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Sensitivity of RADM to Point Source Emissions Processing

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SENSITIVITY OF RADM TO POINT SOURCE EMISSIONS PROCESSING

Daewon W. Byun
Computer Sciences Corporation.
P.O. Box 12767
Research Triangle Park, North Carolina 27709

Francis S. Binkowski[1]
Atmospheric Sciences Modeling Division
Air Resources Laboratory
National Oceanic and Atmospheric Administration
Research Triangle Park, North Carolina 27711

1. INTRODUCTION

The Regional Acid Deposition Model (RADM) and associated Engineering Model have been developed to study episodic source-receptor relationships on a regional scale. The RADM includes transport, chemical transformation, and deposition processes as well as input of emissions into the vertical layers using a plume-rise submodel. As wind speed and direction change with height, and as atmospheric turbulence varies significantly with distance from the earth's surface, the model predictions can be affected considerably by the height at which the emissions are injected. Atmospheric emissions can be divided into area and point sources. The area sources include mobile emissions, biogenic emissions, and other emissions that are often related to the surface area of the earth. Area sources are more difficult to control and have inherent diversities in their physio-chemical processes. Point sources include stacks at power plants and manufacturing facilities. Usually, point sources are the target of emission reduction programs.

The comprehensive emissions system for RADM includes processing of point sources, area sources, mobile sources, and biogenic emissions. In order to reliably evaluate effectiveness of future emission control strategies in reducing acid deposition, quantification of the influence of emissions processing on the RADM predictions is necessary. One important part of point source emissions processing is the plume-rise computation. The effect of using different plume-rise algorithms on the RADM's prediction of the sulfur deposition needs to be investigated. The objective of the present study is to compare two different plume-rise calculation methods that are described below.

2. PLUME-RISE SUBMODELS

Two types of plume rise estimation algorithms that have been used for the RADM emissions processing are compared here. Method-1 is based on the early formulas by Briggs (1969) and uses wind and ambient temperature data at stack height. However, wind and temperature data are available at a number of layers above the ground for the RADM system. Thus, a plume-rise algorithm that uses these additional meteorological data was developed.

Method-2 uses more recent plume rise formulas by Briggs (1975, 1984) to replace earlier versions (Briggs, 1969). The procedure is similar to the one proposed by Turner (1985), which is intended for use in Gaussian-type plume dispersion, but has been somewhat modified for use in a regional-scale model such as RADM. It requires point source stack parameters and meteorological input files generated by a meteorological model, such as MM-4 (Anthes and Warner, 1978). The NAPAP point-source stack parameters include: stack flow rate, stack height, temperature of the plume, stack diameter and effluent velocity, and stack identification code.

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2.1 Meteorological Data Processing

The RADM's point-source plume-rise submodel utilizes wind, temperature, and moisture profiles generated by the MM-4 model. A meteorological preprocessor for RADM estimates surface friction velocity (u_*) and sensible heat flux based on the surface layer similarity theory. For the unstable case, mixing height is estimated from the virtual potential temperature profile. For neutral and stable cases, dynamic boundary layer heights are estimated based on the boundary layer theory. Estimates of wind speed and ambient temperature at the stack top are interpolated based on the surface layer similarity theory when stack top is within the surface layer and simple linear interpolation when it is located above the surface layer.

2.2 Plume-rise Calculation

Initial buoyancy flux (F_b) of the plume is computed using the equation

$$F_b = g\frac{(T_s - T_a)}{T_s}\frac{(v_s d^2)}{4}, \quad \text{if } T_s > T_a$$
$$F_b = 0, \quad \text{if } T_s \le T_a \qquad (1)$$

where: F_b is the initial buoyancy flux (m^4/s^3)
g is gravitational acceleration (m/s^2)
T_s is the temperature of the plume (K)
T_a is the ambient temperature at stack height (K)
v_s is the initial plume effluent velocity (m/s)
d is the diameter of the stack at stack height (m).

Since buoyant plume rise is very sensitive to atmospheric stability, a layer-by-layer plume penetration and plume rise concept is utilized for calculating buoyant plume rise.

For neutral stability, Briggs' equation for buoyant plume rise at break-up is:

$$\Delta h = 1.2\,[F_b / (u \cdot u_*^2)]^{3/5}\,[h_s + \Delta h]^{2/5} \qquad (2)$$

where: Δh is the plume rise above the stack (m)
u is the average wind speed at stack height (m/s)
h_s is stack height (m)

An approximate solution of above, suggested by Briggs (personal communication, April 23, 1983), is used in actual computation:

$$\Delta h = 1.2[F_b/(u \cdot u_*^2)]^{3/5}\,[h_s + 1.3F_b/(u \cdot u_*^2)]^{2/5} \qquad (3)$$

For stable cases, the new plume-rise algorithm defines plume rise as the minimum of (a) Δh calculated by the above approximate equation for neutral stability and (b) Δh estimated by Briggs' equation for the rise of bent-over plumes:

$$\Delta h = 2.6\,[F_b/(u \cdot s)]^{1/3} \qquad (4)$$

where: $s = \frac{g}{T_a}\frac{\partial \theta}{\partial z}$ is the stability parameter.

For both neutral and stable cases, if the projected plume rise is found to be located at the layer above the top of the current layer, the rise is limited to the top of the current

layer and residual buoyancy flux is computed. With the residual buoyancy flux, the above procedures for the buoyancy plume rise are repeated until all of the buoyancy of the plume is exhausted. Finally, plume top and bottom heights are estimated using (a) the assumption of a top-hat-shaped concentration distribution, and (b) the assumption that plume thickness is the same as plume rise (Turner et al., 1986).

For unstable cases, it is assumed that the plume is dispersed throughout the mixing layer. However, if the distance between the stack top and the top of the mixing layer (z_b') is less than 200m, fractional plume penetration (p) is computed using Briggs' equation (1984):

$$p = 0, \quad \text{if} \quad z_b' > 3.9\,[F_b/(u \cdot s)]^{1/3}$$

$$p = 1, \quad \text{if} \quad z_b' < 1.3\,[F_b/(u \cdot s)]^{1/3}$$

$$p = \frac{3.9 - \dfrac{z_b'}{[F_b/(u \cdot s)]^{1/3}}}{2.6}, \quad \text{otherwise} \qquad (5)$$

When the stack top is located above the mixing height, the minimum of: (a) the approximation of plume rise for the neutral case [Eq. (2)] and (b) Δh estimated by the rise of bent-over plumes [Eq. (4)] is used to estimate the plume center height. Again, the thickness of the plume is assumed to be the same as plume rise for this condition.

The fractional portion of the plume for each layer is determined using hourly plume top and bottom heights and RADM's layer interface heights computed by the hypsometric equation. Figure 1 provides a schematic of the plume partitioning procedure. Note that the RADM layers are defined in σ-level surfaces, so the actual height varies depending on the surface pressure values. Table 1 provides layer definitions for 6-layer RADM.

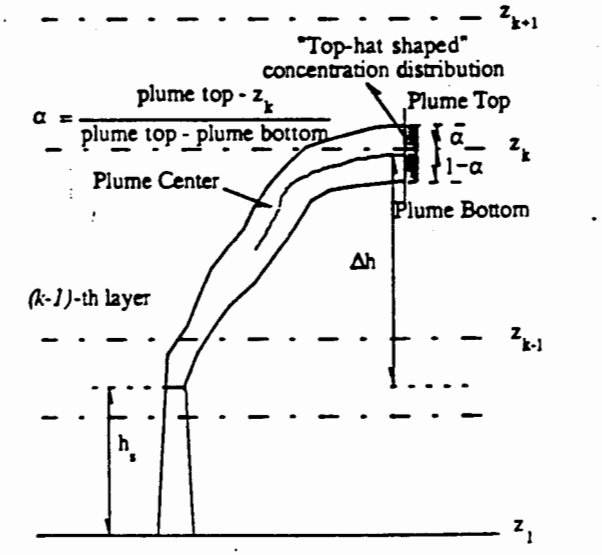

Fig. 1. Schematic of plume partitioning.

Table 1. Layer definitions of 6-layer RADM

Layer (k)	1	2	3	4	5	6
σ-level	1.0	.99	.96	.90	0.7	0.4	0.0

where $\sigma = \dfrac{P - P_{sfc}}{P_{top} - P_{sfc}}$, P_{top}=100 mb in RADM.

3. POINT SOURCE EMISSION PROCESSING

Using stack parameters as well as SO_2, NO_x, and total hydrocarbon (*THC*) data from 1985 NAPAP point-source emissions inventory, estimates of plume rise and emission distributions for the RADM layers were determined by two versions of plume-rise algorithms. The NAPAP point-source data contains general identifying information (such as Source Classification Code, latitude and longitude of stack), stack parameters, major pollutant annual emissions, temporal allocation factors, and speciation factors. Since the total number of stacks in the RADM modeling domain exceeds 50,000, it is very expensive to process plume rise for all stacks for each meteorological episode. Therefore, we classified point sources as major and minor stacks, based on annual emission tonnage. We classified stacks as major if:

SO_2 emissions exceed 500 tons/yr, or
NO_x emissions exceed 210 tons/yr, or
Total hydrocarbon (THC) emissions exceed 400 tons/yr.

The remaining stacks were classified as minor. Out of the 53,386 point sources in the 1985 NAPAP data, 5,924 were classified as major and 47,462 as minor. Among the major sources selected, stacks with physically consistent stack parameters were used in the plume-rise calculations and the remaining sources are combined with the minor stacks. The emissions from major stacks were allocated to six model layers using the plume-rise algorithms described above. For minor stacks, we computed seasonal average diurnal plume fractions for each layer and applied them to corresponding episodic case. After speciation and temporal allocation, the minor source emissions were summed by grid cell and by layer together with the major sources. Figure 2 shows the flow of point-source emissions processing in the RADM system.

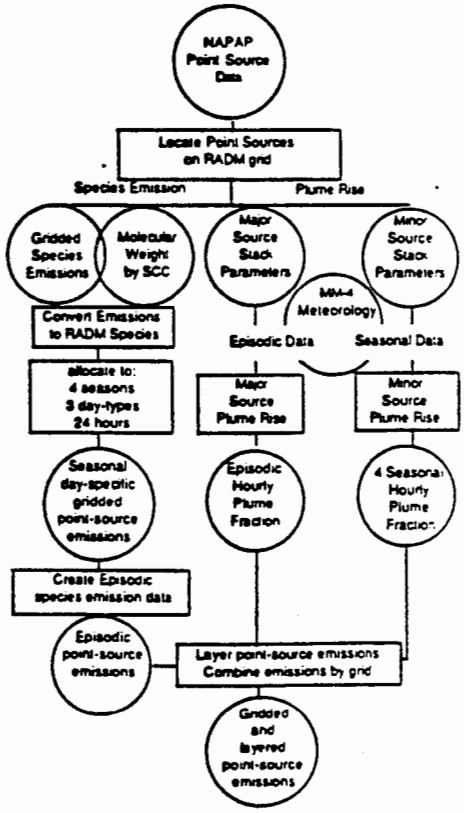

Fig. 2. Flowchart of the point-source emissions processing in the RADM system.

4. SENSITIVITY OF RADM PREDICTIONS TO POINT-SOURCE EMISSIONS PROCESSING

The objective of this study is to compare the effect of two different plume-rise processing methods, method-1 and method-2, on the sulfate deposition prediction by RADM for two five-day periods -- in summer (A9), and winter (A1). Case A1 (30 Jan. 1982 - 4 Feb. 1982) was selected as a representative winter episode. This case began with a large 1,031mb high pressure system over the eastern U.S. A surface low pressure center tracked eastward across southern Canada and a cold front that extended southward from the center of surface low moved off the east coast of the U.S. Very little precipitation was observed or simulated in conjunction with the frontal system. Case A9 (2 Aug. 1983 - 7 Aug. 1983) was selected to represent a typical summer episode. This case began with a high pressure cell over the central U.S. A weakening cold front, located just east of the high pressure cell, was moving slowly toward the east coast. During the last half of the case study period, a weak quasi-stationary front that extended from Illinois to New England induced light amounts of precipitation. Out of five days in each episode, the first two days were used for the initialization of RADM and remaining three days were used for the simulation of acidic deposition.

4. 1 Differences in Emission Input

Figures 3-a,b show RADM-domain total hourly major source plume fractions estimated with method-1 and method-2 for winter A1 case. Method-1 does not show a distinct day-night difference. Method-2 estimates higher plume rise especially during daytime because the plumes are assumed to be well mixed within the mixed layer. For summer case (Figures 4-a,b), method-2 produces very pronounced diurnal variation of the plume rise pattern. During mid-day, some portions of plume reaches the fourth layer of the 6-layer RADM. Again, method-1 does not show a distinct day-night difference: only a few sources reach the fourth-layer even during a very convective period. Since extremely small amount of plume reached above the fourth layer, we limited our analysis up to fourth-layer of the 6-layer RADM.

Method-2 plume-rise algorithm is very sensitive to the variation of the atmospheric stability while method-1 does not show a pronounced day-nighttime difference. The difference between the two methods is more pronounced for the summer case (A9) than the winter case (A1).

Gridded and layered major point-source emissions were computed using the procedure described in the previous section. Figures 5-a,b and 6-a,b present RADM domain-total layered SO_2 emissions allocated with both methods for case A1 and A9. Since taller stacks emit larger volumes of pollutant than smaller ones, the total emission fractions show heavier weighting in the upper layers than the layered plume fractions. A basic difference between the two methods is vertical allocation of the gridded emissions. Depending on which level the pollutant is injected, subsequent transport, diffusion, gas-phase chemistry reaction, transformation inside clouds, and removal processing will be affected. The SO_2 emissions from the major sources accounts for about 85 percent or higher of the total emissions (from major and minor point sources and area sources) in the RADM domain.

4. 2 Sensitivity of RADM

Atmospheric deposition processes are significantly influenced by where we inject point-source emissions. Method-2, which distributes point-source emissions throughout the depth of the mixed layer during daytime when deposition velocities are large, results in more dry deposition of primary pollutants such as SO_2 than the method-1. On the other hand, method-2 sometimes injects point-source emissions into one upper layer. Then the

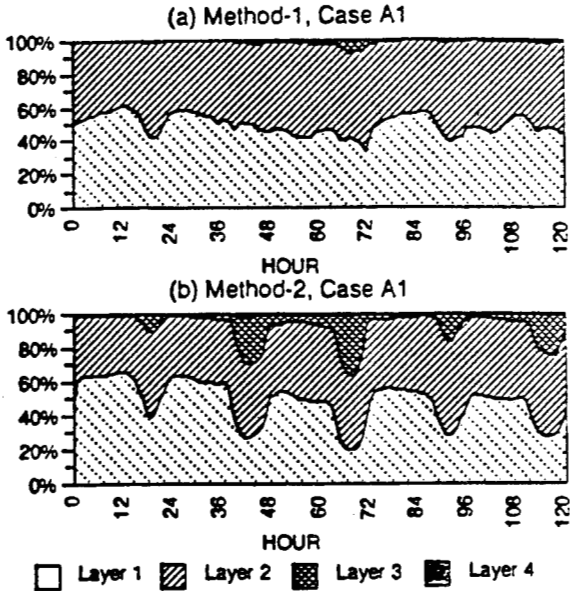

Fig. 3. Domain-averaged percentage of plume by RADM layers (A1: Winter)

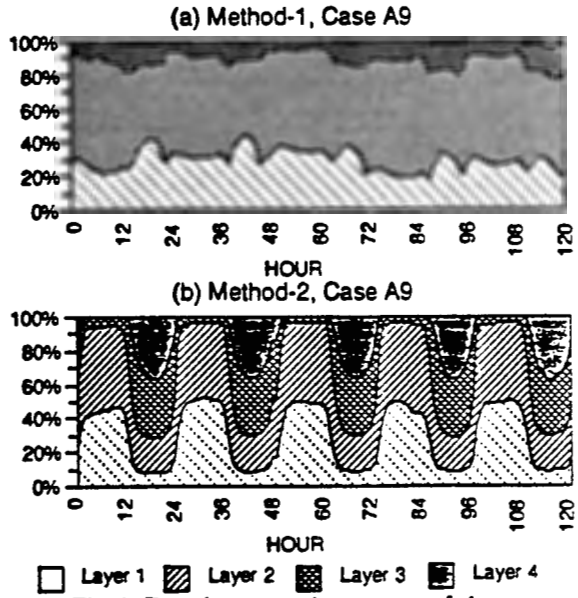

Fig. 4. Domain-averaged percentage of plume by RADM layers (A9: Summer)

emissions are transported farther downwind before they are available for dry deposition by turbulent mixing process. As the wet-deposition process is competing for the same primary pollutants with the dry-deposition process, method-2 produces less overall wet deposition than method-1. Therefore, the ratio of sulfur in dry and wet deposition can be a good indicator of the effect of different plume rise methods.

Figures 7-a and -b show the percentage difference of the two methods in the ratio of sulfur in dry depositions to sulfur in total (wet and dry) depositions for winter (A1) and summer (A9) cases. Differences of about 10 % or over occurs near the high source regions such as Alabama-Georgia-Lousiana areas and Sudbury areas for the winter case; and for Detroit and western Tennessee areas for the summer case. Note that the areas of larger negative percentage difference are found at the downwind sides of the positive percentage difference areas.

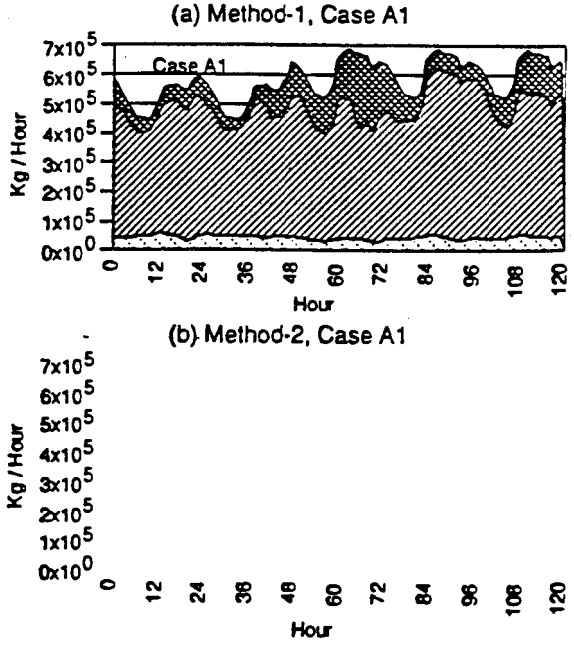

Fig. 5. Layered SO_2 emission rate for 6-layer RADM (A1: Winter)

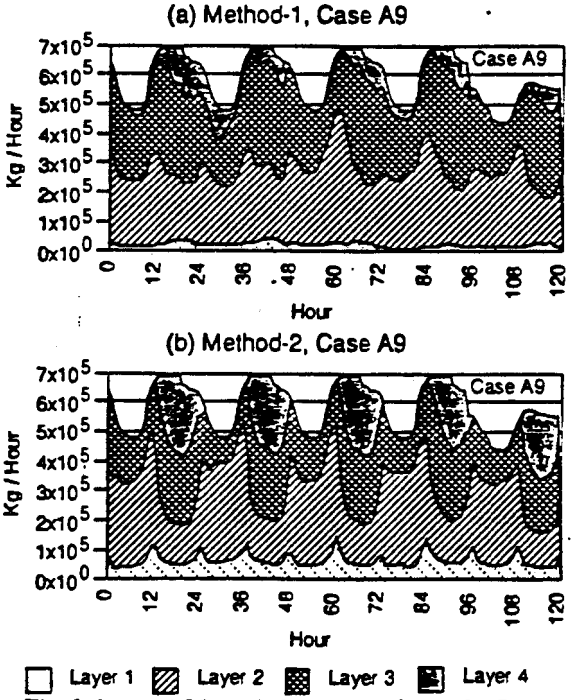

Fig. 6. Layered SO_2 emission rate for 6-layer RADM (A9: Summer)

Based on the figures above and other analyses, the effects of using different plume-rise methods are summarized as: (1) Method-2 produces 2-3 percent higher domain total dry deposition and 2-3 percent lower domain total wet deposition than method-1. Total (wet and dry) deposition is affected by the episodic precipitation amount and pattern. (2) Method-2 predicts higher dry deposition closer to the sources than the method-1. (3) Maximum difference in the dry/total sulfur deposition ratio is about 15 % near the high emission region with persistent airflow.

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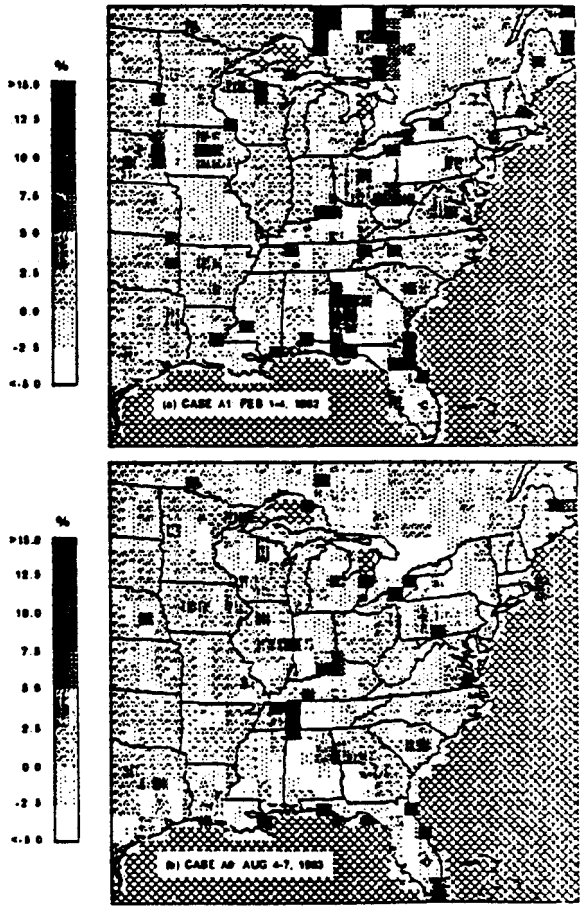

Fig. 7. Percentage difference between plume-rise method-1 and method-2 in the ratio of dry to total (wet and dry) sulfur deposition. (a) winter case A1, and (b) summer case A9.

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16. ABSTRACT

The Regional Acid Deposition Model (RADM) and associated Engineering Model have been developed to study episodic source-receptor relationships on a regional scale. The RADM includes transport, chemical transformation, and deposition processes as well as input of emissions into the vertical layers using a plume-rise submodel. As wind speed and direction change with height, and as atmospheric turbulence varies significantly with distance from the earth's surface, the model predictions can be affected considerably by the height at which the emissions are injected. Atmospheric emissions can be divided into area and point sources. The area sources include mobile emissions, biogenic emissions, and other emissions that are often related to the surface area of the earth. Area sources are more difficult to control and have inherent diversities in their physio-chemical processes. Point sources include stacks at power plants and manufacturing facilities. Usually, point sources are the target of emission reduction programs.

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