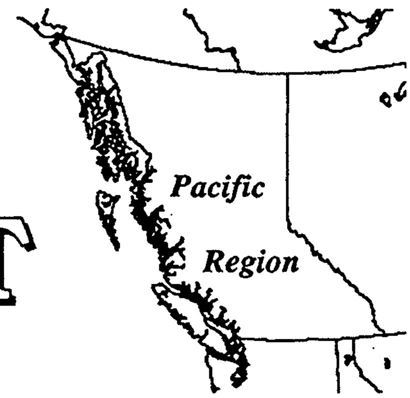
SCIENTIFIC SERVICES DIVISION

REPORT



STATISTICAL LRTAP MODELS FOR WESTERN CANADA

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August 15, 1990
Report PAES-90-6

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ABSTRACT

The Western and Northern LRTAP Technical Committee (WNCLTC) formed a mesoscale modelling task group to review three scales of air pollution models. As a result of this review, it was recommended that three statistical LRTAP models; Fisher (SERTAD), Regional Climatological Dispersion Model (RCDM) and Ontario Ministry of Environment Statistical Model (MOE), be considered for application in western Canada.

The three LRTAP statistical models were installed on a mainframe computer. An input database required to run the models was developed with particular attention paid to the geographic and atmospheric conditions in western and northern Canada. Each of the three models was then executed using these input data to test the installation of the models and to ascertain the need for further development of the input database.

All three models predicted similar patterns for the concentration of sulphur dioxide over the Prairies. Concentrations predicted by the RCDM were considerably lower than values from the Fisher or MOE models, particularly in the vicinity of major point sources. The pattern of wet deposition of sulphur predicted by the Fisher (SERTAD) model and the RCDM was similar. The highest maximum values were predicted by the MOE model. Percentages of wet and dry deposition to total deposition were evaluated at locations both near and distant to a major point source. The Fisher and MOE models gave similar results as dry deposition dominated wet deposition. RCDM predicted more wet deposition at both locations.

After the installation and application of the three models, the Fisher (SERTAD) is expected to be the best overall model for predicting annual sulphur loadings over the Prairie Provinces. However, if a new modelling application is anticipated then the performance, simplicity of the input data requirements and the minimal usage of computer resources would make the RCDM more desirable.

1. Introduction

The Western and Northern LRTAP Technical Committee (WNCLTC) formed a mesoscale modelling task group in June of 1985 to review three scales of air pollution models. As a result of this review, it was recommended that three statistical LRTAP models; Fisher (SERTAD), Regional Climatological Dispersion Model (RCDM) and Ontario Ministry of Environment Statistical Model (MOE), be considered for application in western Canada.

Atmospheric Environment Service (AES), Environment Canada, was given the task to acquire and implement the three statistical LRTAP models. This work was completed through two contracts. The first was to acquire the computer code and install the three models on the AES mainframe computer in Toronto. The second portion of the work was to develop an input data set for each of the models appropriate for application to western Canada.

This report will review the three models described above, focusing on their application to western Canada. Reference will be made to various reports and scientific journals for more detailed information.

2. The Models

All three models are based on the parameterization of atmospheric processes. A statistical model can be defined as a model which employs statistical averages over long times and large areas for its input parameters such as wind speed, wind direction, inversion height, deposition parameters, chemical transformation rate constants, etc., as opposed to employing time and space dependent inputs or parameterizations for the parameters (Alp et al., 1984). Modelling atmospheric processes in this manner makes the models best suited to provide estimates of seasonal and annual pollutant loadings.

The performance of the models has been described in considerable detail by Alp et. al. (1984) and Clark et. al. (1987). Information on the scientific and technical aspects of the three models can be obtained from the following references; Fisher model (Fisher 1975, 1978), MOE (Venkatram et al, 1982), and RCDM (Fay and Rosenzweig, 1980).

Each of these models incorporates the general, transient, three dimensional transport equation. To provide estimates of long term pollutant loadings, assumptions are made concerning atmospheric processes to simplify this transport equation. An understanding of the key assumptions and their physical interpretation for each of the models is very important.

2.1 Regional Climatological Dispersion Model

The key assumptions for the RCDM are as follows:

- transport is assumed steady state
- diffusion in the vertical is assumed instantaneous and well mixed below the mixing height
- horizontal diffusion described using an eddy diffusivity, is uniform in space with the spread in the x and y directions assumed equal
- horizontal advection uses a single, regional, layer-averaged wind speed and direction
- chemical transformations and deposition processes are uniform in space and time
- primary pollutants come from a point source at the centre of the grid square
- the only source of secondary pollutants is through chemical reactions from primary pollutants

Physically these key assumptions mean that the model will only estimate pollutant loadings, with some degree of accuracy, after long averaging periods (seasonal to annual). The flow over the region must be unidirectional to justify the use of a single, regional, layer-averaged wind. Synoptic disturbances must be generally of a uniform size and velocity to incorporate a continental horizontal diffusivity. Assumptions about deposition processes require homogenous precipitation patterns and landuse over the study area. Through the calculation of the lifetime of primary and secondary pollutants undergoing wet and dry deposition, some of the large scale variability in the precipitation patterns can be modelled. Sources of secondary pollutants are not considered, hence significant contributions to the concentrations of these pollutants from other than primary pollutants must be incorporated by tuning other model parameters.

2.2 Ontario Ministry of Environment Model

The key assumptions for the MOE Model are as follows:

- the transient term of the transport equation is retained
- emission of the pollutant is assumed to be a 'puff' released instantaneously
- unidirectional flow through a point source is assumed
- horizontal diffusion is assumed to be Gaussian
- vertical diffusion is instantaneous and uniformly mixed below the mixing height
- concentrations and depositions of primary and secondary pollutants are calculated separately
- chemical transformations and deposition processes are time dependent and uniform in space

The MOE model is basically a simple mass balance model that assumes the release is a 'puff' of either 'wet' or 'dry' particles. Travel times are associated with a certain concentration of these particles with conversion occurring between the 'wet' and 'dry' primary or secondary pollutants.

This model is similar to the RCDM in that both use a single, regional, layer-averaged wind and space averaged chemical transformations and deposition processes. MOE incorporates a Gaussian formulation to solve the horizontal diffusion but still requires continental scale parameters. Individual sources of primary and secondary pollutants can be considered with this model as emission sources are identified by latitude and longitude. Deposition velocities, chemical transformation and scavenging rates are also included in the model. Large scale precipitation patterns can be modelled through the calculation of the fraction of time of wet and dry deposition.

2.3 Fisher Model

The version of the Fisher Model implemented in this study has been modified by Concord Scientific Corporation (Reid et al., 1985; Wright et al., 1985) and is referred to as the Statistical Estimates of Regional Transport and Acidic Deposition (SERTAD) model. The primary modifications of interest to this study were the stratification of emissions by height and the increased efficiency of parameter field arrays.

The key assumptions for the Fisher (SERTAD) Model are as follows:

- transport is assumed to be steady state
- downwind advection dominated diffusion
- crosswind diffusion is modelled using a pollution 'rose' approach
- vertical diffusion is assumed to follow 'K theory' with Kz assumed constant in space
- the horizontal wind speed and direction are constant in space
- meteorological parameters vary seasonally
- an initial fraction of SO_2 is converted to SO_4 at the source
- chemical transformations are constant in space
- scavenging coefficient for SO_2 and SO_4 assumed the same and constant in time
- dry deposition for SO_2 assumed constant
- SO_4 is assumed uniform in the vertical with dry deposition neglected

The Fisher Model combines a plume pattern under steady state conditions with statistical factors which account for the yearly variability of such meteorological parameters as wind speed and direction, mixing height and vertical diffusivity. The gridded definition of precipitation patterns allows for regionally varying wet deposition amounts; however, the dry deposition does not have the definition of landuse input.

3. Model Installation

The three statistical LRTAP models were installed on a mainframe computer. Subsequently the RCDM and the MOE Model have been successfully transported to a micro-computer. The installation of the Fisher Model as not been attempted; however, comparative runs on the mainframe computer would suggest that this installation would not be very efficient. The Fisher Model, MOE Model and the RCDM require 2:59.80, 0:14.31 and 0:07.19 minutes of central processing unit (CPU) and input/output (I/O) time respectively for the runs using the emission and receptor grids for western Canada. The Fisher (SERTAD) Model is by far the most demanding on computer time; however, computer costs are such that multiple applications could be accomplished with minimal resources. RCDM and the MOE Model are very inexpensive with run-times less the a few minutes on a microcomputer.

4. Input Datasets for Western Canada

As discussed in the previous sections, all three models require input datasets that differ slightly. In many cases the input data must be derived for the study area to adequately describe the atmospheric processes while in other cases values from the published literature are used. Tables 1 through 4 indicate the input data requirements for each of the three models.

Input datasets have been constructed for each of the models with details provided by Leahey et al. (1987). The meteorological data were compiled for two periods. The first period was from 1974 to 1985 and the second was for 1982. These intervals were chosen to provide climatologically averaged conditions and specific data for one year for comparison. The emissions of sulphur dioxide for western Canada and northwestern United States were complied using inventories up to and including 1985.

The implementation of the models and trial runs used the datasets described by Leahey et al. (1987) with two exceptions. The horizontal wind speeds for mid convective mixing depths in the Fisher Model were re-evaluated and found to be too low. Wind speeds were recalculated giving values of 6.1 (m/s) for Spring, 5.6 (m/s) for Summer, 5.2 (m/s) for Autumn and 5.1 (m/s) for Winter. Upper winds were initially taken from all of the AES Upper Air Stations in western Canada. The resulting frequency statistics were then compared with upper wind statistics derived using Prairie stations only. The result was a shift in the wind direction frequencies from easterly to east-southeasterly. South to southwesterly winds are frequent over western British Columbia hence these directions influenced the predominant west-northwesterly flow over the Prairies. As a result of this analysis, wind statistics for BC and the Prairies were separated.

Table 1. Meteorological Input Requirements

	RCDM	Fisher	MOE
Wind Speed	mean annual wind speed	joint frequency table describing wind speed and mixing height in each meterological category	mean annual wind speed
Mixing Height	mean annual height		mean annual height
Wind Direction	mean annual wind direction	ratio of the frequency with which the wind is in the mean annual direction to the frequency assuming that all wind directions are equally likely	mean annual wind direction
Precipitation	mean length of wet and dry periods	rainfall categories at each grid square and the mean dry period for each category	mean lengths of wet and dry periods

Table 2. Emissions Requirements

RCDM	Fisher	MOE
annual SO2 inventory corresponding to a 127 x 127 km grid square	seasonal or annual SO2 inventory corresponding to 127 x 127 km grid square at 4 different ranges of height 0 - 100 m 101 - 350 m 351 - 650 m 651 - 800 m	annual emissions corresponding to a latitude - longitude grid system

Table 3. Physical and Chemical Parameterization Data

RCDM	Fisher (SERTAD)	MOE
lifetime of primary and secondary pollutants under-going, - dry deposition - wet deposition lifetime of primary pollutants under- going, - dry chemical changes - wet chemical changes	initial fraction of SO2 converted to SO4 rate of conversion of SO2 to SO4 scavenging coefficient of SO2 and SO4 SO2 dry deposition velocity	SO2 and SO4 dry deposition velocity SO2 wet scavenging rate SO4 wet deposition velocity dry and wet conversion rate of SO2 to SO4 fraction of time of wet and dry deposition fraction of SO2 and SO4 to the total emissions released at the source

Table 4. Diffusion Parameters

	RCDM	Fisher	MOE
Horizontal	continental scale horizontal diffusivity	through wind direction frequency (wind roses)	horizontal velocity fluctuations of synoptic scale turbulence
Vertical	not used, instantaneous vertical mixing below mixing height	vertical eddy diffusivity	not used, instantaneous vertical mixing below mixing height

5. Output From the Models

Although all of the models are predicting the transport and deposition of sulphur, there are differences in the way the results are presented.

5.1 RCDM

Concentrations are for primary (SO2) and secondary (SO4) pollutants. It must be noted that in each species both wet and dry processes are considered. Wet and dry deposition of sulphur are also predicted.

5.2 Fisher (SERTAD)

The Fisher Model provides output for every species except the dry deposition of sulphate, which is not considered. Values of wet, dry, and total depositions of SO2 are available along with wet SO4, total wet (sum of SO2 and SO4) and total deposition (sum of dry SO2, wet SO2 and wet SO4). Ground level concentrations of SO2 and SO4 are also provided.

5.3 MOE

This model calculates pollutant species separately; therefore, output comprises wet and dry concentrations of SO2 and SO4. A unique feature of the MOE output is a tabular listing of specified stations giving total wet and dry deposition of sulphur.

6. Model Performance

After careful consideration of the geographical area to be covered by the three statistical LRTAP models, the Prairie Provinces were chosen. This decision was based on the dissimilar upper wind regimes over British Columbia and the Prairies as discussed earlier. The rugged terrain of British Columbia was also considered. Perturbations in the transport and deposition of pollutants which are caused by terrain influences are beyond the capabilities of these models. Therefore, the three models were run to estimate sulphur loadings over the Prairie Provinces using the input parameters as described earlier. The physical and chemical parameters and the values used are listed in Table 5.

The prediction of sulphur dioxide concentration was chosen for comparison as it was the field common to all three models. Also, the concentration calculations do not include the further complication of deposition processes.

Table 5.

Physical and Chemical Parameterizations

Fisher (SERTAD)		RCDM		MOE	
Form	Value	Form	Value	Form	Value
SO_2 dry deposition velocity	1.0 (cm/s)	Lifetime of SO_2, SO_4 undergoing dry deposition	1.0 E5 (s)	Dry deposition velocity SO_2 SO_4	 1.0 (cm/s) 0.1 (cm/s)
SO_2, SO_4 scavenging coefficient	0.0001 (/s)	Lifetime of SO_2, SO_4 undergoing wet deposition	1.0 E4 (s)	SO_2 scavenging rate	0.0001(/s)
				wet deposition velocity	0.0001(/s)
rate of conversion of SO_2 to SO_4	0.0000027 (/s)	Lifetime of SO_2 undergoing dry chemical changes	3.6 E5 (s)	Dry conversion rate of SO_2 to SO_4	1 (%/h)
		Lifetime of SO_2 undergoing wet chemical changes	3.6 E5 (s)	Wet conversion rate of SO_2 to SO_4	1 (%/h)
Fraction of SO_2 converted to SO_4	2%			Fraction of SO_2 converted to SO_4 at source	2 %

Figures 1 to 3 depict the concentration fields of SO2 as predicted by each of the models. At first glance, the Fisher (SERTAD) and the MOE appear to agree very well. The RCDM captures the general pattern but the concentration values are lower than the other two models over the entire area. Concentrations related to point sources appear to be the largest departure between the RCDM results and those of the other two. For a region containing a number of small sources, such as the foothills area of Alberta, all three models have a similar pattern with the RCDM and the Fisher Model indicating lower concentrations compared with the MOE model. It is interesting to note that the regions away from the major point or area sources have predicted concentrations in the 0.4 to 0.5 micrograms per cubic metre range in all three model outputs. There appears to be some general agreement between the models on this 'regional background' concentration.

In Figures 4 and 5, the wet deposition of sulphur is presented as predicted by the RCDM and the Fisher (SERTAD) model. Both models consider the concentrations of SO2 and SO4 in calculating the wet deposition of sulphur. The MOE model results are presented in Table 6. In all cases, the values given do not include background sulphur. Isopleths of wet sulphur deposition (kg/ha/yr) follow the same general pattern as seen in the sulphur dioxide concentrations. The Fisher (SERTAD) and the RCDM generally agree in both pattern and deposition amounts, particularly close to point sources. For area sources and regions away from point sources, the RCDM deposition values are higher than those of the Fisher (SERTAD) model. The MOE model agrees with the Fisher (SERTAD) model in areas away from point sources. In the vicinity of point sources, the MOE model has the highest deposition values (see Table 6. Fort McMurray and Calgary) of all three models. If all of the sulphur is in the form of sulphate, then isopleths of wet sulphate can be prepared as in Figures 6 and 7. Since the deposition amounts are simply three times those for wet sulphur deposition, very little has to be said about the patterns and values predicted. Wet sulphate deposition given in this manner is more easily compared with monitoring data.

The MOE model is to only one of the three that predicts site specific dry deposition of sulphur (see Table 6.). The results show that dry sulphur deposition dominates wet sulphur deposition in all cases which agrees with earlier modelling applications over the Prairies (Kociuba, et. al. 1984). The percentage of dry and wet deposition to total predicted deposition was investigated for each model. A location near a major point source (Fort McMurray) and a location some distance from any sources (Cree Lake) were considered. It was found that near the source both the Fisher and the MOE models predicted more dry deposition than wet, 72% and 62% respectively. The RCDM predicted 31%. At a distant site, the Fisher model predicted 65% dry deposition, the MOE model 87% and RCDM 28%.

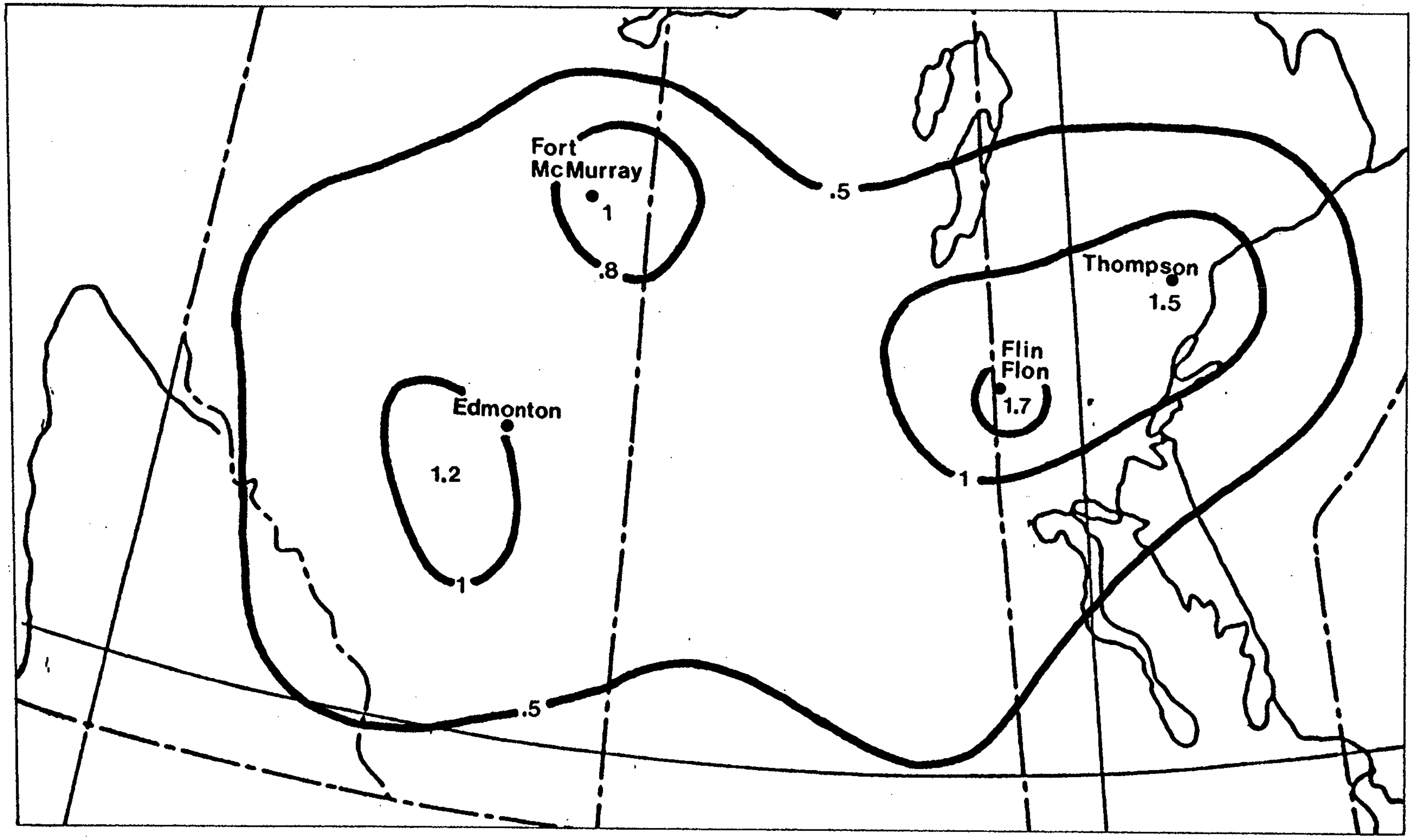

Figure 1. RCDM - Concentrations of Sulphur Dioxide (micrograms/cubic metre)

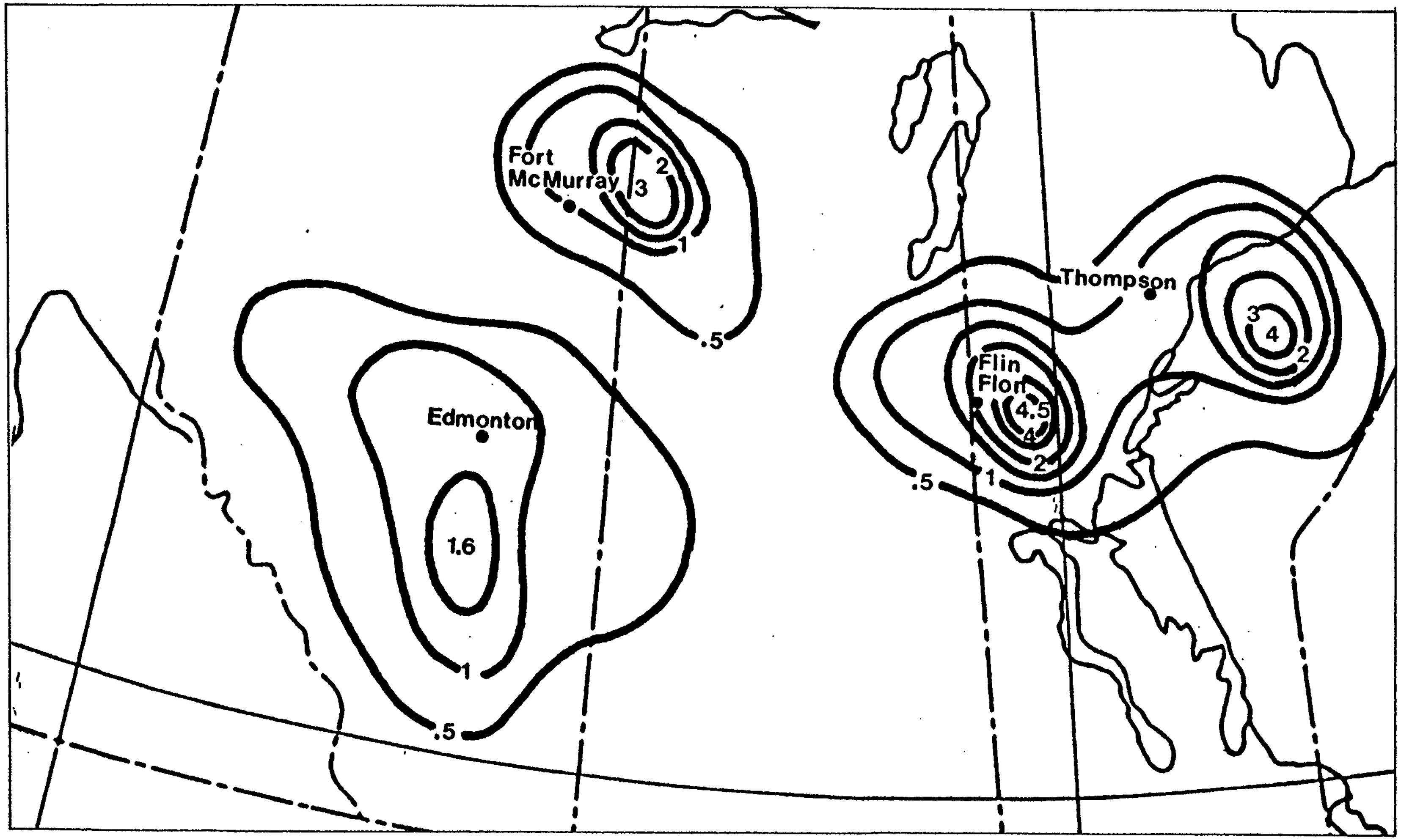

Figure 2. Fisher (SERTAD) Model - Concentration of Sulphur Dioxide (micrograms/cubic metre)

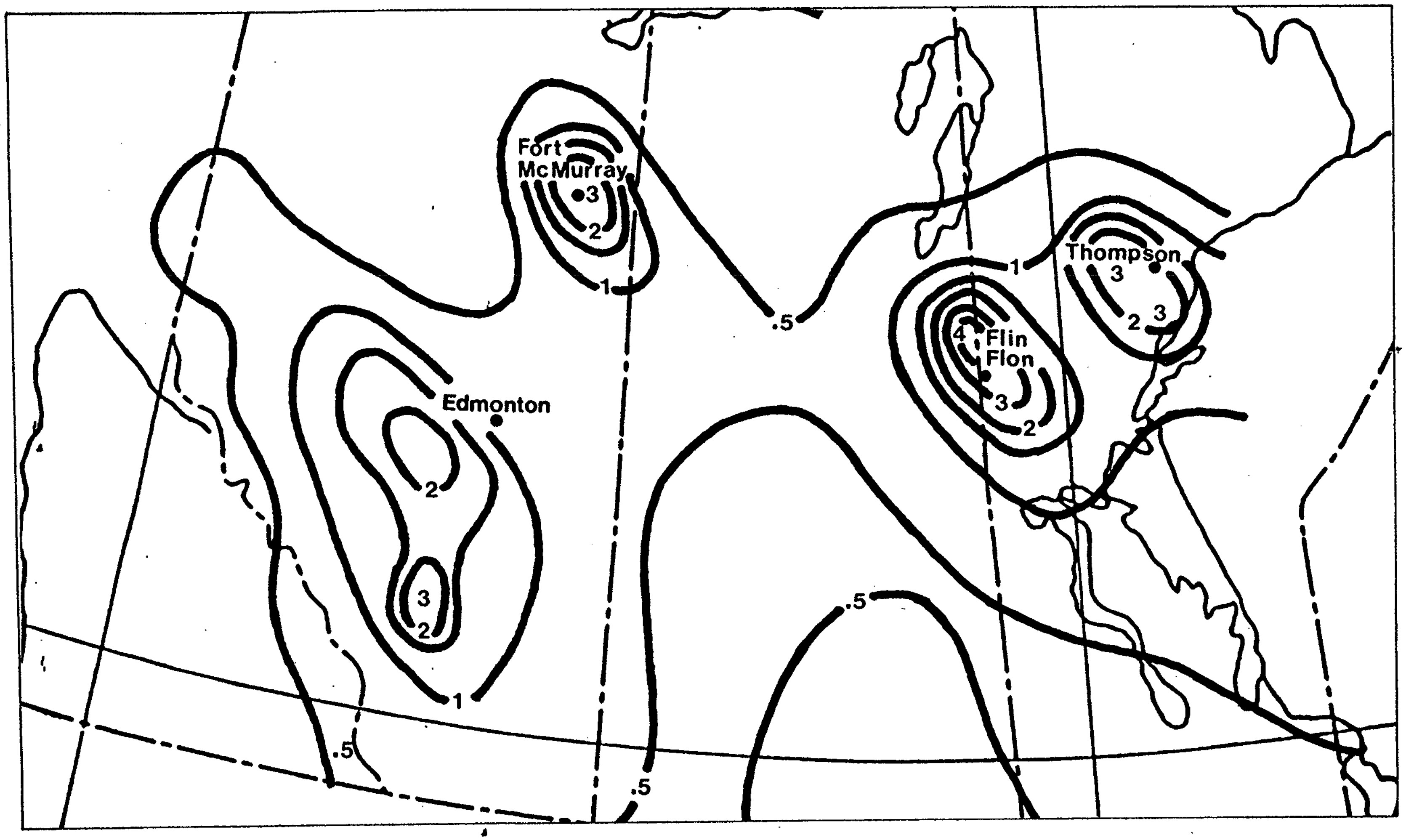

Figure 3. MOE Model - Concentration of Sulphur Dioxide (micrograms/cubic metre)

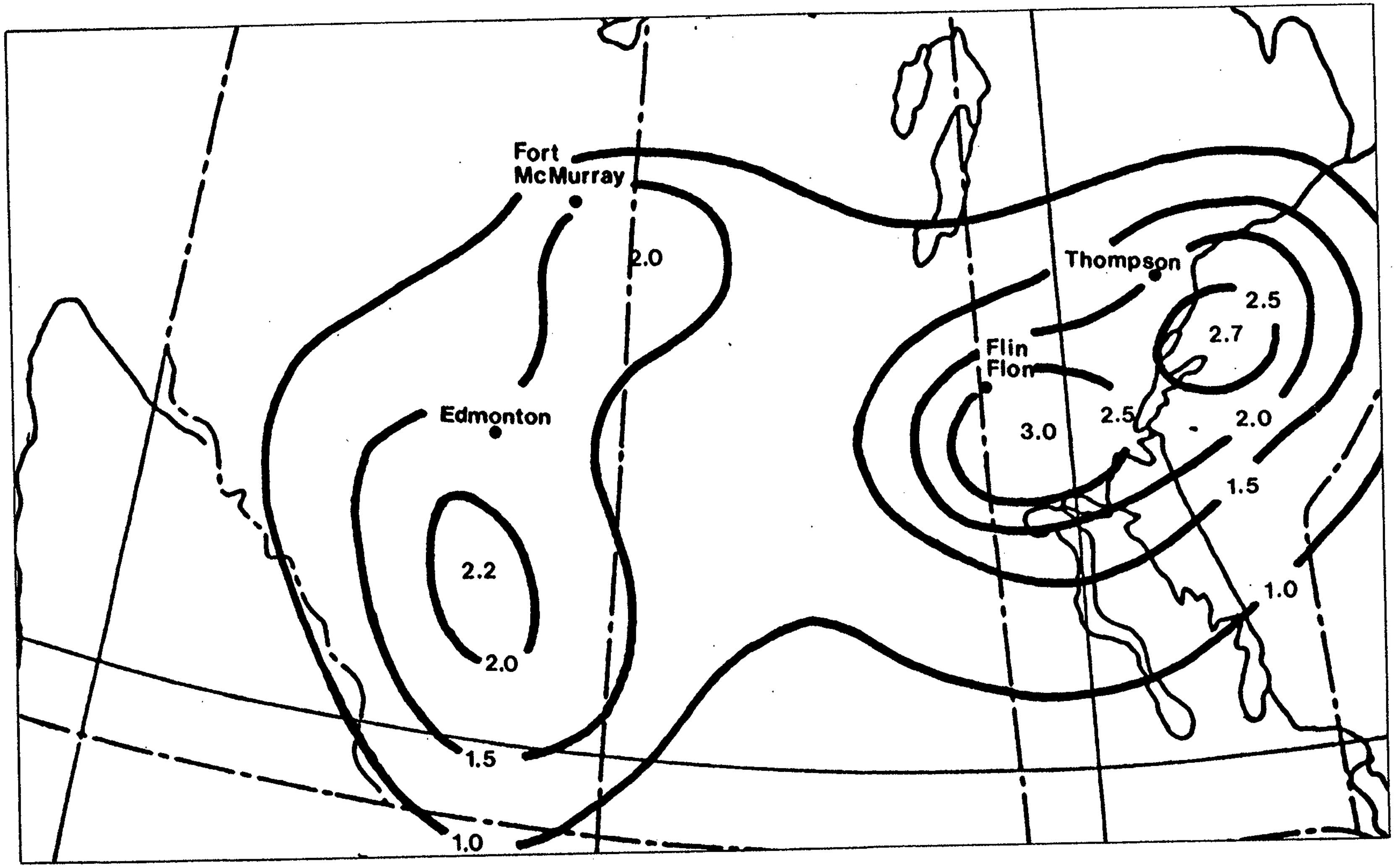

Figure 4. Wet Deposition of Sulphur Predicted by the RCDM without background sulphur (kg/ha/yr)

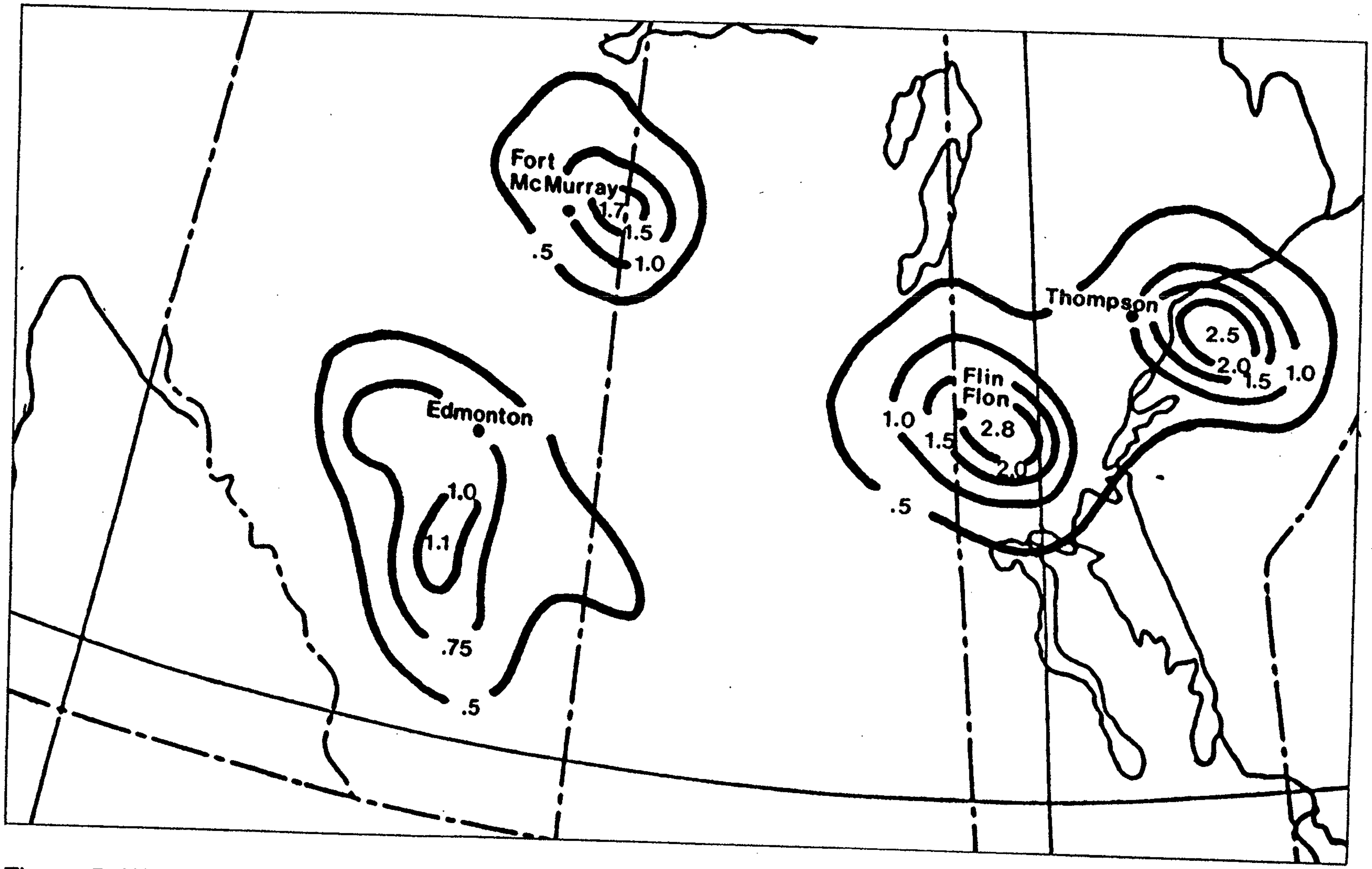

Figure 5. Wet Deposition of Sulphur Predicted by the Fisher (SERTAD) Model without background sulphur (kg/ha/yr)

Table 6. Wet and Dry Deposition of Sulphur as Predicted by the MOE Model (no background sulphur)

Site Name	Wet Deposition (kg/ha/yr)	Dry deposition (kg/ha/yr)
Beaverlodge	0.16	0.87
Calgary	2.86	5.09
Coronation	0.62	2.01
Edson	0.61	1.97
Ellerslie	0.67	2.18
Esther	0.11	1.09
Fort McMurray	4.13	6.73
Peace River	0.01	0.59
Red Deer	0.56	2.27
Rocky Mountain House	0.64	2.33
Suffield	0.11	1.14
Whitecourt	0.41	1.62

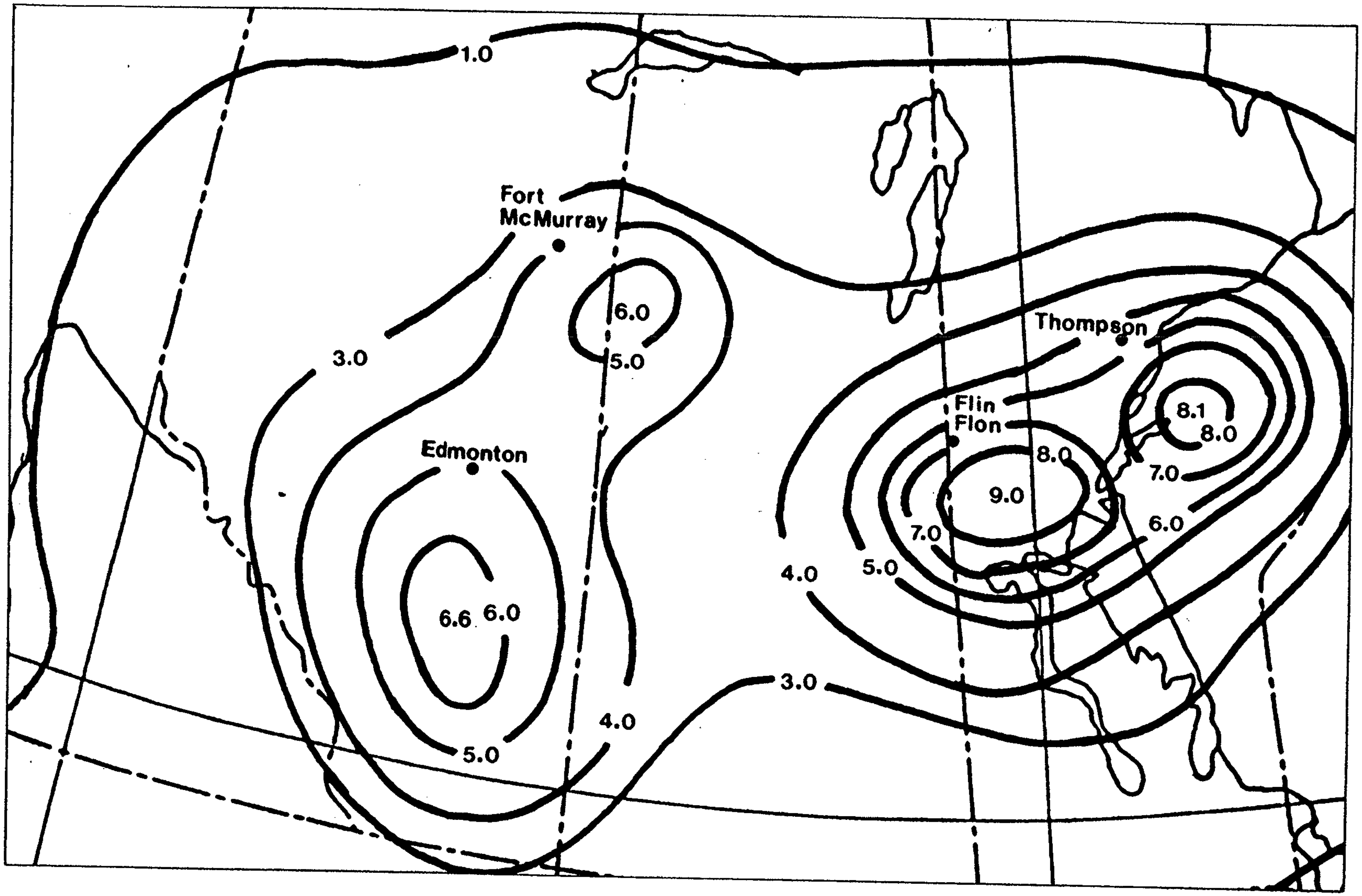

Figure 6. Wet Deposition of Sulphate Predicted by the RCDM without background sulphur (kg/ha/yr)

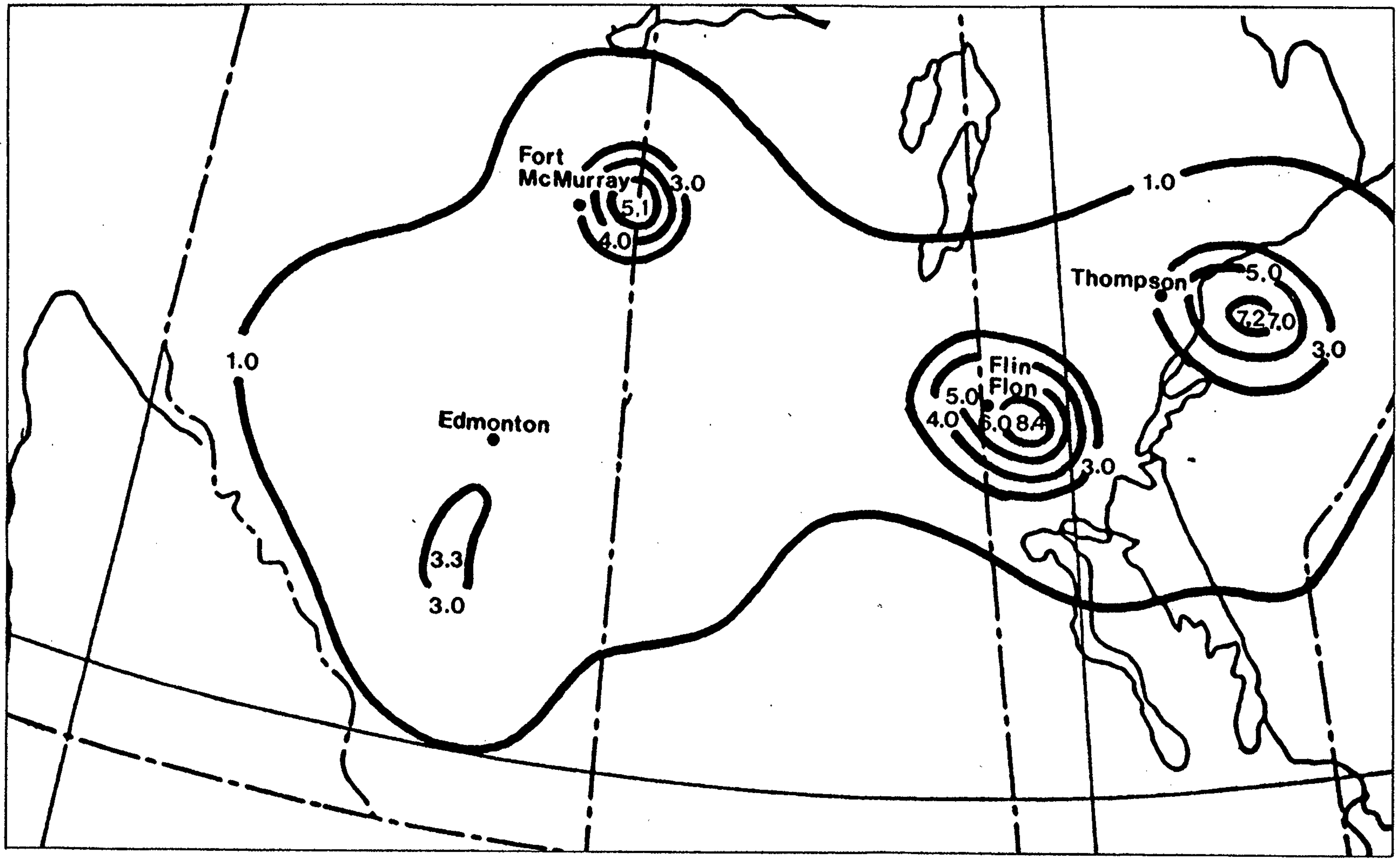

Figure 7. Wet Deposition of Sulphate Predicted by the Fisher (SERTAD) Model without background sulphur (kg/ha/yr)

7. Summary and Conclusions

The three statistical LRTAP models; Fisher, MOE and RCDM have been successfully installed on a mainframe computer. The MOE Model and RCDM have been transported to an IBM microcomputer. On the mainframe computer, the Fisher Model requires the largest amount of CPU and I/O time, approximately three minutes using the input data discussed earlier. The MOE Model and RCDM execute within a few seconds.

Meteorological data were compiled to describe average seasonal and annual atmospheric conditions in western Canada. Precipitation patterns and upper winds were analyzed and configured into computer files suitable for the three models. The only changes made to these data files were associated with the upper winds. To accurately describe the upper flow regime over western Canada, the winds from British Columbia were separated from those over the Prairie Provinces and excluded from further analysis. Physical and chemical parameters such as scavenging coefficients, deposition velocities and chemical transformation rates were reviewed in light of studies performed in western Canada. The most appropriate of these values were included in the computer input data files.

Without any further adjustments to the input data, the three models were run to describe the sulphur loading over the Prairie Provinces. For the concentration of sulphur dioxide, all three models produced similar patterns with the RCDM values slightly lower than the Fisher or MOE models. The generally low concentrations are likely caused by the values chosen for lifetime of SO2 undergoing wet deposition and chemical transformations. The other noticeable difference between models was the lack of the RCDM to depict the intensity of the concentration patterns near point sources. The use of a continental horizontal diffusivity in RCDM may cause a dilution of the concentration pattern.

Wet deposition of sulphur as predicted by the three models demonstrated similar patterns to that of the SO2 concentrations. This was anticipated since the deposition amounts are controlled to a large degree by the concentration fields. The only exception to this statement is the Fisher (SERTAD) model. Concentrations of SO2 were comparable to that of the MOE values whereas the deposition amounts were considerably less. Therefore the differences in the handling of deposition processes in the two models must be reviewed to determine the cause of this divergence in results.

The percentage of wet and dry deposition predicted by RCDM was reversed to that of the other two models and to what might be expected. It would appear that the wet deposition parameterization used in RCDM is not correct. Correcting the ratio of wet and dry deposition will increase the SO2 concentration which will in turn effect the other deposition patterns. From studies conducted by Matthias and Lo (1985), the RCDM will produce acceptable results after prudent adjustments are completed to the input parameters.

The true assessment of the performance of the three models must wait until comparisons are made with actual sulphur loadings measured on the Prairies. Concentrations of SO2 will be difficult of obtain; however, wet deposition of sulphur can be used to assist in tuning the various input parameters.

Under conditions of limited resources, the Fisher (SERTAD) Model is recommended for further consideration. The Fisher Model predicts patterns similar to the other models but provides more flexibility. Emission sources can easily be turned 'on' or 'off' for application in source-receptor studies. With the use of a wind frequency-pollution 'rose' concept, the Fisher model should provide a more accurate description of the regional sulphur loading. In the situation where a new model application is anticipated that requires the formulation of new input data fields, then the RCDM should be considered. The performance of RCDM over eastern North America has demonstrated that the model can produce useful estimates of annual sulphur loadings. The level of resources required to initialize and execute RCDM is minimal.

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