will operate without breakdowns and, hence, without flaring. The low calculated values of concentration are due to the high effective source heights determined by the model. The stack itself is 183 m high compared with 107 m for the GCOS Powerhouse Stack (Table 3). In addition, the larger values of stack diameter and exit velocity will result in higher plume rise. Thus, despite the fact that Syncrude emission rates will be slightly higher than those of GCOS, the higher effective source height will result in lower ground-level concentrations.

A final experiment was conducted with the Syncrude stack and the four GCOS stacks included as sources. Calculations were made without pollutant removal in order, perhaps, to partially compensate for the optimistic assumptions regarding the Syncrude operation. The contoured calculated results are shown in Figure 4. The pattern is very similar to that of Figure 3; magnitudes are at most about 2 $\mu g \cdot m^{-3}$ higher.

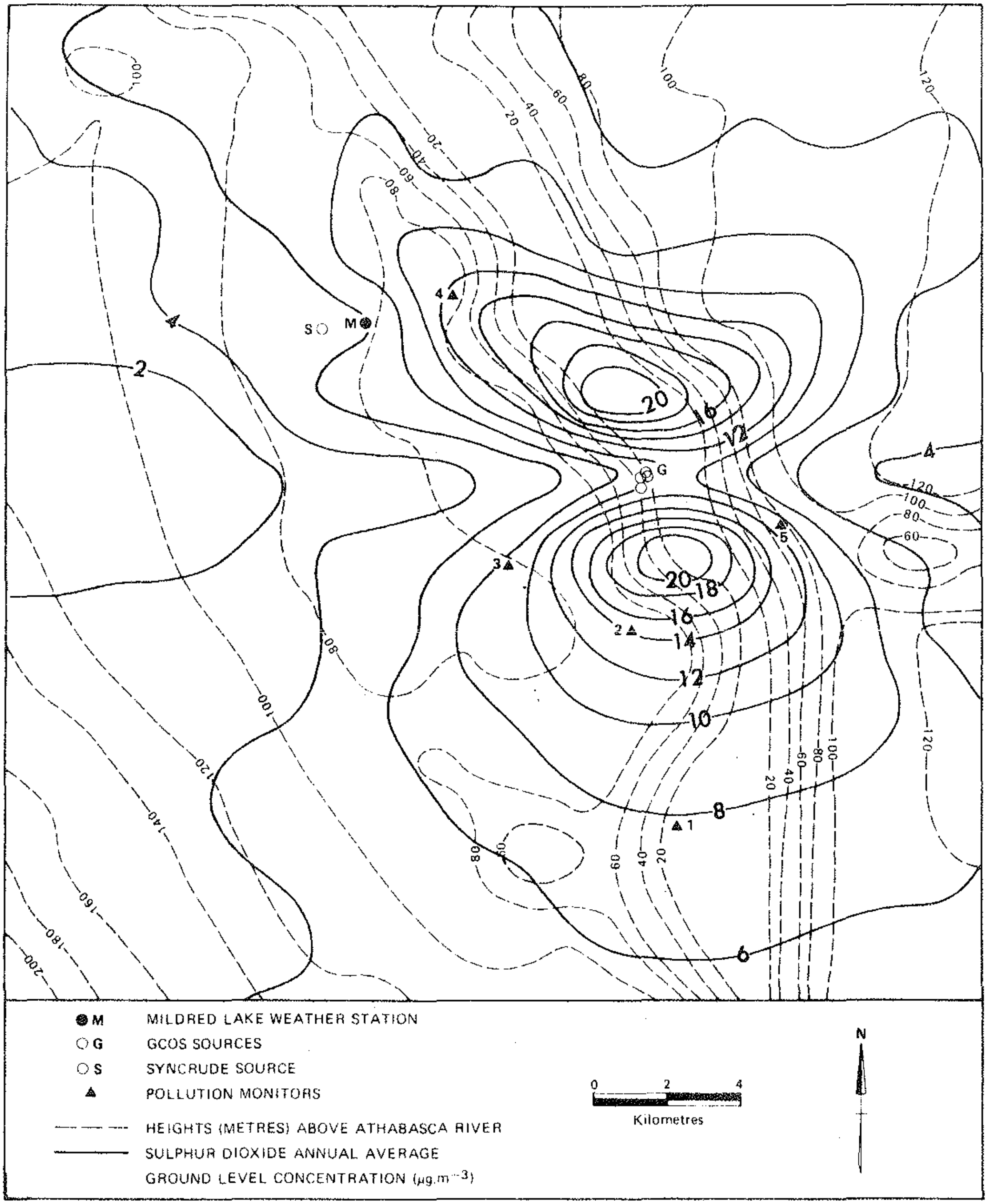

Figure 4. Annual Averaged Sulphur Dioxide Concentrations at Ground Level: Five Sources, No Pollutant Removal

2.3 VERIFICATION OF THE RESULTS

2.3.1 Pollution Monitor Data

GCOS is currently monitoring the ambient air at five locations (Table 4). Data from these stations are presented in Table 5. The period of record for Stations 2, 3 and 5 was only five months (July-November 1976) so that the values shown in Table 5 may not be truly representative of an annual average.

Reasonably precise locations of stations 1, 2, 4 and 5 were obtained from topographic maps, evidence from air photographs and from personal knowledge. The assumed locations agreed with land survey designations provided by GCOS via M. Strosher of AOSERP in all cases except Station 1 which is believed to lie within the southern part of NE 1/4 rather than in SE 1/4 as indicated in Table 4. This position is indicated correctly on the map, Figure 2. Due to the digitization and contouring processes however, the elevation contours show the station in the valley, whereas it is just at the top of the hill leading to the upland plain. It is felt that the UTM coordinates are accurate to within about 50 m (i.e., ± 0.05 km). In the case of Station 2 a position was selected on Highway 63 close to the GCOS mine site and within the land survey quarter-section indicated in Table 4. This position seemed to agree quite well with observations of AES participants in the intensive field study of February 1977. Accuracy of the UTM coordinates is probably about ± 0.2 km.

Sulfur dioxide concentrations expressed in parts per million (ppm) in Table 5 were converted by multiplying by the factor 2650 $\mu g \cdot m^{-3} . (ppm)^{-1}$. In the case of Stations 1 and 4 for which three years of data are available, statistics reflecting the annual variability were computed in order to evaluate how well an individual year's observations represent a longer-term average. In Table 5 are shown values of standard deviation and its modified version which is applicable for small samples. Formulae are given in the Appendix.

The modified standard deviation is about 3 $\mu g \cdot m^{-3}$ for the two locations. It must be assumed, therefore, that at Stations 2, 3, and 5 the observed values may be in error by ± 3 $\mu g \cdot m^{-3}$

TABLE 4. AMBIENT AIR MONITORING STATIONS.[1]

Station Number	1	2	3	4	5
Station Name	Supertest Hill	Mannix	Ruth Lake	Mildred Lake	Fina Airstrip
Land Survey Designation:					
Quarter-Section	NE¼ [4]	NE¼	NE¼	SE¼	NW¼
Section	25	11	16	8	20
Township	91	92	92	93	92
Range	10	10	10	10	9
UTM Location, Block 12VVU:[2]					
East (km)	71.88	70.68	67.50	65.88	74.64
North (km)	8.68	13.93	15.70	22.88	16.78
Model Grid Coordinates:					
x	25.96	25.34	23.75	22.94	27.32
y	19.45	21.97	22.85	26.44	23.39
Elevation[3] (m)	85	90	84	85	85

---

[1] Land survey designations provided by M. Strosher of AOSERP.

[2] UTM locations estimated to nearest 10 m (Stations 1,2,4,5) and to nearest 100 m (Station 3) from topographic maps and air photographs.

[3] Elevations above the Athabasca River from topographic maps of scale 1:50,000.

[4] Location in NE¼ confirmed by GCOS in May 1977. Previously location was indicated as SE¼.

TABLE 5. AMBIENT AIR MONITOR DATA.[1]

Station Number	1	2	3	4	5
Station Name	Supertest Hill	Mannix	Ruth Lake	Mildred Lake	Fina Airstrip
SO_2 Concentration,[2]					
Annual Averages:					
1974 (ppm)	0.0033	-	-	0.0020	-
1975 (ppm)	0.0011	-	-	0.0014	-
1976 (ppm)	0.0019	0.0031	0.0027	0.0037	0.0065
Average (ppm)	0.0021	0.0031	0.0027	0.0024	0.0065
Average (μg.m^{-3})	5.6	8.2	7.2	6.4	17.2
Standard Deviation (μg.m^{-3})	2.4	-	-	2.6	-
Modified Standard Deviation (μg.m^{-3})	2.9	-	-	3.2	-

---

[1] Observational Data supplied by M. Strosher of AOSERP. Data for Stations 2,3,5 are for the period July-November 1976.

[2] Values for 1974, 1975 may be low by approximately 10% due to method of recording low concentrations in those years (M. Strosher, personal communication).

when used as estimates of annual averages over a period of several years. With an ever-increasing period of record, however, the data at all five stations should prove to be more reliable estimators of the true annual average values.

2.3.2 Comparison of Calculations with Monitor Data

In Table 6 are shown verification statistics for three numerical experiments employing the four GCOS sources and varying the half-life of sulphur dioxide. A discussion of appropriate half-life values is found in Section 2.4. The statistics shown are the standard error; the modified standard error; the slope, m, and the intercept, b, of the linear regression curve, $y = mx+b$, which is fit to the observations, y, and calculations, x; the linear correlation coefficient and the rank difference correlation coefficient. Formulae are given in the Appendix.

During the intensive field studies of March 1976 and February 1977, the GCOS plumes were frequently observed to be fumigating in the vicinity of Station 5 at the Fina Airstrip during periods of westerly to northwesterly flow (Dr. F. Fanaki, personal communication). Since the CDM does not attempt to simulate fumigation, it was decided to compute verification statistics from 1 to 4, inclusive, for comparison with those statistics computed using all five stations.

Results for all three experiments shown in Table 6 are quite similar, indicating that the calculations are not very sensitive to the half-life assumed. The modified standard error results are all about 6 $\mu g \cdot m^{-3}$. Of this amount about 3 $\mu g \cdot m^{-3}$ may be accounted for by uncertainty in the observed values as estimators of the time annual average concentration. Compared with ideal values of $m=1$, $b=0$, the slopes and intercepts of the linear regression curves are poor for all cases shown.

The linear correlation coefficient is very low for cases where all five monitors are included but does indicate some CDM skill when Station 5 is excluded, values of almost 0.7 being achieved. It should be pointed out, however, that because of the small amount of verification data available and due to the short period of record of Stations 2,3 and 5 causing uncertainty in

TABLE 6. MODEL VERIFICATION STATISTICS.[1]

	Half-life (h)	∞	20	10
Monitor Number	Observations (μg m^{-3})	Calculations (μg m^{-3})		
1	5.6	7.3 (8.6)[2]	7.1	6.9
2	8.2	14.6 (15.3)	14.4	14.2
3	7.2	7.6 (7.9)	7.5	7.4
4	6.4	11.8 (13.3)	11.6	11.4
5	17.2	10.6 (11.1)	10.5	10.4

Monitors Included:	1-5	1-4	1-5	1-4	1-5	1-4
STATISTICS:						
Standard Error (μg m^{-3})	4.8 (5.4)[2]	4.3 (5.2)[2]	4.8	4.1	4.7	4.0
Modified Standard Error (μg m^{-3})	6.2 (6.9)	6.0 (7.3)	6.1	5.8	6.0	5.6
Linear Regression, Slope	0.28(.13)	0.21(.17)	0.30	0.22	0.32	0.22
Linear Regression, Intercept (μg m^{-3})	6.1 (7.4)	4.6 (4.9)	5.9	4.6	5.7	4.6
Linear Correlation Coefficient	0.18(.09)	0.68(.56)	0.19	0.68	0.20	0.69
Rank Difference Correlation Coefficient	0.50(.10)	0.80(.40)	0.50	0.80	0.50	0.80

[1] Comparison of observed and model calculated values of sulphur dioxide concentration, annual averaged at ground-level. Formulae are given in the Appendix.

[2] Figures in parentheses are the results of calculations with gas temperatures of 232 and 538^{o}C (see Table 3, footnote 7).

the observations, calculations of correlation coefficient are quite sensitive to small (e.g., ± 1 $\mu g \cdot m^{-3}$) changes in the observed values.

A more reliable estimator of correlation between observed and calculated values is the rank difference correlation coefficient which, by correlating only the order or rank of the two sets of numbers (see Appendix), is generally much less sensitive than the linear correlation coefficient to small changes in values of either observations or calculations. These statistics are more impressive, especially in the case of exclusion of Station 5, when a value of 0.8 is obtained. Although the available observational data are still not sufficient for proper verification, the indications shown in Table 6 are somewhat encouraging.

2.3.3 Comparison with Snowpack Measurements

Barrie and Whelpdale (1977) have measured the sulphur loading in snowpack at 56 sites in the period March 3-9, 1976. All sites lay within a 25 km radius of GCOS, several being within a distance of 5 km. Contoured results for the total snowpack for the winter of 1975-76 up to the time of measurement exhibit a maximum of about 59 $mg\text{-}S \cdot m^{-2}$ at a location about 4.1 km south southwest of GCOS. In Figure 3 of the present report a long-term maximum in SO_2 concentration of 22 $\mu g \cdot m^{-3}$ is located about 2.3 km to the south southeast of GCOS, or about 2.8 km from the position of Barrie and Whelpdale for the winter of 1975-76. A secondary maximum in their results is located within about 0.9 km of the northern maximum shown in Figure 3.

Comparison of the magnitudes of these two maxima is much more difficult as both wet and dry deposition processes would be inherent in the measured values. Furthermore, due to a series of thaws earlier in the winter, the bottom layer of the snowpack would have been subject to leaching, causing removal of sulphur. The latter difficulty may be overcome by considering the sulphur loading in the top layer of snow which did not experience a thaw. For that layer, Barrie and Whelpdale give a maximum value of 21 $mg\text{-}S \cdot m^{-2}$. The time period during which sulphur could have been deposited in the top layer of snow prior to measurement was approximately 18 days (Dr. L.A. Barrie, personal communication). Extrapolation of the data to an annual average would give a value of approximately 430 $mg \cdot m^{-2} \cdot y^{-1}$ for combined wet and dry deposition of sulphur. For CDM derived estimates of dry deposition a deposition velocity is required. Dovland and Eliassen (1976) give a value of 0.1 $cm \cdot s^{-1}$, and Whelpdale and Shaw (1974) estimate 0.05 $cm \cdot s^{-1}$ for dry deposition on a snow surface during stable atmospheric conditions (such as would be expected in northern Alberta in winter). Assuming a deposition velocity of 0.1 $cm \cdot s^{-1}$, an estimate for dry deposition of sulphur of 350 $mg \cdot m^{-2} \cdot y^{-1}$ is obtained. This is certainly as good agreement with the snowpack measurement derived values as could be expected considering the crude assumptions involved.

2.4 SULPHUR DIOXIDE REMOVAL PROCESSES AND ESTIMATES OF DEPOSITION

Removal of sulphur dioxide by processes of deposition and transformation is parameterized in the CDM by the input of an appropriate value of the half-life.

Eliassen and Saltbones (1975) estimate a rate of transformation to sulphate of 2.10^{-6} s^{-1}, corresponding to a residence time (time for SO_2 concentration to reduce to 1/e of its value at initial time) of 139 h or a half-life of 97 h.

An estimate of the half-life due to dry deposition may be arrived at by assuming a deposition velocity of the order of 1 $cm \cdot s^{-1}$ (Prahm et al., 1976, estimate 2 $cm \cdot s^{-1}$ ± 50%; Heffter and Ferber, 1975, indicate 0.1 to a few $cm \cdot s^{-1}$; Dovland and Eliassen, 1976, give 0.1 $cm \cdot s^{-1}$ for snowpack in stable atmospheric conditions; Whelpdale and Shaw (1974) give values in the range 0.05 to 4.0 $cm \cdot s^{-1}$ depending on surface type and atmospheric stability) and a mixing height of the order of 1000 m (Portelli, 1977). Under these assumptions a decay rate of 10^{-5} s^{-1} is calculated, which corresponds to a residence time of 28 h or a half-life 19 h. Eliassen and Saltbones (1975) estimate a half-life of 10 h.

When the two processes of transformation and dry deposition are combined, the decay rates (or the inverses of the residence times) are additive. Thus a half-life due to the two processes is estimated at 16 h, whereas a value of 9 h would be derived from Eliassen and Saltbones.

Although the assumptions going into the above estimates are rather crude, the results of Section 2.3.2 suggest that the sulphur dioxide concentrations are not very sensitive to the half-life. Thus it seems as if a value of 20 h will give sufficient accuracy.

In order to estimate sulphur deposition, however, the results are much more sensitive to the half-life or, for a given mixing height, the corresponding value of deposition velocity. Estimates of dry deposition of sulphur may be obtained by the formula:

$$D = 1/2\ q\ u_d\ \Delta t \tag{18}$$

where D = Sulphur deposition,
q = Sulphur dioxide concentration,
u_d = Deposition velocity
Δt = Time period of deposition

This implies that a simple relabelling of the contours of Figure 4 will give estimates of future dry deposition of sulphur. The results of Sheih (1977) who used a more sophisticated model show that this is indeed a very good assumption. Thus for q values in $\mu g \cdot m^{-3}$ and D values in $mg\text{-}S \cdot m^{-2} \cdot y^{-1}$, the conversion factor is

$$\frac{\frac{1}{2} u_d \Delta t}{1000}$$

where Δt is the number of seconds in one year. For $u_d = 1\ cm \cdot s^{-1}$ the conversion factor is about 160 $(mg \cdot m^{-2} \cdot y^{-1})/(\mu g \cdot m^{-3})$.

2.5 SUMMARY OF EXPERIMENTAL RESULTS

Results of Section 2 may be briefly summarized as follows:

a) For the small slopes involved in this region, the effect of incorporating topography in the CDM has an insignificant effect on the calculations of sulphur dioxide concentrations.

b) Concentrations along the valley of the Athabasca River may be higher than calculated by the CDM due to channelling and impingement effects.

c) Maximum concentrations attributable to GCOS sources are about 20 $\mu g \cdot m^{-3}$, somewhat below the Maximum Desirable Level of 30 $\mu g \cdot m^{-3}$ for an annual average.

d) The contribution of Syncrude to the total annual average sulphur dioxide concentration at ground-level is expected to be of the order of 1 $\mu g \cdot m^{-3}$ or less provided that stack design characteristics (Table 3) are met and that no breakdowns that necessitate flaring occur.

e) Small decreases in sulphur dioxide concentration, generally less than 10%, result from pollutant removal processes as parameterized in the CDM. The calculations are not very sensitive to the particular value of the half-life assumed.

f) The available ambient air monitoring data are still not sufficient for proper verification of the model. This situation should improve with time as the period of record lengthens, making the observations more reliable as estimators of long-term average values. Nevertheless, the verification statistics appear to indicate some model skill.

g) The CDM results appear to be consistent with snowpack measurement data, although its is not possible to make more than a crude comparison.

h) Estimates of sulphur deposition patterns may be made from the sulphur dioxide concentration results simply by relabelling the contours. The conversion factor is proportional to deposition velocity and would have a value of about 160 $(mg \cdot m^{-2} \cdot y^{-1})/(\mu g \cdot m^{-3})$ for a deposition velocity of 1 $cm \cdot s^{-1}$.

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4. APPENDICES

4.1 METHOD OF INCORPORATING TERRAIN

The CDM was modified to incorporate terrain using the following algorithm in the computer program:

$$\Delta h = h_r - h_b$$

$$d = (d_o{}^2 + (\Delta h)^2)^{\frac{1}{2}}$$

$$\cos \alpha = d/d_o$$

$$H = H_o \cos \alpha$$

$$\sin \alpha = (1 - \cos^2 \alpha)^{\frac{1}{2}}$$

$$\text{IF } (\Delta h<0) \ \sin \alpha = - \sin \alpha$$

$$x = x_o - H_o \sin \alpha$$

where h_r = height of receptor above reference level,

h_b = height of stack base above reference level,

d_o = source-receptor distance for flat terrain,

H_o = effective source height for flat terrain,

α = mean slope of terrain between source and receptor,

x_o = component of source-receptor distance in direction of wind for flat terrain (used in the Gaussian dispersion formula),

d,H,x = values corresponding to d_o, H_o, x_o, respectively, for terrain with slope α.

4.3. MILDRED LAKE SYNTHETIC STAR DATA, 1963-75

STABILITY CLASS= 1 A

		0-3	4-6	7-10	11-16	17-21	>21 Knots
		1	2	3	4	5	6
N	1	.000349	.000224	.000102	.000007	0	.000000
	2	.000286	.000199	.000072	.000006	0	.000000
NE	3	.000224	.000174	.000043	.000005	0	0
	4	.000164	.000095	.000022	.000002	0	0
E	5	.000105	.000016	.000000	0	0	0
	6	.000217	.000132	.000027	.000001	0	0
SE	7	.000329	.000249	.000054	.000002	0	0
	8	.000343	.000193	.000038	.000001	0	0
S	9	.000356	.000137	.000022	0	0	0
	10	.000279	.000106	.000029	.000000	0	0
SW	11	.000201	.000075	.000036	.000000	0	0
	12	.000174	.000043	.000019	.000000	0	0
W	13	.000146	.000011	.000002	.000000	0	0
	14	.000216	.000079	.000035	.000002	0	0
NW	15	.000286	.000147	.000067	.000003	0	0
	16	.000317	.000185	.000085	.000005	0	.000000

STABILITY CLASS= 2 B

	1	2	3	4	5	6
1	.003261	.002065	.001085	.000184	.000012	.000007
2	.002665	.001864	.000850	.000128	.000006	.000003
3	.002069	.001662	.000614	.000072	0	0
4	.001567	.000904	.000316	.000036	0	0
5	.001065	.000146	.000018	0	0	0
6	.001993	.001342	.000455	.000043	.000001	0
7	.002921	.002539	.000892	.000086	.000001	0
8	.003175	.002027	.000626	.000059	.000001	0
9	.003429	.001515	.000361	.000031	0	0
10	.002792	.001415	.000659	.000085	.000001	0
11	.002156	.001316	.000957	.000140	.000002	0
12	.001847	.000841	.000559	.000081	.000003	0
13	.001539	.000366	.000162	.000022	.000004	0
14	.002171	.001062	.000673	.000100	.000004	0
15	.002803	.001757	.001185	.000177	.000003	0
16	.003032	.001911	.001135	.000181	.000008	.000003

STABILITY CLASS= 3 C

	1	2	3	4	5	6
1	.004698	.003033	.001779	.000497	.000047	.000009
2	.003863	.002868	.001476	.000346	.000024	.000005
3	.003028	.002704	.001173	.000195	0	0
4	.002407	.001503	.000632	.000101	0	0
5	.001786	.000303	.000091	.000008	0	0
6	.003225	.002598	.001507	.000302	.000004	0
7	.004665	.004892	.002923	.000596	.000008	0
8	.004945	.003710	.001933	.000407	.000004	0
9	.005225	.002528	.000944	.000219	0	0
10	.004352	.002778	.002177	.000625	.000013	0
11	.003479	.003027	.003410	.001031	.000026	0
12	.002884	.001922	.002018	.000597	.000020	0
13	.002288	.000816	.000626	.000163	.000014	0
14	.003121	.001906	.001782	.000463	.000025	.000001
15	.003953	.002996	.002938	.000764	.000036	.000001
16	.004326	.003014	.002359	.000630	.000042	.000005

```
STABILITY CLASS= 4    D DAY

            1          2          3          4          5          6
   1    .005185    .004770    .003620    .001645    .000272    .000029
   2    .004527    .004879    .003493    .001203    .000136    .000014
   3    .003870    .004989    .003366    .000761          0          0
   4    .002987    .002745    .001911    .000491          0          0
   5    .002105    .000502    .000456    .000220          0          0
   6    .003260    .003748    .003983    .001927    .000007          0
   7    .004415    .006993    .007509    .003634    .000014          0
   8    .004182    .004671    .004510    .002151    .000007          0
   9    .003949    .002349    .001512    .000667          0          0
  10    .003694    .003408    .004625    .002431    .000140          0
  11    .003438    .004466    .007739    .004195    .000281          0
  12    .002784    .002891    .004591    .002406    .000155          0
  13    .002130    .001315    .001444    .000617    .000029          0
  14    .002993    .003044    .004293    .001952    .000157    .000016
  15    .003855    .004772    .007142    .003286    .000285    .000031
  16    .004520    .004771    .005381    .002466    .000278    .000030
STABILITY CLASS= 5    D NIGHT

            1          2          3          4          5          6
   1    .005869    .004690    .003018    .001188    .000186    .000018
   2    .004968    .004592    .002854    .000826    .000093    .000009
   3    .004067    .004494   .002691   .000465          0         0
   4    .003231    .002554    .001560    .000338          0          0
   5    .002396    .000614    .000429    .000210          0          0
   6    .003917    .004152    .003950    .001458    .000008          0
   7    .005438    .007689    .007470    .002705    .000016          0
   8    .005145    .005113    .004517    .001632    .000008          0
   9    .004852    .002536    .001564    .000559          0          0
  10    .003992    .002890    .003187    .001413    .000055          0
  11    .003132    .003244    .004809    .002266    .000109          0
  12    .002670    .002071    .002889    .001307    .000065          0
  13    .002208    .000898    .000969    .000349    .000020          0
  14    .003232    .002512    .003234    .001219    .000080    .000006
  15    .004255    .004127    .005498    .002090    .000140    .000012
  16    .005062    .004408    .004258    .001639    .000163    .000015
STABILITY CLASS= 6    E & F

            1          2          3          4          5          6
   1    .012847    .006866    .003259    .000537    .000031    .000017
   2    .010765    .006470    .002749    .000379    .000016    .000009
   3    .008682    .006073    .002240    .000222          0          0
   4    .007522    .003538    .001209    .000111          0          0
   5    .006361    .001003    .000179          0          0          0
   6    .011683    .010641    .005253    .000598    .000006          0
   7    .017004    .020278    .010328    .001196    .000012          0
   8    .018133    .015458    .007083    .000901    .000006          0
   9    .019263    .010639    .003839    .000607          0          0
  10    .015038    .009207    .005106    .000927    .000009          0
  11    .010813    .007775    .006374    .001247    .000018          0
  12    .008779    .004664    .003515    .000687    .000016          0
  13    .006745    .001552    .000655    .000127    .000013          0
  14    .008640    .003799    .002300    .000360    .000011          0
  15    .010536    .006047    .003945    .000592    .000010          0
  16    .011692    .006457    .003602    .000564    .000020    .000009
          N                 NE                 E                SE        DIRECTION
GSUM=   .071408   .062645   .053883   .035948   .018013   .066436   .114858   .090980
          S                 SW                 W                NW           TOTALS
GSUM=   .067102   .071432   .075762   .050496   .025231   .049487   .073743   .072575
         0-3       4-6       7-10     11-16     17-21      >21        WIND SPEED TOTALS
  GS=   .407556   .302756   .219080   .067177   .003179   .000251

SIGG=  1.000000    GRAND TOTAL
```

4.4 STATISTICAL FORMULAE

The formulae used in calculating the statistics shown in Table 5 and 6 are given below.

The standard deviation is calculated from:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\bar{y} - y_i)^2} ,$$

where $\bar{y}$ is the mean of the N values of y_i. The modified standard deviation, used for small samples, is:

$$\hat{\sigma} = \sqrt{\frac{N}{N-1}}\, \sigma \quad .$$

When comparing two sets of data, y_i and x_i, where, for example, the y_i are observed values and the x_i are calculated values, the standard error is computed from:

$$s = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - x_i)^2}$$

and the modified standard error, applicable for small samples, is determined by the following relation:

$$\hat{s} = \sqrt{\frac{N}{N-2}}\, s \quad .$$

The slope, m, and intercept, b, of the linear regression curve fit to the data sets y_i vs. x_i are computed by standard methods:

$$m = \frac{N\Sigma x_i y_i - \Sigma x_i \Sigma y_i}{N\Sigma x_i^2 - (\Sigma x_i)^2}$$

$$b = \frac{\Sigma y_i \Sigma x_i^2 - \Sigma x_i \Sigma x_i y_i}{N\Sigma x_i^2 - (\Sigma x_i)^2} \quad .$$

The corresponding linear correlation coefficient is:

$$r = \frac{N\Sigma x_i y_i - \Sigma x_i \Sigma y_i}{\sqrt{[N\Sigma x_i^2 - (\Sigma x_i)^2][N\Sigma y_i^2 - (\Sigma y_i)^2]}} \quad .$$

Finally, if each y_i value is ranked with a number v_i, where $v_i = 1$ for the largest y_i value, 2 for the next largest, etc., and $v_i = N$ for the smallest value, and if u_i is the corresponding rank for the value x_i, then the rank difference correlation coefficient is computed from:

$$\rho = 1 - \frac{6 \sum_{i=1}^{N} (v_i - u_i)^2}{N(N^2 - 1)} \quad .$$

5. LIST OF AOSERP REPORTS

1		AOSERP First Annual Report, 1975
2	AF 4.1.1	Walleye and Goldeye Fisheries Investigations in the Peace-Athabasca Delta - 1975
3	HE 1.1.1	Structure of Traditional Baseline Data System
4	VE 2.2	Preliminary Vegetation Survey of the AOSERP Study Area
5	HY 3.1	Evaluation of Wastewaters from an Oil Sands Extraction Plant
6		Housing for the North-Stackwall System Construction Report
7	AF 3.1.1	Synopsis of the Physical and Biological Limnology and Fishery Program within the Alberta Oil Sands Area
8	AF 1.2.1	Impact of Saline Waters upon Freshwater Biota (A Literature Review and Bibliography)
9	ME 3.3	Preliminary Investigation into the Magnitude of Fog Occurrence and Associated Problems in the Oil Sands Area
10	HE 2.1	Development of a Research Design Related to Archaeological Studies in the Athabasca Oil Sands
11	AF 2.2.1	Life Cycles of Some Common Aquatic Insects of the Athabasca River
12	ME 1.7	Very High Resolution Meteorological Satellite Study of Oil Sands Weather, a Feasibility Study
13	ME 2.3.1	Plume Dispersion Measurements from an Oil Sands Extraction Plant
14	HE 2.4	Athabasca Oil Sands Historical Research Project (3 volumes) (in preparation)
15	ME 3.4	Climatology of Low Level Air Trajectories in the Alberta Oil Sands Area
16	ME 1.6	The Feasibility of a Weather Radar near Fort McMurray, Alberta
17	AF 2.1.1	A Survey of Baseline Levels of Contaminants in Aquatic Biota of the AOSERP Study Area
18	HY 1.1	Alberta Oil Sands Region Stream Gauging Data (in preparation)
19	ME 4.1	Sulphur Dioxide Concentrations at Ground Level in the AOSERP Study Area(in preparation)
20	HY 3.1.1	Evaluation of Organic Constituents (in preparation)
21		AOSERP Second Annual Report , 1976-77
22	HE 2.3	Maximization of Technical Training and Involvement of Area Manpower (in preparation)
23	AF 1.1.2	Acute Lethality of Mine Depressurization Water on Trout, Perch and Rainbow Trout(in preparation)
24	ME 4.2	Review of Dispersion Models -Possible Applications in the Alberta Oil Sands Area (in preparation)
25	ME 3.5.1	Review of Pollutant Transformation Processes Relevant to the Alberta Oil Sands Area
26	AF 4.5.1	An Interim Report on an Intensive Study of the Fish Fauna of the Muskeg River Watershed of Northeastern Alberta (at print)
27	ME 1.5.1	Meteorology and Air Quality Winter Field Study, March 1976 (in preparation)