AN OBSERVATIONAL STUDY OF FOG IN THE AOSERP STUDY AREA

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Fog observations in the Alberta Oil Sands Environmental Research (AOSERP) study area during 1977 and 1978 are analyzed with respect to the prevailing synoptic weather patterns and the local micrometeorological and air quality measurements. Descriptive weather reports, aircraft observations, photographs, concurrent minisondes, and meteorological data were available during most winter fog episodes.

In all the winter fog episodes, a stationary weather front is oriented northwest-southeast over southern Alberta and British Columbia. The fog episodes are preceded by cold air advection aloft which lowers air temperatures to the range at which the fogs form.

A variety of weather patterns were associated with the autumn fogs. The most common one was an upper air flow from the northwest with a cold surface high pressure cell over northern Alberta. Steaming of the Athabasca River due to the temperature difference between air and water contributes to the formation of the autumn valley fogs.

Generally, the low temperature fogs begin to form before 0800 Mountain Standard Time (MST) near the extraction plants of Great Canadian Oil Sands Limited (GCOS) and Syncrude Canada Limited. The fogs are normally less than 100 m in depth and thin rapidly with distance. Movement of the fog tends to follow the Athabasca River. Individual fog events are short-lived, dissipating by noon in every case which was examined.

Recorded sulphur dioxide (SO_2) concentrations are negligible during both autumn and winter fog episodes. Pollutants emitted by the tall stacks of GCOS evidently do not mix to ground level while the fog is present. However, an increase in ground level concentrations is sometimes observed when the fog dissipates.

ACKNOWLEDGEMENTS

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The authors wish to acknowledge the assistance in the preliminary analysis of the ice fog photographs of Dr. R.B. Charleton of the Meteorology Division, Department of Geography, University of Alberta.

1. INTRODUCTION

A fog study was implemented by the Alberta Oil Sands Environmental Research Program (AOSERP) during 1977-1978 to provide more detailed observations of fog occurrences, especially during the winter when the possibility of ice fog exists.

The objectives of the study are to:

1. Assemble and collate the AOSERP fog information together with the relevant meteorological data and synoptic weather maps;
2. Analyze the relationship between the occurrence of fog with the meteorological conditions; and
3. Evaluate the air quality during the fog episodes.

The 1977-1978 observational program was primarily visual in nature. It consisted of written notations of the occurrence and duration of fog near the AOSERP Mildred Lake Research Facility, and observations of the areal and vertical extent of the fog during several aircraft flights. Minisonde flights and a meteorological tower provided a description of the micrometeorological conditions. Air quality information was obtained from the continuous monitors operated by Great Canadian Oil Sands (GCOS)[1] and Syncrude.

AOSERP encompasses an area in northeastern Alberta which harbours the largest reserves of oil-bearing material in Canada. GCOS and Syncrude operate large refineries there for the extraction of petroleum products. Because of the enormous size of these oil deposits, more refinery operations are being proposed for the near future. Accompanying the establishment of any heavy industry is concern regarding the environmental impact of such activity. One aspect of this concern is the possible stimulus that increased industrial activity would have on the frequency of fog occurrences in the area, along with the potential interaction of this fog with the industrial emissions.

[1] GCOS amalgamated with Sun Oil Company in August 1979, after the completion of this report, to become Suncor, Inc.

2. BACKGROUND

2.1 PREVIOUS OIL SANDS RESEARCH

A preliminary study into the frequency and magnitude of fog occurrences in the AOSERP study area was completed by Croft et al. (1977). The study was based on reports of fog incidents at the Fort McMurray Airport and that data set was compared to the climatology records at Embarras (an abandoned weather station 200 km north of Fort McMurray) and to fog occurrences at Fairbanks, Alaska.

It was found that the Fort McMurray airport experienced an average of 18 days of fog per year, 44% of which occurred during the months of August, September, and October. Of the total fog events, four to five days with ice fog are experienced. Potentially 10 to 18 days of ice fog per year could occur. These projections were based on the annual frequency of days with minimum temperatures below $-37^{\circ}C$ and were contingent on the continued development of the town. An estimation of the town water vapour emission rates gave an areal average of 36 to 100 km^2 for the ice fog around Fort McMurray.

Using the simple mass balance ice growth equation of Benson (1970), similar estimates were made for the oil sands area. These calculations gave a maximum coverage by ice fog of 1580 km^2 due to water vapour emissions of GCOS and Syncrude. Projected expansion of the industry increased this estimate to 4000 km^2.

The Croft et al. (1977) study was based on extrapolations from experience in other areas and only limited data from the local area were used. The need for routine fog observations and investigation of water vapour emission rates in the study area was indicated.

Murray and Kurtz (1976) conducted a preliminary study of ice fog potential at Mildred Lake, Alberta for Syncrude Canada Limited. The study consisted of a literature search, a site visit to determine local controls on ice fog, and theoretical calculations of potential ice fog. The lack of local data was noted and recommendations for a detailed site-specific study were made.

To improve the data base on fogs in the study area, a routine observational study was carried out by AOSERP personnel during 1977-1978 to provide more detailed observations of fog occurrences.

2.2 MICROPHYSICAL BACKGROUND

Fog is the suspension of water particles in the atmosphere at elevations close to the ground. Its formation occurs when the surface air temperature reaches the dew point and the atmosphere can no longer hold all its moisture in vapour form. As saturation is reached, the vapour condenses onto activated cloud condensation nuclei. Further growth of the droplet embryo occurs through vapour diffusion to the liquid surface or by way of collisions and coalescence between the droplets.

The two main types of fog are distinguished by the phase of the suspended water particles. Warm fog consists of liquid water droplets in the order of a few micrometres in diameter. These liquid droplets may exist in supercooled form in the atmosphere commonly to temperatures as low as -20°C, and often as low as -35°C. However, below -40°C, the tiny droplets of water freeze spontaneously into ice (Mason 1971). At these low temperatures, the ice phase forms through the homogeneous aggregation of small groups of water molecules which become locked into ice-lattice configurations. As the temperatures drop lower, these continually forming structures surpass a critical size and become a stable nucleus for further growth of the ice phase. When the majority of the suspended water particles are in solid form, the low level cloud is termed an ice fog. If there is a coexistence of water both as liquid drops and ice particles, the ice phase would grow at the expense of the liquid droplets because the saturation vapour pressure over water is higher than that over ice at sub-zero temperatures. This results in a migration of water vapour from the liquid to the ice surface.

At temperatures above the point of spontaneous nucleation, the water drops can freeze when contaminated with foreign particles called ice nuclei. These ice nuclei include dry mineral particles brought up from the soil, combustion particles, biogenic nuclei, microorganisms, or even secondary ice particles produced on the shattering and splintering of freezing drops.

3. STUDY AREA

The project study area is within the AOSERP boundaries as shown in Figures 1 and 2. The aircraft flights were within the 20 x 23 km rectangle shown in Figure 2.

Topography of this area is an undulating muskeg plain, drained by the Athabasca River and its three main tributaries, the Mackay, Beaver and Steepbank rivers. Each river cuts deeply into the gentle slopes, with the Athabasca River valley floor 60 to 100 m below the surrounding terrain at the southern end of the study area. The river valley is about 2 km wide with steep banks in the south. The valley broadens in a northerly direction with the valley walls becoming less sharply defined.

Topographical cross-sections centred on the Athabasca River valley are shown in Figures 3 and 4. In addition, the relative heights of the stacks for Syncrude and GCOS with respect to the local topography are shown.

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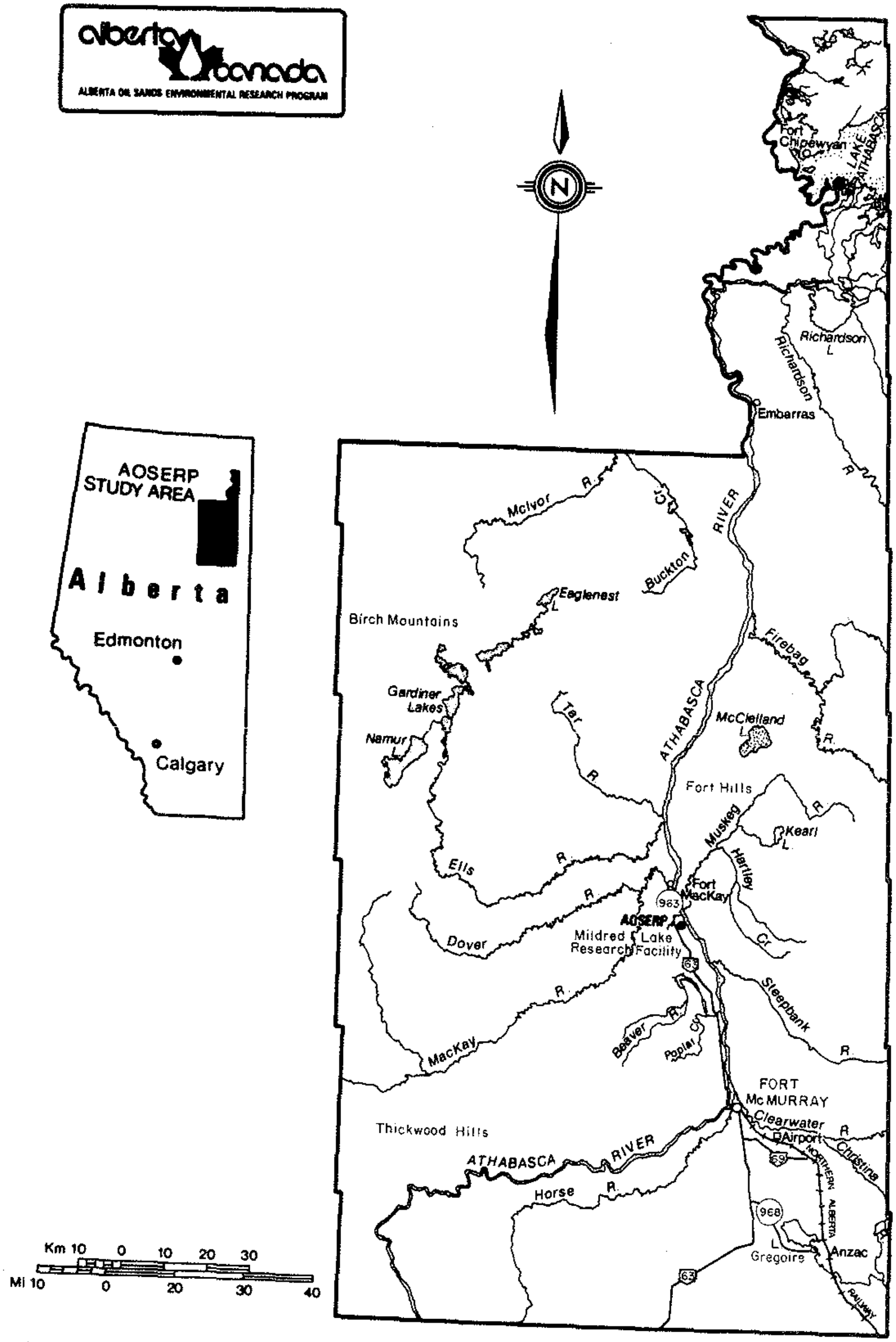


Figure 1. The AOSERP study area.

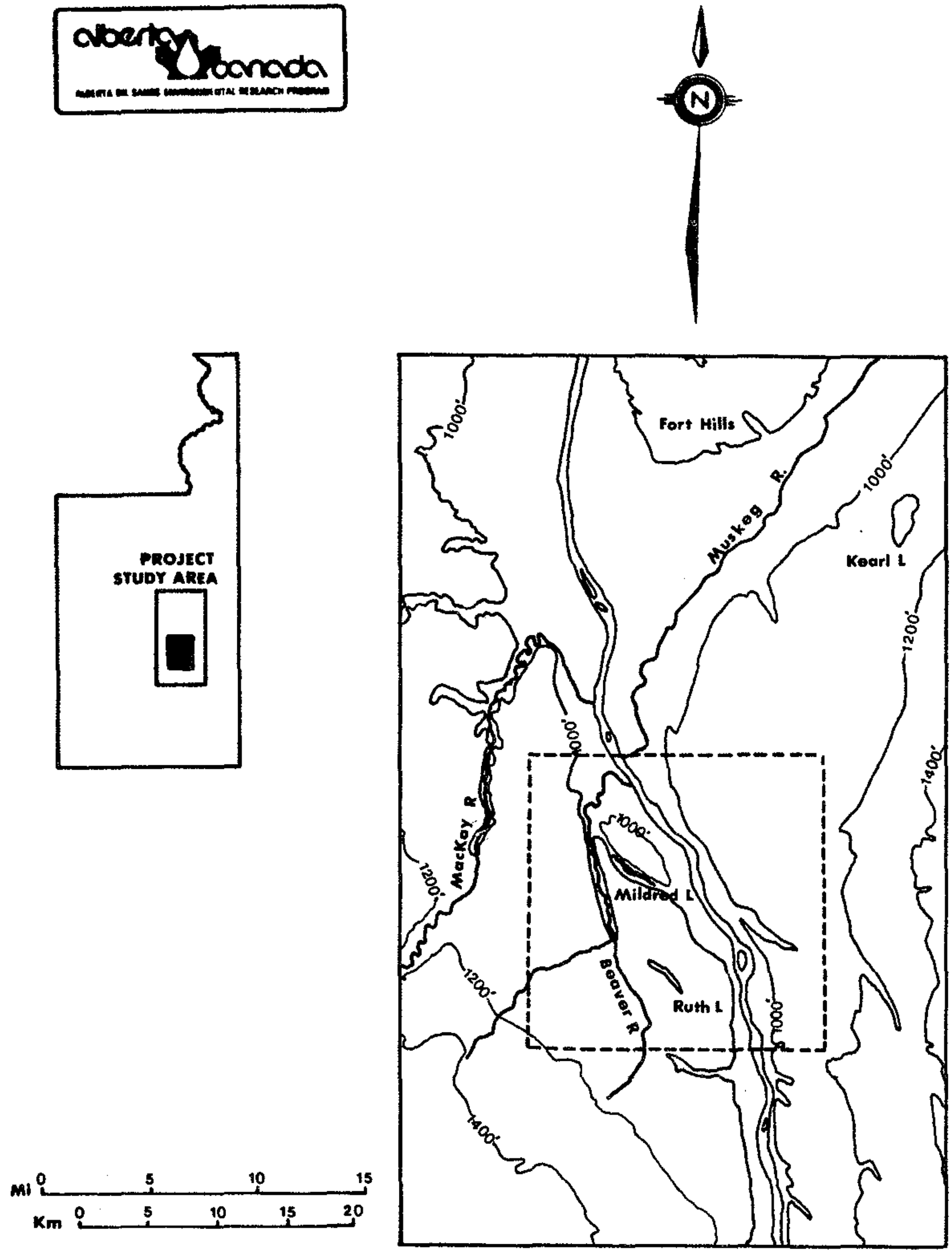


Figure 2. The project study area. Contours are measured in feet above sea level.

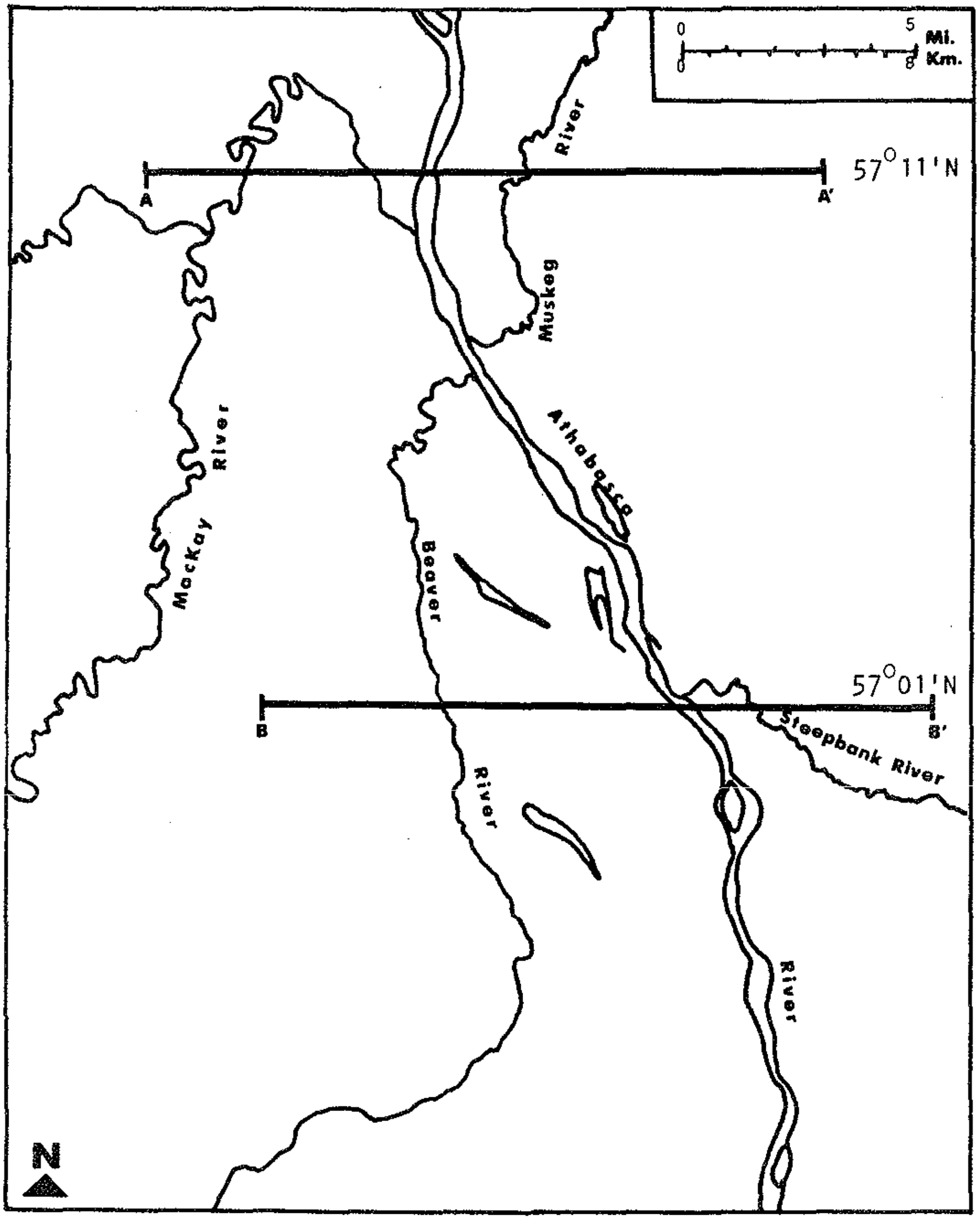


Figure 3 Transects within the study area. Topographic profiles are shown in Figure 4.

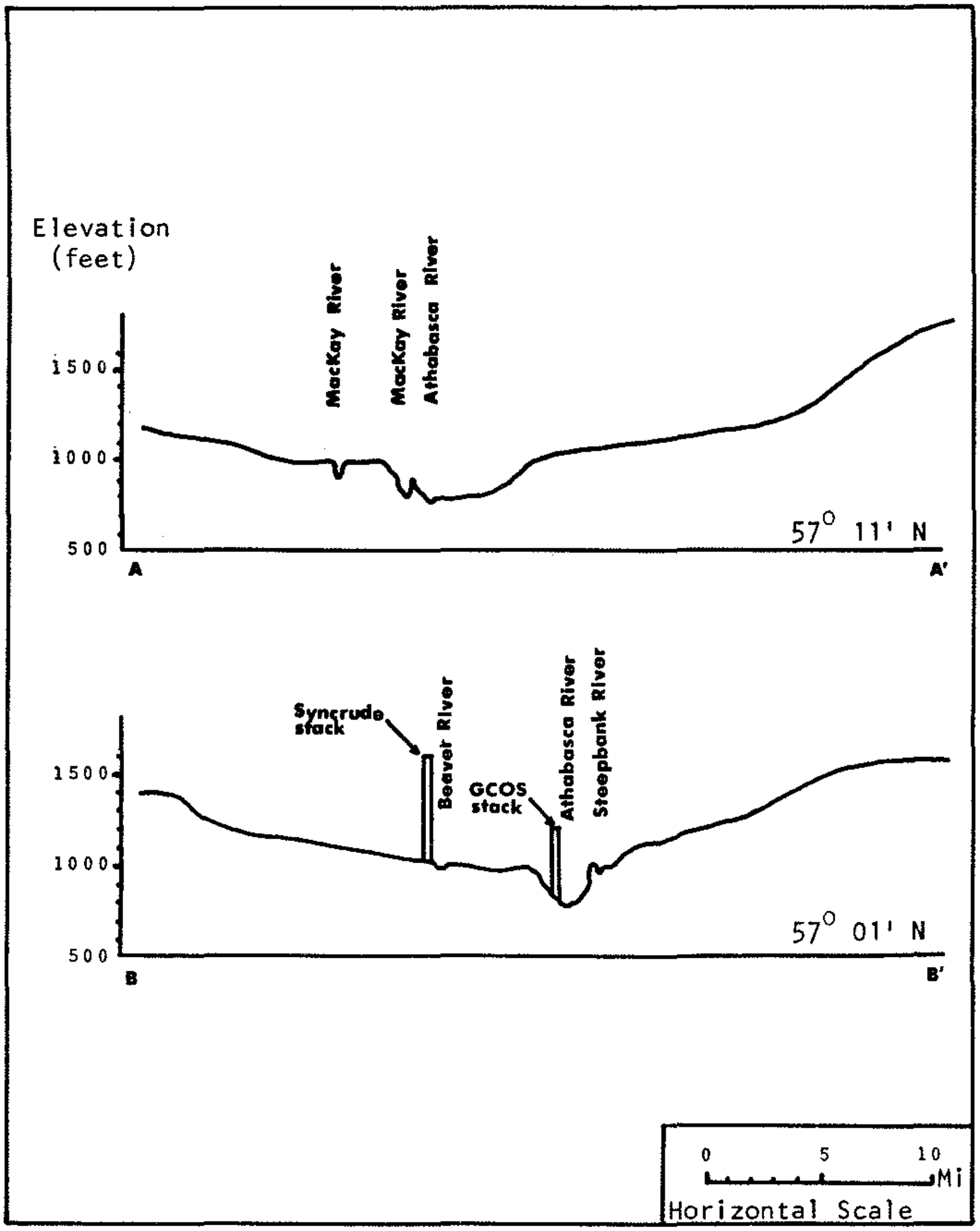


Figure 4. Topographical cross-sections along transects shown in Figure 3 within the study area. The stacks of Syncrude and GCOS have been drawn in for comparison to the surrounding topography. Syncrude is located to the north of the cross-section at 57°01'N. Broadening of the Athabasca River valley occurs in a northerly direction. This figure is adapted from an earlier study (Croft et al. 1977).

4. METEOROLOGICAL DATA

As this study is predominantly meteorological in nature, the first step after the selection of the fog incidents to be investigated was to gather the available pertinent data. This included meteorological information on the synoptic scale, the mesoscale, and any micrometeorological measurements available for the study days, in addition to the special observational reports collected by AOSERP.

For synoptic considerations, surface and upper air weather maps from the Atmospheric Environment Service (AES) along with the daily weather maps (surface and 500 mb charts) published by the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce were consulted. The upper air charts (500 mb) were supplemented with copies of plotted radiosonde flight data from Fort Smith and Stony Plain (Edmonton). Also available were the hourly surface weather observations from airports at Fort McMurray, Fort St. John, and Fort Smith.

Local data from the oil sands provided by AES in Edmonton included: (1) the climatological station register from the AOSERP base camp at Mildred Lake; (2) micrometeorological tower measurements of winds and temperatures from lower Syncrude; and (3) vertical temperature profiles from minisonde flights released at Mildred Lake.

The climatological register gives the maximum and minimum temperature and the amount of precipitation for the day. In addition, remarks are included about the weather conditions. The AOSERP base camp, where these observations are made (at $57^{\circ}05'$ Latitude, $111^{\circ}35'$ Longitude), is the same point from which the minisondes are released.

The minisonde information consists of vertical temperature profiles at fixed times during the day. Temperatures are abstracted at 15 second, or 45 m intervals above the release point given the assumed balloon ascent rate of 180 $m \cdot min^{-1}$. The minisonde flights took place twice daily from February 1978 to the present generally at 0800 Mountain Standard Time (MST) and 1400 MST. The month of

January 1978 provided a better temporal resolution of the thermal conditions as four releases were made per day, at 0800, 1000, 1200, and 1400 MST. No regular flights from this location took place prior to this date.

The meteorological tower data are collected on a tall tower erected at the lower Syncrude site (57°02' Latitude, 111°31' Longitude) approximately 6.5 km southeast of the AOSERP base camp. Measurements of winds are made at the 10 m, 90 m, and 142 m levels, while temperature is measured at the 1.5 m, 10 m, 30 m, 90 m, and 152 m heights.

The ground temperatures noted during the minisonde flights agree with the climatological records for the same location, but a comparison between the minisonde temperatures and the tower data reveals some differences. When fog is present, the temperature values from the lowest level of the tower are generally lower than the minisonde ground temperatures. As the tower base at 241 m MSL was 69 m below the elevation of the AOSERP camp, the tower information may indicate that colder air is trapped in the lower reaches of the Athabasca River valley.

The locations of the data sources in the AOSERP study area are shown in Figure 5, and a summary of the data used for each case study is given in Table 1.

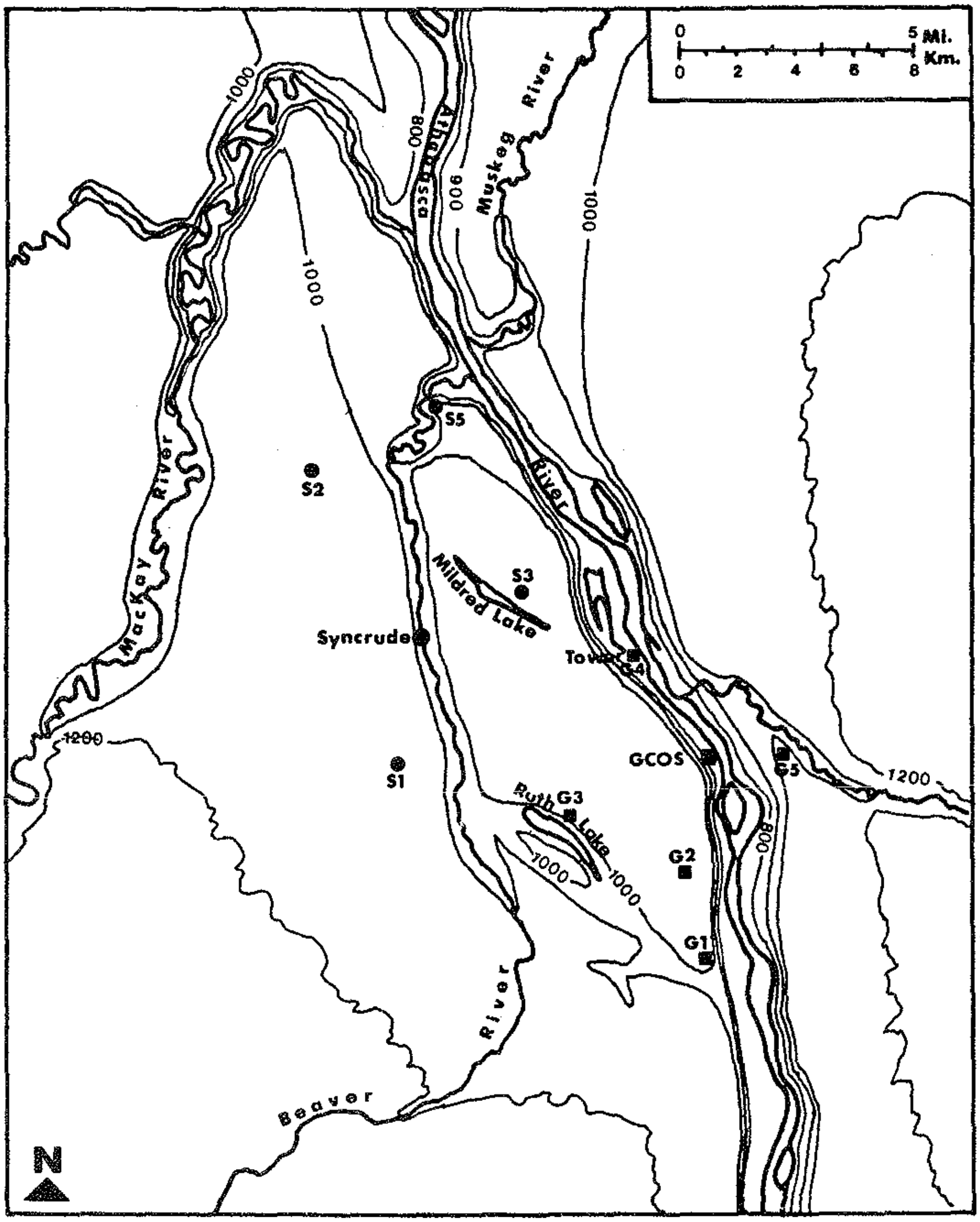


Figure 5. Locations of the data sources used in the project study area. Syncrude SO_2 pollution monitors are designated by the letter S while those of GCOS have the prefix G. Topographic contours show the elevation in feet above sea level. More detailed information about the monitoring network is given in Table 2.

Table 1. Available observational and meteorological data consulted for selected days of intensive fog study.

	Descriptive	Aircraft Observations	Photos	Minisondes	Tower Data	Climatological Record	Weather Maps	Radiosondes	Hourly Weather Observations
9-12 January 1977	X	X	X		X	X	X	X	X
18 January 1978	X	X	X	X	X	X	X	X	X
31 January 1978	X	X	X	X	X	X	X	X	X
2 February 1978		X	X	X	X	X	X	X	X
25 February 1978	X	X	X	X	X	X	X	X	X
27 February 1978	X			X	X	X	X	X	X
2-3 March 1978	X			X	X	X	X	X	X

Table 2. SO_2 pollution monitoring network used in fog study. All monitors are TECO model 43 pulse fluorescent analyzers fixed at ground level near the Syncrude and GCOS refineries (see Figure 3). Adapted from original table in Milgate (1978).

	Monitor Desigination	Name	Latitude	Longitude	Elevation (MSL)
Syncrude	S1		57°01'	111°38'	320 m
	S2	Tailings Pond	57°07'	111°41'	330 m
	S3	Mildred Lake	57°04'	111°34'	320 m
	S5	Beaver Road	57°07'	111°37'	265 m
GCOS	G1	Supertest Hill	56°57'	111°27'	305 m
	G2	Mannix	57°00'	111°29'	315 m
	G3	Ruth Lake	57°01'	111°32'	320 m
	G4	Lower Camp	57°02'	111°31'	241 m
	G5	Fina Airstrip (Steepbank)	57°00'	111°25'	305 m

5. ANALYSIS

5.1 WARM FOG

According to Croft et al. (1977), almost half the fogs at Fort McMurray airport take place from August to October inclusive. As a result, the observations of warm fog were taken mainly during these three months of the year. AOSERP fog reports indicated 14 incidents of fog during August and September in total, and two in October 1977. August 1978 had 13 days with fog (the 30-year mean for August was 3.5 days at the Fort McMurray airport). The AOSERP notes included a special remark stating that "absence of entries does not necessarily denote fog-free days", hence these figures represent the minimum number of fog incidents. The reports consist only of notations regarding the existence of fog and its general location (i.e., situated in valley, near town, or around refineries). In view of the lack of detailed supporting observations at the AOSERP Mildred Lake Research Facility, analysis of the warm fog cases is based primarily on the hourly weather observations at Fort McMurray Airport and the surface weather maps for August, September, and October 1977 and 1978.

5.1.1 Synoptic Weather Conditions

The warm fogs are associated with a variety of synoptic weather patterns; however, two weather types predominate. In the first type, the upper flow is from the north or northwest and at the surface a high pressure cell is present over northern Alberta. The light winds and clear skies of this weather pattern result in nocturnal cooling of the surface air. This can result in radiation fog if the air temperature drops to the dew point. Colder than normal temperatures associated with this circulation can lead to steam fog over the relatively warm Athabasca River. In the second common weather type, a cold low aloft is present on the Pacific coast and the upper flow is from the southwest over Alberta. Fog may occur with precipitation associated with weather disturbances moving across Alberta in this circulation. Radiation fog, perhaps augmented by evaporation from wet surfaces, may occur between disturbances.

5.1.2 Winds

Surface wind speeds were generally calm or light. The most frequent direction was southeast.

5.1.3 Temperature

Minimum temperatures were generally cooler than normal when fog was reported. In 82% of the cases examined, the temperature at Fort McMurray Airport was 6C^{o} or colder than the long-term mean river temperature below Fort McMurray.

5.1.4 Dewpoint

In 84% of the cases, the difference between the dewpoint and air temperatures was less than 0.9C^{o} at Fort McMurray airport. Valley fog was reported twice when the dewpoint spread at the airport was 3C^{o}. However, on both occasions the air temperature was much colder (about 11C^{o}) than the river temperature.

5.1.5 Diurnal Variation

The AOSERP fog records indicate that valley fog occurs in the early morning hours, but specific times and durations were not recorded. Valley fog was reported in the remarks column of the Fort McMurray hourly weather observations on five days in 1977 and 1978. It occurred in the period 0000 to 0900 MST.

5.1.6 Valley Fog

Longley and Janz (1978) indicate that evaporation from a warm water body is a contributing factor to fog in the study area. In the fall period, the river tends to remain warm relative to the air. Evaporation from the warm water forms vapour which recondenses when it meets colder air aloft, resulting in steam or "valley" fog.

In about one third of the cases examined, valley fog was observed near the AOSERP Research Facility, but was not reported at Fort McMurray airport. The occurrence of steam fog depends on both the temperature difference between river and air, and the relative humidity of the air. The lower the humidity, the greater the temperature difference which is required for steaming to occur. Saunders (1964) gives a nomogram to determine the critical temperature difference for different humidities. In Figure 6, this critical temperature difference is plotted together with observed temperature differences and humidities. In most cases the temperature difference between the air and the river water exceeded the critical value for steaming.

5.2 LOW TEMPERATURE FOG

Reports of ice fog should be regarded as a subjective interpretation by the observers. It is defined as "a suspension of numerous minute ice crystals in the air" (Government of Canada 1970) which limits visibility to 10 km or less.

During the winter of 1976-1977, which was warmer than normal, ice fog was reported by AOSERP observers on six days in January. No fog was observed in the other winter months. However, during the winter of 1977-1978, there were 17 days of ice fog as noted in the AOSERP climatological records and pilot sketches; eight in December, three days in January, three days in February, and three days in March. The 30-year mean for this four-month period was 2.9 days with fog at the Fort McMurray airport (Croft et al. 1977). During the winters of 1977 and 1978, Fort McMurray airport recorded ice fog only 12 of the 23 days that it was recorded near the AOSERP base camp. Within the period from the 5th to the 10th of December 1977, four of the six AOSERP fog days were confirmed at the airport. These figures suggest that fog (mainly ice fog in these cases) observations at the airport are not representative of conditions in the AOSERP project area. Water vapour is released by the refineries as well as from the tailings ponds and the Athabasca River when they remain unfrozen.

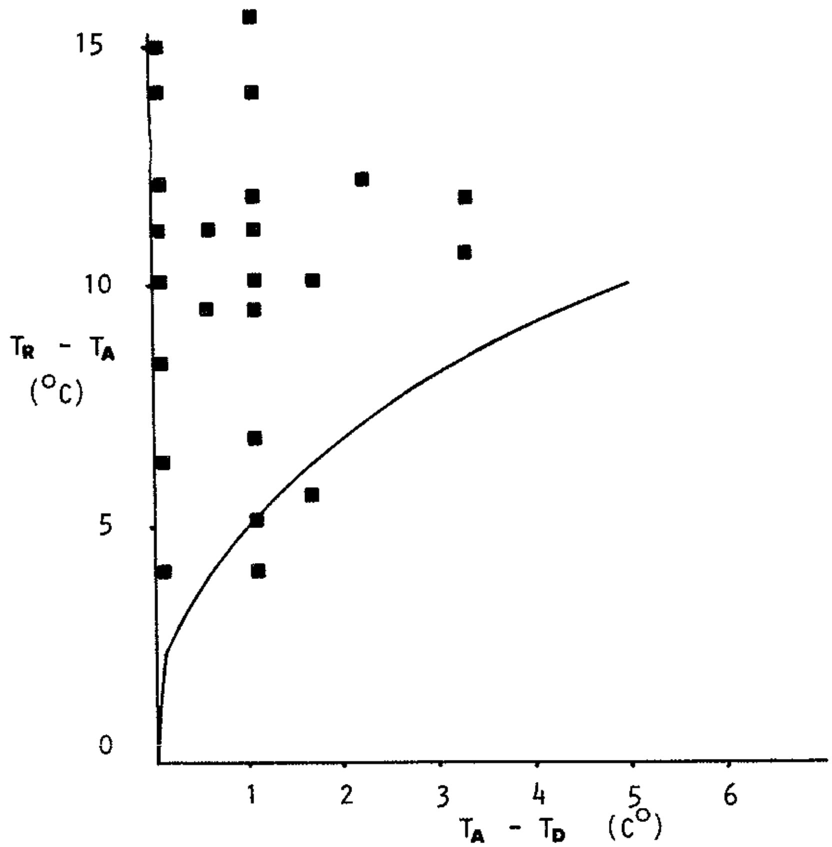


Figure 6. Occurrence of valley fog at Mildred Lake as a function of dewpoint spread and temperature difference between air (T_A) and river (T_R). Air and dewpoint (T_D) temperatures are from 0500 MST observations at Fort McMurray Airport. River temperatures are long-term averages for the Athabasca River below Fort McMurray for the years 1959-1975. The solid curve represents the critical conditions for the onset of steaming according to Saunders (1964).

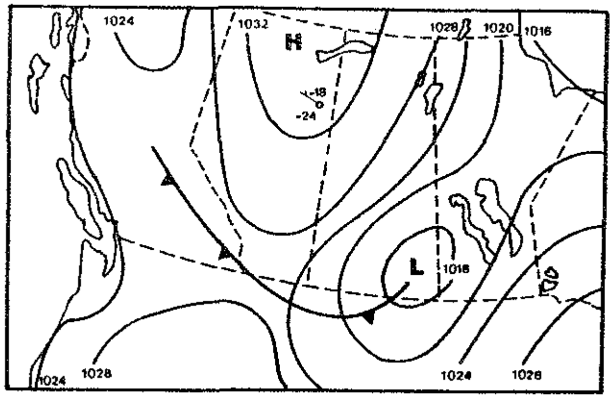
The temperature range, when ice fog was reported, extended to values as warm as -24.0°C on 20 December 1977. Ice fogs can occur when temperatures are as high as -20°C (Csanady and Wigley 1973).

Eight sets of low temperature and ice fog incidents were selected for a comparative meteorological study. These sets of fog events are shown in Table 1 along with the supportive data available for each case. Their selection was based on two criteria: (1) coincidence with the most intensive sets of observations; and (2) presence of persistent conditions favourable for fog formation. Two of the eight cases had fog occurring for five or more successive mornings while one other case had fog reported on two consecutive days.

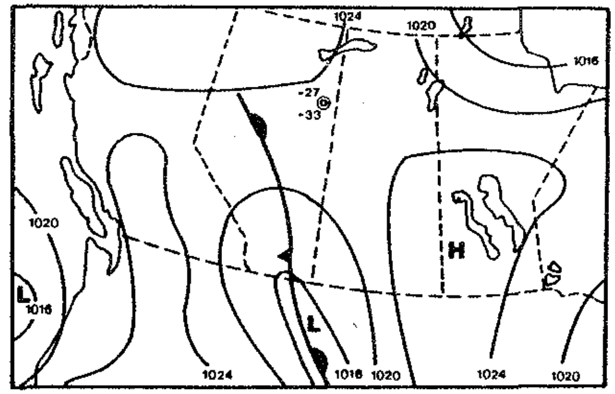
5.3 ICE FOG ON SUCCESSIVE MORNINGS

There are many features of the atmosphere which are common to all the fog incidents. The synoptic state of the atmosphere most conducive to extended periods of low temperature or ice fog is the appearance of a stationary or quasi-stationary Arctic front southwest of the AOSERP study area. Such a front developed over southern Alberta and British Columbia on 9 January 1977 and remained through to the 13th before dissipating. During this time, fog was reported by the AOSERP observers on successive mornings from the 9th to the 13th.

The northwest-southeast oriented front accompanied a ridge of high pressure over northern Alberta which produced light to calm surface winds and generally clear skies over the area. Figure 7 gives the surface weather patterns from the 9th to the 12th of January 1977. Examination of the upper air charts and radiosonde plots shows that strong cold air advection aloft occurs for one to two days prior to an ice fog incident as shown in Figure 8. A sharp increase in temperature aloft occurs near the end of the incident. The 0500 MST radiosonde flights from Stony Plain (Edmonton) and Fort Smith indicate both locations to be in the same Arctic



9 January 1977



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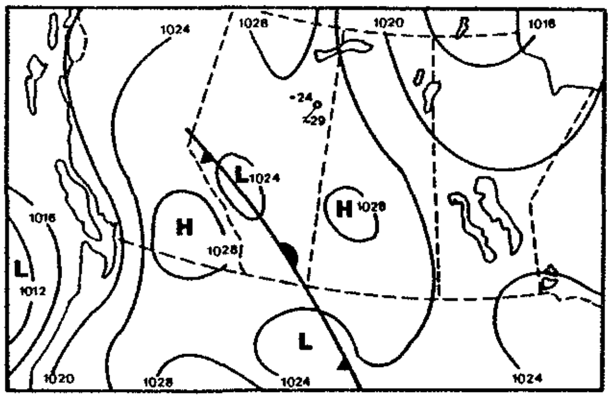

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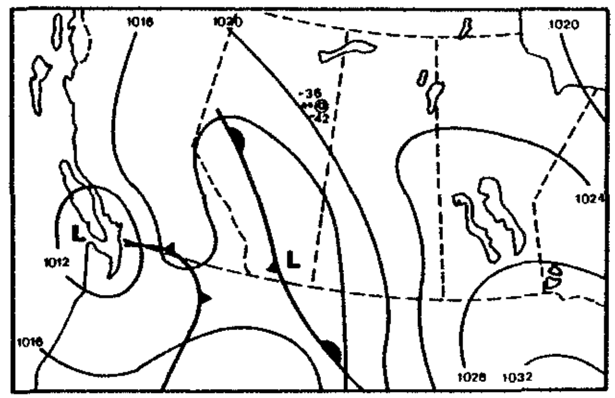

12 January 1977

Figure 7. Surface synoptic weather maps during fog events in January 1977. Time of the Maps is 0500 MST. The weather for Fort McMurray (YMM) at the time of observation is also plotted.

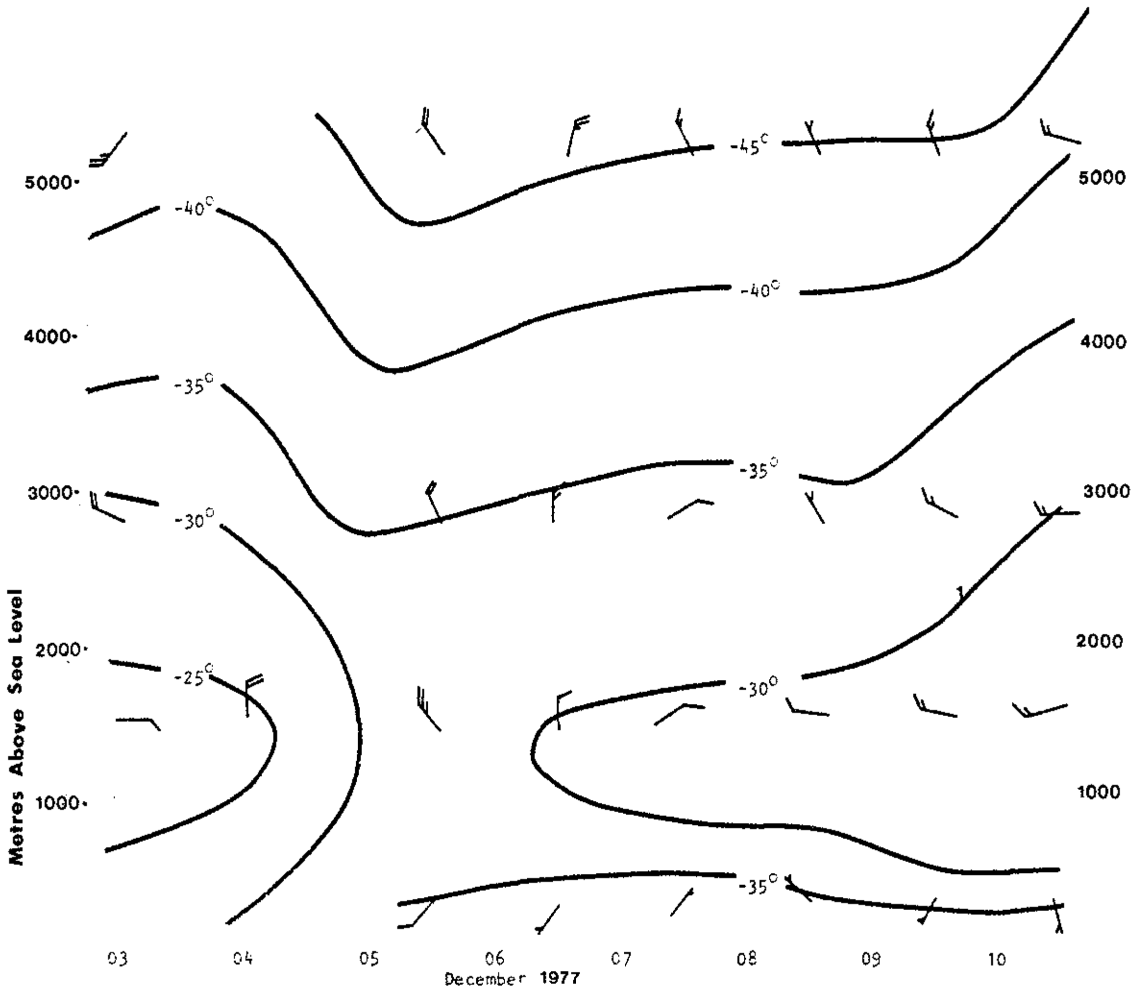

Figure 8. The variation of temperatures and winds aloft during the period 3 to 10 December 1977 at Fort Smith, Northwest Territories. Ice fog was observed in the AOSERP study area on the mornings of 5 to 10 December.

air mass with similar persistent ground based inversions throughout the lower troposphere. These findings are similar to the conclusions of Bowling et al. (1968) that the extreme cold which accompanies ice fog formation in Alaska invariably is preceded by cold air advection. Local radiation cooling is found to be important only in producing the observed steep ground inversions. This applies to low temperature and ice fog formation in the AOSERP study areas as well. The conditions for the January 1977 case created a favourable environment for the formation of ice crystals as the hourly weather observations at Fort McMurray and Fort Smith had reported.

The surface temperatures gradually dropped until the minimum temperature at Mildred Lake fell from a low of $-33.4^{\circ}C$ on the 9th of January to a minimum of $-41.7^{\circ}C$ on the 12th of January. Fog particles which formed at the beginning of this period would tend to be a mixture of supercooled water droplets and ice particles, as noted from flight observations, but solid ice forms were more prevalent with the lower temperatures.

The synoptic similarity is seen in comparing the surface weather maps from the 5th to the 8th of December 1977 (Figure 9). The same type of quasi-stationary front is much in evidence during this period, positioned along the Alberta-British Columbia border.

The surface temperatures at Mildred Lake ranged from $-38.0^{\circ}C$ on the 5th and dropped to a frigid minimum of $-43.5^{\circ}C$ on the 7th. Ice fog was noted each day of this period.

The detailed observations and aerial photographs taken during the January 1977 event show the development of each fog incident. On 9 January 1977, the onset of fog formation was at 0927 MST at the southeast end of Mildred Lake. As the temperature from Fort McMurray airport was $-33^{\circ}C$ (see Section 9), and the tower temperature ($^{T}1.5$) was $-36.1^{\circ}C$, the fog was likely to be in ice form. Initial descriptions gave the fog to be 10 m thick and deepening to a 30 m height at the Syncrude minisonde release site

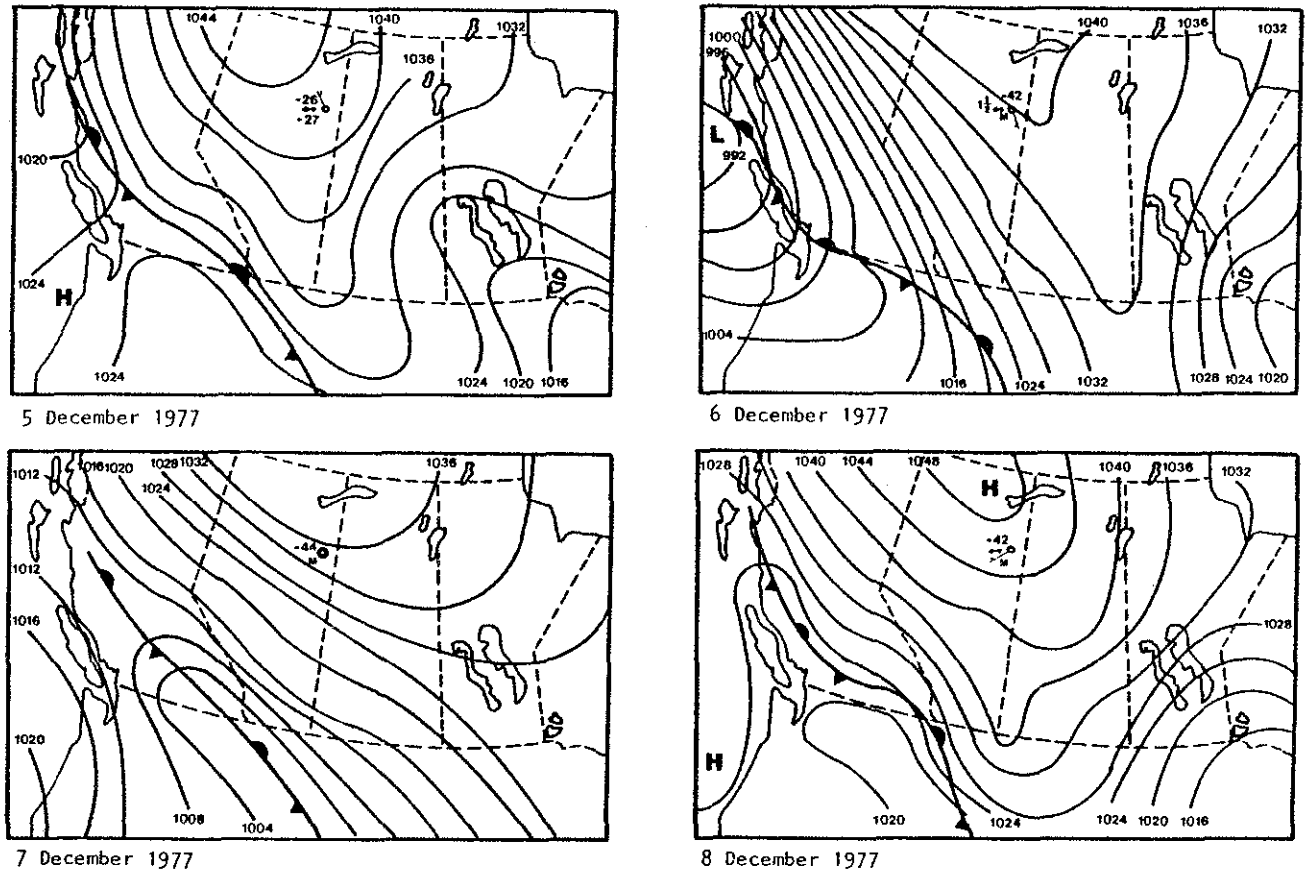

Figure 9. Surface synoptic weather maps during fog events in December 1977. Time of the maps is 0500 MST. The weather for Fort McMurray (YMM) at the time of observation is also plotted.

by 0940 MST. According to the observers located at the Syncrude minisonde release site, the fog was generated at the Syncrude lower camp, possibly by heating exhausts. Although the fog was thickening, the photographs show it not to be very dense. The overall density decreased as the fog passed northward along the Athabasca valley, but became deeper and denser as it spread southward toward the GCOS plant. By 1006 MST, visibility in the thin fog was estimated to be 0.5 km. Within the next half hour, ground observers reported the fog height to have increased to 60 m. This was confirmed from photographs which showed the top of the fog layer to extend to about a third of the way up the 183 m Syncrude stack. Fog was then seen to develop from the GCOS plant site as well and was observed on the road between the lower Syncrude camp and GCOS. The fog episode lasted until 1115 MST.

The hourly progression of the atmospheric thermal structure and stability during the morning of the 9th of January 1977 is seen in Figure 10, the vertical temperature profiles measured by the meteorological tower. At 0800 MST, just before the onset of the fog, the change in temperature with height over the lowest 30 m was calculated to be 7.6°C/100 m. The stability near the ground changed quickly as atmospheric mixing began to develop. (At 1200 MST, the lapse rate in the layer from 1.5 to 30 m had become isothermal.) By this time, the fog had dissipated because of turbulent downward mixing. The 1.5 m height temperature had increased to -28.8°C from a low of -36.6°C at 1000 MST. The development of turbulent mixing had produced a more uniform temperature distribution at 1200 MST. By 1500 MST, a temperature gradient of 0.2°C/100 m was recorded between the 1.5 m and the 152 m levels of the tower as mixing had become fully entrenched. Winds during the morning were light or calm at all three measurement levels. No wind was detected by the anemometer at the 10 m height from 0500 MST until noon when a light, 8 km/h breeze from the southeast developed.

A similar situation occurred on the next morning with the following reports. The temperatures at Mildred Lake ranged from a high of -23.6°C to a low of -31.1°C. The 1.5 m level tower

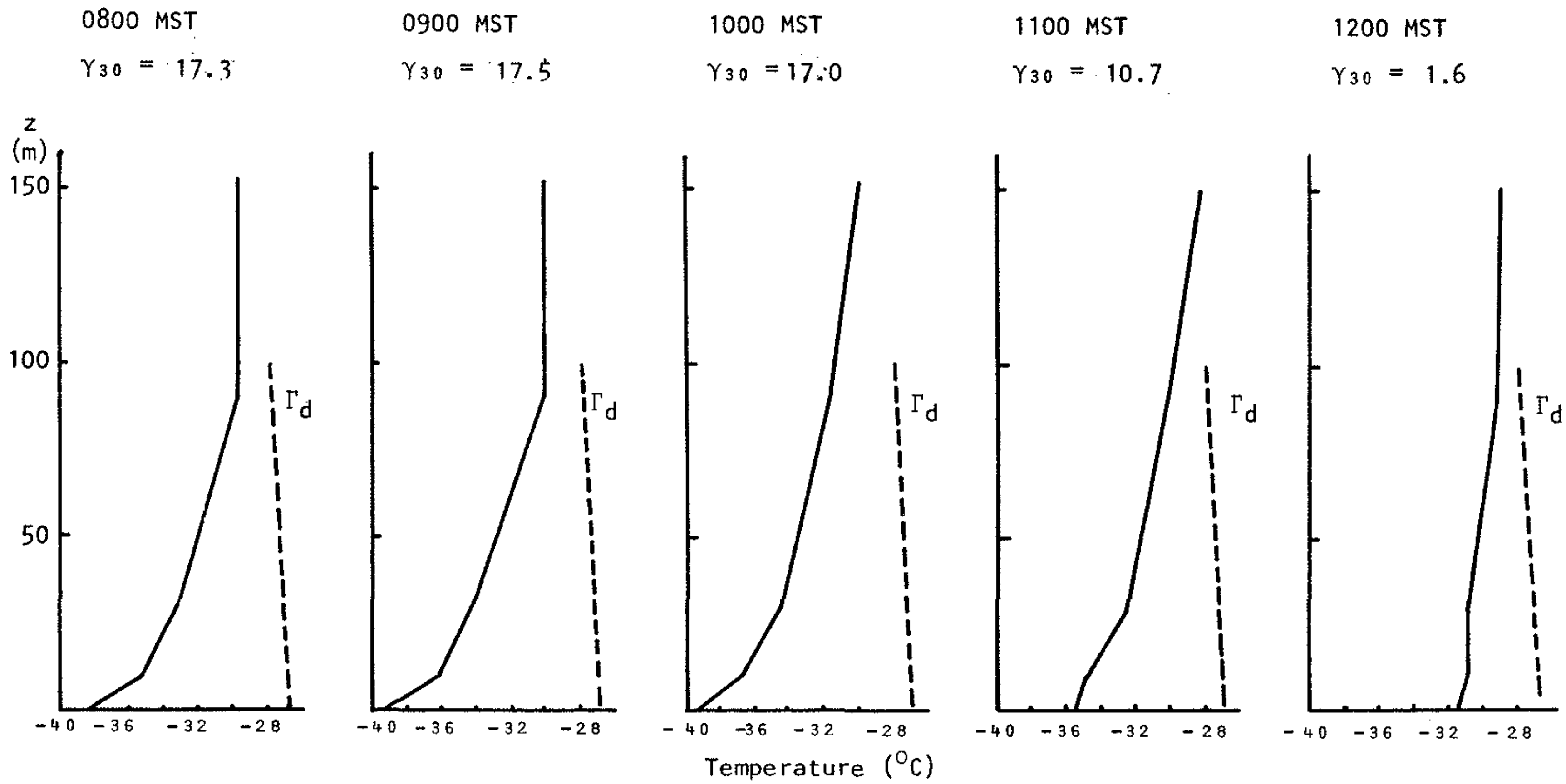

Figure 10. Hourly temperature profiles from data collected at the meteorological tower for 9 January 1977. γ_{30} is the temperature gradient from the 1.5 m to the 30 m level. Γ_d is the dry adiabatic lapse rate.

temperature at Lower Syncrude was -30.8°C to -32.2°C during the fog period. At Fort McMurray, skies were clear to broken during the day. Winds were calm. In contrast, near the Arctic front to the west, Fort St. John reported snow showers under overcast skies. The fog observations in the AOSERP project study area indicated very light fog forming at the GCOS mine site around 0900 MST. There were plumes from the stacks of the GCOS plant and light low level fog from the tailings pond drifting slowly southward along the river valley. Most of this fog dissipated within a few kilometres from the GCOS source. Some did move across the highway just north of the mine site. By 1014 MST, a thick fog of 100 m depth had developed around the Syncrude plant with visibility reduced to as low as 0.5 km. Evidence of fog formation from vehicular sources was seen in the photographs which show pockets of moisture from automobile and truck exhausts lingering along the roads. The high stability and low wind speed near ground level suggest that fog formed by the traffic could linger along the roads for a significant period of time.

Because of the range of temperatures observed daily, fog could be in liquid droplet form. Many of the pilot reports and sketches showed difficulty in discerning the difference between actual fog and the stack plumes spreading out from GCOS and Syncrude.

The AOSERP observations report fog occurring on the mornings of the 11th through to the 13th of January. Most of the fog incidents originate from the Syncrude or GCOS mine sites, forming around 0900 MST with an initial depth of 10 m, gradually thickening, then spreading and disappearing totally between 1100 to 1200 MST. The maximum depth ranges from 80 to 100 m and thins as the fog drifts away from the source. By the morning of the 12th, the minimum temperatures had dropped to -41.7°C and, as a result, the fog that had previously formed became solid ice particles rather than liquid droplets. At Fort McMurray, ice fog particles and temperatures ranging from -31°C to -41°C were reported from 0400 to 1100 MST.

The stability conditions shown in Figure 10 are characteristic of most of the mornings during this period. The highly stable lapse rates of the night and early morning gradually eroded to produce vertical mixing soon after sunrise. This pattern was repeated in all seven fog events studied.

The meteorological conditions described for the January 1977 incident are typical of the other fog incidents such as on several successive mornings from the 5th to the 10th of December 1977. This was true from the synoptic weather maps (see Figures 7 and 9) down to the microscale. A summary of the meteorological conditions during the January 1977 fog episodes are given in Section 9.

It is interesting to note the extremely stable conditions that the lower boundary layer can experience under the intense nocturnal radiative cooling conditions during the winter. The most stable temperature gradient found was $22.0^{\circ}C/100$ m in the lowest 30 m of the atmosphere at 0700 MST on 2 March 1978. The 1.5 m level temperature of the AOSERP tower registered $-32.3^{\circ}C$ and local fog was seen around Syncrude on that morning. However, by 0900 MST, the temperature had risen to $-27.5^{\circ}C$ and the temperature gradient had dropped to $-0.9^{\circ}C/100$ near the ground.

5.4 FOG-EMISSIONS INTERACTIONS

One of the prime concerns of this study is the possibility of the stack emissions from GCOS and Syncrude plants reacting with the fog (either water or ice) to produce potentially hazardous smog conditions. In order to evaluate the extent of this interaction, data from the SO_2 monitors in the project study area were examined. Monitoring is carried out mainly in the valley near the refineries. Figure 5 indicates the locations of the nine monitoring stations. The locations and designations of the SO_2 monitors are summarized in Table 2.

Table 4 in Section 9 contains a summary of 11 days of the fog observation cases studied in detail. The reports on these days are particularly valuable in that the times of fog observations are included. This permits a direct check of the SO_2 monitor values during the known fog events. These values, in parts per million (ppm), are listed for each half hour during the relevant hours of each observation day. With these factors in mind, it can be concluded that, during the highly stable conditions of the fog incidents, the elevated emissions of SO_2 do not mix down to ground level. The lifting of the fog in each case takes place after sunrise when turbulent mixing begins to develop. This is seen in the change of lapse rate near the ground during the mornings studied. Accompanying the change in the vertical temperature gradient and the fog dissipation is an increase in SO_2 concentration values.

One example of this is shown on 2 March 1978 (see Section 9). During the times of reported ice fog, the GCOS Mannix monitor (G2) registered zero. By 0830, the fog was no longer in evidence and the SO_2 monitor showed 0.01 ppm increasing to 0.02 ppm by 0900 as emissions aloft were brought down to ground level by inversion breakup. The monitor record showed a continued fumigation of the plume as SO_2 concentrations reached a maximum of 0.05 ppm at 1300 MST before returning to 0.0 ppm at 1600 MST. This pattern occurs in almost all of the 11 days summarized in Table 4 (Section 9).

A similar trend was observed for warm fogs. The average SO_2 concentrations at the GCOS monitors when warm fog was present are compared in Table 3 to the averages when it was absent. The fog is not associated with a significant increase in ground level SO_2 concentration. However, in the three-hour period after the fog dissipated, the concentrations are about 1.7 times higher than when fog was present.

Table 3. SO_2 concentrations during warm fogs for August, September, October 1977 and August 1978.

Monitor	G1 (ppb)	G2 (ppb)	G3 (ppb)	G4 (ppb)	G5 (ppb)
Fog	0.3	1.4	1.0	0.1	3.6
No Fog	1.7	0.8	0.4	0.4	4.6
Three-hour period after fog lifted	4.0	0.6	0.5	0.4	5.3

It can be concluded that, when fogs exist at the observation sites, the plume emissions have very little chance of interacting with the fog droplets or ice particles due to the high source of the emissions. It should be kept in mind that the Syncrude plant was not in operation yet during this time and any emissions are due to low level sources. However, with a 183 m stack, it would not be expected to add significantly to ground level SO_2 concentrations.

The dispersion conditions during each of the low temperature fog events are also included in Section 9. The winds at the 10 m and 90 m levels of the AOSERP tower were usually very light. Strong inversions are usually present from the 1.5 to the 152 m level (γ_{152}) during the fogs. Minisonde releases show a generally lower stability as the potential temperature gradients were not as steep as those calculated from the tower measurements. However, the balloon sensors were released from a point 69 m above the base of the tower site and the changes in potential temperature with height ($d\theta/dz$) were calculated as an average over the lowest 540 m rather than 1.5 to 152 m above ground.

5.5 AREAL EXTENT OF FOG

The observational program, on which this study was based, provides the first data on the extent of fog in the AOSERP project study area. Photographs were taken from aircraft during fog events on eight separate occasions during the winters of 1977 and 1978. Estimates of fog heights (i.e., highest vertical limits) and densities were made from the photographs. The most comprehensive evaluation of areal coverage was provided by pilot sketches of the fog with estimates of its vertical height above ground. Only three of these were drawn, and are reproduced in Figures 11, 12, and 13. All were done during the January 1977 fog episode. While there may have been difficulty in separating the refinery plumes from the fog, these sketches do provide an indication of where the fog was deepest.

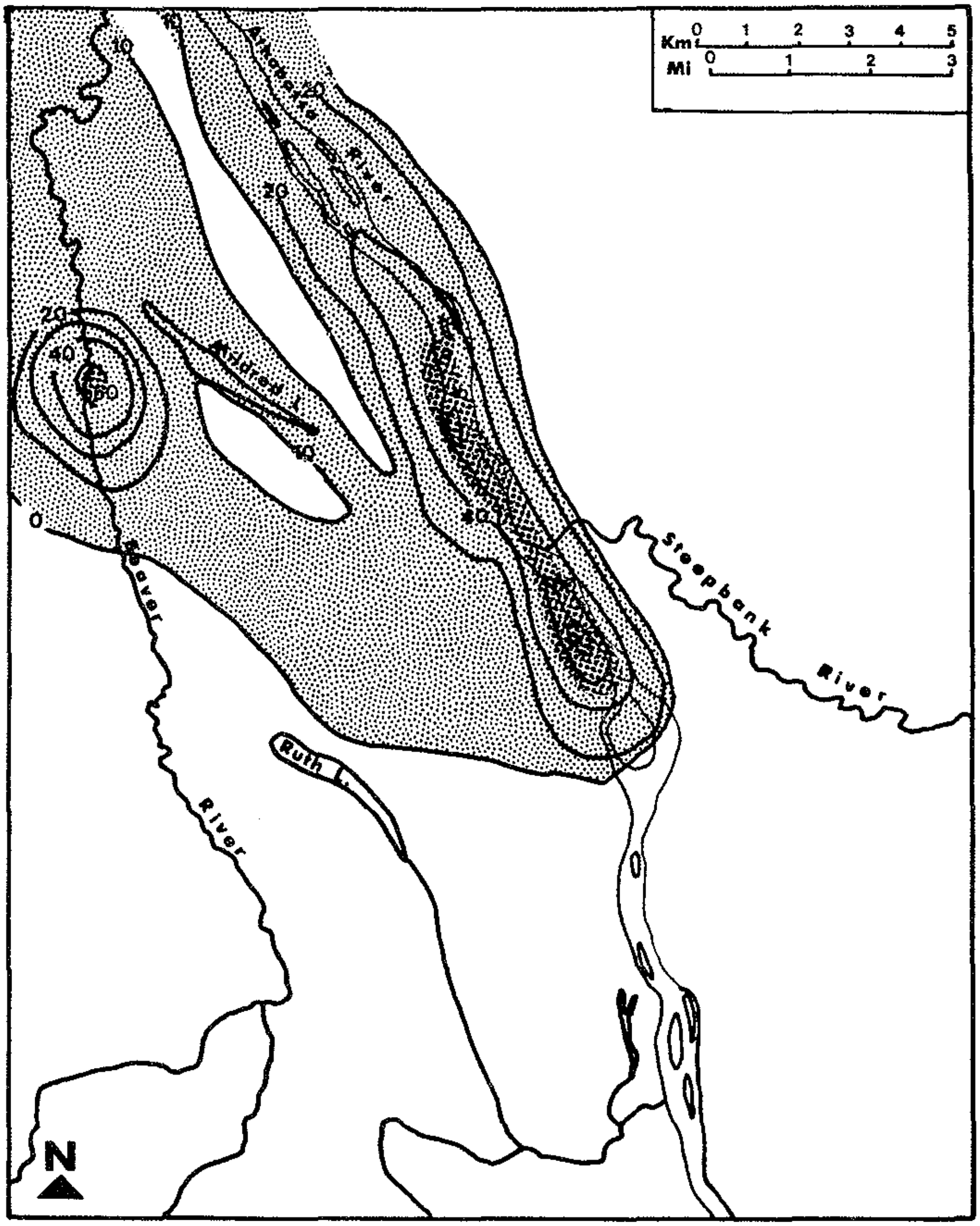

Figure 11. Estimated areal coverage of ground level fog during fog event of 9 January 1977. Information derived from sketches made by an aircraft observer. Light shading indicates fog depth of more than 10 m but less than 50 m. Heavy shading represents those areas estimated to have fog heights greater than 50 m.

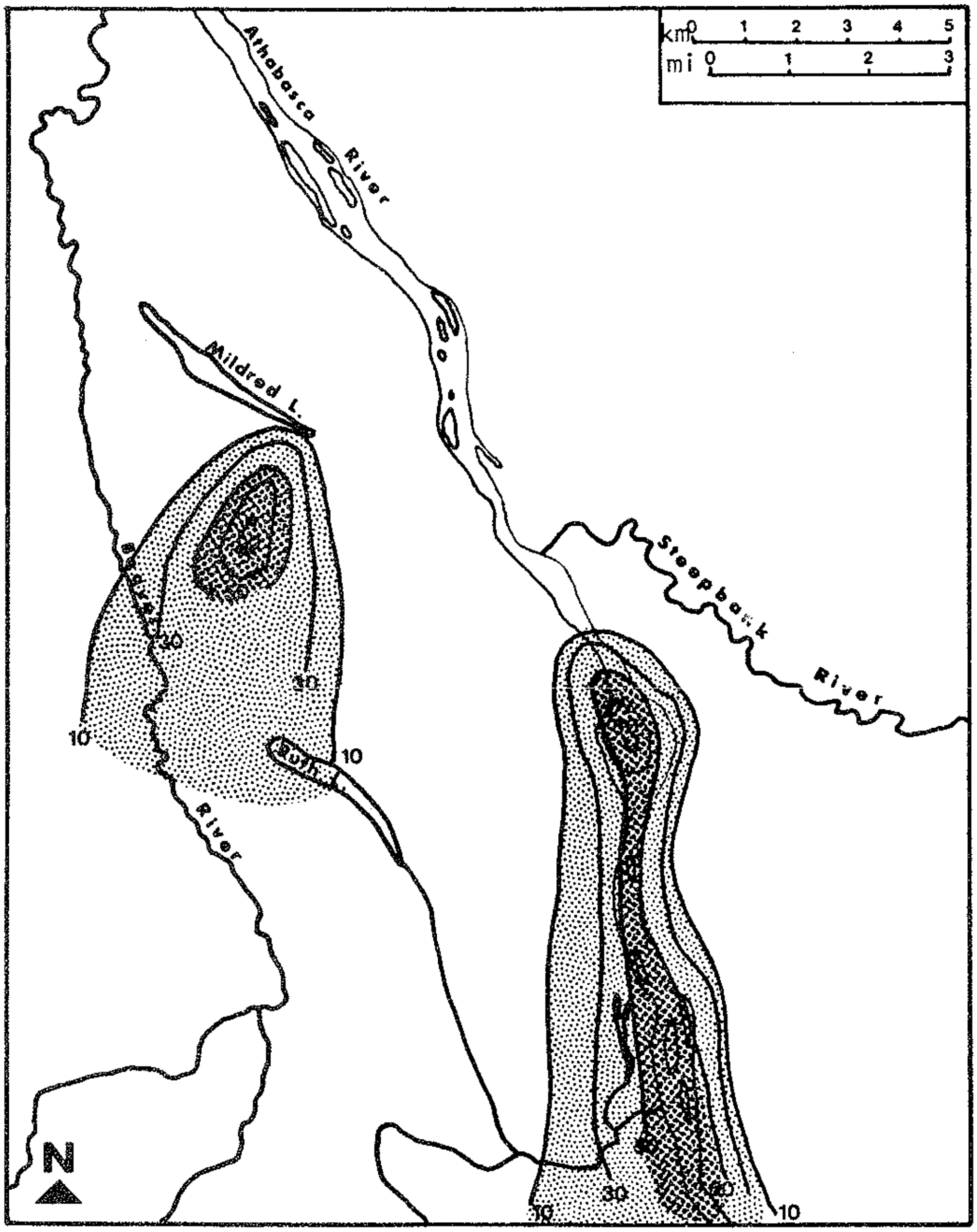

Figure 12. Estimated areal coverage of ground level fog during fog event of 10 January 1977. Information was derived from sketches made by an aircraft observer. Light shading indicates fog depth of more than 10 m but less than 50 m. Heavy shading represents those areas estimated to have fog heights greater than 50 m.

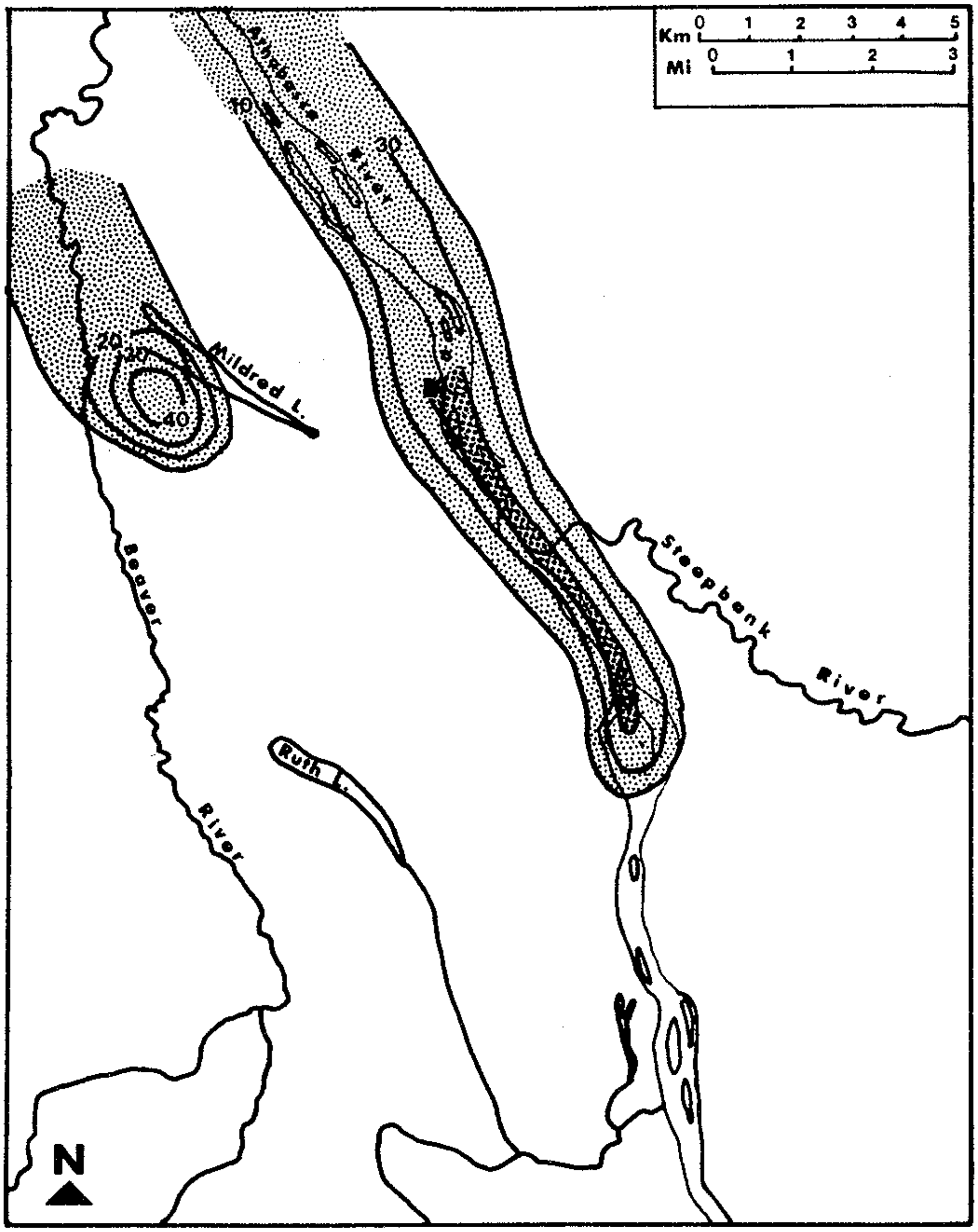

Figure 13. Estimated areal coverage of ground level fog during fog event of 12 January 1977. Information was derived from sketches made by an aircraft observer. Light shading indicates fog depth of more than 10 m but less than 50 m. Heavy shading represents those areas estimated to have fog heights greater than 50 m.

Two major sources of water vapour are indicated in these sketches: the GCOS and Syncrude refineries. As the Syncrude plant was not in full operation until August 1978, it can be safely assumed that the contours drawn represent fog heights rather than plume levels. The GCOS plant represents the larger source of moisture as it was operating at that time. The fog originating from GCOS was generally deeper than that from the Syncrude plant.

As shown in Figure 11, and confirmed by the photographs and written descriptions, the fog depth at the GCOS source may be as high as 100 m, but decreases rapidly as distance from the source increases. As noted on all three days, the fog thickness often decreases to 10 m at less than 2 km from where the depth is a maximum. This is true of fog originating from both plants. The actual location of the fog is controlled by the topographic features of the area. Fog originating from GCOS invariably follows the Athabasca River Valley. The 20 m depth contour of the fog sketches on all three days (Figures 11, 12, 13) follows very closely the 800 ft contour of the topographical survey map along both sides of the river. The 12 January 1977 sketch showed the GCOS fog to have dissipated to less than 10 m in depth after a 15 km drift downstream in a 15 km/h wind. If this is accepted as being representative, it is unlikely that low-level fog from the present sources could reach the town of Fort McMurray, 50 km to the south of the oil sands refineries. The fog events observed during this study all dissipated by noon with the increase in turbulent mixing. Hence, the fogs dissipate before they can drift as far as Fort McMurray.

Since the sketches shown in Figures 11, 12, and 13 are the first indicators of fog coverage in the AOSERP study area, it would be useful to derive quantitative measurements from the drawings to be used in numerical calculations.

The 9 January 1977 incident was the most widespread of the three surveyed. The area between the 10 and 20 m height contours of the GCOS fog covers 86 km^2 while the fog deeper than

20 m covers approximately 26 km^2. Benson (1970) developed a mass balance equation for growth (or dissipation) of ice fog depths based on moisture input and removal from the atmosphere. The fundamental equation is in the form of

$$I = PA + EA = \rho A \frac{dz}{dt} \qquad (1)$$

where, I = the rate of water input into the atmosphere,

P = the precipitation rate of ice crystals

A = area of fog coverage (assuming top and bottom area of fog is the same)

E = the evaporation rate for water in the air

ρ = the density of ice crystals in air

z = fog depth

and, $\frac{dz}{dt}$ = the rate of growth of fog

Thus, the rate of fog growth is dependent on the moisture input from the source, removal by way of precipitation from the bottom of the fog, and evaporation from the top. If the input rate is greater than the removal rate, then the fog deepens, whereas, if the reverse is true, then the fog dissipates. When the processes are at equilibrium, the rate of change of fog depth is zero. As the temperatures on 9 January 1977 during the hours of fog observation were near -39°C at lower Syncrude, it may be assumed that ice particles were formed to produce an ice fog on that day, although the observations did not explicitly specify the state of the fog particles. In that case, the Benson equation would apply.

For further refinement, each term of the right side of Equation (1) was further divided by Benson (ibid.) into two components. The fog was thought to have consisted of an inner case and an outer case with different values for each section. It would be unnecessary to use this refinement for the AOSERP fog because division of the core regions would be an artificial boundary. Benson's separation criteria were based on urban-rural differences in his sampling area.

The rate of total water input into the air by GCOS was given by Croft et al. (1977) as 1.5×10^5 $kg \cdot h^{-1}$. This is assumed to be a constant value during all the winter cases. The extent of the fog is assumed to be an area of 86 km^2 . Rearrangement of Equation (1) would provide an estimate of the evaporation rate for the dissipation of the fog as:

$$E = \frac{I}{A} - P - \rho \frac{dz}{dt} \qquad (2)$$

where $I = 1.5 \times 10^5$ $kg \cdot h^{-1}$

and $A = 86$ km^2.

Precipitation rates were not available for the AOSERP area although the observational records showed that attempts were made to collect ice crystals on plastic sheets due to gravitational fallout. It is necessary to assume mean values for P and ρ from measurements made by Kumai (1964) and Benson (1970). Although their values are for urban ice fogs, the AOSERP fogs are derived from comparable industrial sources. Benson gives an estimate for P of 1.79×10^{-4} g $H_2O \cdot cm^{-2} \cdot h^{-1}$ for the inner case. As the AOSERP fog occurred fairly close to the source, this value is used in our calculations. The density of ice crystals in the fog area varies with distance from the moisture sources, yielding a mean value of 0.11 $g \cdot m^{-3}$ based on Benson's density values for inner and outer fog case areas, and the relative fog thicknesses for the 9 January 1977 case. (Ice crystal density was 0.21 $g \cdot m^{-3}$ and 0.07 $g \cdot m^{-3}$ for the inner and outer regions, respectively.) A mean depth of 15 m over the 86 km^2 area was used. Since the fog observations began at 0900 MST on the 9th and no fog was recorded after 1130 MST, the total duration was in the order of 2.5 hours. This gives a mean dissipation rate $\left(\frac{dz}{dt}\right)$ of 6 $m \cdot h^{-1}$. Substitution of these values into Equation (1) gives an estimate for the mean evaporation value (E) of 6.1×10^{-5} g $H_2O \cdot cm^2 \cdot h^{-1}$. This compares quite favourably to the evaporation rates of 6.3×10^{-5} g $H_2O \cdot cm^{-2} \cdot h^{-1}$ found by Benson for the inner fog regions. This mean evaporation rate would be quite useful in any modelling process for fog formation in the AOSERP study area. Further refinements to these mean calculations would require actual measurements in the area during fog episodes.

6. CONCLUSIONS

The synoptic weather patterns are similar in each of the winter fog episodes. A quasi-stationary arctic front is 500 to 1000 km southwest of the AOSERP study area, oriented northwest to southeast. Cold air advection aloft generally precedes the ice fog incidents.

The growth and dissipation of the low temperature fogs follow a similar progression in each of the events. Fog usually forms before 0800 MST at the industrial complexes in the project study area. The winter fogs dissipate by noon local time.

The estimate of mean evaporation rate during an ice fog event shows good agreement with Benson's results for Fairbanks, Alaska.

Ground level sulphur dioxide concentrations (0.5 hour average) are very low, 0.04 ppm or less, during both warm and low temperature fog incidents. There is a tendency for the ground level concentrations to increase when the fog dissipates. This result confirms the conclusions of Croft et al. (1977) and Murray and Kurtz (1976) which were based on intuitive arguments about dispersion of elevated emissions under stable atmospheric conditions.

7. RECOMMENDATIONS

The results of the special observational efforts by AOSERP show clear differences between actual fog incidents in the oil sands area and the fog potential as estimated by extrapolating meteorological data from Fort McMurray airport. Preliminary indications (Croft et al. 1977) show that winter fogs can be much more frequent in the oil sands area than the Fort McMurray observations suggest.

The detailed special observations of the past two winters are very helpful in determining the synoptic and micrometeorological conditions under which fog formed. It is recommended that a more detailed observational program be implemented during the summer and fall seasons.

The ground observers should make a special effort to record the time of observations as part of the routine. This allows the extraction of meteorological and air quality data specific to the time of fog occurrences.

In addition, the visibility (km) should be recorded at each hour so that mist can be distinguished from fog. Observations or perhaps time lapse photography on a 24-hour basis would give a better description of the time of day at which fog is most likely to occur and to what extent.

The aircraft observations are helpful in delineating the areal coverage of the fog, particularly the pilot sketches, more so than simple photographic records. However, only high altitude photography gives an indication of fog density.

More extensive and detailed microphysical measurements should be attempted. This is important for an understanding of the physics involved and would give the detailed characteristics of the fog formation and dissipation process. Measurements of the actual fog particles as well as their form, density, and size distribution, for both liquid drops and ice crystals should be included. The collection of ice particles precipitated during an ice fog episode should be continued throughout the event. Measurement of a particle size distribution could be made either through replication (Mason 1971), light extinction techniques (Knollenburg 1970) or in microphotography. The results from these measurements could be used in calculations of the total water or ice mass in the fog and the rate of fog development.

If solar radiation measurements and surface turbulent flux values for water vapour sources were available, a theoretical fog model could be developed and compared with field measurements. Such a model would be useful for the evaluation of future fog potential in the area as further industrial and urban development proceeds. Because of the importance of local topographic effects, the predictive qualities of such a model would be more meaningful than a climatological assessment based on observations from far afield.

Once the fog can be modelled, then the pollution-fog interactions can also be evaluated in terms of possible chemical reactions between the pollutants and the fog particles. These calculations should be performed concurrent with field programs designed to provide information on the chemical characteristics of the fog particles.

The observations recorded thus far have been concentrated in the oil sands area. Of equally pressing concern are the effects of fog in the town of Fort McMurray. Fine-scale observations in the town should be taken during fog episodes, both in the horizontal and vertical directions in terms of the temperature structure and fog density. For example, what effect, if any, does the town's heat island have on the turbulence characteristics of the immediate surface boundary layer and how does this effect the fog structure and potential.

In summary, the concern for the effects that fog resulting from human activity in the AOSERP (including Fort McMurray) study area would have on the quality of life as it applies to human, wildlife, and vegetative processes has produced the stimulus for fog research. The present networks for meteorological and air quality measurements provide a good data base for analysis. However, it was found in this study that there is still an inadequate data base to model the evolution of winter fog. The special AOSERP observations should be increased in detail and duration and supplemented with microphysical measurements to undertake a thorough study of fog in the area.

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9. APPENDIX

9.1 SUMMARY OF WINTER FOG OBSERVATIONS

This section contains a summary of meteorological and emissions data, which were collected during two winter field studies. Included are surface temperatures, temperature and wind vertical profiles, subjective fog observations, and ground level measurements of SO_2 concentrations for the field studies conducted in January 1977 and January and February 1978.

Table 4. Summary of meteorological and emmissions data during timed fog observations.

Time[a] (MST)	T_{YMM}[b] (°C)	T_G[c] (°C)	$T_{1.5}$[c] (°C)	SO_2 Concentration[d] (ppm)	Tower Winds[e] 10 m	Tower Winds[e] 90 m	Tower Winds[e] 152 m	Temperature Gradient[f] Minisonde $d\theta/\partial z$	Temperature Gradient[f] Tower Y152	AOSERP Fog Reports[g]
9 January 1977				G5						
0900	-33	--	-39.2	0.0	000/00	000/00	000/00	--	6.2	(0927) 1.5 km visibility in 10 m deep fog at Mildred Lake growing 10 to 30 m at Syncrude Lower Camp.
1000	-33	--	-39.2	0.0	000/00	000/00	210/03	--	6.2	(1006) Fog of 10 m depth from GCOS spreading over Hwy 63.
1030										(1030) Fog from GCOS extends all the way to Mildred Lake. Fog at Syncrude plant site is 60 m deep - verified by photos relative to stock.
1100	-31	--	-35.7	0.01	000/00	170/07	190/10	--	4.9	(1115) Fog from Syncrude Plant site (machinery) extends past tailings pond.
1130				0.02						
1200	-28	--	-31.7	0.01	150/08	150/07	180/13		1.8	
10 January 1977										
0800	-33	--	-32.1		000/00	000/00	290/10	--	0.7	(0853) This fog at Syncrude.
0900	-32	--	-32.3		000/00	000/00	320/12	--	0.9	(0920) Light fog from GCOS mine site drifting over highway to Supertest Hill.

continued ...

Table 4. Continued.

Time[a] (MST)	T_{YMM}[b] (°C)	T_G[c] (°C)	$T_{1.5}$[c] (°C)	SO_2 Concentration[d] (ppm)	Tower Winds[e] 10 m	90 m	152 m	Temperature Gradient[f] Minisonde dθ/θz	Tower γ152	AOSERP Fog Reports[g]
10 January 1977										
1000	-30	00	-32.3		000/00	000/00	310/13	--	1.8	
1100	-31	00	-31.7		000/00	000/00	320/12	--	1.6	(1014) 0.5 km visibility in thick 100 m fog at Syncrude plant site.
1200	-28	--	-30.8		150/7	000/00	300/7		1.9	
11 January 1977										
0800	-33	--	-40.8		000/00	150/8	000/0	--	7.2	(0900) 10 m fog developing around Syncrude plant site.
0900	-34	--	-41.1		000/00	000/00	250/10	--	7.0	
1000	-35	--	-40.6		150/3	150/11	230/5	--	6.7	
1100	-34		-38.5		170/6	150/11	000/00	--	5.3	
12 January 1977										
0800	-33	--	-37.2		150/14	180/10	150/14	--	3.1	
0900	-40	--	-37.6		150/14	180/13	150/18	--	3.5	
1000	-39	--	-37.4		150/14	160/14	150/22	--	4.1	
1100	-38	00	-36.2		150/14	170/12	160/22	--	3.8	(1100) fog from GCOS 80 to 100 m deep and moving north along valley.
1200	-37	--	-34.5		150/13	150/12	160/16	--	2.6	Fog dissipating by 1130.

continued ...

Table 4. Continued.

Time[a] (MST)	T_{YMM}[b] (°C)	T_G[c] (°C)	$T_{1.5}$[c] (°C)	SO_2 Concentration[d] (ppm)		Tower Winds[e] 10 m	90 m	152 m	Temperature Gradient[f] Minisonde dθ/θz	Tower Y152	AOSERP Fog Reports[g]
<u>18 January 1977</u>				S2							
0800	-38	-32.1	--	0.01		150/11	150/11	160/22	2.5	---	(1015-1045) Thin fog over town spreading into valley.
0900	-38	--	--	0.01		140/14	170/16	160/26	--	---	No ice fog at AOSERP camp.
1000	-36	-31.1	--			150/16	180/14	150/26	2.6	---	
1100	-34	--	--			160/11	170/10	170/21	--	---	
1200	-33	-25.2	-31.4			150/14	150/14	160/22	1.6	3.06	
<u>31 January 1977</u>				*S3	*S5						
0700	-35	--	-36.5	0.02	--	000/00	180/02	320/03	--	5.5	(0700) Thin ice fog (IF) over town.
				0.02							(0730-0800) IF particles over highway south of Supertest hill.
0800	-34	--	-37.0	0.02	--	000/00	280/02	270/11	1.1	5.8	
0900	-34	--	-38.2	0.02	0.02	150/05	230/05	270/11	--	6.0	
				0.02	0.02						
1000	-33	-29.8	-34.9	0.02	0.02	150/10	200/06	250/13	0.3	3.9	
				0.02	0.02						

continued ...

Table 4. Continued.

Time[a] (MST)	T_{YMM}[b] (°C)	T_G[c] (°C)	$T_{1.5}$[c] (°C)	SO_2 Concentration[d] (ppm)		Tower Winds[e] 10 m	90 m	152 m	Temperature Gradient[f] Minisonde dθ/θz	Tower Y152	AOSERP Fog Reports[g]
31 January 1978											
1100	-31	--	-31.6	0.02	0.02	150/10	160/08	250/11	--	2.9	(1100) Thin local IF over Syncrude and GCOS.
				0.02	0.02						
1200	-26	-23.7	-28.8	0.02	0.02	160/13	140/08	250/08	-0.3	2.0	(1200) Local IF lifting.
2 February 1978				*S3	*S5						
0700	-31	00	-30.8	0.04	0.02	160/11	150/08	170/16	--	3.8	
				0.04	0.02						
0800	-29	-30.1	-30.9	0.04	0.02	140/11	170/13	160/19	3.1	4.1	(0830-0900) Very thin IF layer to 33 m from low level sources at Syncrude. Thin IF patches 3 km south of Supertest.
				0.04	0.02						
0900	-30	--	-30.8	0.04	0.02	160/11	150/08	150/14	--	3.4	
25 February 1978				*S3	*S5						
0000	-27	--	-28.2	0.02	0.01	000/00	160/08	180/16	--	6.1	(0000) IF fog particles over highway between town & camp.
				0.02	0.01						
0100	-28	--	-29.6	0.01	0.01	000/00	180/08	190/16	--	6.2	
				0.01	0.01						
0200	-28	--	-29.9	0.01	0.01	180/02	160/13	200/10	--	6.1	

continued ...

Table 4. Continued.

Time[a] (MST)	T_{YMM}[b] (°C)	T_G[c] (°C)	$T_{1.5}$[c] (°C)	SO_2 Concentration[d] (ppm)		Tower Winds[e]			Temperature Gradient[f]		AOSERP Fog Reports[g]
						10 m	90 m	152 m	Minisonde dθ/θz	Tower γ152	
25 February 1978				*S3	*S5						
0300	-30	--	-27.4	--	0.01	160/08	150/14	160/19	--	4.5	
				0.01	0.01						
0400	-30	--	-27.9	0.02	0.01	160/10	160/14	170/24	--	3.7	
				0.02	--						
0500	-29	--	-28.0	--	--	160/06	150/14	160/18	--	4.3	
				--	0.0						
0600	-29	--	-27.8	--	0.0	150/13	160/13	160/26	--	3.7	
				--	0.0						
0700	-29	--	-28.1	--	0.0	160/13	160/16	170/24	--	4.2	(0730) Thin IF particles at Supertest and south.
0800	-29	-30.5	-28.3	--	--	150/13	150/13	160/18	2.9	4.1	
0900	-28		-27.5	--	--	150/16	160/10	160/24	--	4.3	IF particles just north of AOSERP camp crossing McKay Rd.
1000	-24	--	-25.4	--	--	150/13	160/10	170/19		4.7	

continued ...

Table 4. Continued.

Time[a] (MST)	T_{YMM}[b] (°C)	T_G[c] (°C)	$T_{1.5}$[c] (°C)	SO_2 Concentration[d] (ppm)	Tower Winds[e] 10 m	90 m	152 m	Temperature Gradient[f] Minisonde $d\theta/\theta z$	Tower Y152	AOSERP Fog Reports[g]
27 February 1978				*S2						
0700	-25	--	-27.1	0.02 0.02	000/00	160/12	160/13	--	6.2	(0730) Thin local IF around GCOS.
0800	-25	-25.7	-26.5	0.02 0.02	170/02	170/07	160/14	2.7	5.5	(0800) Thin local IF around Syncrude, to north crossing McKay Rd., and just north of AOSERP Camp.
0900	-22	--	-22.9	--	160/12	140/10	170/16	--	3.9	
2 March 1978										
0700	-31	--	-32.3		360/05	340/12	020/13	--	3.8	(0745) Local IF around GCOS.
0800	-31	-29.5	-32.1	0.01	340/02	350/12	020/16	-1.4	3.6	(0815) Local IF around Syncrude.
0900	-29	--	-27.5	0.02	310/03	340/14	010/14	--	0.7	
3 March 1978										
0700	-31	--	-29.6		170/08	140/13	170/16	--	4.0	(0715) Thin IF lower townsite. (0715-0730) Thin IF particles over Supertest highway.
0800	-28	-28.2	-29.4		150/13	160/16	170/22	1.89	4.8	(0745) IF from GCOS to Lower Syncrude along valley.
0900	-29	--	-27.5		150/13	140/12	170/14	--	3.1	(0800) Local IF around Syncrude, all fog beginning to lift.

Continued ...

Table 4. Concluded.

[a]TIME (MST)	Time of fog reports according to AOSERP observers.
[b]GROUND	T_{YMM} = SA temperature at Fort McMurray airport (YMM)
[c]TEMPERATURES	T_G = Minisonde release site (Mildred Lake)
	$T_{1.5}$ = 1.5 m level of AOSERP tower (Lower Syncrude)
[d]SO_2 CONCENTRATION	Concentration of SO_2 values in ppm as monitored by Syncrude (S1-S5) and GCOS (G1-G5) network. Only monitors reading above 0.01 level are shown. Asterisk (*) values indicate measurements recorded after instrument had drifted from 0.0 to the tabulated value.
[e]TOWER WINDS	Winds from 10 m, 90 m and 152 m level of meteorological tower. (DDD/vv = DDD is wind direction to nearest 10 degrees; vv is wind speed in km/h).
[f]VERTICAL TEMPERATURE GRADIENT	$\frac{\delta\theta}{\delta z}$ = average potential temperature change (^{o}C/100 m) from ground to 540 m as measured by minisondes at the AOSERP base camp (Mildred Lake).
	γ_{152} = average temperature change (^{o}C/100 m) from 1.5 m level to 152 m level at AOSERP at Lower Syncrude.
[g]AOSERP FOG REPORTS	Synopsis of written comments of special AOSERP ground and aircraft observers. Time of observations is in brackets. The abbreviation "IF" is used for ice fog.

AOSERP RESEARCH 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 a Traditional Baseline Data System
4.	VE 2.2	A Preliminary Vegetation Survey of the Alberta Oil Sands Environmental Research Program Study Area
5.	HY 3.1	The Evaluation of Wastewaters from an Oil Sand Extraction Plant
6.		Housing for the North--The Stackwall System
7.	AF 3.1.1	A Synopsis of the Physical and Biological Limnology and Fisheries Programs whithin the Alberta Oil Sands Area
8.	AF 1.2.1	The Impact of Saline Waters upon Freshwater Biota (A Literature Review and Bibliography)
9.	ME 3.3	Preliminary Investigations 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 Area
11.	AF 2.2.1	Life Cycles of Some Common Aquatic Insects of the Athabasca River, Alberta
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, March 1976
14.		
15.	ME 3.4	A 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	Interim Compilation of Stream Gauging Data to December 1976 for the Alberta Oil Sands Environmental Research Program
19.	ME 4.1	Calculations of Annual Averaged Sulphur Dioxide Concentrations at Ground Level in the AOSERP Study Area
20.	HY 3.1.1	Characterization of Organic Constituents in Waters and Wastewaters of the Athabasca Oil Sands Mining Area
21.		AOSERP Second Annual Report, 1976-77
22.		Alberta Oil Sands Environmental Research Program Interim Report to 1978 covering the period April 1975 to November 1978
23.	AF 1.1.2	Acute Lethality of Mine Depressurization Water on Trout Perch and Rainbow Trout
24.	ME 1.5.2	Air System Winter Field Study in the AOSERP Study Area, February 1977.
25.	ME 3.5.1	Review of Pollutant Transformation Processes Relevant to the Alberta Oil Sands Area

26. AF 4.5.1 Interim Report on an Intensive Study of the Fish Fauna of the Muskeg River Watershed of Northeastern Alberta
27. ME 1.5.1 Meteorology and Air Quality Winter Field Study in the AOSERP Study Area, March 1976
28. VE 2.1 Interim Report on a Soils Inventory in the Athabasca Oil Sands Area
29. ME 2.2 An Inventory System for Atmospheric Emissions in the AOSERP Study Area
30. ME 2.1 Ambient Air Quality in the AOSERP Study Area, 1977
31. VE 2.3 Ecological Habitat Mapping of the AOSERP Study Area: Phase I
32. AOSERP Third Annual Report, 1977-78
33. TF 1.2 Relationships Between Habitats, Forages, and Carrying Capacity of Moose Range in northern Alberta. Part I: Moose Preferences for Habitat Strata and Forages.
34. HY 2.4 Heavy Metals in Bottom Sediments of the Mainstem Athabasca River System in the AOSERP Study Area
35. AF 4.9.1 The Effects of Sedimentation on the Aquatic Biota
36. AF 4.8.1 Fall Fisheries Investigations in the Athabasca and Clearwater Rivers Upstream of Fort McMurray: Volume I
37. HE 2.2.2 Community Studies: Fort McMurray, Anzac, Fort MacKay
38. VE 7.1.1 Techniques for the Control of Small Mammals: A Review
39. ME 1.0 The Climatology of the Alberta Oil Sands Environmental Research Program Study Area
40. WS 3.3 Mixing Characteristics of the Athabasca River below Fort McMurray - Winter Conditions
41. AF 3.5.1 Acute and Chronic Toxicity of Vanadium to Fish
42. TF 1.1.4 Analysis of Fur Production Records for Registered Traplines in the AOSERP Study Area, 1970-75
43. TF 6.1 A Socioeconomic Evaluation of the Recreational Fish and Wildlife Resources in Alberta, with Particular Reference to the AOSERP Study Area. Volume I: Summary and Conclusions
44. VE 3.1 Interim Report on Symptomology and Threshold Levels of Air Pollutant Injury to Vegetation, 1975 to 1978
45. VE 3.3 Interim Report on Physiology and Mechanisms of Air-Borne Pollutant Injury to Vegetation, 1975 to 1978
46. VE 3.4 Interim Report on Ecological Benchmarking and Biomonitoring for Detection of Air-Borne Pollutant Effects on Vegetation and Soils, 1975 to 1978.
47. TF 1.1.1 A Visibility Bias Model for Aerial Surveys for Moose on the AOSERP Study Area
48. HG 1.1 Interim Report on a Hydrogeological Investigation of the Muskeg River Basin, Alberta
49. WS 1.3.3 The Ecology of Macrobenthic Invertebrate Communities in Hartley Creek, Northeastern Alberta
50. ME 3.6 Literature Review on Pollution Deposition Processes
51. HY 1.3 Interim Compilation of 1976 Suspended Sediment Date in the AOSERP Study Area
52. ME 2.3.2 Plume Dispersion Measurements from an Oil Sands Extraction Plan, June 1977

53.	HY 3.1.2	Baseline States of Organic Constituents in the Athabasca River System Upstream of Fort McMurray
54.	WS 2.3	A Preliminary Study of Chemical and Microbial Characteristics of the Athabasca River in the Athabasca Oil Sands Area of Northeastern Alberta
55.	HY 2.6	Microbial Populations in the Athabasca River
56.	AF 3.2.1	The Acute Toxicity of Saline Groundwater and of Vanadium to Fish and Aquatic Invertebrates
57.	LS 2.3.1	Ecological Habitat Mapping of the AOSERP Study Area (Supplement): Phase I
58.	AF 2.0.2	Interim Report on Ecological Studies on the Lower Trophic Levels of Muskeg Rivers Within the Alberta Oil Sands Environmental Research Program Study Area
59.	TF 3.1	Semi-Aquatic Mammals: Annotated Bibliography
60.	WS 1.1.1	Synthesis of Surface Water Hydrology
61.	AF 4.5.2	An Intensive Study of the Fish Fauna of the Steepbank River Watershed of Northeastern Alberta
62.	TF 5.1	Amphibians and Reptiles in the AOSERP Study Area
63.	ME 3.8.3	Calculate Sigma Data for the Alberta Oil Sands Environmental Research Program Study Area.
64.	LS 21.6.1	A Review of the Baseline Data Relevant to the Impacts of Oil Sands Development on Large Mammals in the AOSERP Study Area
65.	LS 21.6.2	A Review of the Baseline Data Relevant to the Impacts of Oil Sands Development on Black Bears in the AOSERP Study Area
66.	AS 4.3.2	An Assessment of the Models LIRAQ and ADPIC for Application to the Athabasca Oil Sands Area
67.	WS 1.3.2	Aquatic Biological Investigations of the Muskeg River Watershed
68.	AS 1.5.3 AS 3.5.2	Air System Summer Field Study in the AOSERP Study Area, June 1977
69.	HS 40.1	Native Employment Patterns in Alberta's Athabasca Oil Sands Region
70.	LS 28.1.2	An Interim Report on the Insectivorous Animals in the AOSERP Study Area
71.	HY 2.2	Lake Acidification Potential in the Alberta Oil Sands Environmental Research Program Study Area
72.	LS 7.1.2	The Ecology of Five Major Species of Small Mammals in the AOSERP Study Area: A Review
73.	LS 23.2	Distribution, Abundance and Habitat Associations of Beavers, Muskrats, Mink and River Otters in the AOSERP Study Area, Northeastern Alberta
74.	AS 4.5	Air Quality Modelling and User Needs
75.	WS 1.3.4	Interim report on a comparative study of benthic algal primary productivity in the AOSERP study area

76. AF 4.5.1 An Intensive Study of the Fish Fauna of the Muskeg River Watershed of Northeastern Alberta
77. HS 20.1 Overview of Local Economic Development in the Athabasca Oil Sands Region Since 1961.
78. LS 22.1.1 Habitat Relationships and Management of Terrestrial Birds in Northeastern Alberta.
79. AF 3.6.1 The Multiple Toxicity of Vanadium, Nickel, and Phenol to Fish.
80. LS 22.3.1 Biology and Management of Peregrin Falcons (*Falco peregrinus anatum*) in Northeastern Alberta.
81. LS 22.1.2 Species Distribution and Habitat Relationships of Waterfowl in Northeastern Alberta.
82. LS 22.2 Breeding Distribution and Behaviour of the White Pelican in the Athabasca Oil Sands Area.
83. LS 22.2 The Distribution, Foraging Behaviour, and Allied Activities of the White Pelican in the Athabasca Oil Sands Area.
84. WS 1.6.1 Investigations of the Spring Spawning Fish Populations in the Athabasca and Clearwater Rivers Upstream from Fort McMurray; Volume I.
85. HY 2.5 An Intensive Surface Water Quality Study of the Muskeg River Watershed. Volume I: Water Chemistry.
86. AS 3.7 An Observational Study of Fog in the AOSERP Study Area.

These reports are not available upon request. For further information about availability and location of depositories, please contact:

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