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REVIEW OF THE ATTRIBUTES AND PERFORMANCE OF SIX URBAN DIFFUSION MODELS

by

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ABSTRACT

The American Meteorological Society conducted a scientific review of a set of six urban diffusion models. TRC Environmental Consultants, Inc. calculated and tabulated a uniform set of statistics for all the models. The report consists of a summary and copies of the three independent model reviews conducted to evaluate the models. General conclusions included: (1) all of the six models are very similar to each other and represent simple approximations of the urban diffusion situations in a given time period with no horizontal variability of the boundary layer structure or depth; (2) none of the models can be considered state-of-the-art since a great deal has been learned about the planetary boundary layer that could be incorporated into such models; (3) the models all use an all or nothing approach to plume penetration; either the plume penetrates the elevated inversion and is lost to the computation or it is completely trapped; and (4) the four annual models all produced good estimates of the observed concentrations, while, of the short-term models, TEM-8A seriously overpredicted at night and RAM seriously underpredicts during the day.

CONTENTS

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INTRODUCTORY AND SUMMARY

As one task of the current Cooperative Agreement between the American Meteorological Society (AMS) and the Environmental Protection Agency (EPA), the AMS agreed to conduct a scientific review of a set of six urban diffusion models. This review was a follow-on to an earlier examination of rural models which was summarized in a report to EPA, January 1983, entitled Synthesis of the Rural Model Reviews.

As in the review of the rural models, EPA arranged with TRC Environmental Consultants, Inc. to calculate and tabulate a uniform set of statistics for all the models. These statistics, which are included in TRC report "Evaluation of Urban Air Quality Simulation Models," April 1983, (EPA 450/4-83-020) provided the reviewers with a consistent set of measures for evaluating model performance.

The data base to which model predictions were compared was acquired with a 13-station network of continuous SO_2 monitors operated in metropolitan St. Louis. The data were obtained from the EPA/RAMS/RAPS archive. Coincidental air quality and emissions data for calendar year 1976 were used in this study.

The six urban dispersion models reviewed are all based on the Gaussian plume and apply to area and point, stationary sources. Two of these models, RAM and TEM-8A, provide short-term concentration averages and the remaining four, AQDM, CDM, ERTAC and TCM, provide annual average concentrations.

Three members of the AMS Steering Committee which oversees this Cooperative Agreement performed this scientific review. They were John C. Wyngaard, National Center for Atmospheric

Research, Boulder, Colorado; Jeffrey C. Weil, Martin Marietta Corporation, Baltimore, Maryland; and Maynard E. Smith, Meteorological Evaluation Services, Inc., Amityville, New York. Copies of their independent reviews form the basis of this report.

The scientific reviews were prepared during the spring of 1983. On completion, the reviews were then transmitted to other members of the AMS Steering Committee: Gabriel Csanady, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; Douglas G. Fox, U.S. Forest Service, Fort Collins, Colorado; and Fred D. White, National Academy of Sciences, Washington, D.C. Collectively we met to discuss the reviews of the six urban models.

No synthesis of these reviews is planned since the complete texts are included in this report. However, we would like to call attention to the following points.

- All of the six models are essentially very similar to each other and represent simple approximations of the urban diffusion situations in a given time period with no horizontal variability of the boundary layer structure or depth.

- None of the models can be considered state-of-the-science since a great deal has been learned about the planetary boundary layer that could be incorporated into such models. All such improvements could be handled easily by currently available computers.

- The plume penetration problem that was discussed in the earlier rural model evaluation is of equal concern in this review. The models all use an "all or nothing approach;" either the plume penetrates the elevated inversion and is lost to the computations or it is completely trapped (an unlikely situation).

- The four annual models all produced fairly decent estimates of the observed concentrations. The two short-term models left a lot to be desired. TEM-8A seriously over-predicts at night. RAM seriously underpredicts during the day. Of these two short-term models, RAM appears to be better.

URBAN MODEL REVIEW

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June 1, 1983

I. SUMMARY

At the request of the AMS-EPA Steering Committee, I have prepared a review of the set of urban diffusion models submitted to me, basing my evaluation on the description of the models in the User's Guides and on the draft TRC report of the model performance as judged against the RAPS/RAMS field data obtained in 1976.

From a scientific standpoint, these models are all very simplified Gaussian representations of the urban diffusion processes, differing in detail but not in basic approach. None of the models can faithfully represent many urban situations, because the complex wind fields, heat island effects and recirculation patterns that are known to exist in cities like St. Louis cannot be reproduced. Furthermore, even in less complicated situations, spatial variations in the key input parameters would have to be taken into account for a physically realistic representation, and the models cannot do this.

Another very important scientific weakness is the lack of time resolution in these models. Pollutant concentrations in cities do not respond instantly to changing meteorological conditions, and the time needed to reach equilibrium must be many hours in light-wind, poor-ventilation situations.

These scientific limitations are included in my review largely for completeness rather than for practical importance. The RAPS/RAM data base, although conceded to be the best available, would not have permitted very sophisticated modeling representations, although something might have been done to represent a more detailed wind field.

In terms of performance, three of the four annual models, AQDM, CDM and TCM performed fairly creditably on this data base, with the individual predictions generally falling within the reasonable statistical limits. However, the ERTAQ seems to be a modest overpredictor.

The short-term modeling evaluation, in which only two models were involved, reveals far more about model strengths and weaknesses, and it even suggests some possible reasons for poor model performance. On the regulatory three-hour and twenty-four-hour time scales, TEM-8A is an overpredictor and RAM is an underpredictor. Which might be chosen would depend upon whether one wanted to maximize or minimize the calculated values.

The TRC tables summarizing the 25 highest, unpaired observations show that the observed data do not differ significantly when segregated into four time periods of the day, but the predictions show marked variations for these same time periods, with TEM-8A grossly overpredicting during nocturnal hours and RAM grossly underpredicting during daylight hours. Certainly careful attention to the data in these tables might result in some helpful adjustments to the modeling concepts and assumptions.

The TRC case study tables have been rearranged in my review so that meteorological, observational and modeling data could be compared. As with the rural models, there was very little correspondence between a given prediction and the observed data. This is not a surprising result, but it does reinforce some of my contentions about the weaknesses of urban modeling as it now stands. For example, several of the high concentration periods represented rural, not urban diffusion, and they should be so treated. In other cases, the models seemed to have predicted high concentrations associated with low-level stable cases that did not occur in the city.

II. MODELS AND MODELING CONCEPTS

A. Models and Their General Characteristics

In this review, four models providing long-term (annual) estimates and two models providing short-term (one, three and twenty-four-hour) estimates were evaluated. The TRC draft report (Apr. 1983) describing the adjustments, data processing and performance data for this study includes a reasonably good description of the characteristics of the model functions, so that there is no point in reiterating them here.

As in the case of the rural model review completed earlier in 1983, there is little to choose among the models from a scientific standpoint. All are relatively simple applications based on the Gaussian plume model adapted for broad scale, multi-scource use. They contain, in various combinations, familiar algorithms for dealing with plume rise, reflection from the ground surface and from the top of the mixed layer, wind speed profiles, and in some cases pollutant decay and deposition. The models have several different methods of dealing with area sources, including the typical virtual source or initial area and depth representations, and they also differ in their systems for handling lateral diffusion, some using uniform concentrations within angular sectors, others using techniques for smoothing the boundaries between sectors, and one using the Gaussian approximation itself for the lateral distribution.

One could dwell on these individual differences, and it is important to return to some of them in describing the performance of the models in this particular study, but fundamentally they are all very similar to each other in concept, differing essentially only in details.

B. Scientific Status of the Models

It may seem unfair to criticize these models scientifically because there is no doubt that it would currently be impossible to provide a sophisticated model with the input data necessary for it to function properly. However, it does not seem unreasonable to document some of the disparities between the concepts used in the models and our knowledge of urban flow and diffusion problems. One should at least recognize that much more is known scientifically than is included in these modeling systems.

1. Many Input Variables Are Assumed to be Constants in Space

None of the models permit spatial variation of any of the following parameters:

Wind Speed
Wind Direction
Temperature
Mixing Depth
Wind Profile
Diffusion Rates

There is no question that in a city such as St. Louis all of these parameters vary significantly over the area included in this study. In fact, the meteorology over this area varies from urban to rural, and on many occasions the assumptions of constancy in space must be seriously in error.

The failure to take account of the variations in mixing height may be especially important because of the assumption that pollutant rising above the mixing depth no longer can contribute to the concentrations.

2. Heat Island Effects

There is also no provision in any of the models for dealing with the upwelling of air that is known to take place over a city during very light gradient winds. This vertical outflow certainly must act as a ventilating agent, tending to reduce the concentrations that would otherwise accumulate.

3. Time Dependence is Not Accounted For

These urban models use the same sort of reasoning applied to rural point source models, assuming that the air flow extant during a given hour or joint frequency class must transport pollutant to the limits of the calculation area, but that the next hour is an entirely new and independent situation. This assumption is occasionally inappropriate for an isolated point source, but clearly it does not represent the urban situation at all well, especially in light and variable wind conditions. Pollutant that has been transported over only a portion of the city dimensions is still there, and should be reckoned with during the next hour of calculation. Similarly, pollutant that has passed beyond the calculation limits or has risen above the current mixing depth may often return to contribute to later concentration patterns. Again, the lighter and more variable the wind, the more likely it is that recirculation would be important.

Surely, pollutants must gradually build up and decrease with time. Even with a steady, invariant wind flow and diffusion rate, a city will not reach an equilibrium concentration immediately. In fact, it can be shown by the simplest of approximations (e.g. Smith, 1961) that both the equilibrium concentration and the time it takes to reach it are proportional to $S/\bar{u}$, where S is a parameter related to the overall size of the city and $\bar{u}$ is the transport wind speed through the volume of the city air (the ventilation rate). For a city the size of St. Louis, it may take twenty-four hours or more to reach an equilibrium concentration if the mean wind is no more than 1 m/sec, especially if there is a rather slow decay or removal process operating on the polluting substance.

The point of the foregoing is not to suggest that sophisticated models would necessarily do a more accurate job than the simple ones we are reviewing, but rather to point out that these models do not make any pretense of depicting the details of the urban pollution situation. Furthermore, modern computer capabilities would permit introducing some of the sophistication, should anyone desire to update the modeling systems. Self-consistent wind fields and real-time, variable-trajectory transport and diffusion representation are within the state of the science today.

There are other uncertainties that might be addressed, such as our lack of experimental verification of the urban diffusion parameters and the questions about the initial vertical and horizontal mixing of the pollutants after release, but these considerations are secondary to the more fundamental limitations discussed above.

III. REVIEW OF THE DATA SET

A. General Considerations

Although it is conceded that the RAPS/RAMS data are the most appropriate for a model validation study, the reviewer must be concerned with the fact that the entire exercise is based on a single batch of information. As with the rural evaluation completed earlier, the reviewer is left with a nagging concern that there may be little generality in whatever performance has been observed.

A second basic problem is that the SO_2 recorders were incapable of measuring concentrations greater than 1 ppm, a concentration level that could have been reached and exceeded in a city like St. Louis on time scales shorter than one hour. Thus, very important values near the upper end of the concentration range may not be reflected in the data.

B. Concerns on Specific Problems

1. High Readings at Station 104

The processed data showed an annual average of 116 ug/m^3 at Station 104, a value more than a factor of two larger than the next highest station and grossly in excess of all predictions for that Station. One must conclude that there was either an important source that was unaccounted for or that there were serious instrumental problems.

2. Overall Hourly Maximum at Station 104

The highest observed one-hour maximum in the entire data set occurred at Station 104 on December 6, (2487 ug/m^3) immediately following an extended period of "missing data" in the listing. The hour after this showed a concentration of only 755 ug/m^3. One wonders whether there was something odd about this first hour after the outage, if it was an outage.

Parenthetically, this type of problem raises once again the problems inherent in regulatory systems geared to the extreme upper end of the data set. Too much depends upon a very few observed or predicted values.

3. Uncertainty About Mixing Depths

The equilibrium concentration that would be reached in a city is directly dependent upon the depth of the mixed layer, and it is clear that the observational network did not permit adequate specification of this variable. This is an important defect in the data set.

IV. RESULTS OF THE COMPARISONS

Partly because the evaluation involved urban models, four of them predicting only annual numbers, and partly because EPA-TRC responded to the distress of the earlier rural reviewers, the data set to be digested was mercifully smaller than that prepared for the earlier model review. It was therefore considerably easier to do some manipulation of the results to reveal other facets of the comparisons, and it was also easier to investigate the individual cases resulting in high predicted and observed short-term concentrations.

A. Annual Comparison

Three of the four annual models, AQDM, CDM and TCM performed rather similarly in this evaluation. Averaged over all stations as shown below, they were reasonably close to the observed value, and there is little choice among them. The ERTAQ model, however, is a bit farther from the mark, overpredicting by a modest amount.

Station	Measured	AQDM	CDM	TCM	ERTAQ
Average	42	42.2	39.2	37.4	50.7

The data become more interesting if one separates them by station and the level of the measured values (Table A). My own immediate reaction was to ask what is wrong with the measured value of 116 ug/m^3 that occurred at Station 104. It is about twice the predicted values and begs for a detailed investigation. Either the measured value is strange or a major source was misrepresented.

TABLE A

ANNUAL COMPARISON
GROUPED BY
LEVEL OF THE MEASURED VALUES

Range of Measured Values	Station	Meas.	AQDM	CDM	TCM	ERTAQ
>40 ug/m³	104	116	62	62	53	80
	101	55	82	83	102	101
	106	52	61	46	40	58
	105	43	57	46	34	57
	Mean	67	66	59	57	74
As above without Station 104	Mean	50	67	58	58	72
35-40 ug/m³	108	37	42	42	42	53
	103	36	50	51	44	61
	113	36	40	33	27	43
	114	35	33	32	29	44
	Mean	36	41	40	36	50
<35 ug/m³	121	30	25	18	17	30
	115	28	29	44	47	50
	120	27	23	15	12	25
	122	27	20	14	15	27
	116	24	26	23	24	31
	Mean	27	25	23	23	33

Less startling but also interesting is the situation at Station 101, where 55 ug/m^3 was measured and all of the predictions were much larger. This too should be investigated, especially since any predicted value of 80+ ug/m^3 has a special regulatory significance.

On a broader perspective it is evident that ERTAQ overpredicts in comparison to the other models at almost all concentration levels, and I would consider it the least promising of the group.

It is interesting to note that among the other three models, there is a slight tendency for overprediction at Stations where the measured levels are themselves high, shifting to a slight tendency for underprediction where the measured levels are low. This same comment applies to distance from the center of the city. One could indulge in numerous speculations as to the reasons for this shift, but the exercise would be beyond the scope of this review.

B. <u>Short-term Comparison</u>

Although there are only two models involved in this part of the study, the comparative exercise is far more interesting and informative with respect to urban diffusion and modeling problems. Tables 5-3 and 5-4 of the TRC draft report summarize most of the salient details, and they are reproduced as part of this review.

Table 5-3 clearly indicates that there are significant differences between the two models, as well as

TABLE 5-3

COMPARISON OF 25 HIGHEST OBSERVED AND PREDICTED SO_2 CONCENTRATION VALUES
(UNPAIRED IN TIME OR LOCATION) FOR THE ONE, THREE AND TWENTY-FOUR HOUR AVERAGING PERIODS
RAPS (1976)

Model	Average Observed Value (ug/m^3)	Average Predicted Value (ug/m^3)	Difference of Averages* (Obs.-Pred.) (ug/m^3)	Difference of Medians (Obs.-Pred.) (ug/m^3)	Variance Comparison* (Obs./Pred.)	Maximum Frequency Difference
Averaging Time: One Hour						
TEM-8	1929	3998	-2069 (-2460, -1678)	-1838 (-2100,-1614)	0.07 (0.03, 0.16)	1.00 (0.385)
RAM	1929	1622	307 (137, 477)	325 (224, 456)	0.47 (0.21, 1.07)	0.76 (0.385)
Averaging Time: Three Hours						
TEM-8	1351	2821	-1470 (-1757, -1183)	-1223 (-1493, -1101)	0.05 (0.02, 0.11)	1.00 (0.385)
RAM	1351	811	540 (457, 623)	584 (476, 614)	1.07 (0.47, 2.43)	1.00 (0.385)
Averaging Time: Twenty-Four Hours						
TEM-8	664	1312	-648 (-792, -504)	-647 (-750, -524)	0.61 (0.27, 1.38)	0.88 (0.385)
RAM	664	334	330 (237, 423)	282 (194, 357)	19.32 (8.51, 43.86)	0.96 (0.385)

*95 percent confidence interval in parentheses

TABLE 5-4

COMPARISON OF 25 HIGHEST OBSERVED AND PREDICTED SO_2 CONCENTRATION VALUES (UNPAIRED IN TIME OR LOCATION) FOR THE ONE HOUR AVERAGING PERIOD RAPS (1976)

Data Sets	TEM-8A Average Observed Value (ug/m^3)	TEM-8A Average Predicted Value (ug/m^3)	TEM-8A Difference of Averages* (Obs.-Pred.) (ug/m^3)	TEM-8A Variance Comparison (Obs./Pred.)	RAM Observed Value (ug/m^3)	RAM Average Predicted Value (ug/m^3)	RAM Average of Averages (Obs.-Pred.) (ug/m^3)	RAM Difference Variance Comparison (Obs./Pred.)
By Station:								
Station 1 (101)[a]	921	3940	-3019	0.18	921	904	17	10.50
Station 2 (103)	511	1678	-1167	0.54	511	599	-88	16.46
Station 3 (104)	1886	1721	165	0.23	1886	1133	753	1.72
Station 4 (105)	421	1798	-1377	0.11	421	884	-463	0.33
Station 5 (106)	652	1419	-767	1.78	652	603	48	16.10
Station 6 (108)	427	1595	-1168	1.61	427	626	-199	16.64
Station 7 (113)	440	1047	-607	1.43	439	514	-75	5.28
Station 8 (114)	452	1585	-1133	0.13	452	1053	-601	0.35
Station 9 (115)	353	2336	-1983	0.02	353	1461	-1108	0.04
Station 10 (116)	438	1351	-913	0.10	438	497	-59	3.12
Station 11 (120)	398	1093	-695	0.29	398	426	-28	4.66
Station 12 (121)	320	1139	-819	0.02	320	544	-224	0.19
Station 13 (122)	435	1022	-587	0.65	435	451	-16	9.11
By Time of Day:								
0000-0600	1561	3801	-2240	0.11	1561	1424	137	0.60
0600-1200	1474	2274	-800	0.21	1474	881	593	1.55
1200-1800	1467	1443	24	1.11	1467	792	675	1.72
1800-2400	1329	2772	-1443	0.21	1329	1305	24	2.21
By Meteorological Condition:								
A. Wind Speed								
<2.5 m/s	1671	3998	-2327	0.10	1671	1620	51	0.68
2.5 to 5 m/s	1696	1830	-134	3.87	1696	982	714	3.79
>5 m/s	881	977	-96	3.87	881	472	409	4.88
B. Stability Group								
Class A & B	657	784	-127	8.43	657	441	216	22.20
Class C	1333	1131	202	0.96	1333	539	794	15.21
Class D	1509	2463	-954	0.36	1509	688	821	6.49
Class E & F	1774	3970	-2196	0.09	1774	1622	152	0.65

RAPS/RAMS monitoring ID codes in parenthesis

significant differences between each of the models and the measured values. The data presented here are summaries of the 25 highest unpaired observed and predicted values, and they show that TEM-8A is definitely an overpredictor while RAM is an underpredictor. Using the three-hour and twenty-four-hour time periods as guides because of their regulatory significance, one would be grossly disappointed in the performance of either. Perhaps the best solution would be to average the mean results of the two models; it would provide a fairly good estimate of the measured means!

I find it hard to limit my comments strictly to model performance, especially when Table 5-4 lends itself so well to suggesting what may be wrong with the two models. First, the segregation by time of day in the center of the table shows that the measured values are almost identical throughout the four six-hour periods of the day, whereas both models show marked variation from night to day. TEM-8A is close to the mark in the afternoon but overpredicts seriously at other times, especially at night. RAM, on the other hand, does well at night but seriously underpredicts during the daylight hours.

One must speculate that the observed lack of variability over the day-night grouping may well imply that diffusion in a city does not vary nearly as much from day to night as the modeling concepts imply, or, equally likely, that there is such a long lag time in the change of pollutant concentrations in a city that no model of the type under investigation would perform satisfactorily.

V. CASE STUDIES

The TRC draft report includes complete data for those situations that result in the highest and second-highest one-hour, three-hour and twenty-four-hour predicted and observed data. As part of my review, I have copied these tables and rearranged them so that one can look at the meteorological and field data together to try to glean some understanding of what may have been happening. The sets of data are arranged in order of increasing time period starting with one-hour and ending with twenty-four hours. Table D-1 identifies the receptors and the cases involved.

Highest Observed One-Hour Case

Tables 1A and 1B and Figure 1 together show the details of the highest hourly observation of the data set. One feature stands out, and it is the fact that this very high reading follows hours of "missing data," as we have noted before. Perhaps it is a real observation, but perhaps it is not.

Highest One-Hour Prediction - RAM

The tables and figure designated as 2 show the same type of information for the highest hourly prediction by the RAM model. In this case, the receptor (9) was downwind of the so-called Wood River refinery complex and the Sioux power plant near Alton, Illinois. This is <u>not an urban situation</u> and it might have been treated more accurately with a rural model. Interestingly, either nothing much happened at the monitor, or the data were

TABLE D-1

SELECTED DAYS OF DATA AND SELECTION CRITERIA

Date	Criterion	Hour Ending	Receptor
01/15/76	RAM-H3	3	104
01/26/76	RAM-2H24	24	115
01/26/76	TEM-2H24	24	115
01/27/76	RAM-H1	5	115
08/23/76	RAM-2H1	5	114
08/23/76	TEM-2H1	5	114
10/28/76	TEM-H1	5	101
10/28/76	TEM-H3	6	101
11/15/76	TEM-H24	24	101
11/16/76	*	*	*
12/06/76	OBS-H1	14	104
12/11/76	OBS-H3	18	104
12/15/76	OBS-H24	24	104
12/31/76	RAM-H24	24	101

* Several high or second-high values were observed and predicted for one, three and twenty-four-hour averaging periods on 11/16/76.

RAM - RAM model predicted concentration
TEM - TEM-8A model predicted concentration
OBS - observed concentration

H1, H3, H24 = Highest one, three and twenty-four-hour average concentration for the year.

2H1, 2H3, 2H24 = Second highest one, three and twenty-four-hour average concentration for the year.

bad, as indicated by the frequent missing designations for the day.

Second-Highest One-Hour Predictions - RAM and TEM-8A

The tables and figure in the "3" set represent the second-highest one-hour prediction by both RAM and TEM-8A. With the northeast wind indicated at the time, this case again represents the effect of the Wood River complex, and it is not a truly urban situation. Once again the monitor allegedly affected showed nothing of any significance.

Highest One-Hour and Three-Hour Predictions - TEM-8A

TEM-8A predicted its highest one-hour and highest three-hour concentrations on the same day and during the same time interval, as shown in Tables 4A and 4B and Figure 4. The wind speeds were very light and variable during these early morning hours and the calculated concentrations were associated with stable diffusion and a low mixing depth. The monitor appears to have been totally unaware of the situation.

Highest Observed Three-Hour Case

The highest observed three-hour case was associated with light SSW winds and neutral stability. The several large sources lying upwind of the receptor were no doubt responsible for the concentrations.

Highest Three-Hour Prediction - RAM

In this instance, the RAM model seems to have singled out the same sources and receptor as in the highest observed three-hour case, but in this instance the air was supposedly more stable and the mixing depth was very shallow. The monitor did show some SO_2, but the values were modest.

Highest Observed Twenty-Four-Hour Concentration

This particular day, summarized in the "7" series, probably identifies the source or source area contributing so substantially to the high annual average at this station. The winds were consistently between SW and W, with a very steady wind speed and temperature. The designated stabilities, ranging from 6 to 3 throughout the period, probably do not reflect the nearly-neutral conditions suggested by the winds and temperatures.

Highest Twenty-Four-Hour Prediction - RAM

The "8" series shows that the RAM model predicted its three-hour maximum on a day with persistent WNW winds of moderate speed. It is difficult to see from the map layout just which source(s) was supposed to be responsible, and the monitor showed no such effect.

Highest Twenty-Four-Hour Prediction - TEM-8A

The "9" series shows that TEM-8A predicted its twenty-four-hour maximum with light NE winds. The monitor did receive some SO_2, but significantly less than Station 104.

Second-Highest Twenty-Four-Hour Predictions - RAM and TEM-8A

The final set of data selected by both models again represented an essentially rural situation, with the Wood River complex and the Sioux power plant as the responsible sources. In this instance, the chosen monitor did show elevated SO_2 concentrations, although not as high as those predicted.

REFERENCES

Londergan, R.J. et al. 1983. Evaluation of Urban Air Quality Simulation Models, (Draft) TRC Env. Consultants, Proj. 1829-R81.

Smith, M.E. 1961. The Concentrations and Residence Times of Pollutants in the Atmosphere, Proceedings, Symposium on "Chemical Reactions in the Tower and Upper Atmosphere," SRI.

TABLE 1A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
12/6/76

HIGHEST ONE-HOUR OBSERVED

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	133	2.42	273.71	132.00	5
2	130	2.38	273.71	132.00	5
3	124	2.16	273.71	132.00	5
4	135	2.01	274.26	132.00	6
5	144	1.41	274.26	132.00	5
6	142	1.29	273.71	712.30	4
7	164	1.57	274.26	704.63	4
8	168	2.36	274.82	696.97	4
9	179	2.05	275.37	689.31	4
10	187	1.70	275.93	681.65	4
11	184	2.07	276.48	673.99	4
12	192	1.77	277.04	666.32	4
13	213	1.68	277.04	658.66	4
14	328	1.69	275.93	651.00	4
15	348	4.75	274.26	651.00	4
16	352	5.21	273.71	651.00	4
17	353	5.31	273.15	647.98	4
18	348	5.40	272.04	640.50	4
19	350	6.24	271.48	633.03	4
20	348	6.12	270.93	625.55	4
21	340	5.84	269.26	618.08	4
22	334	6.18	268.15	610.60	4
23	334	6.58	266.48	603.13	4
24	332	6.83	265.37	595.65	4

TABLE 1B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
12/6/76

HIGHEST ONE-HOUR OBSERVED

Hour Ending	Station 101	103	104	105	106	108	113	114	115	116	120	121	122
1	238	52	-1	84	466	35	144	26	37	7	89	93	39
2	185	50	-1	78	469	26	177	12	35	7	133	110	45
3	205	38	-1	73	472	18	138	8	36	7	148	75	38
4	198	-1	-1	63	443	12	113	9	29	7	196	48	37
5	136	45	-1	57	394	13	109	12	-1	7	140	57	45
6	126	22	-1	52	291	12	88	10	22	7	116	89	97
7	140	14	-1	38	213	41	94	111	28	7	91	96	96
8	163	24	-1	23	748	110	160	140	32	7	82	118	83
9	142	32	-1	41	1268	105	335	208	9	7	52	78	88
10	120	88	-1	27	1007	192	-1	154	7	7	28	70	78
11	116	-1	-1	59	400	191	-1	195	7	7	13	62	46
12	63	58	-1	85	-1	122	-1	75	7	7	7	133	29
13	106	40	-1	43	1260	176	-1	131	7	-1	7	65	32
14	144	199	2487	243	327	124	-1	56	29	7	9	30	34
15	77	74	755	79	290	31	48	23	32	49	23	56	38
16	-1	33	187	108	459	31	64	32	37	7	42	48	31
17	56	31	152	90	412	28	45	16	-1	7	43	38	-1
18	42	26	262	69	320	14	27	7	29	7	46	-1	15
19	36	19	176	49	289	10	19	7	24	7	34	27	8
20	23	7	331	41	254	7	-1	7	9	7	22	26	7
21	35	12	121	27	174	7	-1	7	62	7	7	7	12
22	7	10	118	10	74	7	-1	7	110	11	7	7	7
23	7	11	273	-1	-1	7	-1	-1	45	-1	-1	-1	-1
24	-1	13	-1	-1	-1	8	-1	-1	-1	-1	-1	-1	-1

(-1 indicates missing data)

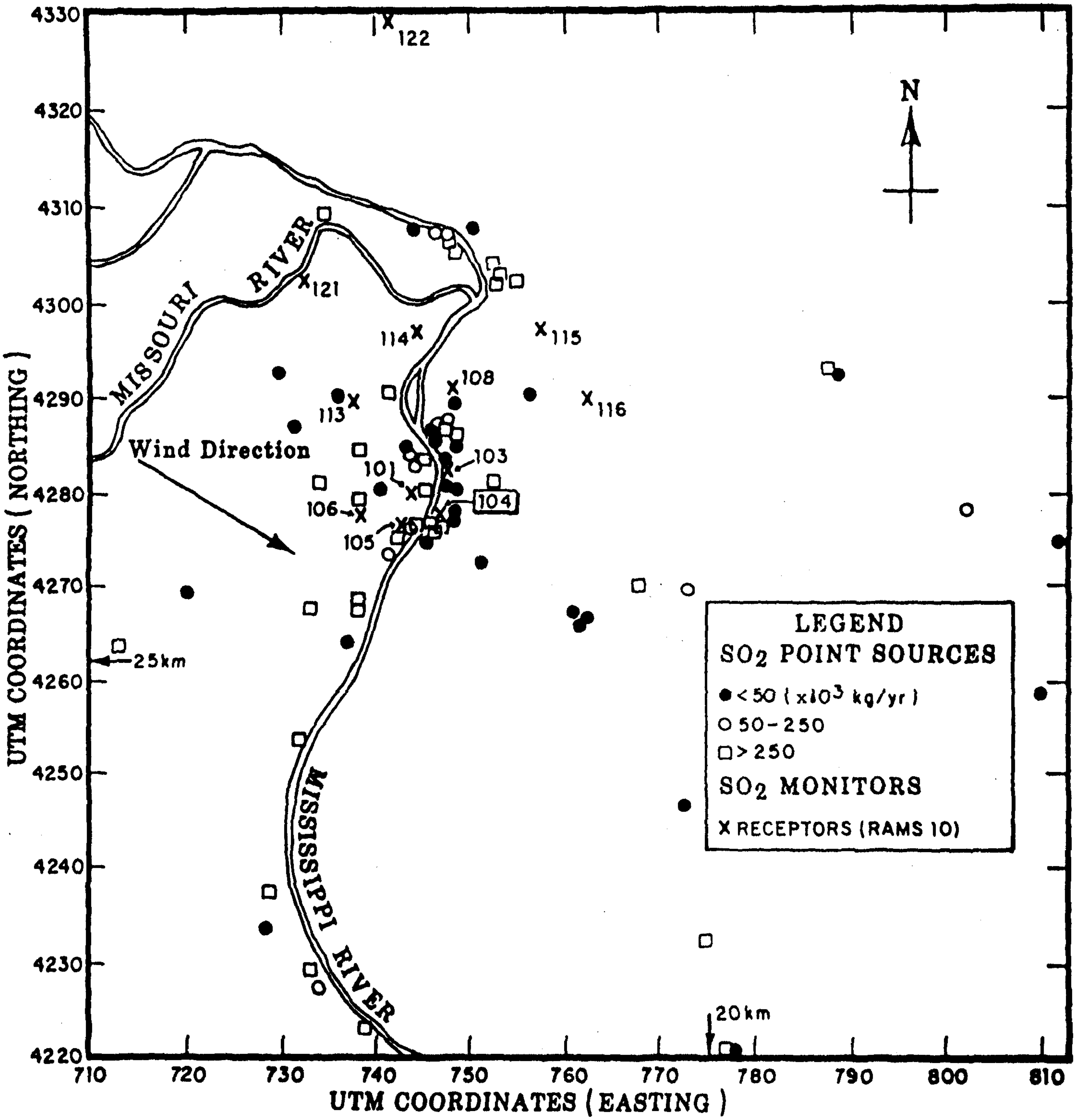

FIGURE 1

Highest One-Hour Observed

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 2A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
1/27/76

HIGHEST ONE-HOUR PREDICTED - RAM

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	350	2.40	263.70	159.00	7
2	348	1.62	263.15	159.00	7
3	333	1.69	263.15	159.00	7
4	328	1.50	262.59	159.00	7
5	314	1.48	262.59	159.00	6
6	300	1.92	262.04	159.00	6
7	301	1.92	262.59	159.00	6
8	295	2.06	263.70	244.33	5
9	304	1.83	265.37	363.94	4
10	323	1.95	266.48	483.55	3
11	318	1.93	267.59	603.16	2
12	302	1.48	268.71	722.78	2
13	293	1.68	269.82	842.39	2
14	296	1.38	270.37	962.00	2
15	289	.79	270.93	962.00	2
16	203	1.21	270.93	962.00	3
17	170	1.19	269.82	962.00	3
18	106	1.38	269.26	952.37	4
19	120	1.81	268.71	747.87	5
20	116	2.36	268.71	630.10	6
21	132	2.96	268.71	512.32	5
22	149	3.52	268.71	394.55	5
23	152	4.14	268.71	276.77	5
24	158	4.44	268.71	159.00	5

TABLE 2B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
1/27/76

HIGHEST ONE-HOUR PREDICTED - RAM

Hour Ending	Station 101	103	104	105	106	108	113	114	115	115	120	121	122
1	22	7	14	99	56	8	7	7	7	9	7	10	10
2	14	7	42	23	162	7	7	7	7	24	7	7	7
3	22	7	63	28	127	7	7	7	-1	57	7	7	7
4	29	17	71	44	12	8	7	7	7	60	7	7	7
5	17	12	100	14	12	7	7	7	7	35	7	7	7
6	38	7	94	20	13	7	8	7	-1	9	7	7	7
7	49	10	146	79	10	7	17	7	8	7	7	7	7
8	53	9	112	84	23	7	21	7	-1	7	7	7	7
9	-1	27	153	81	25	7	16	7	-1	76	7	7	7
10	-1	31	85	56	15	7	7	7	-1	205	7	7	9
11	-1	19	114	46	7	168	8	25	-1	290	7	7	10
12	-1	9	106	39	13	10	7	7	-1	188	7	7	7
13	-1	35	98	30	7	8	7	7	-1	152	7	7	7
14	12	51	25	14	7	7	7	7	-1	128	7	7	7
15	-1	40	46	23	7	8	7	7	-1	36	7	7	7
16	80	46	68	28	7	7	7	7	27	7	7	7	7
17	55	39	26	38	7	7	7	7	9	7	7	7	7
18	50	13	52	58	15	7	8	7	7	7	7	7	7
19	51	28	83	11	10	7	7	7	10	17	7	7	7
20	106	44	77	21	66	7	10	7	90	41	66	7	7
21	81	32	67	30	66	8	30	7	74	67	186	7	7
22	171	39	55	31	60	11	122	32	64	61	123	-1	11
23	-1	115	98	-1	-1	41	127	89	-1	-1	75	153	-1
24	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

(-1 indicates missing data)

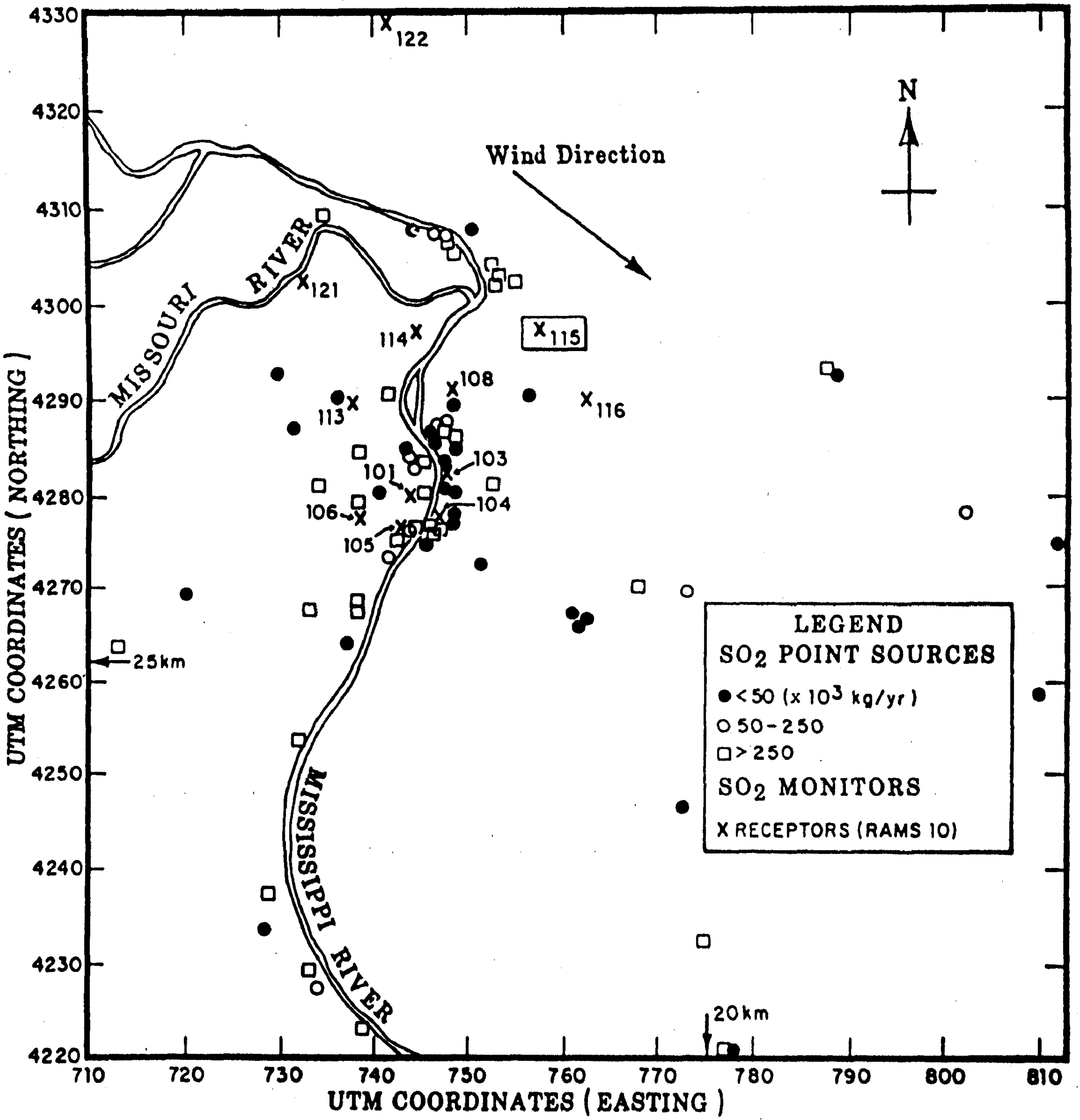

FIGURE 2

Highest One-Hour Predicted - RAM

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 3A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
8/23/76

SECOND-HIGHEST ONE-HOUR PREDICTED - RAM & TEM

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	157	1.04	293.71	135.00	7
2	140	1.33	293.15	135.00	7
3	146	1.34	292.60	135.00	7
4	34	.91	292.04	135.00	7
5	62	.75	291.48	135.00	7
6	82	.76	292.04	266.78	6
7	59	1.04	294.82	504.06	5
8	56	1.12	297.04	741.33	4
9	58	1.19	299.82	978.61	3
10	88	1.78	301.49	1215.89	2
11	112	2.34	302.60	1453.17	2
12	106	3.03	303.15	1690.44	2
13	93	3.56	302.60	1927.72	3
14	90	4.07	302.04	2165.00	3
15	76	4.18	302.60	2165.00	4
16	74	4.31	302.04	2165.00	3
17	75	3.96	301.49	2165.00	3
18	75	3.19	300.37	2165.00	4
19	75	2.82	299.26	2047.15	5
20	78	2.57	298.15	1664.72	5
21	86	1.94	297.60	1282.29	5
22	83	1.94	297.04	899.86	6
23	83	1.50	296.49	517.43	6
24	52	1.53	295.37	135.00	6

TABLE 3B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
8/23/76

SECOND-HIGHEST ONE-HOUR PREDICTED - RAM & TEM

Hour Ending	Station 101	103	104	105	106	108	113	114	115	116	120	121	122
1	11	-1	7	7	27	-1	-1	7	7	7	7	42	24
2	7	-1	7	7	25	-1	-1	7	7	7	7	37	10
3	7	-1	7	7	20	-1	-1	7	7	7	7	10	15
4	28	-1	7	7	17	7	-1	7	7	7	7	7	25
5	39	-1	7	7	12	7	-1	7	7	7	7	7	-1
6	10	-1	7	7	18	7	-1	7	7	7	7	7	16
7	10	-1	7	7	16	7	-1	7	7	7	7	7	-1
8	24	-1	21	9	49	-1	-1	6	6	6	6	34	15
9	30	-1	42	178	92	10	-1	-1	6	6	6	30	21
10	13	-1	40	143	101	6	-1	-1	6	6	6	234	14
11	57	19	40	143	-1	6	73	6	-1	6	34	141	17
12	76	-1	58	64	-1	6	-1	-1	6	6	54	-1	13
13	12	-1	21	69	-1	12	-1	-1	6	6	-1	-1	24
14	7	-1	7	92	71	-1	-1	6	6	6	-1	-1	15
15	6	-1	6	70	36	-1	-1	6	6	6	-1	-1	18
16	6	-1	6	111	29	10	-1	6	6	6	15	45	20
17	6	-1	6	103	32	6	-1	6	6	6	13	42	15
18	6	-1	6	68	32	7	-1	6	6	6	9	36	-1
19	6	-1	6	29	36	6	-1	6	6	6	6	34	13
20	6	6	6	44	42	-1	-1	6	6	6	6	33	-1
21	18	6	6	191	32	7	-1	6	6	6	6	-1	12
22	9	6	6	152	78	-1	-1	6	6	6	6	-1	-1
23	11	-1	6	202	-1	-1	-1	7	-1	-1	-1	-1	22
24	-1	-1	-1	-1	-1	7	-1	-1	-1	-1	-1	-1	-1

(-1 indicates missing data)

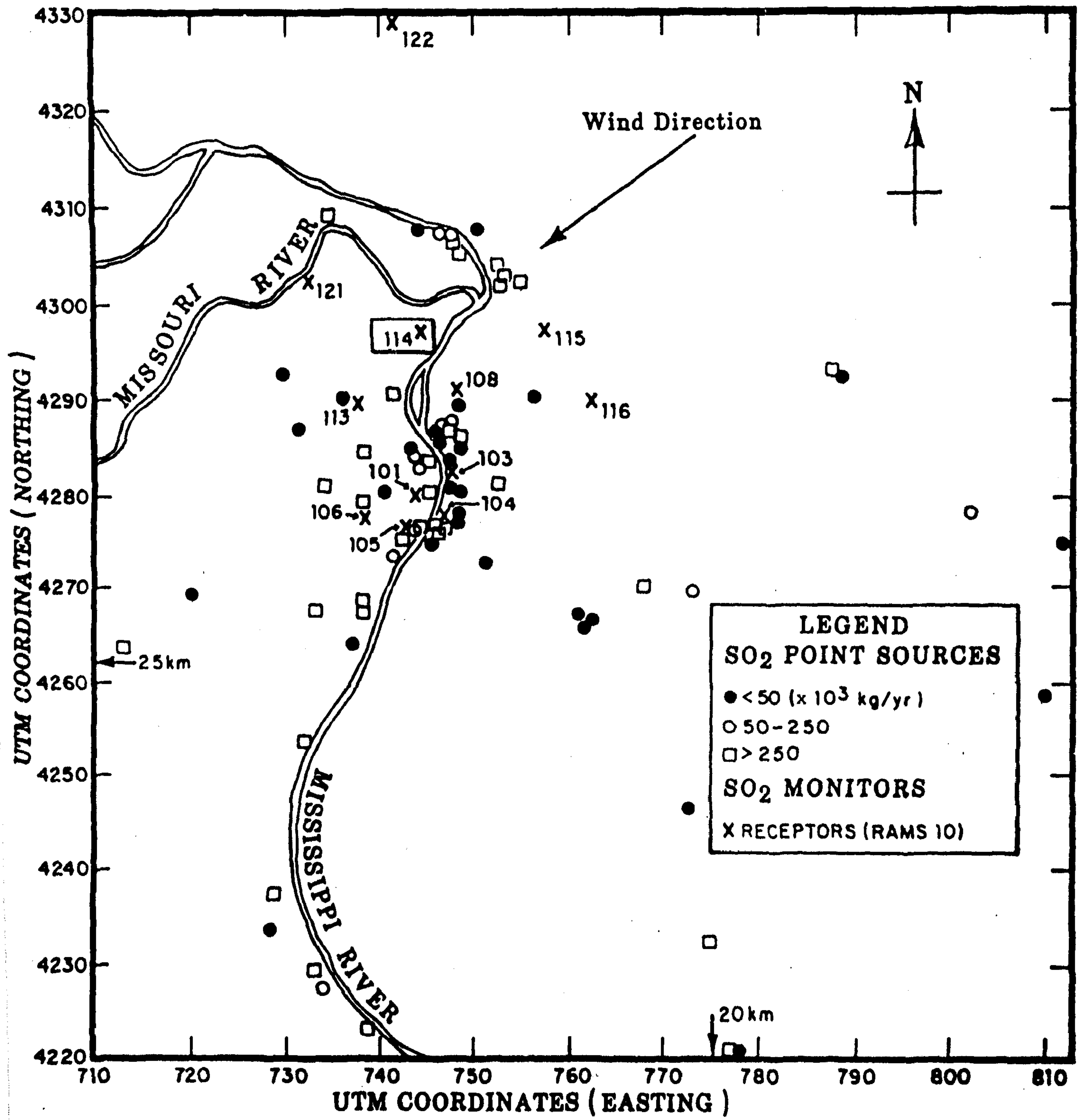

FIGURE 3

<u>Second-Highest One-Hour Predicted - RAM & TEM</u>

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 4A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
10/28/76

HIGHEST ONE-HOUR PREDICTED - TEM
HIGHEST THREE-HOUR PREDICTED - TEM

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	40	.80	273.15	116.00	7
2	46	.70	272.59	116.00	7
3	270	.58	272.59	116.00	7
4	340	.67	272.04	116.00	7
5	16	.51	271.48	116.00	7
6	135	.71	271.48	116.00	7
7	178	1.01	272.59	179.73	6
8	184	1.11	275.37	301.34	5
9	187	1.71	277.04	422.95	4
10	198	2.86	278.71	544.56	3
11	194	2.47	279.82	666.17	2
12	183	1.28	280.37	787.78	2
13	187	1.98	281.48	909.39	2
14	196	2.20	282.04	1031.00	3
15	209	2.46	282.04	1031.00	3
16	202	2.39	281.48	1031.00	4
17	191	2.17	279.82	1031.00	4
18	174	1.82	278.71	902.93	5
19	161	2.03	277.04	770.44	6
20	168	2.40	277.04	637.95	6
21	173	2.42	276.48	505.46	6
22	177	2.50	275.93	372.98	6
23	180	2.92	275.93	240.49	6
24	188	3.33	275.37	108.00	6

TABLE 4B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
10/28/76

HIGHEST ONE-HOUR PREDICTED - TEM
HIGHEST THREE-HOUR PREDICTED - TEM

Hour	Station												
Ending	101	103	104	105	106	108	113	114	115	116	120	121	122
1	9	-1	9	-1	26	8	7	8	7	7	-1	10	7
2	11	7	18	9	22	9	7	7	7	7	-1	8	7
3	19	7	32	20	-1	10	7	-1	7	7	-1	8	7
4	11	7	26	72	23	8	7	-1	7	7	-1	7	7
5	11	7	40	50	11	8	7	-1	7	7	-1	7	7
6	9	7	84	8	12	7	8	-1	7	7	-1	7	7
7	10	11	86	9	22	12	17	-1	7	7	-1	7	7
8	21	26	63	8	34	9	42	-1	7	7	-1	7	7
9	17	32	37	23	229	69	37	-1	9	7	-1	8	7
10	140	62	264	52	366	121	71	-1	10	7	-1	48	42
11	81	28	92	-1	167	62	159	-1	36	7	-1	112	138
12	48	-1	66	45	50	70	121	-1	88	7	-1	81	172
13	55	-1	67	48	46	82	87	-1	94	7	-1	44	136
14	59	-1	85	55	79	98	72	-1	88	7	-1	90	230
15	74	-1	54	81	132	70	61	-1	76	7	-1	86	158
16	126	55	61	80	146	97	110	-1	63	7	-1	60	60
17	108	62	66	70	147	132	94	-1	49	7	-1	80	38
18	147	116	159	140	178	91	92	-1	41	31	-1	71	60
19	115	129	183	102	140	127	152	-1	45	24	-1	68	41
20	73	48	105	58	94	99	173	-1	45	7	-1	129	22
21	61	23	103	30	45	50	110	-1	31	7	-1	171	33
22	41	9	80	25	-1	54	56	-1	-1	7	-1	206	22
23	-1	22	45	18	21	50	-1	-1	-1	7	-1	-1	58
24	-1	10	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

(-1 indicates missing data)

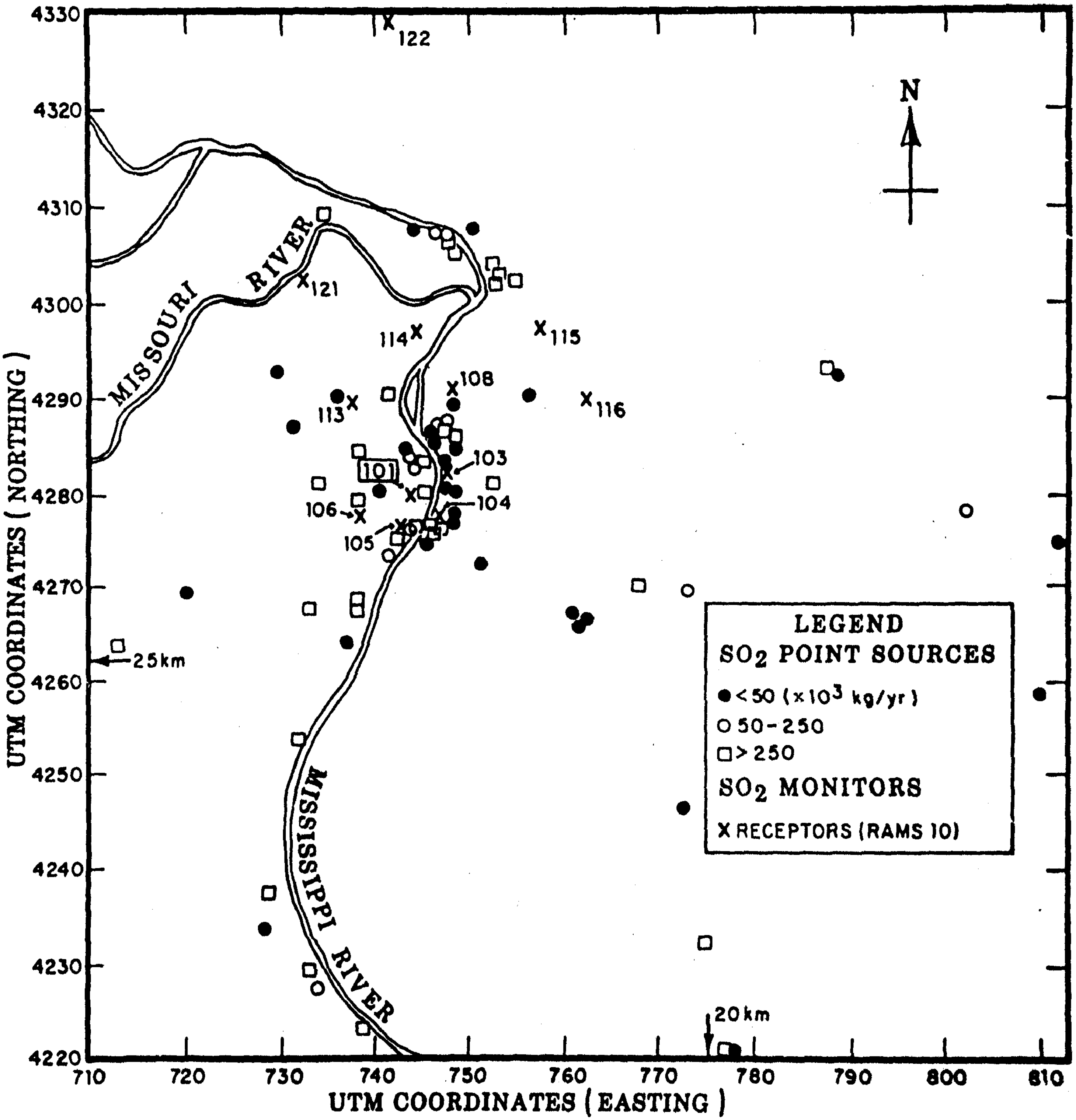

FIGURE 4

Highest One-Hour Predicted - TEM
Highest Three-Hour Predicted - TEM

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 5A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
12/11/76

HIGHEST THREE-HOUR OBSERVED

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	11	4.04	266.48	622.45	4
2	13	3.68	265.93	188.00	5
3	13	3.24	265.93	188.00	5
4	6	2.99	265.93	188.00	5
5	10	2.59	265.93	188.00	5
6	10	2.99	265.93	188.00	5
7	8	3.17	265.93	188.00	5
8	19	2.77	265.93	256.90	4
9	27	2.48	266.48	349.91	4
10	26	2.32	266.48	442.93	3
11	40	1.56	267.04	535.95	4
12	36	.94	268.15	628.97	3
13	21	.66	269.26	721.98	3
14	296	.72	269.82	815.00	3
15	250	.91	269.82	815.00	4
16	180	1.81	270.37	815.00	4
17	190	1.63	270.37	815.00	4
18	192	1.80	270.93	815.00	4
19	199	1.16	270.93	815.00	4
20	194	1.10	271.48	815.00	4
21	177	1.27	271.48	815.00	4
22	191	1.34	271.48	815.00	4
23	200	2.32	272.04	815.00	4
24	211	2.41	272.04	815.00	4

TABLE 5B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
12/11/76

HIGHEST THREE-HOUR OBSERVED

Hour Ending	Station 101	103	104	105	106	108	113	114	115	116	120	121	122
1	32	52	360	63	63	7	7	7	7	10	7	147	7
2	30	81	570	73	36	12	7	7	7	7	7	125	7
3	50	117	702	97	59	18	7	7	11	8	-1	156	7
4	59	-1	788	143	93	31	7	15	19	28	15	177	7
5	78	78	541	159	102	45	7	7	15	36	34	64	7
6	94	124	1114	198	121	36	11	7	17	42	50	53	-1
7	87	83	776	179	121	26	8	7	10	63	29	60	9
8	89	108	793	160	109	38	8	27	19	47	36	61	11
9	123	117	473	276	90	111	47	69	51	36	61	31	27
10	124	116	-1	249	134	141	109	97	58	42	39	36	44
11	166	106	-1	314	151	155	159	159	51	36	55	45	49
12	165	86	757	247	221	76	200	218	45	36	64	5[illegible]	73
13	194	98	1126	300	227	83	188	203	-1	35	76	72	82
14	-1	139	1564	314	283	159	202	202	-1	35	67	74	118
15	-1	228	1741	330	191	285	129	141	193	60	58	64	163
16	360	300	1998	325	172	279	136	198	138	157	63	86	122
17	300	333	1711	286	324	324	217	245	174	217	64	73	69
18	301	238	1476	359	-1	-1	-1	342	-1	361	61	-1	69
19	371	456	-1	532	-1	401	-1	347	291	554	59	60	69
20	385	498	2099	556	-1	309	-1	334	337	-1	60	58	68
21	415	441	-1	513	-1	423	-1	311	389	500	73	64	61
22	350	494	-1	347	-1	464	-1	305	368	406	58	85	66
23	258	331	1735	227	-1	413	-1	378	383	437	58	80	95
24	153	195	1894	153	-1	292	-1	262	386	305	39	60	84

(-1 indicates missing data)

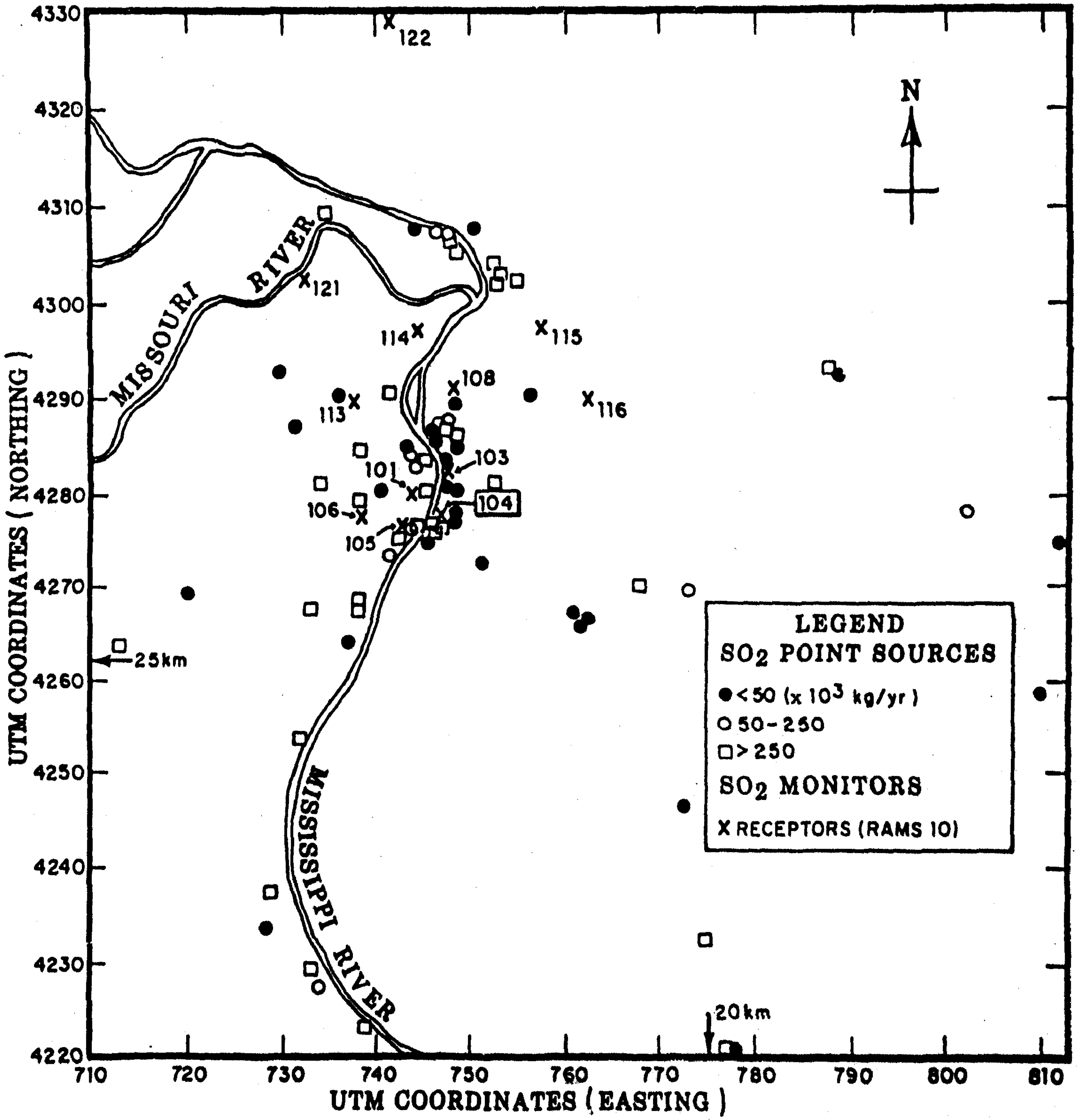

FIGURE 5

Highest Three-Hour Observed

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 6A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
1/15/76

HIGHEST THREE-HOUR PREDICTED - RAM

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	213	2.89	270.37	159.00	6
2	203	2.72	269.82	159.00	6
3	198	2.52	269.82	159.00	6
4	190	2.53	269.82	159.00	6
5	191	2.93	269.26	159.00	6
6	186	3.14	269.82	159.00	6
7	176	3.32	270.37	159.00	5
8	175	4.36	272.04	249.94	4
9	179	4.52	273.71	400.12	4
10	177	5.22	275.37	550.29	4
11	182	5.70	278.15	700.47	4
12	181	6.68	279.82	850.65	4
13	186	6.83	280.37	1000.82	4
14	193	7.40	280.93	1151.00	4
15	203	6.61	280.93	1151.00	4
16	207	5.76	280.93	1151.00	4
17	232	8.48	280.37	1150.49	4
18	228	8.22	279.82	1137.85	4
19	222	6.32	279.82	1125.21	4
20	223	5.43	279.82	1112.56	4
21	230	5.15	279.82	1099.92	4
22	230	4.58	279.26	1087.28	4
23	233	3.98	279.26	1074.64	4
24	257	4.15	279.26	1061.99	4

TABLE 6B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
1/15/76

HIGHEST THREE-HOUR PREDICTED - RAM

Hour Ending	Station 101	103	104	105	106	108	113	114	115	116	120	121	122
1	37	20	202	32	18	56	-1	23	40	47	7	7	7
2	35	21	123	27	34	94	-1	50	62	29	7	7	7
3	84	8	106	24	40	66	-1	44	30	33	7	11	7
4	187	11	121	24	120	115	-1	107	11	25	9	25	7
5	253	24	89	23	85	147	31	55	7	44	16	15	7
6	259	27	82	27	101	195	-1	73	19	99	8	16	7
7	241	95	92	54	159	240	-1	142	181	70	14	11	20
8	306	96	98	30	85	194	-1	159	82	-1	7	14	118
9	41	51	135	12	63	72	-1	202	7	-1	7	109	249
10	48	107	96	20	93	70	-1	62	7	22	7	75	269
11	73	28	55	17	80	68	-1	62	7	8	7	8	122
12	7	33	45	7	85	30	-1	35	7	7	7	96	131
13	33	46	40	8	151	37	-1	69	7	7	7	12	60
14	68	56	182	7	200	64	-1	66	7	7	7	7	68
15	186	7	215	43	153	132	-1	86	7	7	7	7	16
16	84	56	279	282	13	179	-1	7	20	7	7	7	8
17	8	52	185	106	14	7	-1	7	12	11	11	19	7
18	8	-1	129	163	19	7	-1	7	7	7	7	75	7
19	17	-1	178	145	14	7	-1	7	7	7	7	106	7
20	7	-1	193	242	18	7	-1	7	7	30	7	9	7
21	9	-1	78	74	18	8	-1	14	7	70	86	104	7
22	10	-1	69	58	14	7	119	116	18	75	277	9	7
23	-1	-1	79	113	20	-1	-1	-1	-1	-1	8	-1	-1
24	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

(-1 indicates missing data)

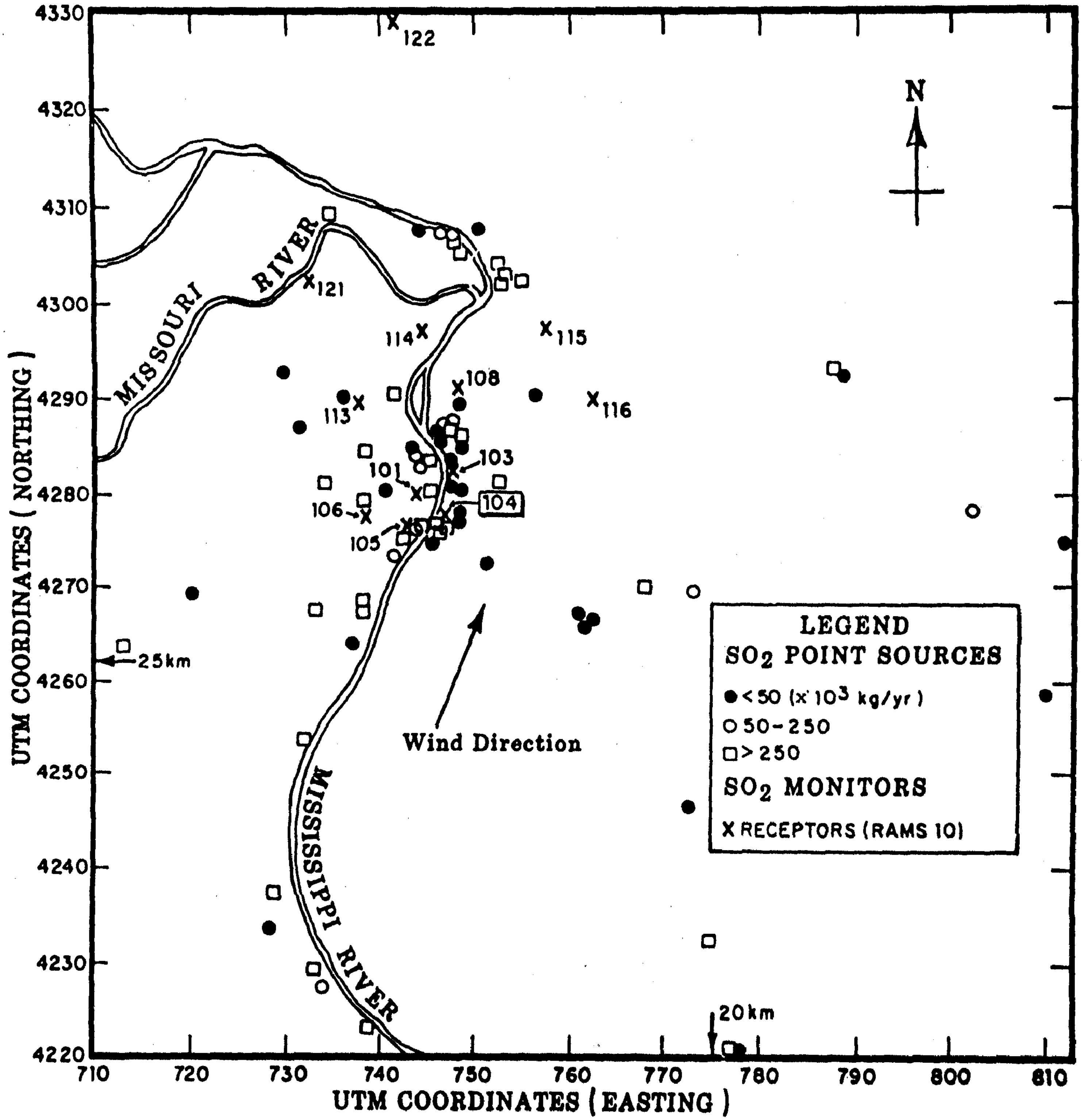

FIGURE 6

Highest Three-Hour Predicted - .RAM

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 7A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
12/15/76

HIGHEST TWENTY-FOUR HOUR OBSERVED

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	214	2.90	274.82	124.00	6
2	217	3.02	274.26	124.00	6
3	224	2.60	274.26	124.00	6
4	237	2.54	273.71	124.00	6
5	260	2.44	273.71	124.00	6
6	262	2.48	273.15	124.00	6
7	265	2.35	273.15	124.00	6
8	244	2.37	275.37	189.93	5
9	243	2.02	277.04	285.10	4
10	244	2.26	278.71	380.28	3
11	261	2.24	280.37	475.46	3
12	262	2.13	282.04	570.64	3
13	270	2.70	283.71	665.82	3
14	269	2.78	284.26	761.00	3
15	269	2.72	284.26	761.00	4
16	271	2.50	282.60	761.00	4
17	245	2.09	280.93	730.09	5
18	237	2.18	279.26	650.94	6
19	219	2.47	278.71	571.78	6
20	230	2.80	278.71	492.63	6
21	237	3.06	278.15	413.47	5
22	248	3.57	278.71	334.31	5
23	282	4.91	278.15	255.16	5
24	303	5.34	277.04	176.00	5

TABLE 7B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
12/15/76

HIGHEST TWENTY-FOUR HOUR OBSERVED

Hour Ending	Station 101	103	104	105	106	108	113	114	115	116	120	121	122
1	-1	95	1835	62	83	93	20	38	53	-1	25	-1	7
2	-1	53	-1	68	56	112	27	56	78	-1	9	-1	7
3	75	60	1807	64	130	101	50	48	82	85	20	-1	8
4	52	65	1365	53	64	112	44	58	119	80	13	-1	12
5	43	51	1551	33	40	93	13	47	87	112	7	-1	8
6	32	62	1129	42	71	87	8	7	58	113	7	-1	7
7	51	65	-1	44	45	53	7	7	61	-1	7	-1	7
8	55	125	1725	108	46	47	7	7	64	-1	7	-1	7
9	77	90	1302	101	34	44	8	7	78	-1	8	-1	7
10	59	79	1376	79	58	28	7	7	80	48	-1	-1	8
11	52	72	1163	148	34	13	9	7	28	53	7	7	8
12	38	65	518	28	24	82	7	7	7	9	7	-1	7
13	37	34	341	30	28	73	7	7	7	7	7	-1	7
14	25	19	206	26	36	119	7	7	8	7	8	-1	7
15	21	29	237	46	42	82	7	7	7	7	8	-1	7
16	40	31	466	122	-1	11	-1	7	7	7	12	-1	7
17	160	71	1367	297	-1	7	-1	7	7	7	16	-1	7
18	349	271	2206	582	610	9	39	7	7	7	15	-1	7
19	493	419	-1	497	588	38	89	22	7	54	34	-1	7
20	124	260	1460	100	286	110	78	41	28	120	46	-1	7
21	72	76	2135	63	78	87	48	12	109	29	25	10	-1
22	70	55	-1	54	64	68	8	7	108	60	11	7	-1
23	73	120	-1	63	-1	24	24	7	80	-1	-1	7	-1
24	-1	45	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

(-1 indicates missing data)

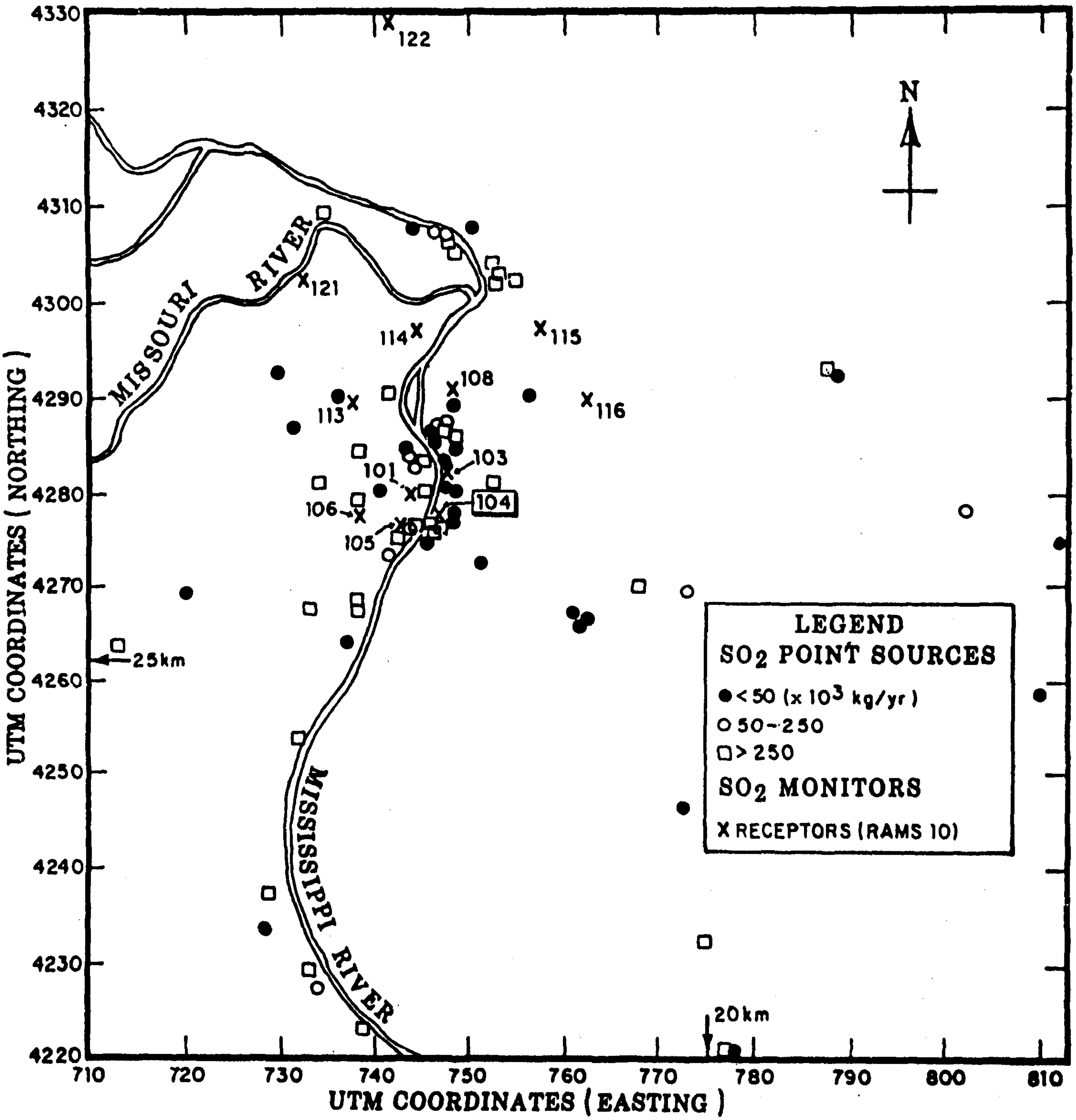

FIGURE 7

Highest Twenty-Four Hour - Observed

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 8B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
12/31/76

HIGHEST TWENTY-FOUR HOUR PREDICTED - RAM

Hour Ending	Station 101	103	104	105	106	108	113	114	115	116	120	121	122
1	8	8	127	8	9	8	8	8	117	8	8	8	-1
2	8	8	423	8	11	8	8	8	210	48	8	8	-1
3	8	8	253	8	15	17	8	45	244	72	-1	8	-1
4	8	8	146	8	17	11	8	20	166	34	8	8	-1
5	33	-1	69	14	8	-1	8	8	88	8	8	8	-1
6	22	10	72	22	8	8	14	8	19	20	-1	8	-1
7	34	10	60	30	8	8	15	8	19	18	-1	8	-1
8	13	8	13	73	8	8	8	8	8	8	-1	8	-1
9	59	8	163	55	8	8	10	8	8	8	-1	8	-1
10	22	9	631	44	20	124	8	71	29	35	8	8	-1
11	32	72	683	49	23	-1	23	120	101	187	8	8	-1
12	25	73	198	17	9	7	17	7	181	212	7	7	-1
13	20	82	257	9	11	7	10	7	71	35	7	7	-1
14	47	40	242	25	16	8	10	7	57	8	7	7	-1
15	15	20	104	25	9	8	15	7	59	19	7	7	-1
16	33	11	119	24	17	8	9	7	92	37	7	7	-1
17	33	8	121	22	9	8	10	7	98	79	7	7	-1
18	13	11	96	23	10	8	13	7	8	30	7	7	-1
19	26	20	148	21	7	8	8	7	7	7	7	7	-1
20	45	18	113	15	7	7	8	7	7	7	7	7	-1
21	52	24	187	42	10	7	8	7	7	7	7	7	-1
22	65	23	258	22	25	9	17	8	8	8	8	8	-1
23	8	-1	150	-1	39	8	9	8	8	-1	8	8	8
24	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

(-1 indicates missing data)

TABLE 8A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
12/31/76

HIGHEST TWENTY-FOUR HOUR PREDICTED - RAM

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	316	5.20	254.26	245.00	5
2	316	4.40	254.26	245.00	5
3	317	4.30	253.70	245.00	5
4	312	3.84	254.26	245.00	5
5	303	3.66	254.82	245.00	5
6	298	3.60	254.26	245.00	5
7	299	3.47	254.26	245.00	5
8	299	3.55	254.26	271.78	4
9	302	3.96	254.26	317.82	4
10	306	3.02	255.37	363.86	3
11	284	2.84	256.48	409.89	3
12	281	3.09	258.15	455.93	3
13	284	3.22	259.26	501.96	3
14	300	3.23	260.37	548.00	3
15	300	3.20	260.93	548.00	3
16	303	3.24	260.37	548.00	4
17	304	3.18	259.26	534.62	5
18	297	2.88	258.70	482.25	6
19	298	3.06	258.70	429.87	6
20	299	3.17	258.15	377.50	6
21	295	2.71	257.59	325.12	6
22	292	2.84	257.59	272.75	6
23	304	3.15	257.59	220.37	5
24	305	3.60	257.59	168.00	5

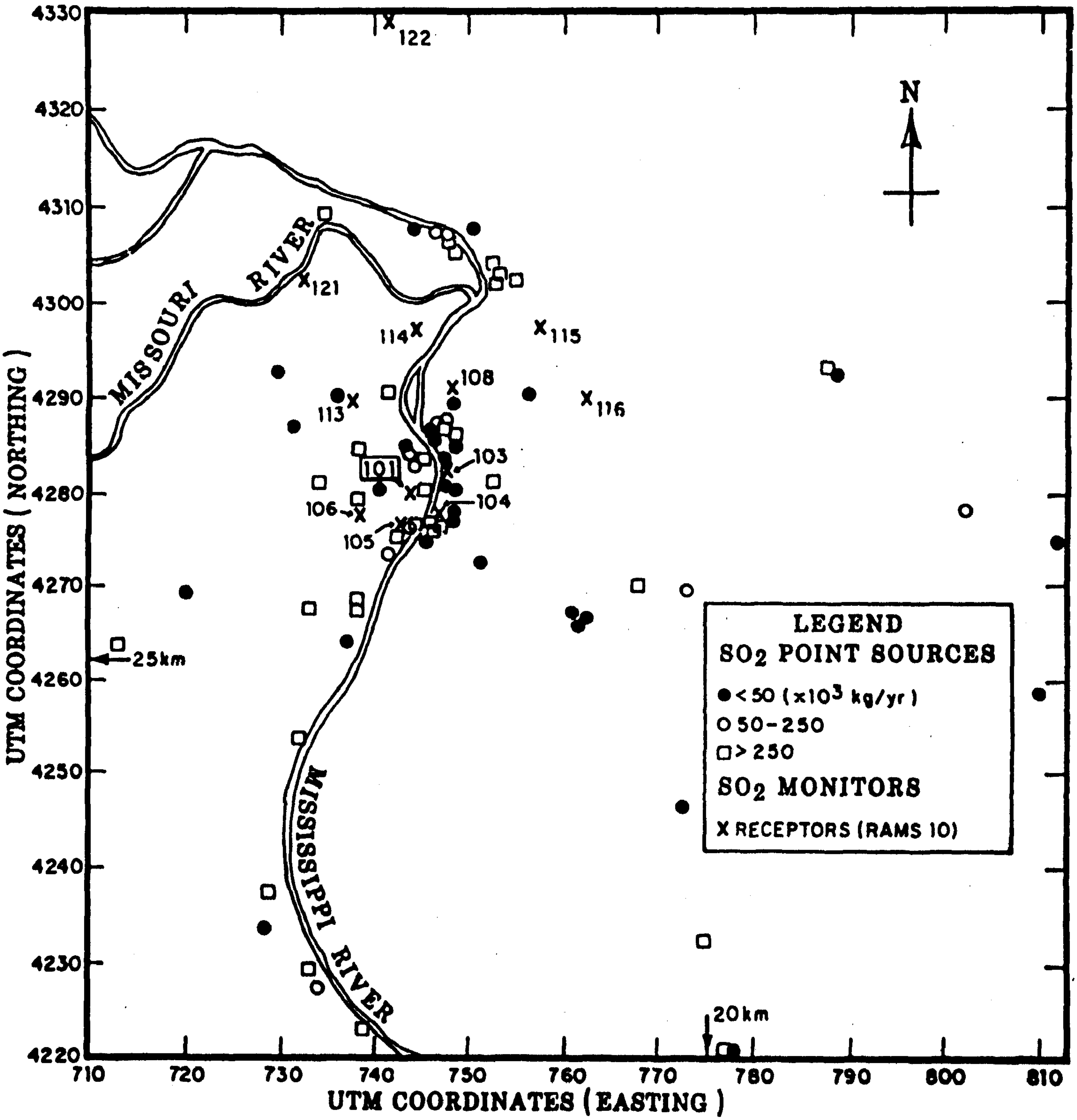

FIGURE 8

Highest Twenty-Four-Hour Predicted - RAM

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 9A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
11/15/76

HIGHEST TWENTY-FOUR HOUR PREDICTED - TEM

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	115	.65	273.15	96.00	6
2	87	.58	273.15	96.00	6
3	34	.86	273.15	96.00	6
4	16	1.32	272.59	96.00	7
5	19	1.41	272.04	96.00	7
6	16	1.08	271.48	96.00	7
7	22	.85	271.48	117.31	6
8	20	.76	273.71	236.41	5
9	68	.74	275.93	355.51	4
10	91	1.16	277.59	474.61	3
11	77	1.26	278.71	593.70	2
12	62	1.01	279.26	712.00	2
13	39	.89	279.82	831.90	2
14	115	.59	280.37	951.00	2
15	167	.63	280.37	951.00	2
16	83	.67	279.82	951.00	3
17	90	.82	278.15	954.56	4
18	76	1.22	277.04	802.59	5
19	104	1.36	275.93	684.82	6
20	108	1.48	274.82	567.06	7
21	114	1.45	274.26	449.29	7
22	148	1.76	274.26	331.53	7
23	163	1.68	273.71	213.76	7
24	165	1.36	273.15	96.00	7

TABLE 9B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
11/15/76

HIGHEST TWENTY-FOUR HOUR PREDICTED - TEM

Hour Ending	Station 101	103	104	105	106	108	113	114	115	116	120	121	122
1	63	20	314	10	52	10	33	7	-1	7	26	30	-1
2	41	26	386	-1	-1	13	29	7	-1	7	30	30	7
3	47	12	415	10	25	7	24	8	-1	7	28	25	7
4	52	8	323	14	42	7	14	12	-1	7	44	32	7
5	34	17	146	25	78	12	9	9	-1	7	18	33	7
6	45	22	140	31	40	10	24	17	-1	7	14	28	7
7	45	23	232	28	39	15	23	26	-1	7	7	26	7
8	66	30	404	28	75	16	43	23	-1	7	7	29	7
9	72	67	809	31	260	60	63	136	-1	7	24	-1	30
10	155	29	454	127	226	58	127	144	-1	7	64	-1	69
11	139	71	456	105	240	48	191	122	-1	7	122	-1	60
12	119	44	376	51	203	27	296	120	-1	7	124	-1	51
13	66	24	313	47	125	21	190	140	-1	7	117	-1	33
14	116	45	237	43	116	15	205	60	-1	7	113	-1	34
15	141	42	647	32	129	21	75	19	-1	7	-1	-1	31
16	153	67	734	32	125	32	82	11	-1	7	88	121	27
17	111	51	401	36	179	45	92	37	-1	7	89	123	28
18	66	48	420	33	194	79	139	22	-1	9	90	123	21
19	73	46	622	32	135	62	64	44	-1	8	68	133	13
20	104	48	801	23	89	45	67	35	-1	18	56	141	7
21	88	26	580	47	86	36	62	38	-1	137	69	132	8
22	147	32	782	20	37	36	59	48	-1	231	86	76	8
23	-1	-1	-1	8	-1	63	-1	-1	-1	-1	-1	-1	-1
24	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

(-1 indicates missing data)

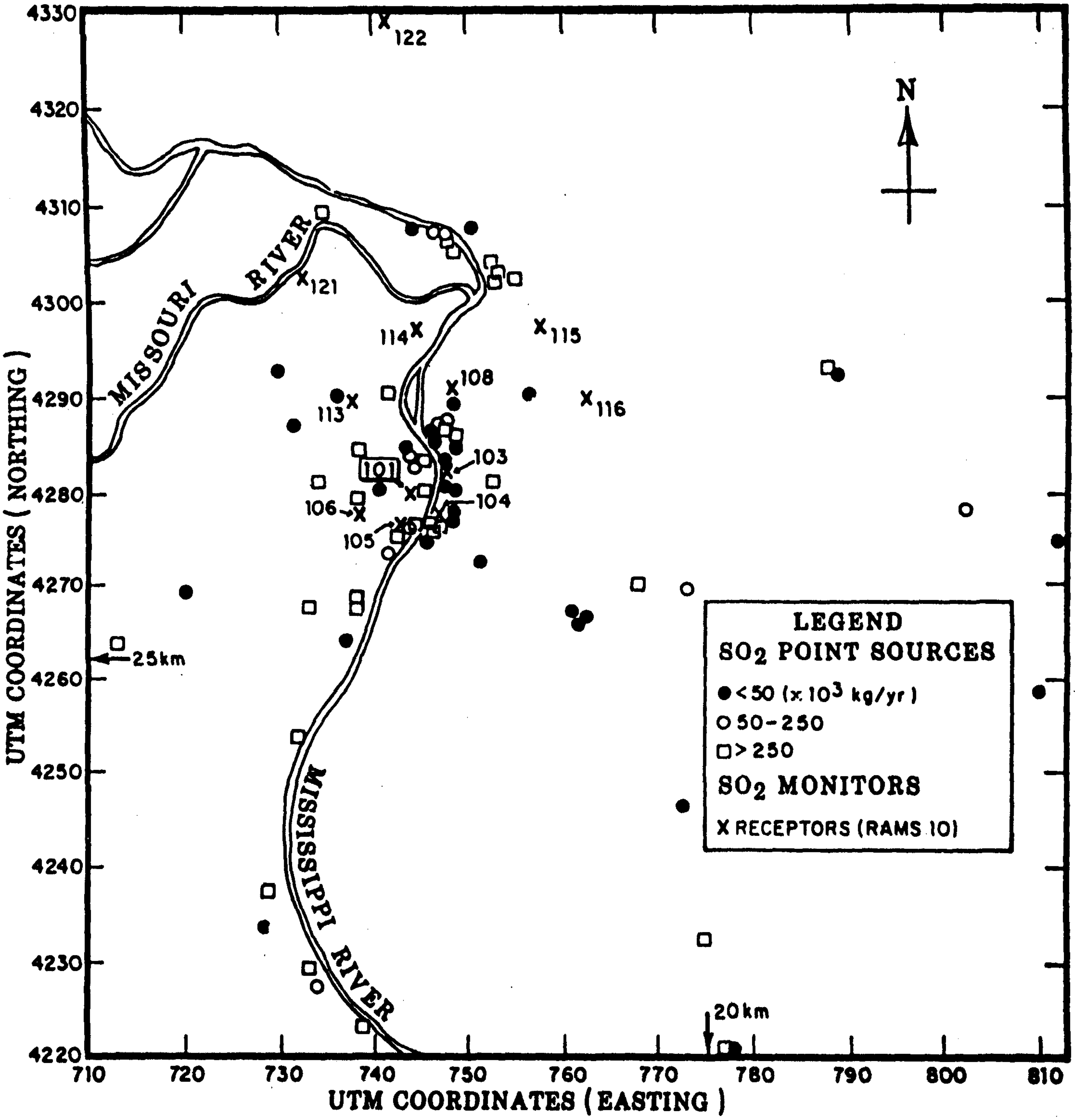

FIGURE 9

Highest Twenty-Four-Hour Predicted - TEM

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

TABLE 10A

HOURLY METEOROLOGY
COMPOSITE FROM 25 ST. LOUIS RAPS/RAMS STATIONS
1/26/76

SECOND-HIGHEST TWENTY-FOUR HOUR PREDICTED - RAM & TEM

Hour Ending	Wind Direction (Degrees)	Wind Speed (M/S)	Temperature (Degree K)	Mixing Height (Meters)	Stability Class
1	321	3.59	272.04	810.27	4
2	322	3.70	272.04	805.71	4
3	321	3.33	271.48	801.15	4
4	317	3.83	270.93	796.59	4
5	318	4.37	270.37	792.03	4
6	319	4.74	269.82	787.47	4
7	313	3.88	269.26	782.91	4
8	316	3.74	268.71	778.35	4
9	313	3.83	268.71	773.80	4
10	311	4.21	268.71	769.24	4
11	312	3.38	269.26	764.68	4
12	313	3.23	270.37	760.12	3
13	305	3.23	270.93	755.56	4
14	304	5.01	270.93	751.00	4
15	305	5.52	270.93	751.00	4
16	303	5.12	270.37	751.00	4
17	305	5.05	268.71	751.00	4
18	308	4.39	268.15	678.49	5
19	311	4.52	267.04	591.91	5
20	317	4.53	266.48	505.33	5
21	321	4.34	265.93	418.75	5
22	330	4.11	265.37	332.16	6
23	346	3.18	264.82	245.58	6
24	350	2.89	264.26	159.00	6

TABLE 10B

SELECTED MODEL EVALUATION INPUT DATA FOR RAPS DATA BASE
HOURLY MEASURED SO_2 CONCENTRATIONS (UG/M^3) BY STATION
1/26/76

SECOND-HIGHEST TWENTY-FOUR HOUR PREDICTED - RAM & TEM

Hour Ending	Station 101	103	104	105	106	108	113	114	115	116	120	121	122
1	27	7	45	12	7	37	7	32	160	38	7	7	7
2	26	7	96	7	7	13	7	36	204	63	7	7	7
3	23	7	76	7	7	17	7	21	239	85	7	7	7
4	15	7	48	7	7	10	7	8	46	43	7	7	7
5	18	7	34	7	7	10	7	10	80	22	7	7	7
6	21	7	50	7	7	7	7	7	66	43	7	7	7
7	17	7	61	19	7	7	7	7	86	46	7	7	7
8	12	7	35	45	8	7	7	29	38	34	7	7	7
9	-1	7	59	43	7	7	7	7	54	31	7	7	7
10	-1	7	22	32	7	7	7	96	41	43	7	7	7
11	-1	7	13	36	7	103	7	-1	80	-1	7	7	7
12	-1	7	11	44	7	105	7	26	159	-1	7	7	7
13	-1	7	18	28	7	15	7	16	83	83	7	7	7
14	57	7	23	34	7	38	7	15	24	112	7	7	7
15	41	7	8	8	7	10	9	7	45	110	7	8	7
16	33	7	8	7	8	7	8	7	95	159	7	-1	7
17	-1	-1	7	8	7	7	9	7	121	147	7	7	7
18	-1	7	8	8	7	7	7	7	240	60	7	7	7
19	40	7	13	12	7	7	7	7	288	129	7	8	7
20	43	7	65	7	7	7	7	7	161	140	7	7	7
21	43	7	38	7	7	7	7	7	152	139	7	8	7
22	39	7	90	10	7	162	7	61	72	20	7	7	10
23	-1	7	17	14	7	84	-1	-1	12	8	7	7	-1
24	-1	-1	-1	-1	-1	-1	-1	-1	7	-1	-1	-1	-1

(-1 indicates missing data)

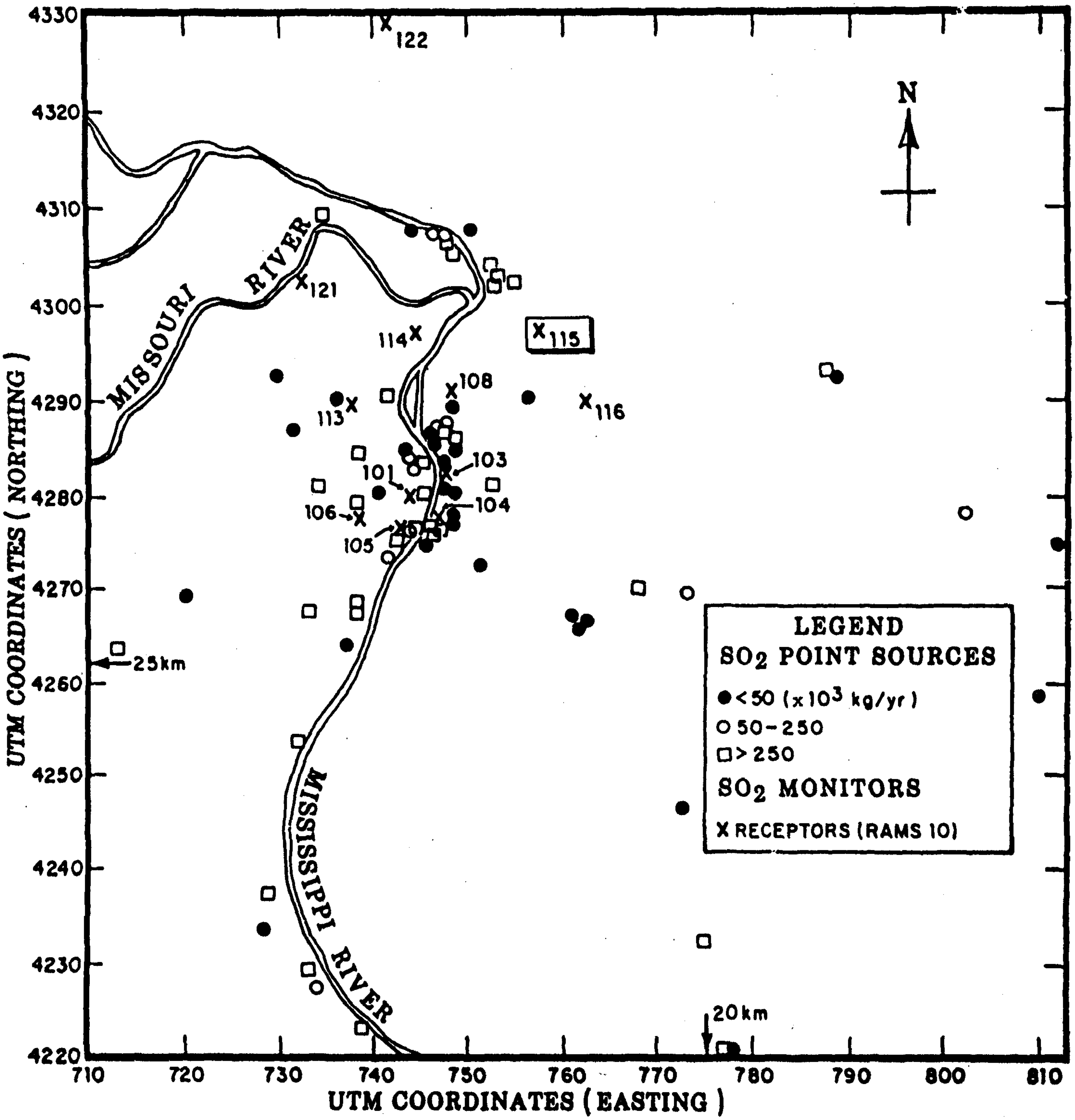

FIGURE 10

Second-Highest Twenty-Four-Hour Predicted - RAM & TEM

(A receptor number enclosed in a rectangle denotes a maximum observed or predicted value.)

REVIEW OF URBAN DISPERSION MODELS

J. C. Weil
Martin Marietta Corporation
Baltimore, MD
June 14, 1983

I. OVERVIEW

Six urban dispersion models for relatively inert pollutants were reviewed for their scientific merits as well as their operational performance. All models are based on the Gaussian plume and apply to area and point, stationary sources, the typical pollutants of concern being sulfur dioxide and particulate matter. Two of these models, RAM and TEM-8A, pertain to short-term concentration averages (one, three, and twenty-four-hour periods) and remaining four, AQDM, CDM, ERTAQ, and TCM, apply to annual average concentrations. The short-term models use hourly inputs of source and meteorological conditions and are generally run for a year's record of data to determine the cumulative frequency distributions of the one, three, and twenty-four-hour concentration averages at a number of sites (receptors). The long-term models calculate annual average concentrations through the use of a joint frequency function, which gives the relative frequency of occurrence of various categories of meteorological conditions - wind direction, wind speed, and stability. The latter models contain only a vertical Gaussian distribution; the crosswind (Gaussian) distribution is eliminated by averaging it over finite wind direction sectors comparable to or larger than the angular plume width. A nice derivation of the formula used for the annual averages is given by Calder (1971) (see Appendix D of CDM User's Guide).

The Gaussian model components (plume rise formulas, dispersion parameters, and stability classification methods) are much the same in all models and are quite similar to those in the rural models reviewed earlier; typically they are 10 to 20 years out of date. Most of the six models use the Pasquill-Gifford (PG) dispersion curves developed for surface releases in smooth open countryside and all use the Turner (1964) stability criteria. Only one model, RAM, uses dispersion curves (Briggs urban; see Gifford, 1975) developed from tracer releases in an urban area, St. Louis. Two models (CDM, ERTAQ) account for the increased roughness or building wake effects on dispersion by adopting an initial vertical dispersion parameter $\sigma_z(0)$. Also, several models attempt to account for the effect of increased urban heat flux on stability and dispersion by dropping the Turner class by one towards the unstable side. However, sound theoretical and/or empirical support for many of these approaches is not given.

Overall, the urban models are a poor representation of current understanding of turbulence and diffusion in the planetary boundary layer (PBL) as was also the case for the rural models. This is especially true for the convective boundary layer (CBL) where significant advances in our knowledge of turbulence structure have been achieved through numerical modeling (Deardorff, 1972), field observations (Kaimal et al., 1976), and laboratory experiments (Willis and Deardorff, 1974). These studies all demonstrate the importance of convective scaling parameters (z_i, the CBL depth, and w_*, the convective velocity scale) in ordering turbulence data; w_* is proportional to $(Q_o z_i)^{1/3}$, where Q_o is the surface heat flux. The utility of these parameters in CBL diffusion modeling has been shown through the laboratory experiments of Willis and Deardorff (1978, 1981) and the numerical simulations of Lamb (1979). Furthermore, Weil and Brower (1982) have applied convective scaling concepts to stability and dispersion estimates in an operational Gaussian model for tall stacks and shown that such concepts lead to far better predictions of ground-level SO_2 concentrations than does the EPA CRSTER model. The latter model is based on the older PG dispersion curves and the Turner stability criteria.

The point of the above discussion is that improved PBL understanding within the past decade or so has indeed made a demonstrable improvement in both the science and performance of a simple Gaussian model for elevated sources in relatively uncomplicated terrain. I believe that such understanding can similarly be applied to elevated and near surface releases in the urban environment. More strongly, I believe it must be done to improve the abysmal "science" exemplified in the existing models. Such an application needs to consider the two major effects of the urban surface on the turbulence structure and dispersion; the increased heat flux and the larger roughness elements with the correspondingly larger u_*'s (friction velocity). These effects can be incorporated within the same framework applied to the tall stack, rural terrain problem (Weil and Brower); a discussion of the prospects and problems of this application is given in Section 2.

The performance of the six urban dispersion models was assessed with SO_2 measurements from a 13-station monitoring network in St. Louis. For the annual average models, the performance evaluation is relatively straightforward and simple and consists of comparing observed and predicted concentrations at each of the 13 stations. With one exception (station 104), the models perform fairly well with little difference between them (see Fig. 1). I would be hard pressed to recommend one model over another, based on performance. However, I should note that the correlation coefficient, r, from a regression fit to plots of the observed vs. predicted concentration (Fig. 1) is slightly smaller from TCM ($r = 0.46$) than for AQDM, CDM, and ERTAQ ($r = 0.64$, 0.62, 0.67, respectively). If we delete the station 104 result in Fig. 1, we obtain r values for AQDM, CDM, and ERTAQ of 0.95, 0.85, and 0.81, respectively; oddly, the oldest model, AQDM developed in 1969, has the highest correlation coefficient (although the differences in r are probably not statistically significant).

The most disconcerting feature of the comparisons in Figure 1, with station 104 deleted, are the low slopes (b) of the regression equations, $b \leq 0.05$, and the positive intercepts, a. The departures of the a and b from their ideal values (0 and 1, respectively) are attributed to model formulation problems. Such departures (and in the same direction as found here) appear to be endemic to these models (see Calder, 1971).

For the short-term models, a significant difference between TEM-8A and RAM occurs in the bias, i.e., the average of the differences between observed and predicted concentrations. Based on comparisons paired in space and time, TEM-8A has a negative bias typically equal to twice the observed average concentration (for the one to twenty-four-hour averages); a negative bias means that the model prediction is greater than the observed concentration. This overall bias is dominated by the especially high model overprediction for stable conditions and is discussed further in Section 3. In contrast, the RAM model overpredicts the one to twenty-four-hour concentration values by 25% or less on average. However, the standard deviation (SD) of the residuals (observed-predicted concentration) is quite large, being typically twice the average observed concentration ($\bar{c}_{obs}$); for TEM-8A, the SD is about five times $\bar{c}_{obs}$. To put the SD of the residuals in proper perspective, it is necessary to compare it to the observed concentration fluctuation resulting from natural variation in meteorological variables; i.e., fluctuations in hourly-averaged concentrations for nominally the same hourly-averaged wind direction, wind speed, and stability condition.* Hanna's (1982) analysis of SO_2 concentration fluctuations from the 1976 St. Louis data show that the geometric standard deviation (GSD) of $\bar{c}_{obs}/Q$, where Q is the total emission rate, is 2.6. Unfortunately, we do not have the GSD's of the residuals

*The degree to which the hourly-averaged conditions can be held fixed is somewhat limited due to the finite number of data points available. One common practice, as followed by Hanna (1982), is to categorize the concentrations by ranges ("bins") of wind direction, wind speed, and stability; this then permits one to accumulate a large number of data points in specific bins.

from the TRC model comparisons, but my guess (based on the arithmetic SD's) is that they are larger than 2.6 for RAM and certainly so for TEM-8A. This indicates the potential and need for improvements in the model formulation.

On the whole, I would have to judge the RAM model a better performer than TEM-8A based largely on the bias and SD results; this is not to be construed as a strong endorsement of the model, as its performance in many ways is not good. For example, the correlation coefficient for the paired data (Table 5-12 of the TRC report) is low and about the same for RAM as for TEM-8A (r ranges from ~ 0.1 for one-hour averages to ~ 0.33 for twenty-four averages). The reasons for the large differences in bias between RAM and TEM-8A as well as some other aspects of model performance are taken up in Section 3.

II. DISCUSSION OF MODEL COMPONENTS

The specific model features discussed in the following are: plume rise formulas, plume penetration of elevated stable layers, dispersion parameters (σ_y and σ_z), stability classification, area source treatment, and meteorological inputs. Some of the remarks are repetitious of those made in an earlier review of rural dispersion models (Weil, 1982a) but are restated for completeness. Finally, some thoughts are given on prospects for an updated urban dispersion model.

A. Plume Rise

For elevated, buoyancy dominated sources, all of the urban models use Briggs' (1971) model for computing final rise in neutral conditions and apply the same model to unstable conditions. However, this model did not even consider convectively generated turbulence, which is clearly most important for buoyant plumes rising in the CBL. I think that Briggs' (1975) models, "breakup" and "touchdown," are much better choices for final rise because they incorporate more sound and up-to-date physics of the neutral and convective PBL than the 1971 model. Furthermore, they agree much better with the maximum observed rise of power plant plumes as reported by Weil (1979a).

There is no quarrel with the formula chosen for final rise of buoyant plumes in stable conditions, i.e., Briggs (1975); this formula is well-documented by Briggs and others.

Several of the models (TCM, TEM-8A, RAM) compute plume rise due to source momentum flux when this dominates the buoyancy effect. (The dominating effect is simply determined by that formula, for buoyancy or momentum, yielding the larger rise.) I believe this consideration is a necessity for all models because some of the point sources in the emission inventory indeed have a near ambient temperature, i.e., little buoyancy. However, I object to the formula chosen for neutral and convective conditions, the one given by Briggs (1969); it is simply outdated. Final rise formulas based on more contemporary understanding of the neutral and convective PBL are given by Briggs (1975) and should be adopted. The formulas used for momentum dominated rise in stable conditions (Briggs, 1969) appears adequate and consistent with later formulas given by him (Briggs, 1975, 1980).

Actually, the state-of-the art formulas for final rise for both buoyancy and momentum-dominated sources are all summarized in Briggs (1980). However, one detail should be noted. The empirical constant 4.3 in Eq. (86) of Briggs (1975) is preferred over the value 3.0 in Eq. (8.101) of Briggs (1980) because the former was more consistent with plume rise observations as reported by Weil (1982b); the specific equation involved is that for final rise of buoyant plumes due to the breakup model for convective conditions.

The urban models only consider plume rise for point sources; i.e., they neglect it for area sources with the exception of an adhoc approach used in RAM. The neglect for area sources bears further scrutiny because under very light winds, when building wakes are much less intense, emissions from small roof-top sources may indeed have a rise comparable to the building height; the emissions are mostly from space heating and thus are hot. Clearly, such rise would mitigate the ground-level concentrations, which are computed to be highest under the lightest winds ($u < 2.5$ m/s, see Table 5-4 of TRC report). In addition, it should be noted that the TCM and TEM-8A models assume the area source height to be zero, which magnified the concentrations for the light wind cases even more.

B. Plume Penetration of Elevated Stable Layers

The urban models adopt an "all or none" criterion for determining plume penetration of elevated stable layers. Either complete or zero penetration occurs, i.e., no partial penetration, with the criterion being $h_e > kz_i$, where h_e is the effective stack height and $k = 1$ for all models except for TEM-8A, $k = 2$, and TCM, which dismisses the penetration situation. If the plume penetrates the stable layer (i.e., the above inequality is satisfied), no ground-level concentrations are assumed to occur; if penetration does not occur (the inequality is not satisfied), the plume remains trapped in the CBL with reflection occurring at $z = z_i$. The h_e is based on the final rise formula for neutral conditions, which effectively assumes that the stratification below z_i exists above z_i as well, i.e., up to the point of final rise. Clearly, this assumption is wrong. The major pitfall of this criterion is that it ignores the stratification change at $z = z_i$, i.e., the degree of stable stratification in the overlying air ($z > z_i$). Any realisti. penetration criteria must take into account the stable stratification of the elevated layer since this is the major impedance to further rise.

In summary, I believe that the "all or none" criterion is a poor approach and should not be used. A much preferred alternative is the penetration criteria given by Briggs (1980); it does include the stratification in the elevated stable layer. In addition, it has been successfully tested against field observations by Briggs (1930) and Weil (1980). Furthermore, I note that Weil and Brower (1982) used this criteria in their Gaussian model and found that it predicted no occurrences of plume penetration of the elevated stable layer, consistent with their observed ground-level concentrations. In contrast, the "all or none" criterion predicted several occurrences (26 out of 145 cases) of full penetration, i.e., zero ground-level concentrations were predicted when in fact significantly high concentrations were measured.

C. Dispersion Parameters

Three sets of dispersion curves (σ_y, σ_z versus x and stability) are used in the urban models: the PG curves in AQDM, CDM, ERTAQ, TCM, and TEM-8A, the Gifford-Hanna curves in TCM and TEM-8A for low level, area sources only, and the Briggs urban curves in RAM. As pointed out earlier, the PG curves were devised from ground-level releases over flat, smooth terrain and should not be applied to elevated point sources especially under the most unstable conditions, Class A. The reason is that plumes from elevated sources ($h_e > 0.1z_i$) disperse in a rather homogeneous turbulence region within the CBL and exhibit a vertical as well as horizontal growth proportional to downwind distance, σ_z, $\sigma_y \propto x$, close to the source (Willis and Deardorff, 1978, 1981; Lamb, 1979); this behavior is consistent with statistical theory of diffusion. Elevated plumes do not show an accelerated vertical growth, σ_z increasing faster than linearly with x, as predicted (Lamb, 1979, Yaglom, 1971) and observed (the PG A σ_z curve) for dispersion from ground-level sources; the accelerated growth occurs because of the inhomogeneity of σ_w with z in the surface layer of the CBL ($z < 0.1z_i$). (Further discussion of these differences is given in Weil, 1982a, 1983.)

It should be emphasized that the surface roughness height, z_0, relevant to the PG curves is 0.03 m, far smaller than z_0's (~ 1 m) typical of urban areas (see Clark et al., 1981). Only two of the urban models (CDM, ERTAQ) attempt to make some adjustment to the PG curves to account for the large roughness elements. They adopt an initial vertical dispersion parameter $\sigma_z(0)$ which essentially simulates the rapid plume growth induced by the cavity region of a building wake. However, the general effect of increased roughness on increasing u_* and the turbulence velocities is not addressed. Furthermore, while the $\sigma_z(0)$ for the lowest releases ($h_s < 20$ m, where h_s is the source height) is tied to the earlier St. Louis diffusion experiment (McElroy, 1969), the variation of $\sigma_z(0)$ with h_s for h_s > 20 m is quite arbitrary (Calder, 1971). It seems to me that wind tunnel modeling could be put to good use in determining the appropriate initial vertical as well as horizontal growth and the subsequent rate of spread (beyond the immediate building cavity). In summary, the urban model authors for the most part have misapplied and misadapted the PG curves; I am not sure it is worth pursuing these curves further.

The Gifford-Hanna (1971) curves as applied to low-level area sources, are essentially the ASME dispersion parameters (Smith, 1968), which were derived from an elevated (~ 100 m) point source release. Their applicability to low-level releases in cities is not clear and to my knowledge has not been justified. Furthermore, no account is taken of initial dispersion due to building wakes.

The Briggs' urban curves (see Gifford, 1975) were developed from the McElroy-Pooler empirical curves (McElroy, 1969) which were based on neutrally buoyant tracer releases of a one-hour duration; the releases were made near the ground (my guess is within 20 m or so of the surface) in St. Louis. These curves empirically account for the effects of increased roughness and heat flux in the urban environment and are probably the most legitimate curves for near surface releases. However, I believe that their application to tall sources, as is done in RAM, is incorrect and unjustified; the reason is that for the most unstable A-B conditions, the Briggs' curve gives $\sigma_z \propto x^{3/2}$. However, in the urban CBL, we should expect a near homogeneity of σ_w with z to exist for heights above $\sim 0.1z_i$ just as it does in the CBL over rural areas. This character is expected because of the dominance of convective over mechanical turbulence during very unstable conditions; i.e., the boundary layer structure is effectively independent of roughness effects. For plumes dispersing in homogeneous turbulence, we expect $\sigma_z \propto x$ as discussed earlier.

For tall sources in the urban environment, I think that Briggs' rural curves may be more appropriate; these curves show σ_y, $\sigma_z \propto x$ close to the source for all stability conditions. The major task in applying the Briggs' urban and rural curves is defining their limits of applicability in terms of a scientifically meaningful stability parameter. This is discussed next.

D. <u>Stability Classification</u>

All of the urban models apply the Turner stability criteria, an empirical scheme for classifying turbulence and choosing dispersion curves. For rural applications these criteria have been shown to be strongly biased toward neutral stability when unstable conditions actually exist (Weil, 1979b; Weil and Brower, 1982); typically, the Turner criteria predicts neutral conditions to occur 40-50% of the time in contrast to other work (Deardorff and Willis, 1975) which indicate that the neutral PBL is a rarity. To account for the increased heating in the urban area, several dispersion models shift the stability class down by one towards the unstable side. While qualitatively in the right direction, the number of downward shifts is quite arbitrary; it has not been backed up by theory or experiments. Moreover, it seems difficult to properly adjust this criteria to the urban environment when it is so far off the mark for rural terrain.

For convective conditions, a much more theoretically sound criteria for stability classification is the ratio $z_i/-L$, where L is the Monin-Obukhov length. This ratio measures the relative heights of importance of convection and surface friction; typically, it exceeds 10 during daytime. Two useful alternatives to $z_i/-L$ are w_*/u_* and w_*/u, where u is the mean wind speed in the CBL. The first is related to $z_i/-L$ using the definitions of w_* and L, $w_*/u_* = (-z_i/\kappa L)^{1/3}$, where κ is the von Karman constant. The second, w_*/u, follows from the first upon choosing a typical value for u_*/u (~ 0.05). Weil and Brower(1982) adopted u/w_* as the stability parameter in their model and related it to Briggs' rural dispersion curves (see their report or Weil, 1983 for details). In applying the model to tall stacks, they found that it resulted in concentration predictions in far better agreement with observed SO_2 concentrations than did the EPA CRSTER model; the latter employs the PG curves and the Turner stability criteria.

The favorable results achieved with the Weil and Brower framework give us confidence that the convective scaling concepts are working properly and that they have a strong positive effect on model performance. The framework shows the explicit relationship between dispersion curves and the key meteorological variables, Q_o and z_i (in w_*) and u; it would probably be better to adopt u_* instead of u since u^* incorporates roughness changes directly. We should be able to extend this framework to the urban setting and relate w_*/u_* to the appropriate dispersion curves for both ground and elevated releases. The key task is the proper parameterization of the heat flux perturbation induced by the urban area; for rural terrain Q_o can be assumed proportional to the insolation. Once the heat flux is parameterized, u_* can be determined from a wind speed measurement at one height using the similarity wind profile and an appropriate z_o estimate.

E. <u>Area Source Treatment</u>

There are three points that come up regarding the treatment of area sources in the urban models. First, as was already discussed, the source height should be included (TCM and TEM-8A) and plume rise should be considered; at the minimum, the effect of plume rise on the surface concentration in light winds needs to be assessed.

Second, the degree of spatial resolution required for integrating the area source distribution to compute ground-level concentrations needs to be resolved. The resolution ranges from the area source grid size (typically 1 km by 1 km) in TCM and TEM-8A (which use the Gifford-Hanna model) to small fractions of the grid size (CDM, RAM, ERTAQ). It seems to me that a sensitivity analysis should be done to see how important the spatial resolution is; at issue is whether a lot of unnecessary computation is being done.

Third, it should be made clear that the adequacy of the narrow plume assumption used in this treatment depends on the source grid size, downwind distance, and the σ_y curve used (or stability class). Effectively what this assumption means is that one can ignore "end effects" due to the finite size (or side length) of a source grid; the concentration downwind of the grid center is the same as if the area source were infinitely wide in the crosswind direction. The assumption remains valid for a receptor downwind of the center of a grid square as long as $\sigma_y \lesssim 0.3w$, here w is the grid side length. For the Briggs' urban curves and for w = 1 km, the narrow plume assumption breaks down for distances beyond: ~ 1.1 km (A-B curve), ~ 1.7 km (C curve), ~ 2.5 km (D curve), and ~ 4.2 km (E-F curve).

F. Meteorological Inputs

The six urban models basically treat the meteorological inputs in the same manner. For the short-term models, there are two basic problems currently used (same as discussed earlier in Weil, 1982a). The first is the interpolation scheme for predicting the mixed layer height z_i. It is linearly interpolated with time from twice-daily estimates of z_i (early morning and mid-afternoon), the estimates being determined by the intersection of a surfaceextrapolated adiabat with the early morning temperature profile. These estimates are then modified, quite arbitrarily, using z_i obtained from the previous and succeeding days and the Turner stability class. The use of such an overly simplified approach seems unnecessary because mixed layer height models based on an energy balance of the lowest air layers, initial stratification, and the integrated surface heat flux have been around for a decade (Carson, 1973; Tennekes, 1973). I believe a model of the latter sort should become part of the meteorological preprocessor package. (Recently, Weil and Brower, 1983, adopted a slightly modified form of Carson's model to be used for z_i estimates in diffusion model applications; they also included schemes for other important CBL parameters (u, u_*, and Q_o) all to be determined from routinely available data.)

The second basic problem with the short-term models is in the treatment of light winds or calms, to which the Gaussian model does not apply. For $u < 1$ m/s, the RAM model arbitrarily assumes $u = 1$ m/s whereas TEM-8A uses the input wind no matter how small it is. I believe that both approaches are wrong. Given the importance of light wind situations (both in convective and stable conditions), I think that the Gaussian model should be extended to include along-wind dispersion; alternatively, another model could be formulated. Until an appropriate model is developed, it is better to remove the "calm" hou · from the modeling.

Two additional and untouched problems that arise for the short-term models are the parameterization of the urban heat flux perturbation and the horizontal inhomogeneity in it as well as z_i. Horizontal inhomogeneity should be a problem more at night when the urban perturbations are more significant relative to the rural background area.

For the annual average models, I wonder whether seasonal variations in winds, stability, and z_i have been examined to determine their effect on the annual average concentration computed; all of the urban models use the annual average frequency function. Since the area source strength is highest in winter, a strong difference in the frequency function between the winter and annual values could significantly change the computed concentration.

G. Prospects for an Updated Urban Dispersion Model

Based on the above discussion, I feel that sufficient technology exists to develop a much more scientifically sound model for urban dispersion. Such development would entail relating existing dispersion curves (McElroy-Pooler or Briggs) for the urban environment to w_*/u_*. This can be done by coupling the statistical (Taylor, 1921) and similarity theories (Yaglom, 1971) of diffusion to the σ_w, σ_v versus w_*/u_* relationship (see Weil and Brower). Evidence exists that during strong convection, σ_w and σ_v over an urban area bear essentially the same relationship to w_* as over a rural area (Ching et al., 1982). As stated earlier, a key task is to parameterize the urban heat flux perturbation. Available data from the St. Louis RAPS program (e.g., Godowitch et al., 1981; Ching et al., 1982) as well as from other programs Oke (1982) should make this task feasible.

One important problem is the assessment of the horizontal inhomogeneity in Q_o, z_i, roughness, etc. on turbulence and diffusion. Here it seems that there will be a need to come up with a simple boundary layer height model, of the Carson flavor, but with a spatially as well as temporally varying heat flux. More complex numerical models as well as observations will be invaluable.

Finally, as already noted, wind tunnels can be used to assess the role of roughness on dispersion from low-level sources. An informative experiment here would consist of progressive increases in the number of buildings (roughness elements) from 0 and 1 to a larger and larger area of same until an asymptotic dispersion curve is attained. Huber and Snyder (1976) have done systematic experiments with and without a single building; experiments with a large number of buildings may also have been done and should be checked.

I am optimistic that an urban model based on contemporary understanding of turbulence and diffusion in the PBL will lead to predictions in much better agreement with observations; this is based on our experience with the tall stack, rural terrain problem.

III. DISCUSSION OF MODEL PERFORMANCE

Further examination of the short-term models, TEM-8A and RAM, was made to better understand their performance and the large differences between the two. In looking at the highest 25 predicted and observed values (one to twenty-four-hour averages) by monitoring station, one observes the same general results as seen using all data paired in both time and space; typically, TEM-8A predicts high by a factor of 2 to 4 whereas RAM is relatively close to the observed value on average but can differ by factors of 2 at individual stations. In examining the highest one-hour averaged concentrations by time of day, wind speed, and stability class, one finds that: both models predict their highest values during the night, in the lightest ($u < 2$ m/s) winds, and for stable conditions (Class E and F). In contract, the highest observations tend to be about the same throughout the day. They do, however, show the same trend with stability as predicted by the models: lowest for A-B stability and highest for E-F stability.

The significant differences in the TEM-8A and RAM concentration predictions occur for all stability conditions (Table 5-4 of TRC report), but are largest for D, E, and F stability. The differences are attributed primarily to three factors: 1) the smaller dispersion parameters given by the PG and Gifford-Hanna curves used in TEM-8A than by the Briggs' urban curves used in RAM (differences are especially large for the D, E, and F curves), 2) the more severe penetration criteria used in TEM-8A than in RAM (a plume stays trapped below z_i more often in TEM-8A), and 3) the use of the "as measured" wind speed in TEM-8A rather than the restricted speed, $u > 1$ m/s, in RAM (some very low winds, $u \sim 0.5$ m/s, result in high concentrations). The smaller dispersion parameters in TEM-8A lead to higher concentrations for low-level area and point sources but lower concentrations for very tall stacks. A scan of the point source emission inventory reveals a predominance of low to moderate point source emissions of SO_2 from relatively short stacks, typically 40 to 50 m high. Thus, TEM-8A would tend to predict higher concentrations for them. Quite a few of such sources are in the neighborhood of monitoring stations 101-106, in the center of St. Louis.

Examination of the highest and highest second-highest one and three-hour averaged concentrations in Tables C1-C4 (TRC report) reveals that the observed values are nearly split equally between day and night, whereas both models predict the highest values at night as already mentioned. The high daytime observations suggest that elevated point sources are contributing. However, most of the high observations (day or night) as well as the highest twenty-four-hour averaged concentrations occur in the winter. This occurrence would suggest the importance of area sources (i.e., wintertime space heating) or limiting meteorological conditions (e.g., smaller z_i's) for point sources in winter or perhaps both. Further examination of this problem and with a better model is needed to really sort out which sources, area or point, are contributing most to the ground-level concentrations.

As a final point, we note that RAM significantly underpredicted concentrations at station 104 as did the annual average models. High anomalies at this station were reported to occur over about a one-month period (Ruff, 1980). As discussed by Ruff, the anomalies may have been due to an uncatalogued source. This may also have been caused by some upset condition in an existing source or to a special flow problem--building downwash. A scan of the point source emission inventory shows that several point sources are located within ~ 1 km of the monitor (104). Typical stack heights are 45 m and two of the sources have quite low buoyancy fluxes (F = 0.3 and 15 m^4/s^3).

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AN URBAN MODEL REVIEW

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I. INTRODUCTION

This review of urban models concentrates first, and most heavily, on their scientific foundations, and assesses the strength of these foundations in the light of our current understanding of the planetary boundary layer (PBL). It then reviews the performance statistics from the test runs made with the 1976 St. Louis data base.

This is a comfortable and convenient perspective for me, but is also, I feel, an appropriate perspective. More than 20 years have passed since the basic element of these six urban models, the Gaussian plume parameterization, was published. I believe that history will record that as a milestone. I believe that history will also record the sweeping advances that occurred in boundary-layer meteorology in this same 20-plus years. I feel, however, that history will note further that few of these advances had been used in urban dispersion modeling by the time of this review.

My approach here is influenced by the hope that this review process can serve a larger purpose than simply assessing six urban diffusion models. I hope it can also restimulate the technology transfer between PBL research and diffusion modeling that seems to have faltered in recent years.

II. ASSESSING THE SCIENTIFIC FOUNDATIONS OF THE MODELS

A. Description of the Urban Models

I find that the differences between members of this six-model set are small, even though their publication dates range from 1969 (AQDM) to 1980 (ERTAQ and TCM). I do not minimize the improvements in the later models, but I find these differences to be small compared to the difference between any of them and a model which would truly reflect our current understanding. In view of this, and in order to simplify this discussion, I will not refer in this section to the details of specific models, but instead to the characteristics of the "generic" model which reflects the attributes of the group as a whole. In so doing, I will ignore the detailed differences between individual models and this generic model.

The model is based on the Gaussian-plume parameterization now associated with Pasquill and Gifford. The underlying concept is that the (ensemble average) plume downwind of a continuous point source has a Gaussian-like shape. Furthermore, turbulent diffusion is mathematically linear in the concentration, and (in the simplest cases) mass-conserving. These facts led to the simple, elegant Pasquill-Gifford representation of downwind concentration in terms of a minimum of parameters: mean wind speed, pollutant source strength, and the characteristic dimensions (laterally and vertically) of the plume, the so-called "sigmas."

Although this formulation was an impressive engineering achievement, it relied on a data base which probably seemed more adequate 20 years ago than it does today. The difficulty of determining statistically reliable mean concentrations in diffusion experiments, which has become a matter of widespread scientific discussion only in the past several years, probably prevented any early, definitive assessment of the Gaussian assumption, particularly in the vertical. Only recently, in fact, have researchers been able to document departures from vertical Gaussianity, and to explain them in terms of the PBL physics (Willis and Deardorff, 1976; Lamb, 1982).

The height of the pollutant source appears directly in the Gaussian parameterizatio . If the source has buoyancy, the resulting initial plume rise is calculated (with Briggs' technique) and added to the actual source height, yielding the "effective source height." The model assumes that the sigmas are independent of the effective source height.

The growth of the sigmas with downwind distance is specified through use of stability categories based on the 1964 Turner classification. These categories are based on surface wind speed, cloud cover, and solar insolation data (cloud cover, time of year, latitude, time of day) and are tailored to routine, operational applications. These stability categories do not use directly any information on PBL depth, even if that were to be available.

The model has "perfect reflection" of the plume at the surface; this is done through use of an "image source" placed at one effective source height below the surface. The model assumes that this reflected plume diffuses upward from the surface in the same way that the upper portion of the plume diffuses from the source.

The model recognizes the existence of a top to the PBL or "mixed layer," and uses perfect reflection downward from this top as well. It does this by determining the downwind distance at which the concentration at mixed-layer top is appreciable (say 0.1 that at plume centerline) and assuming that the plume achieves a flat vertical profile of concentration at twice this distance; in between, it interpolates.

The model has a simple mean wind profile, with stability-dependent speed shear, but no shear in direction. Entrainment- or baroclinity-induced shear is not included. Mixing height is an input variable, and there is a simple parameterization of pollutant decay, to be used when appropriate.

Although the model has a short-term application mode, the writeups explain that the predictions give averaged rather than instantaneous behavior. I saw no mention of the ensemble average; the references were to a time average, and the implied averaging time ranged from several minutes to about one hour.

B. A Contemporary View of PBL Structure and Physics

Because of the experimental and numerical modeling advances of the 1960s and 70s, we know much more about PBL structure, physics, and measurements than we did 20 years ago. I will briefly summarize some of these advances here, borrowing from my recent review paper (Wyngaard, 1983).

Pe·haps the most significant advance has been in our k.owledge of the effects of stability on the PBL. At the same time, we have come to realize that the neutral state is quite elusive in nature; very small surface heating or cooling rates drive the PBL into convective or stably stratified states.

Several large field programs, together with the pioneering large-eddy simulations of Deardorff, have given us a fairly complete picture of the entire convective PBL. We now have similarity scales for its turbulence structure. The PBL depth h, which in practice is the base of the lowest inversion, sets the length scale of the dominant eddies, and in conjunction with the buoyancy parameter g/t and the surface temperature flux determines the turbulent velocity scale w*. Simple thermodynamic models (Driedonks 1982a,b) are known to be capable of remarkably good operational predictions of the evolution of h during the day. Effective, simple models of the surface energy budget, which allow realistic predictions of the surface temperature flux, now also exist.

Simple "mixed layer" scaling has proven to be quite effective for many aspects of convective PBL structure, and is now part of the language of PBL research. In addition, there is now evidence that many scaled parameters do not depend continuously on a stability index, say h/L. Instead, it seems that for such parameters all unstable data can collapse to a point upon proper scaling. A principal remaining uncertainty concerns the effects of entrainment-induced turbulence on mixed-layer structure.

The advent of the acoustic sounder in the early 1970s revealed dramatically the nature of the nocturnal PBL. This stimulated serious experimental, theoretical, and numerical modeling study throughout its depth, which the sounder showed could be quite shallow at times. Although today our understanding of the nocturnal PBL still lacks somewhat that of the convective PBL, there are now dynamical models for the evolution of its structure (Brost and Wyngaard, 1978) and for the evolution of its depth (Nieuwstadt and Tennekes, 1981).

A by-product of the intensive PBL research over the past 20 years has been a growing appreciation of the meaning of the scatter in measurements. Similarity theories, simple models, and parameterizations are inevitably deterministic; however, PBL data, no matter how carefully gathered, always have a random component. We learned early that this "scatter" could be very large in the unstable surface layer. During the 1968 Kansas experiments, for example, it was found that surface-layer stress could have the "wrong sign" locally for a good part of an hour (Haugen, Kaimal, and Bradley, 1971).

A formalism for interpreting scatter, or more precisely the difference between finite-length time averages and the ensemble averages upon which our theories are based, appeared in the Lumley-Panofsky (1964) monograph on atmospheric turbulence. Its applications to PBL data came somewhat later (e.g., Wyngaard, 1973). It is now generally appreciated that large scatter is to be expected in convective PBL data, even for averaging periods of an hour or more. PBL researchers today recognize the challenge of not only gathering good-quality data, but also of gathering enough data to produce statistically reliable averages.

C. A Contemporary View of Diffusion in the PBL

Perhaps the best single reference here is the Nieuwstadt-Van Dop (1982) collection, where recent advances in our understanding of both unstable and stable PBLs are applied to dispersion problems. The most dramatic advances could be those summarized there by Lamb for dispersion in the convective PBL. Departing from traditional practice, he uses mixed-layer scaling very successfully to explain dispersion from both ground-level and elevated sources.

Purely mathematical approaches to PBL diffusion, such as attempts to solve the pollutant conservation equation with eddy-diffusivity (K) closure, seem to be looked at more skeptically than say 20 years ago. Perhaps this is because evidence has accumulated over the past decade that K is not well-behaved in the convective PBL. Lamb and Durran (1978) demonstrated this by deducing K from calculations of continuous point source diffusion in the convective PBL of Deardorff's large-eddy simulations. They found K to depend strongly on the source height, for the same turbulent velocity field. Wyngaard and Brost (1983) argue that this "geometry-dependent" scalar diffusivity is an inherent property of the convective PBL, and trace its origin to the non-uniform distribution of buoyant production of turbulent kinetic energy with height. They show, again through large-eddy simulations, that the diffusivity of a scalar introduced as an area source near the top of a convective PBL is much different from its diffusivity when introduced near the surface. This complicated and essentially nonlinear behavior of K would seem to bring into question much of the past work with K-closures.

Since the early 1970s another mathematical approach to PBL diffusion, "second-order" or "higher-order" closure, has attracted much interest and also much controversy. This approach is based on the mean pollutant concentration equation plus a set of equations for second moments, including one for the pollutant flux; this set is closed through a variety of approximate techniques, most of which have been discussed by Wyngaard (1982). The controversy concerns the underlying rigor of the approach, which some find lacking. For example, consider the following quote from Liepmann (1979), who is writing about second-order modeling applied to turbulent flows in general:

> "Turbulent modeling is still on the rise owing to rapid development of computers coupled with the industrial need for management of turbulent flows. I am convinced that much of this huge effort will be of passing interest only. Except for rare critical appraisals such as the 1968 Stanford contest for computation of turbulent boundary layers, much of this work is never subjected to any kind of critical or comparative judgment. The only encouraging prospect is that current progress in understanding turbulence will restrict the freedom of such modeling and guide these efforts toward a more reliable discipline."

Those are discouraging words, but one should not conclude that the prospects for all modeling approaches are so bleak. One can find in the Nieuwstadt-Van Dop volume other approaches which hold considerable promise for numerical modeling of PBL diffusion.

The importance of scatter in finite-length time averages of PBL concentration fields is now widely recognized. Venkatram (1979a,b) has extended the time-ensemble average variance arguments to the diffusion problem, and has emphasized the importance of concentration fluctuations in this context. Hanna's (1982) study of the natural variability of averaged pollutant concentration in St. Louis dramatically illustrates the importance of this issue. He finds a factor-of-two natural variability in hourly concentrations of SO_2 and CO.

Direct evidence of the scatter inherent in time-averaged, continuous point source dispersion comes from the laboratory measurements of Willis and Deardorff (1976). They simulated seven realizations of dispersion from a near-surface source, and averaged the downstream concentration fields for times equivalent to 20-30 minutes in the atmosphere. Their realizations had great scatter; the average of the seven still had scatter on the order of 50% of the mean, even though the equivalent averaging time in the atmosphere was about three hours.

D. <u>A Contemporary View of the Urban Models</u>

The last three sections make it clear that the foundations of the urban models under review are not consistent with today's knowledge. It is now also clear, however, that there are strict limits on how well any model can do in predicting time-averaged pollutant concentrations. Hanna's (1982) St. Louis RAPS study reminds us that even a perfect model could do no better than the factor-of-two variability he found in hourly-averaged concentrations.

Thus the urban model builders were mistaken when they wrote that their models represent conditions averaged over several minutes to an hour; we know now that such models can aspire to represent conditions only over far larger averaging times.

Given today's large computers, and the advances in dynamic mesoscale modeling and large-eddy simulation, it would be possible to build a fine-mesh model capable of realistically simulating urban meteorology, including the important details of the urban boundary layer. In this way one could simulate the important, diurnally varying urban circulations which are ignored by the current generation of models. Such a model could then be used to do "brute force" simulations of urban air pollution dispersion. That might be a straightforward application of existing technology, but would also be expensive. In view of that, and the natural variability problem, it might well be judged not feasible. Thus I feel we should not dismiss completely the simple approach underlying these urban models, but instead consider it as a base on which to build. Lamb (1982) also takes this point of view.

The basic element of the urban models, the Pasquill-Gifford Gaussian plume parameterization, remains a good approach, in my opinion. It is simple, efficient, but should be modernized. The assumed Gaussian shape in the vertical needs to be revised, as does the model of plume reflection, both at top and bottom. The possibility that the effective source height should enter the model in other ways (for example, by influencing the sigmas) should be carefully considered. Lamb's (1982) concept of a virtual source height, which allows him to accommodate within the Gaussian model framework some of the strange behavior of plumes in the convective PBL, is a first step along this path. The stability categories should be redone to make them consistent with today's knowledge of both stable and unstable PBLs. The routines for the mean wind profile and the mixed-layer depth, particularly at night, can also be brought up-to-date.

Some of this updating, of course, has already been done; more modern models than the six we are considering now exist (e.g., Weil and Brower, 1982). This is, in my opinion, as much an engineering challenge as a scientific one, and therefore each candidate model improvement must be carefully assessed in cost/benefit terms. An important aspect of this challenge is obtaining the input data needed for updated models. This need not require sophisticated turbulence measurements; indirect techniques show great potential (Weil and Brower, 1983).

One of the important developments in air-quality research over the past decade is the documentation of the natural variability (inherent uncertainty) problem. One unfortunate side effect, however, is the emerging suspicion that field measurements of air pollution are not as valuable for verifying models as we once assumed; or, put another way, it now seems that we need much more data than we ever suspected in order to do definitive model verifications. Consequently, we should use alternative means of generating data bases - for example, large-eddy simulation, which Deardorff/Lamb have so profitably used; or laboratory modeling, which has been so skillfully done by Willis/Deardorff in the convection chamber and Snyder/Hunt in the stably stratified towing tank of the EPA Fluid Modeling Facility. Such data bases could provide an excellent means of testing and refining dispersion parameterizations. They would also allow us to begin the serious study of inherent uncertainty, which ultimately will have to be addressed by air-quality models.

III. ASSESSING THE PERFORMANCE STATISTICS

A. Factors Influencing the Statistics

I have separated the factors which influenced the performance statistics of the urban models into three categories: model factors, data-base factors, and natural variability.

Model factors include the treatment of point and area sources within the model, the treatment of removal processes such as surface deposition and chemical reactions, and the treatment of transport and dispersion. All the models seem to use similar techniques for handling the area sources; most of them in fact use the Gifford-Hanna scheme. None allows surface deposition. Several of the model writeups discuss a simple parameterization of decay (as, for example, through reaction), but only two models were run in this mode. Perhaps one can neglect SO_2 deposition and decay in urban applications, but I saw no discussions justifying it. Finally, as I indicated in Section 2, all models use basically the same transport/dispersion physics.

As data bases go, this was a good one. The meteorological data set was unusual in that it had measurements of PBL depth, although evidently these data were not used in the annual-average model runs. One suspects that this data set would be useful in assessing a new generation of urban models using stability categories based in part on PBL depth. I found no discussion of the fidelity of the emissions or concentration data, or any discussion of the extent to which the emissions were correlated with the meteorology. The latter consideration enters with annual-average models.

Finally, the natural variability of the SO_2 concentration data is important here in view of Hanna's (1982) finding that their hourly averages have a factor-of-two scatter. This scatter, which could be due entirely to natural causes, severely constrains the inferences that one can make from the performance statistics.

B. Annual-Average Model Performance

The summary of the annual-average models was given as Table 1 of the TRC statistics. I find the performance of the models remarkably good; the average of the measurements over the 13 stations was 42 micrograms/cubic meter, the model predictions ranging from 37 to 51. On a station-by-station basis, the agreement for all four models was generally well within a factor of two. Some might see subtle trends in Table 1 (e.g., the models might tend to overpredict near the city center, and underpredict in the outskirts). However, in view of the many factors which influence these results, I conclude simply that all four models performed well.

Some model guidebooks discuss a procedure for "calibrating" the model against a data set. It is not clear to me that any of these four annual-average models have been so calibrated. If not, their good performance here is surprising, since there are many areas where the models could now be improved. One tends to associate better models with better predictions, but judging from these performance test results the annual-average predicions could not be radically improved. Judging from Table 1, the weakest aspect of the models' performance was in their inability to reproduce the large station-to-station variability within the inner city.

C. Short-Term Model Performance

The performance tests of the short-term models produced an order of magnitude more data than the annual-average models, and perhaps relatively more insight. My perusal of the results indicates that RAM far outperforms TEM. While RAM seems to underpredict somewhat during the day, TEM far overpredicts at night. Thus TEM overpredicts the extremes by about a factor of two, for one, three and twenty-four-hour averaging times.

Table F-1 of the TRC report summarizes quite dramatically the difference in performance between RAM and TEM. This table, for one-hour averages, shows that TEM overpredicted concentration at every station, in most cases by more than a factor of two. For the city as a whole, it overpredicted at all times of day, although much more at night; it overpredicted for all wind speeds and for all stability categories.

The performance of RAM seems quite encouraging, in view of the natural variability problem. Judging from the one-hour statistics, the scatter in the RAM predictions is not an order of magnitude larger than the minimum implied by natural variability, as seems to be the case with TEM. The RAM scatter seems only a factor of two or three larger than this natural limit. This should be small enough to give support to those who use models, and yet large enough to give incentive to those who hope to improve models.

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