# MINIMUM METEOROLOGICAL DATA REQUIREMENTS FOR AERMOD -- STUDY AND RECOMMENDATIONS

draft document

Version: 98314 (AERMOD & AERMET)
98022 (AERMAP)
(December 14, 1998)

By:

Alan J. Cimorelli, U. S. Environmental Protection Agency, Region 3

Robert B. Wilson, U. S. Environmental Protection Agency, Region 10

Steven G. Perry[1], Atmospheric Sciences Modeling Division/Air Resources Laboratory, EPA/NOAA

Akula Venkatram,College of Engineering, University of California at Riverside

Jeffrey C. Weil,Cooperative Institute for Research in Environmental Sciences, University of Colorado

Robert J. Paine, ENSR Corporation

Russell F. Lee, Trinity Consultants

Warren D. Peters, U.S. Environmental Protection Agency, OAQPS

---

[1]On assignment to the Atmospheric Research and Exposure Assessment Laboratory, U. S. Environmental Protection Agency.

AERMIC RECOMMENDATIONS REGARDING
MINIMUM METEOROLOGICAL DATA
REQUIREMENTS FOR AERMOD

AERMOD's performance depends on the type of meteorological data that is used for input. The purpose of this paper is to specify the minimum meteorological data input requirements for a regulatory application of AERMOD. The first requirement is that all meteorological data used as input to AERMOD must be both laterally and vertically representative of the transport and dispersion within the analysis domain. Guidance concerning the assessment of data representativeness is provided in "On-Site Meteorological Program Guidance for Regulatory Modeling Applications" (U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC 27711, EPA-450/4-87-013). Additionally, the determination of representativeness should depend on a comparison of the surface characteristics in the vicinity of the meteorological monitoring site with the surface characteristics that generally describe the analysis domain. Furthermore, since the spatial scope of each variable, could be different, representativeness must be judged separately for each variable.

AERMOD was designed to run with a minimum of observed meteorological parameters. As a replacement for the ISC3 model, AERMOD can operate using data of a type that is readily available from a representative National Weather Service (NWS) station. AERMOD requires at least one surface measurement of wind speed and direction (generally, at a height of 10 meters) and ambient temperature (generally, at a height of 2 meters). The wind speed and the temperature measurement must meet certain criteria to become reference values used in developing vertical profiles. The reference wind speed measurement height must be greater than seven times the surface roughness height and less than 100 meters. Similarly, the reference temperature measurement height must be greater than the surface roughness height and less than 100 meters. The wind direction measurement should be representative of the plume transport direction, since AERMOD makes no adjustments to the wind direction in its profiling scheme. Like ISC3, AERMOD also needs observed cloud cover and the morning sounding from an upper air station. Finally, the user must specify surface characteristics (surface roughness, Bowen ratio, and albedo) in AERMOD to allow the model to construct boundary layer profiles.

In both the development and performance testing phases of the AERMOD project, a variety of concentration data bases were employed. Each of these data bases contained both concentration and meteorological data. The type of meteorological data collected as part of these data bases varied among sites. In all cases a multi-level tower was used with data collected to a height of at least 100 meters above stack base. A Meteorological Data Degradation Analysis (see Appendix A) was performed to assess minimum meteorological data requirements. The concept of this analysis is to systematically degrade the meteorological input data to evaluate how the model performance is affected. The methodology compared concentration predictions using the full complement of site-specific meteorological data with predictions made using: 1) a degraded subset of the site-specific meteorological data (i.e., only data from the 10-meter level of the tower was used), and 2) only data taken from the closest NWS site, if these data were deemed representative.

Three data bases were used in performance of the Meteorological Data Degradation Analysis: Lovett, Martins Creek, and Kincaid $SO_2$. Lovett and Martins Creek are both complex terrain data sets. For each of these complex terrain cases, data from the closest NWS station was determined to not be adequately representative from both a lateral and vertical perspective. Therefore, for these two sites, comparisons were made using the full complement of meteorological data and the degraded 10-meter site-specific data. However, for the Kincaid site, which is located in simple terrain, data from the nearest NWS site was determined to be representative, and comparisons were therefore made using the full complement of meteorological data, only the 10-meter site-specific data, and, finally, only the NWS data.

For AERMOD to be a practical ***regulatory*** replacement for ISC3, the minimum meteorological data required to run AERMOD need to be readily available. Our air quality management programs would be severely impacted (from an operational point of view) if ISC3 were replaced by a model which required the collection of site-specific meteorological data for each application. Therefore, in deciding what minimum meteorological data should be required for a regulatory application of AERMOD, we begin with the presumption that adequate model performance is achieved using AERMOD's designed minimum requirements (i.e., representative NWS-type data -- as is the case with ISC3). Starting with this presumption, we examined the results of the Meteorological Data Degradation Analysis to see if there was any evidence that contradicted this presumption. This approach recognized the fact that we had limited resources with which to accomplish the analysis.

After reviewing the results from the Meteorological Data Degradation Analysis, we found no evidence which suggests that data other than AERMOD's minimum design requirements are needed to provide adequate concentration estimates for regulatory actions. Considering the basic underlying design of AERMOD, the needs of the regulatory program in which AERMOD will be used, as well as the results of the Meteorological Data Degradation Analysis, AERMIC recommends that the following minimum meteorological data requirements be established for regulatory applications of AERMOD:

Data must be laterally and vertically representative. Representativeness should be judged independently for each variable.
Surface characteristics around the meteorological site must be similar to the surface characteristics within the modeling domain.
Surface characteristics around the meteorological site should be used as input for AERMOD.
Adequately representative data for each of the following variables constitutes the minimum set of meteorological variables that AERMOD requires for a regulatory application:
Wind speed (at least one level between 7 times the surface roughness and 100 meters)

Wind direction
Ambient temperature (between the surface roughness height and 100 meters)
Cloud cover
Morning radiosonde observation
Surface roughness
Bowen ratio
Albedo

The length of record needed should be the same as is presently required for ISC3. That is, a minimum of 5 years of most recent readily available ***representative*** data. If no such data exists then the applicant should be required to collect no less than one year of representative site-specific data.

Present guidance makes a distinction between "on-site" data (i.e., data which are collected at a particular site for a specific action) and "off-site" data (primarily the nearest NWS station). This concept of "on-site" has caused significant confusion within the regulatory community as it has been interpreted in some cases to mean "on-property." Since what is needed by the model is ***representative*** data, independent of its precise geographic location, we recommend that the term "on-site" be removed from the guidance, and the concept of "adequately representative" (as discussed above) be used in its place. This has the benefit of removing the artificial distinctions that are made among NWS data, data collected on plant property, and data collected off plant property but in close proximity to the source, and replacing them with guidance based on a general technical principle.

# APPENDIX A

**METEOROLOGICAL DATA DEGRADATION ANALYSIS
FOR THE
AERMOD DISPERSION MODEL**

DRAFT

EPA Contract No. 68D70069
Work Assignment No. 1-011

Prepared for

Warren D. Peters
Emissions, Monitoring, and Analysis Division (MD-14)
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Submitted by

PACIFIC ENVIRONMENTAL SERVICES, INC.
5001 S. Miami Blvd., Suite 300
P.O. Box 12077

PREFACE

The American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) initiated a joint effort in 1991 to develop a more accurate air quality model. Current regulatory models were developed more than two decades ago. The effort to update the models was undertaken by the AMS/EPA Regulatory Model Improvement Committee (AERMIC), which is developing the AERMIC Model (AERMOD) (US EPA, 1998a), along with its associated meteorological preprocessor (AERMET) (US EPA, 1998b), and terrain preprocessor (AERMAP) (US EPA, 1998c). The AERMOD system was designed to make use of National Weather Service (NWS) observations and data collected from on-site observation programs. Concentration estimates from AERMOD can be obtained using NWS data only or a combination of NWS and on-site data collected from one or more levels. This report documents AERMOD's performance when the number of levels of on-site meteorological input to AERMET is degraded from multiple levels to a single level to no on-site data. Three data bases used in the Phase I and Phase II evaluations were employed: Lovett, Kincaid $SO_2$, and Martin's Creek. For all three data bases, AERMOD performed better with the full on-site data than with the single level of on-site data. For Lovett, the improvement for full on-site versus single level on-site was statistically significant.

ACKNOWLEDGMENTS

This report of the meteorological data degradation analysis for AERMOD was prepared by Pacific Environmental Services, Inc., Research Triangle Park, NC, under EPA Contract No. 68D70069, with Warren D. Peters as Work Assignment Manager.

TABLE OF CONTENTS

LIST OF FIGURES

# 1.0 INTRODUCTION

The American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) initiated a joint effort in 1991 to develop a more accurate air quality model. Current regulatory models were developed more than two decades ago. The effort to update the models was undertaken by the AMS/EPA Regulatory Model Improvement Committee (AERMIC), which is developing the AERMIC Model (AERMOD) (US EPA, 1998a), along with its associated meteorological preprocessor (AERMET) (US EPA, 1998b), and terrain preprocessor (AERMAP) (US EPA, 1998c).

The AERMOD system was designed to make use of National Weather Service (NWS) observations and data collected from on-site observation programs. Concentration estimates from AERMOD can be obtained using NWS data only or a combination of NWS and on-site data collected from one or more levels. The purpose of this analysis is to document AERMOD s performance when the number of levels of on-site meteorological input to AERMET is degraded from multiple levels to a single level to no on-site data. Three data bases used in the Phase I and Phase II evaluations of AERMOD were employed for this study: Lovett, Kincaid $SO_2$, and Martin s Creek. Two of these data bases, Lovett and Martin's Creek, are located in complex terrain settings. The Kincaid data base is located in flat terrain.

Section 2 provides a description of each of the three data bases. Section 3 summarizes the results of the analysis, and Section 4 presents conclusions of the study. The results and conclusions of this study will be used by EPA, along with other information, to determine the minimum meteorological data requirements for the AERMOD model.

## 2.0 MODELING DATA BASES

The source parameters, meteorological data, and receptor network used in each of the three data bases is described in this section.

### 2.1 KINCAID $SO_2$

The Kincaid $SO_2$ study (Liu and Moore, 1984; Bowne, et al., 1983) consists of a buoyant, continuous release of $SO_2$ from a 187-m stack nine meters in diameter at the release point. The site is in a rural area in flat terrain about 45 kilometers southeast of Springfield, IL at 39.6EN and 89.5EW (Universal Transverse Mercator (UTM) coordinates 285,665 E and 4,385,100 N in zone 16). The Kincaid $SO_2$ data base includes two separate periods: April 3, 1980 through August 31, 1980 and March 10 through June 17, 1981. There were 30 $SO_2$ monitoring stations from about 2 km to 20 km downwind of the stack. Stack emissions from the single source were available hourly.

The on-site meteorological data at the Kincaid site consisted of a single tower instrumented at four levels: 10, 30, 50, and 100 meters. The following table shows the variables collected at each level. An asterisk in the cell indicates that data were collected at that level for the variable shown; a blank indicates that no data were recorded at that level.

| Height (meters) | Wind speed | Wind direction | Temperature | $\sigma_A$ | $\sigma_w$ |
|---:|:---:|:---:|:---:|:---:|:---:|
| 10 | * | * | * | * | |
| 30 | * | * | | * | |
| 50 | * | * | * | * | |
| 100 | * | * | * | * | * |

For the full on-site data evaluation, all data at all levels were used. For the single level on-site data evaluation, only the 10-meter level was used. Thus, there were no observations of $\sigma_w$ for the single level evaluation.

NWS hourly surface observations for Springfield, IL (WBAN No. 93822) 40 kilometers northwest of the Kincaid facility, and upper air data from Peoria, IL 125 kilometers to the north were used in this analysis.

The site characteristics corresponding to four wind direction sectors used in running AERMET Stage 3 to produce the meteorological input files for AERMOD are shown below (ENSR,1989).

ALBEDO, BOWEN RATIO, AND SURFACE ROUGHNESS LENGTH ($z_0$) BY WIND DIRECTION SECTOR AND MONTH FOR KINCAID

| Wind sector | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 045-060E | albedo | 0.33 | 0.29 | 0.24 | 0.12 | 0.10 | 0.11 | 0.14 | 0.14 | 0.14 | 0.14 | 0.22 | 0.30 |
| | Bowen ratio | 0.55 | 0.55 | 0.30 | 0.40 | 0.40 | 0.30 | 1.10 | 1.10 | 0.50 | 0.55 | 0.50 | 0.55 |
| | $z_0$ (meters) | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.05 | 0.05 |
| 060-120E | albedo | 0.56 | 0.50 | 0.40 | 0.17 | 0.14 | 0.16 | 0.21 | 0.21 | 0.21 | 0.21 | 0.36 | 0.50 |
| | Bowen ratio | 0.91 | 0.91 | 0.46 | 0.64 | 0.64 | 0.46 | 1.81 | 1.81 | 0.82 | 0.91 | 0.91 | 0.91 |
| | $z_0$ (meters) | 0.09 | 0.09 | 0.09 | 0.09 | 0.11 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.09 | 0.09 |
| 120-250E | albedo | 0.61 | 0.54 | 0.44 | 0.19 | 0.16 | 0.18 | 0.23 | 0.23 | 0.23 | 0.23 | 0.40 | 0.56 |
| | Bowen ratio | 1.00 | 1.00 | 0.50 | 0.70 | 0.70 | 0.50 | 2.00 | 2.00 | 0.90 | 1.00 | 1.00 | 1.00 |
| | $z_0$ (meters) | 0.10 | 0.10 | 0.10 | 0.10 | 0.12 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.10 | 0.10 |
| 250-045E | albedo | 0.56 | 0.50 | 0.40 | 0.17 | 0.14 | 0.16 | 0.21 | 0.21 | 0.21 | 0.21 | 0.36 | 0.50 |
| | Bowen ratio | 0.91 | 0.91 | 0.46 | 0.64 | 0.64 | 0.46 | 1.81 | 1.81 | 0.82 | 0.91 | 0.91 | 0.91 |
| | $z_0$ (meters) | 0.09 | 0.09 | 0.09 | 0.09 | 0.11 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.09 | 0.09 |
| NWS model runs | albedo | 0.60 | 0.50 | 0.40 | 0.20 | 0.15 | 01.5 | 0.20 | 0.20 | 0.20 | 0.20 | 0.40 | 0.50 |
| | Bowen ratio | 1.00 | 1.00 | 0.50 | 0.60 | 0.60 | 0.50 | 2.00 | 2.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | $z_0$ (meters) | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |

It should be noted that for the Kincaid $SO_2$ study, about 16% of the data are missing from the full on-site data set when the AERMET option to substitute NWS data is not used. Therefore, NWS substitution was used to run the Kincaid $SO_2$ study. A threshold wind speed of 0.5 m $s^{-1}$ for the on-site wind data was applied.

The location and terrain elevation used to model the 28 receptor sites are shown below. Terrain influences were expected to be negligible for this source given the height of the sources and the small differences in terrain elevation between the sources and the receptors (shown in the following table). For this analysis, therefore, terrain was assumed to be flat. Two of the original 30 receptors were omitted from the analysis because the observed $SO_2$ data were suspect.

RECEPTOR LOCATIONS AND TERRAIN ELEVATIONS FOR KINCAID $SO_2$

| UTM-E (m)* | UTM-N (m) | Elevation (m) | UTM-E (m)* | UTM-N (m) | Elevation (m) |
|---|---|---|---|---|---|
| 283700 | 4392390 | 181 | 291100 | 4389420 | 177 |
| 278890 | 4396510 | 175 | 291970 | 4391420 | 181 |
| 282570 | 4402050 | 175 | 297780 | 4394320 | 183 |
| 284480 | 4391050 | 177 | 294670 | 4395320 | 182 |
| 286570 | 4393030 | 177 | 289800 | 4388550 | 181 |
| 285690 | 4400340 | 177 | 285820 | 4386950 | 181 |
| 283240 | 4399720 | 178 | 282180 | 4396050 | 177 |
| 289400 | 4404320 | 169 | 286180 | 4395680 | 175 |
| 288900 | 4390950 | 181 | 292980 | 4391850 | 175 |
| 289930 | 4392270 | 177 | 277400 | 4385400 | 184 |
| 294390 | 4399230 | 174 | 285180 | 4382900 | 180 |
| 290000 | 4396650 | 179 | 287850 | 4382950 | 186 |
| 289390 | 4399290 | 174 | 287750 | 4376020 | 189 |
| 290840 | 4401350 | 177 | 280600 | 4377880 | 187 |

* UTM Zone 16

## 2.2 LOVETT

The Lovett Power Plant study (Paumier et al., 1992) consists of a buoyant, continuous release of $SO_2$ from a 145-m tall stack with a 4.5 meter diameter at the release point. The site is located in complex terrain in a rural area in the Hudson River valley of New York State about 70 kilometers north of New York City. The data spans one year from December 6, 1987 through December 5, 1988. Data were collected from 12 monitoring sites (nine on a ridge north and northwest of the facility, one on terrain west of the facility, and two south of the facility which served as background monitors), with the ten on terrain located about two to three kilometers north and west of the facility. The important terrain features rise approximately 250 to 330 meters above stack base.

The on-site meteorological data at the Lovett site consisted of a single tower instrumented at three levels: 10, 50, and 100 meters. The following table shows the variables collected at each level.  An asterisk in the cell indicates that data were collected at that level for the variable shown; a blank indicates that no data were recorded at that level.

| Height (meters) | Wind speed | Wind direction | Temperature | $\sigma_A$ | $\sigma_w$ |
|---|---|---|---|---|---|
| 10 | * | * | * | * | * |
| 50 | * | * | * | * | |
| 100 | * | * | * | * | * |

For the full on-site data evaluation, all data at all levels were used.  For the single level on-site data evaluation, the 10-meter level was used.

NWS hourly surface observations and upper air data for Albany, NY (WBAN No. 14735), about 170 kilometers north of the Lovett facility, were used in this analysis.

The following site characteristics, corresponding to six wind direction sectors, were used in running AERMET Stage 3 to produce the meteorological input files for AERMOD.  These values were obtained from Paumier et al. (1992).

ALBEDO, BOWEN RATIO, AND SURFACE ROUGHNESS LENGTH ($z_0$) BY WIND DIRECTION SECTOR AND MONTH FOR LOVETT

| Wind sector | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 000-035E | albedo | 0.35 | 0.35 | 0.35 | 0.25 | 0.25 | 0.12 | 0.12 | 0.12 | 0.20 | 0.20 | 0.20 | 0.35 |
| | Bowen ratio | 1.15 | 1.15 | 1.15 | 0.55 | 0.55 | 0.25 | 0.25 | 0.25 | 0.80 | 0.80 | 0.80 | 1.15 |
| | $z_0$ (meters) | 0.75 | 0.75 | 0.75 | 0.85 | 0.85 | 1.00 | 1.00 | 1.00 | 0.90 | 0.90 | 0.90 | 0.75 |
| 035-060E | albedo | 0.20 | 0.20 | 0.20 | 0.12 | 0.12 | 0.10 | 0.10 | 0.10 | 0.14 | 0.14 | 0.14 | 0.20 |
| | Bowen ratio | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| | $z_0$ (meters) | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| 060-130E | albedo | 0.35 | 0.35 | 0.35 | 0.25 | 0.25 | 0.12 | 0.12 | 0.12 | 0.20 | 0.20 | 0.20 | 0.35 |
| | Bowen ratio | 0.80 | 0.80 | 0.80 | 0.40 | 0.40 | 0.20 | 0.20 | 0.20 | 0.60 | 0.60 | 0.60 | 0.80 |
| | $z_0$ (meters) | 0.30 | 0.30 | 0.30 | 0.50 | 0.50 | 0.70 | 0.70 | 0.70 | 0.50 | 0.50 | 0.50 | 0.30 |
| 130-175E | albedo | 0.20 | 0.20 | 0.20 | 0.12 | 0.12 | 0.10 | 0.10 | 0.10 | 0.14 | 0.14 | 0.14 | 0.20 |
| | Bowen ratio | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| | $z_0$ (meters) | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| 175-225E | albedo | 0.50 | 0.50 | 0.50 | 0.25 | 0.25 | 0.15 | 0.15 | 0.15 | 0.20 | 0.20 | 0.20 | 0.50 |
| | Bowen ratio | 1.50 | 1.50 | 1.50 | 0.70 | 0.70 | 0.30 | 0.30 | 0.30 | 1.00 | 1.00 | 1.00 | 1.50 |
| | $z_0$ (meters) | 0.75 | 0.75 | 0.75 | 1.00 | 1.00 | 1.50 | 1.50 | 1.50 | 1.25 | 1.25 | 1.25 | 0.75 |
| 225-360E | albedo | 0.50 | 0.50 | 0.50 | 0.30 | 0.30 | 0.12 | 0.12 | 0.12 | 0.25 | 0.25 | 0.25 | 0.50 |
| | Bowen ratio | 1.50 | 1.50 | 1.50 | 0.70 | 0.70 | 0.30 | 0.30 | 0.30 | 1.00 | 1.00 | 1.00 | 1.50 |
| | $z_0$ (meters) | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |

It should be noted that for the Lovett study, about 627 hours (7%) of the data are missing from the full on-site data set when the AERMET option to substitute NWS data is not used. Many of the hours of missing data were daytime hours resulting from AERMET not calculating the boundary layer parameters for the entire daytime period even if there was only one hour that could not be calculated. Therefore, NWS substitution was used to obtain a complete meteorological data base for the Lovett study, but the individual hours where substitution occurred were reset to missing to prevent AERMOD from estimating pollutant concentration. A threshold wind speed of 0.3 m $s^{-1}$ for the on-site wind data was applied.

Additionally, a special procedure was used to process the one level on-site data. With the AERMET requirement that the reference height winds be above $7z_0$, any winds in the 225E - 360E sector (over the very rough terrain from the southwest to the north of the meteorological tower and source) would fail this requirement since $z_0$ = 1.5 meters in that sector and $7z_0$ = 10.5 meters, which is greater than the single on-site measurement height of 10 meters. Note that the option to substitute NWS data was not employed in this analysis. Without employing any adjustments to the height or roughness lengths, approximately 60% of the hours would have been missing due to missing reference height winds. Therefore, to overcome this problem, AERMET was run with the roughness length for this one sector set to 1.428 meters such that $7z_0$ = 9.996 meters. Once the two output files for AERMOD were produced, the roughness length in the file of boundary layer parameters (the "surface" file) was changed from 1.428 to 1.50. It is felt that the differences in the final results using a roughness length of 1.428 versus 1.50 are negligible in this degradation analysis, with the benefit that the number of hours with missing data is reduced to about 150 hours, or less than 2%.

The location, terrain elevation, and height scale used to model the nine receptor sites on the ridge north of the facility are shown below.

RECEPTOR LOCATIONS, TERRAIN ELEVATIONS, AND HEIGHT SCALE FOR LOVETT

| UTM-E (m)* | UTM-N (m) | Elevation (m) | Height Scale (m) |
|---|---|---|---|
| 583600 | 4569700 | 320 | 323 |
| 584520 | 4569780 | 293 | 300 |
| 585500 | 4570450 | 232 | 323 |
| 584780 | 4570700 | 323 | 331 |
| 585110 | 4570850 | 320 | 324 |
| 585810 | 4570900 | 250 | 258 |
| 585860 | 4571340 | 168 | 323 |
| 586250 | 4571070 | 274 | 277 |
| 586930 | 4571300 | 152 | 277 |

* UTM Zone 18

## 2.3 MARTIN'S CREEK

The Martin's Creek power station is located on the Pennsylvania/New Jersey border, approximately 30 kilometers northeast of Allentown, PA and 95 kilometers north of Philadelphia, PA on the Delaware River at 40.8EN, 75.1EW. It is operated by Pennsylvania Power and Light (PP&L). In addition to the Martin's Creek (MC) power station, there are three other major, more distant facilities that contributed to the monitored $SO_2$ concentrations. These facilities are the Metropolitan Edison (ED) Portland Station, Hoffman-LaRoche (HL), and the

Warren County Resource Recovery Facility (WCRRF). The area is characterized by complex terrain rising above the stacks toward the southeast.

There were three release points from the Martin's Creek facility, two from the Portland Station, one from Hoffman-LaRoche, and two from the WCRRF. The physical stack parameters used in the modeling are shown in the following table:

STACK PARAMETERS FOR THE EIGHT SOURCES IN THE MARTIN'S CREEK STUDY

| Stack ID | UTM Easting (kilometers)* | UTM Northing (kilometers) | Base Elevation (meters) | Stack Height (meters) | Stack Diameter (meters) |
|---|---|---|---|---|---|
| MC1&2 | 491.020 | 4515.910 | 73.2 | 182.9 | 5.3 |
| MC3 | 491.123 | 4516.030 | 73.2 | 182.9 | 6.9 |
| MC4 | 491.190 | 4516.068 | 73.2 | 182.9 | 6.9 |
| ED1 | 493.350 | 4528.370 | 91.4 | 121.9 | 3.1 |
| ED2 | 493.350 | 4528.370 | 91.4 | 121.9 | 3.6 |
| HL2 | 494.050 | 4521.040 | 103.6 | 59.4 | 2.7 |
| WCRRF1 | 498.950 | 4518.500 | 173.7 | 76.2 | 1.87 |
| WCRRF2 | 498.950 | 4518.500 | 173.7 | 76.2 | 1.87 |

* UTM Zone 18

Two nearby cooling towers present potential downwash influences on the Martin's Creek stacks. In consultation with U.S. EPA and the State of New Jersey, it was suggested that the cooling towers be represented in PP&L's modeling analysis (TRC, 1994) by a hypothetical building with a height of 90 meters, a length of 180 meters, and a width of 90 meters. The same dimensions were used in this analysis.

PP&L's on-site meteorological data for the Martin's Creek station were recorded at three sites and covered the period from May 1, 1992 through May 19, 1993. Hourly temperature, wind speed, wind direction, and $\sigma_A$ at 10 meters were recorded from an instrumented tower located in a flat area approximately 2.5 kilometers west of the Martin's Creek power generation station. In addition, hourly multi-level wind measurements were taken by a SODAR located approximately three kilometers southwest of the Martin's Creek station. Wind speed and direction were measured at 30 meter height intervals beginning at 90 meters and ending at 420 meters. The SODAR data contained a six day gap of missing data from May 5, 1992 through May 10, 1992. A 20-meter tower instrumented at 10 and 20 meters was located northwest of the power station, but the data collected at the tower were not used in this analysis since the tower was located in more complex terrain away from the SODAR. Thus, the 10-meter tower and SODAR data were incorporated into a single file with 13 levels of data. The following table summarizes the data collected at each level. An asterisk in the cell indicates that data were collected at that level for the variable shown; a blank indicates that no data were reported at that level.

| Height (meters) | Wind speed | Wind direction | Temperature | $\sigma_A$ | $\sigma_w$ |
|---|---|---|---|---|---|
| 10 | * | * | * | * | |
| 90-420 (every 30 m) | * | * | | | |

For the full on-site evaluation, all data levels were used. For the single level on-site data evaluation, the 10-meter level was used.

Upper air data for Albany, NY (WBAN No. 14735), about 250 kilometers northeast of the Martin's Creek facility, and hourly surface data for Allentown-Bethlehem-Easton, PA airport (WBAN No. 14737), which is about 30 kilometers southwest of the Martin's Creek facility, were used in this analysis. There were numerous missing soundings in the Albany, NY upper air data. Of particular concern was a period of missing soundings from February 13, 1993 through February 25, 1993. All 00Z and 12Z soundings were missing during this 13 day period. For this period and any other missing upper air data, the soundings from Sterling, VA (Dulles airport) were substituted.

Site-specific characteristics for Martin's Creek were defined monthly for two wind direction sectors as shown in the table below. To determine the monthly moisture conditions, data from NWS at the Allentown-Bethlehem-Easton airport were used. A scheme following procedures defined by Wilks (1995) was used to classify a month as dry, normal, or wet. The 1992 Local Climatological Data (LCD) annual summaries, available from the National Climatic Data Center, were used for this purpose. These summaries contain 30 years of monthly precipitation data through the year of record (i.e., 1963-1992 in this case). A month was classified as 'wet' if the total precipitation recorded for the month at the station was greater than the 70th percentile for the corresponding month of the 30-year record. A month was classified as 'dry' if the total precipitation for that month was less than the 30th percentile of the 30-year record. Otherwise, the monthly precipitation was classified as 'normal.'

ALBEDO, BOWEN RATIO, AND SURFACE ROUGHNESS LENGTH ($z_0$) BY WIND DIRECTION SECTOR AND MONTH FOR MARTIN'S CREEK

| Wind sector | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | moisture conditions | norm | norm | wet | wet | norm[1] | norm | norm[2] | norm | norm | dry | wet | norm |
| 260-180E | albedo | 0.15 | 0.40 | 0.40 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| | Bowen ratio | 1.00 | 1.30 | 0.50 | 0.30 | 0.50 | 0.40 | 0.30 | 0.40 | 0.80 | 2.00 | 0.40 | 1.00 |
| | $z_0$ (meters) | 0.10 | 0.10 | 0.10 | 0.20 | 0.20 | 0.30 | 0.30 | 0.30 | 0.20 | 0.20 | 0.20 | 0.10 |
| 180-260E | albedo | 0.15 | 0.40 | 0.40 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| | Bowen ratio | 1.00 | 1.30 | 0.50 | 0.30 | 0.50 | 0.40 | 0.30 | 0.40 | 0.80 | 2.00 | 0.40 | 1.00 |
| | $z_0$ (meters) | 0.30 | 0.30 | 0.30 | 0.50 | 0.50 | 0.60 | 0.60 | 0.60 | 0.50 | 0.50 | 0.50 | 0.30 |

1 = wetter than normal for 5/92, drier than normal for 5/93; 2 = borderline wet: 5.36" vs 5.37" of 30-year climatological data

For the Martin's Creek data, the threshold wind speed for the SODAR data was set to 0.3 m $s^{-1}$, as reported in the PP&L model comparison report (TRC, 1994). The same threshold was applied to the 10-meter tower data.

The AERMET-generated meteorology produced a total of 199 hours (out of 9216 hours) for which data were missing or the winds were calm.

The seven $SO_2$ monitors used in this evaluation were located on Scotts Mountain, which is about 2.5 - 8 kilometers southeast of the Martin's Creek facility. The monitors were about 90-120 meters above the top of the Martin's Creek sources. The hourly background concentration was removed from the observed concentrations and was defined as the lowest value monitored value each hour at any of the monitors. An eighth $SO_2$ monitor was located about six kilometers northeast of the facility for purposes of estimating background concentrations. The locations, elevations, and height scales for the receptors are shown below.

RECEPTOR LOCATIONS, TERRAIN ELEVATIONS, AND HEIGHT SCALE FOR MARTIN'S CREEK

| UTM-E (m)* | UTM-N (m) | Elevation (m) | Height Scale (m) |
|---|---|---|---|
| 495510 | 4513680 | 353.60 | 353.60 |
| 493900 | 4513200 | 376.60 | 376.60 |
| 492700 | 4513440 | 370.30 | 370.30 |
| 492440 | 4511190 | 340.20 | 340.20 |
| 495400 | 4515180 | 356.60 | 356.60 |
| 495300 | 4513880 | 365.80 | 365.80 |
| 496430 | 4514500 | 341.40 | 341.40 |

* UTM Zone 18

# 3.0 RESULTS

In this section, the results of the meteorological data degradation analysis are presented. Prior to presenting the results, the graphical and statistical procedures used to compare the concentration estimates are discussed.

## 3.1 EVALUATION PROCEDURES

Graphical and statistical procedures are standard methods in comparing the performance of different dispersion models. Graphical methods include quantile-quantile (Q-Q) plots in which quantiles of one distribution (e.g., observed concentrations) are plotted against quantiles of another distribution (e.g., estimated concentrations). A quantile is similar to a percentile except that a quantile refers to a fraction of the data set and a percentile refers to a percentage of the data set. The distributions of observed and predicted concentrations are ranked irrespective of time and space, and plotted as ranked pairs. In this evaluation, Q-Q plots were used to compare the distributions of observed and estimated concentrations from AERMOD run with different meteorological input. While useful in displaying characteristics of the distributions providing qualitative insight into model behavior, graphical techniques alone are not sufficient for evaluating and comparing model performance under regulatory conditions.

A statistical procedure developed by Cox and Tikvart (1990) provides for an objective comparison of the performance between models. In this analysis, 'models' refer to the different meteorological inputs to AERMOD. This procedure relies on the fractional bias, which is defined here as follows:

$$FB = 2\,\frac{[\chi_P - \chi_O]}{[\chi_P + \chi_O]} \qquad (3\text{-}1)$$

where $\chi_P$ is the predicted concentration and $\chi_O$ is the observed concentration. Thus a positive fractional bias indicates an overprediction. Note that the definition used here differs from that originally used by Cox and Tikvart in that the numerator in their paper is $\chi_O - \chi_P$. Two features of the fractional bias are 1) it ranges between 2 (extreme overprediction) and -2 (extreme underprediction), and 2) it is a dimensionless value. The fractional bias can be translated into equivalent "factors" of over and underprediction. For example, a fractional bias of +0.67

represents a "factor of two" overprediction while -0.67 represents a "factor of two" underprediction.

Cox and Tikvart proposed a robust test statistic that represents a "smoothed" estimate of the highest concentrations, based on a tail exponential fit to the upper end of the distribution. In other words, the effect of extreme values on model comparison is lessened. This statistic is the robust highest concentration (RHC) and is given by:

$$RHC = X(N) + [\overline{X} - X(N)] \ln\left[\frac{3N-1}{2}\right] \qquad (3\text{-}2)$$

where

| | | |
|---|---|---|
| $M_0$ | = | number of values used to characterize the "upper end" of the distribution |
| M | = | # values exceeding a threshold value |
| N | = | min($M_0$, M) |
| $\overline{X}$ | = | average of the N-1 largest values, and |
| X(N) | = | $N^{th}$ largest value. |

In this evaluation, the value of $M_0$ was taken to be 26. Fractional biases are then calculated using this test statistic.

There are two components to determining the best performing model as proposed by Cox and Tikvart: an operational component and a scientific or diagnostic component. The operational component compares model performance in terms of the largest network-wide RHC and is based on the 3-hr and 24-hr average concentrations. For the scientific component, data are stratified by categories such as meteorological conditions, and comparisons are based solely on 1-hr average concentrations. For the scientific component in this evaluation, the 1-hr average results were stratified by atmospheric stability (convective or stable) and wind speed ($U < 4$ m $s^{-1}$, $U >$ 4 m $s^{-1}$), creating four diagnostic classes.

A composite performance measure (CPM) based on the absolute fractional bias (AFB) is computed for each meteorological degradation data base input to AERMOD. The AFB is the absolute value of the fractional bias and the CPM is a weighted linear combination of the individual fractional bias components. For this evaluation, the operational and scientific components each receive equal weight. Within the operational evaluation component, the 3-hr and 24-hr average concentration results receive equal weight, i.e., 25% each to the total CPM. For the scientific component, each of the results for the various diagnostic conditions receives equal weight and each receptor receives equal weight. The algebraic expression for the composite performance measure used in this evaluation is:

$$CPM = \frac{1}{2}\,\overline{(AFB)_{r,s}} + \frac{1}{2}\left[\frac{(AFB)_3 + (AFB)_{24}}{2}\right] \quad , \qquad (3\text{-}3)$$

where

| | | |
|---|---|---|
| $(AFB)_{r,s}$ | = | Absolute Fractional Bias for diagnostic condition r at station s, |
| $(AFB)_3$ | = | Absolute Fractional Bias for 3-hour averages, and |
| $(AFB)_{24}$ | = | Absolute Fractional Bias for 24-hour averages. |

The smaller the CPM, the better the overall performance of an individual model.

Because the purpose of the analysis is to contrast performance among two or more versions of the meteorological data input for AERMOD, differences in model performance are characterized by calculating differences in pairs of composite performance measures between the model results. The difference between the CPM of two models is called the model comparison measure (MCM). The expression for the model comparison measure is given by:

$$MCM_{i,j} = CPM_i - CPM_j \quad , \qquad (3\text{-}4)$$

where

| | | |
|---|---|---|
| $CPM_i$ | = | Composite Performance Measure for Model i, and |
| $CPM_j$ | = | Composite Performance Measure for Model j. |

When more than two models are being compared simultaneously, the number of MCM statistics is equal to the total of the number of unique combinations of two models. Again, in this analysis, the comparison between models refers to the different degraded meteorological inputs to AERMOD.

The measure used to determine if the model comparison is statistically significant is the standard error. Because the CPM and MCM are rather involved statistics, the usual statistical methods for estimating the standard error do not apply. Resampling techniques such as the "jackknife" and "bootstrap" are methods for estimating the standard error and for determining confidence limits. The blocked bootstrap used in this evaluation is basically a resampling technique whereby the desired performance measure is recalculated for a number of "trial" years. Cox and Tikvart (1990) provide an explanation of this technique.

When two or more models are being compared, the calculation of simultaneous confidence intervals based on the standard error for each pair of model comparisons provides a means of determining if the differences are statistically significant. If the confidence interval overlaps 0, then the difference in performance of the two models is not statistically significant; conversely, if the confidence interval does not overlap 0, then there is a statistically significant difference between the two models at the stated level of confidence.

To compute these model performance measures, EPA's Model Evaluation Methodology (MEM) software (EPA, 1993) was used.

## 3.2 EVALUATION RESULTS

The results of the Q-Q plots will be presented first, followed by the results of the statistical comparisons.

### 3.2.1 Q-Q Plot Graphical Comparisons

In presenting the results of this evaluation, there are several points common to the Q-Q plots:

1) the observed and predicted concentrations are plotted without being normalized by emission rate;
2) the solid diagonal line represents the 1:1 line and the dashed lines represent the envelope of modeled estimates within a factor of two of the observations; and
3) observed concentrations are plotted along the x-axis and the modeled concentrations are plotted along the y-axis

Regarding the first point, it is not uncommon in model evaluation studies to focus on comparison results using concentrations normalized by the emission rate. This avoids potential problems such as the results being skewed by a few data points associated with unusually high emission rates, and focuses on the model's ability to predict the dispersive capacity of the atmosphere. This approach is especially useful during controlled field experiments using a single emission source, but can be problematic for long-term limited data bases from operating facilities such as those used in this evaluation. In these cases, the high end of the normalized concentration distribution can be unduly influenced by very low emission scenarios during periods of plant startup and/or shutdown. During these conditions, the relative accuracy of the emissions data may become more suspect, and the relative contributions from other sources and background concentrations may become more important. It is for these reasons that the Q-Q results in this report are based on non-normalized concentrations.

Figures 3.1 - 3.3 show the Kincaid Q-Q plots for the 1-hr, 3-hr, and 24-hr average concentration estimates, respectively. The full on-site data appear to give the best results for the 1-hr average concentrations, with modeled concentrations near the 1:1 line above about 500 $\mu g\ m^{-3}$. The 1-level on-site tends to overpredict, and the NWS only tends to underpredict. For the 3-hr plot, the full on-site and NWS show similar trends, with the 1-level on-site still overpredicting. In the 24-hr Q-Q plot, the results using NWS data alone aligns with the 1:1 line more closely than either on-site data base, whereas use of the full on-site data underpredict and the single level on-site overpredict.

Figures 3.4 - 3.6 show the Lovett Q-Q plots for the 1-hr, 3-hr, and 24-hr average concentration estimates, respectively. For the 1-hr average concentration, AERMOD's performance with full on-site data performed better with much of the upper part of the distribution on or near the 1:1 line. Using the 1-level on-site data, AERMOD overpredicted by a factor of two or more for the upper part of the distribution. For the 3-hr averages, the full on-site meteorology still performed better, but with slight overprediction for the top few pairs. Use of the 1-level on-site meteorology continued to overpredict by a factor of two. For the 24-hr averages, the full on-site meteorology slightly overpredicted (with the exception of the highest value), and the 1-level on-site meteorology continued to overpredict by a factor of two.

Figures 3.7 - 3.9 show the Martin's Creek Q-Q plots for the 1-hr, 3-hr, and 24-hr average concentration estimates, respectively. For the 1-hr average concentration, AERMOD's performance with full on-site data performed better, although AERMOD tended to overpredict by 30% or less in the upper part of the distribution. Using the 1-level on-site data, AERMOD overpredicted by about a factor of two. For the 3-hr averages, the full on-site and 1-level on-site performed about the same for observed concentrations less than 250 $\mu g\ m^{-3}$. For the 24-hr averages, both the full on-site and 1-level on-site meteorology generally overpredicted by about 30%, though the 1-level on-site was closer to the 2:1 line at the extreme upper end.

### 3.2.2 Statistical Comparisons of Model Performance

Figure 3.10 shows the CPM results for Kincaid, and Figure 3.11 shows the Kincaid MCM results. These results, with the RHCs in Table 3.1, show that the model performs better with full on-site data than with a single level of on-site data, but that the difference in performance is not statistically significant at the 95 percent confidence level. However, the model performs significantly worse, at the 95% confidence level, with the 1-level data compared to using NWS data only. The RHC for each meteorological data set shows similar trends for the operational components as well as for the annual maximum. Without a more detailed investigation into the meteorological data set for the 1-level on-site data, the reasons for this result are not known.

The CPM results for Lovett are shown in Figure 3.12. AERMOD with full on-site meteorology performed better compared to using the 1-level on-site data. The MCM shows an improved performance for full on-site data relative to a single level of on-site data that is statistically significant at the 95 percent confidence level (Figure 3.13). It is apparent from the RHCs (Table 3.1) that the use of full on-site meteorology yielded better results, with the fractional biases of the operational components essentially equal to zero.

The statistical comparison results for Martin's Creek show less improvement for the full on-site data relative to the single level of on-site data than observed for Kincaid and Lovett (Figure 3.14) and the improvement is not statistically significant at the 95% level (Figure 3.15).

Since there is only one annual average calculated for each receptor in the data bases used in this evaluation, the performance of all of the models for this averaging period is based on a single fractional bias calculation (see Eqn. 3-1) using the maximum predicted and observed annual averages. The results of these comparisons are show in Table 3.1 for the three data bases. For the complex terrain data bases (Lovett and Martin's Creek), the fractional bias of the annual maximum indicates that AERMOD performs better with the full on-site data. However, for the flat terrain data base (Kincaid), the full on-site is the worst performing and the use of NWS data only performed the best. As noted above, the reason for this result is not apparent and would require a detailed investigation into the meteorological data bases.

TABLE 3.1 FRACTIONAL BIASES FOR 3-HR AND 24-HR ROBUST HIGHEST CONCENTRATION AND MAXIMUM ANNUAL AVERAGES

| | 3-hr Operational Component | | | 24-hr Operational Component | | | Annual Maximum | | |
|---|---|---|---|---|---|---|---|---|---|
| | Observed | Predicted | FB * | Observed | Predicted | FB * | Observed | Predicted | FB * |
| **Kincaid** | | | | | | | | | |
| | 618.345 | | | 112.738 | | | 14.54 | | |
| **Full On-site** | | 626.751 | 0.014 | | 108.947 | -0.034 | | 4.42 | -1.07 |
| **1-Level On-site** | | 1153.970 | 0.60 | | 261.347 | 0.79 | | 18.01 | 0.21 |
| **NWS Only** | | 720.845 | 0.15 | | 193.913 | 0.53 | | 15.81 | 0.08 |
| **Lovett** | | | | | | | | | |
| | 186.631 | | | 51.770 | | | 5.01 | | |
| **Full On-site** | | 186.724 | {1} | | 51.614 | -0.003 | | 3.93 | -0.24 |
| **1-Level On-site** | | 346.644 | 0.60 | | 94.722 | 0.59 | | 8.37 | 0.50 |
| **Martin's Creek** | | | | | | | | | |
| | 461.119 | | | 79.350 | | | 13.13 | | |
| **Full On-site** | | 489.031 | 0.06 | | 136.096 | 0.53 | | 9.66 | -0.30 |
| **1-Level On-site** | | 379.807 | -0.19 | | 116.843 | 0.38 | | 8.56 | -0.42 |

{1} FB = 0.0005 (too small to display in table)

* FB = 2*(Pred-Obs)/(Pred + Obs)

Figure 3.1 Q-Q plot for 1-hr average concentration for Kincaid $SO_2$.

Figure 3.2 Q-Q plot for 3-hr average concentration for Kincaid $SO_2$.

Figure 3.3 Q-Q plot for 24-hr average concentration for Kincaid $SO_2$.

Figure 3.4 Q-Q plot for 1-hr average concentration for Lovett.

Figure 3.5 Q-Q plot for 3-hr average concentration for Lovett.

Figure 3.6 Q-Q plot for 24-hr average concentration for Lovett.

Figure 3.7 Q-Q plot for 1-hr average concentration for Martin’s Creek.

Figure 3.8 Q-Q plot for 3-hr average concentration for Martin's Creek.

Figure 3.9 Q-Q plot for 24-hr average concentration for Martin's Creek.

Figure 3.10 Composite Performance Measure for Kincaid $SO_2$.

Figure 3.11 Model Comparison Measure for Kincaid $SO_2$.

Figure 3.12 Composite Performance Measure for Lovett.

Figure 3.13 Model Comparison Measure for Lovett.

Figure 3.14 Composite Performance Measure for Martin's Creek.

Figure 3.15 Model Comparison Measure for Martin's Creek.

# 4.0 CONCLUSIONS

The overall conclusion from the Q-Q plots and statistical model comparisons discussed above is that the AERMOD dispersion model exhibits generally better performance using the full on-site meteorological data as compared to using a single level (10-meter) of on-site meteorological data. The results for Kincaid also support the use of representative off-site data from an NWS surface station. In examining the 3-hr and 24-hr RHCs, the use of the full on-site data yields the best results in five of the six pairings (averaging period by site). For the annual maximum, the use of full on-site data for the complex terrain sites reasonably estimates the observed RHC. However, for Kincaid (a flat terrain site), the full on-site data yielded the poorest comparison for annual averages. For Kincaid and Lovett, the use of a single level of on-site data produced significantly higher concentrations than the full on-site data. An opposite, but less significant trend, is observed for Martin's Creek.

# 5.0 REFERENCES


Bowne, N. E., R. J. Londergan, D. R. Murray, and H. S. Borenstein, 1983: *Overview, Results, and Conclusions for the EPRI Plume Model Validation and Development Project: Plains Site.* EPRI Report EA-3074, Project 1616-1, Electric Power Research Institute, Palo Alto, CA, 234 pp.

Cox, W. and J. Tikvart, 1990: A Statistical Procedure for Determining the Best Performing Air Quality Simulation Model. *Atmos. Envir.*, 24A, 2387-2395.

ENSR, 1989: Plume model development and evaluation: Hybrid approach. Submitted to Electric Power Research Institute, Palo Alto, California. ENSR Document No. 2460-008-200.

Liu, M. K., and G. E. Moore, 1984: Diagnostic validation of plume models at a plains site. EPRI Report No. EA-3077, Research Project 1616-9, Electric Power Research Institute, Palo Alto, CA.

Paumier, J. O., S. G. Perry, and D. J. Burns, 1992: CTDMPLUS: A dispersion model for sources near complex topography. Part II: Performance characteristics. *J. Appl. Meteor.,* **31,** 646–660.

TRC, 1994: Air Quality Model Performance Evaluation and Comparison Study for Martins Creek Steam Electric Station. TRC Project No. 14715-R61. TRC Environmental Corporation, Windsor, CT.

US EPA, 1993: User's Guide for the Model Evaluation Methodology (MEM) System for Comparing Model Performance, Version 1.0 (Draft). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 27711.

US EPA, 1998a: Revised Draft User's Guide for the AMS/EPA Regulatory Model - AERMOD. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 27711.

US EPA, 1998b: Revised Draft User's Guide for the AERMOD Meteorological Preprocessor (AERMET). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 27711.

US EPA, 1998c: Revised Draft User's Guide for the AERMOD Terrain Preprocessor (AERMAP). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 27711.

Wilks, D., 1995: *Statistical Methods in the Atmospheric Sciences: An Introduction*. Academic Press, 467 pp.