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User's Guide to the Rough Terrain Diffusion Model (RTDM)

(Rev. 3.20)

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PREFACE

This manual describes a sequential version of the Rough Terrain Diffusion Model (RTDM, version 3.20), developed by Environmental Research & Technology, Inc. (ERT). RTDM has its origins in the modeling technologies ERT had developed and applied over a period of several years as part of its consulting services to both public and private sectors. In response to the March 1980 Federal Register "Call for Models," ERT submitted RTDM.WC, a case-study version of the model, for consideration by EPA. ERT felt that this model would fill an interim need for realistic assessments of pollutant dispersion in complex terrain settings.

RTDM version 3.20 retains the basic algorithms and features of RTDM.WC, including the unique way in which the model simulates plume behavior near terrain features by limiting reflection from the ground in accordance with the second law of thermodynamics. However, provisions have been made in this sequential version of RTDM to incorporate on-site hourly measurements of turbulence intensity, vertical temperature gradient, horizontal wind shear, and the vertical wind speed profile. In addition, a critical height (H_{crit}) is defined such that in stable conditions, plumes at heights less than H_{crit} will impinge upon terrain. Hourly values of stack emission parameters can also be accommodated by the sequential version of RTDM.

RTDM possesses several features not present in other air quality models routinely used for regulatory applications. Proper application of RTDM requires that the user be thoroughly familiar with the basic modeling concepts applied in the model, and follow the guidance provided in this user's guide for selecting the meteorological and source inputs to be used in the computer calculations. Because the model user must specify the parameter switches and meteorological data, care should be used to avoid inconsistent and physically unrealistic combinations of inputs. The use of incorrect parameter or meteorological input values as well as improper application of RTDM can result in serious calculation errors. Also, because the model provides many input and output options, the user should anticipate the necessity for making a number of trial program runs to become familiar with the various features of RTDM.

ABSTRACT

The Rough Terrain Diffusion Model (RTDM) version 3.20 is a sequential Gaussian plume model designed to estimate ground-level concentrations in rough (or flat) terrain in the vicinity of one or more co-located point sources. It is specifically designed for applications involving chemically stable atmospheric pollutants and is best suited for evaluation of buoyant plume behavior within about 15 km from the source(s). Model results for receptors beyond about 15 km can be used with caution to 50 km, and RTDM can be used as a screening model for distances beyond 50 km. RTDM has special algorithms to deal with plume behavior in complex terrain, and is especially suited for rough terrain applications.

While RTDM version 3.20 is specifically designed for use with sequential data sets, it can also be run in a case-study mode. Various optional features of the model make it useful for either research/sensitivity applications or routine evaluations of source compliance. RTDM has the ability to use hourly on-site measurements of turbulence intensity, vertical temperature difference, horizontal wind shear, and wind speed profile exponents. However, RTDM version 3.20 retains sufficient flexibility in the specification of model inputs to enable the user to obtain results similar to many other Gaussian point source models. The ability of RTDM to read hourly emissions data makes it useful for site-specific model evaluation studies.

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EXECUTIVE SUMMARY

The Rough Terrain Diffusion Model (RTDM) computer code provides a method to estimate air pollutant concentrations from multiple co-located sources in a rural environment. RTDM can be used in flat or complex terrain, but it is especially suited for use in complex terrain.

Special features employed by RTDM in estimating ground-level concentrations are listed below. For applications of the model in a mode approved for general use by the U.S. EPA, certain features are not used (see Section 5 for additional information).

- Reflection of plume mass from the ground is limited by the second law of thermodynamics, so that the maximum concentrations cannot increase with distance downwind.
- In stable conditions, a critical height (H_{crit}) is computed from the wind speed, the terrain height and the strength of the inversion. Plumes below this height are allowed to impinge on the terrain.
- The effects of buoyant entrainment can be accounted for in calculating plume size.
- Momentum effects on plume are ignored; only buoyancy-dominated sources should be modeled with RTDM version 3.2.
- Horizontal wind shear data can be used to make refined estimates of the horizontal extent of the plume.
- On-site turbulence intensity data (I_y, I_z), can be used as estimates of ambient dispersion for input to the model.
- The user can supply hourly values of the wind speed profile exponent.
- On-site values of vertical temperature gradients can be used to better estimate plume rise and H_{crit} values.
- In the presence of a mixing lid, the fraction of the plume that penetrates the lid can be calculated following Briggs (1975), rather than allowing either zero or total penetration of the lid.

- Transitional plume rise may be employed in model computations until the downwind distance to equilibrium plume height is reached by the plume.
- During neutral and unstable conditions or above H_{crit} in stable conditions, a "half-height" correction simulates the effect of terrain-induced plume modifications on ground-level concentrations.
- Decrease in plume rise due to stack-tip downwash can be accounted for.

RTDM can calculate ground-level concentrations at a maximum of 400 receptors from a maximum of 35 co-located point sources. Sources that are not co-located can be modeled separately with the same receptor grid (but different downwind distances to terrain), and the results can then be added using the postprocessor ANALYSIS program. RTDM calculates one-hour average concentrations, considering each hour as an individual steady-state period. The user can input hourly emissions parameters to the model. The resulting one-hour concentrations can be summed to obtain multiple-hour averages.

When the "partial reflection" option is employed in RTDM, the concentration at a receptor point depends upon the travel path of the plume (the upwind concentrations) as well as the location of the receptor itself. This is a feature found in few Gaussian models, and it requires the RTDM user to supply detailed terrain information in each of 36 directions (at 10° intervals). This terrain data consists of downwind distances to successive contour heights (at constant height intervals), starting below stack-top elevation and ending at the highest point within the distance from the source under consideration (e.g., 15 km). This terrain information is summarized in a table as well as presented in map form in the RTDM output.

1. INTRODUCTION

1.1 Model Features

RTDM version 3.20 is a sequential version of the ERT Rough Terrain Diffusion Model, and is based upon the case-study model, RTDM.WC, submitted to EPA in August 1980. The model can be used in flat or complex terrain, but it has features especially suited for simulating plume dispersion in complex terrain.

RTDM is a Gaussian, point-source model which has many parameters and optional features that allow for a wide variety of applications. These features are listed below:

- Wind Speed Determination:

  - Input of anemometer height
  - Adjustment of wind speed to stack top to compute plume rise
  - Use of a wind speed value at either stack-top or plume height for dilution
  - Use of an alternate observed wind speed value for dilution
  - Input of wind speed profile exponents: hourly or as a function of stability class

- Plume path adjustment as a function of Pasquill-Turner stability class
- Calculation of a dividing streamline height in stable conditions
- A choice of transitional or final plume rise
- A choice of dispersion parameters:

  - Pasquill-Gifford,
  - Briggs (1973)/ASME (1979),
  - User-supplied in the form $ax^b + c$

- Buoyancy-induced dispersion
- Stack-Tip downwash
- Multiple reflection from a mixing lid

- Partial plume penetration of a mixing lid
- An option to set the height of the mixing lid to 10,000 meters in stable conditions
- Optional meteorological input:

  - I_y, I_z to compute on-site σ_y, σ_z values
  - On-site vertical temperature difference data used to calculate stable plume rise and the height of the dividing streamline in stable conditions
  - Horizontal wind shear data to provide better estimates of σ_y

- In rough terrain, calculation of the maximum crosswind-integrated plume concentration upstream from each receptor location. The plume concentration is not allowed to increase with distance from the source. Reflection of the plume from the ground is limited to account for this effect.
- Use of hourly stack emissions data
- Maxima of 400 receptors and 35 co-located sources
- Transportable receptor grid of any configuration
- Sector-averaged or centerline concentrations calculated
- Detailed information can be supplied concerning plume behavior and dispersion in "case-study" mode
- Statistical and descriptive information supplied by postprocessor for various averaging times.

1.2 Steps Required to Run RTDM

Input Data

Use of RTDM requires the presence of the following input files:

- a file containing hourly meteorological data;
- optionally, a file containing hourly emissions data;
- a run stream file that specifies model options and gives source, receptor, and terrain information.

If both hourly meteorological data and hourly emissions data are used they must match chronologically for each hour modeled. Successive records of data that are not in an hourly sequence are flagged with a warning, but execution continues. Any number of data hours may be input to RTDM.

Model Execution Modes

RTDM version 3.20 can run in two modes: one with detailed printout for each receptor for each hour (verbose or case-study mode) and one without. In either case, concentrations are written to a disk file for postprocessing. The verbose mode produces a large volume of output, and it is recommended for short RTDM runs only.

Output Files

RTDM produces an output file to be printed that contains

1) a list of program options selected;
2) a list of key program parameters and their initialized values;
3) a description of the source characteristics;
4) a description of the receptor characteristics;
5) a description of the terrain surrounding the source (if using partial reflection).

The case-study mode also produces descriptive information about plume behavior for each hour for each source - receptor combination producing non-zero concentrations.

A disk file of computed ground-level concentrations is always produced. This disk file can be examined with the postprocessor ANALYSIS program.

1.3 Model Assumptions

Major assumptions in RTDM include:

1) The mean stack-top wind speed and direction are uniform in space and constant throughout the period of each concentration calculation (one hour).
2) When the effluent plume enters the atmosphere, it rises until it reaches an equilibrium altitude H.
3) At any downwind distance the distribution of concentration values away from the centerline is given by the product of two Gaussian distributions, one in the y direction (crosswind) and one in the z direction (vertical). A top-hat (sector-averaged) profile can be selected for the horizontal distribution.
4) The concentration profiles described by the Gaussian form are not "instantaneous" plume profiles; instead they represent concentrations averaged over a 1-hour period.
5) If the "partial reflection" option is not employed, it is assumed that all material in the plume is reflected by the ground. If the partial reflection option is used, the effect of full ground reflection is tracked along the plume up to the receptor point of interest. The maximum crosswind-integrated (MCWI) concentration is not allowed to increase with distance downwind. If the MCWI concentration starts to increase with full reflection, the "reflection factor" is "frozen" to prevent downwind increases. More details are provided in subsection 2.6.
6) The effluent rate and the meteorological parameters determining plume geometry are constant during each hour modeled.
7) Plume rise from point sources is calculated with Briggs' plume rise equations (Briggs 1969, 1973, 1975).
8) The effect of momentum (in the plume rise calculation) is ignored, as this is usually small compared to the effect of buoyancy. In this version of RTDM, only buoyancy-dominated sources may be used.
9) It is assumed that dispersion begins from a fictitious height above the actual source (effective stack height) instead of rising and dispersing simultaneously.

10) There are no provisions for building downwash or the merging of nearby buoyant plumes.

11) Both transitional and equilibrium plume rise are calculated.

12) The atmosphere is considered a single layer in the vertical (except for stable layers aloft) in which the rates of horizontal and vertical dispersion are independent of height.

13) The plume is completely reflected at the mixing height, as well as at the ground (except for partial reflection, if applicable) if the plume centerline is calculated to be below the mixing height.

14) Multiple reflection is simulated by means of a trapping model equivalent to that listed in the Turner Workbook, Equation 5-8, Page 36 (Turner 1969).

15) All of the plume mass is assumed to have punched through the mixing lid and to be in the stable layer aloft if the effective plume height is above the mixing lid (unless the partial plume penetration option is specified).

16) If the partial plume penetration option is used, then a fraction of the plume, P, (Briggs 1975) penetrates the mixing lid, and the Gaussian model equation is modified by multiplying the source emission rate by (1-P).

17) If the partial plume penetration option is specified and the penetration fraction P is $\geq$ .5, the final plume height is placed at the base of the elevated stable layer.

18) The simulation of buoyancy-enhanced dispersion is an option. (See subsection 2.7).

19) The simulation of stack-tip downwash is an option. (See subsection 2.9).

20) Although wind speed is measured at anemometer height, it is extrapolated to stack top for plume rise calculations by using a power-law wind speed profile. The dilution wind speed is taken to be either the stack-top speed or the speed at plume height. Extrapolation of wind speed with height levels off at a constant speed at or above 0.1 times the mixing height for unstable conditions, and at a height in meters of 200 multiplied by the 10-m wind speed (in m/sec) in neutral and stable conditions.

21) Hourly wind speeds below 1.0 meters per second (m/sec) are set to 1.0 m/sec. This precludes the possibility of concentration values approaching infinity as the wind speed approaches 0 and represents a lower wind speed limit to organized transport.

22) For calm conditions where there is no measured wind direction, the wind direction from the previous non-calm hour persists.
(<u>**NOTE**</u> - this can cause the model to overestimate pollutant concentrations for multiple-hour averaging times if conditions persist for several hours.)

23) Although RTDM defaults to the ASME (1979) dispersion parameters, the Pasquill-Gifford dispersion parameters or any parameters of the form $ax^b + c$ may be used.

24) If the distance from the source to a receptor is less than 10 meters, it is set to 10 meters for dispersion calculations.

25) Concentrations for a given hour are calculated independently of conditions for the preceding hours.

26) The total concentration determined for any receptor for one hour is the sum of the calculated concentrations for each source.

27) Average concentrations for time periods greater than one hour (as determined by the postprocessing program ANALYSIS) are computed by averaging the appropriate number of hourly concentrations.

28) RTDM can use hourly pollutant emission rate information as well as hourly stack temperature and exit velocity values.

29) Information concerning directional wind shear with height can be used to refine estimates of σ_y.

1.4 Applications and Limits of Use

RTDM has been designed for sensitivity studies, investigations, or for more routine applications, such as the determination of compliance with applicable air quality standards. It incorporates sufficient flexibility in its input specifications so that it can approximate the results of other Gaussian source models, such as EPA models used for complex terrain. It is best suited for applications at distances up to 15 km from the source, but may be used with caution out to 50 km, and as a screening model beyond 50 km.

RTDM has many options desirable for use in flat terrain, but it has special features suitable for use in complex terrain as well. The model can accept up to 35 sources, and is suitable for many routine multiple or single-source applications such as evaluation of control technology, stack-design investigations, prevention of significant deterioration, new source review, and source permitting applications.

RTDM may be run in a case-study mode, which allows the computation of concentrations for any number of selected one-hour periods, such as case-study hours for model validation, a set of hypothetical "worst-case conditions", or cases chosen to investigate the sensitivity of the model to variations in some input parameters or optional features of the model.

RTDM is quite useful for studies for which hourly monitoring data or hourly stack parameters (emission rates, temperature and exit velocity) are available. It can also use values of on-site meteorological data that improve estimates of σ_y and σ_z. RTDM version 3.20 is not able to simulate the behavior of momentum-dominated plumes. Also, it is not equipped to portray situations with complex aerodynamic effects due to nearby tall buildings.

This model assumes that the pollutants of interest disperse as non-reactive gases. There is no provision in RTDM version 3.20 for chemical transformation of plume constituents. No gravitational effects or depletion mechanisms, such as rain-out, wash-out or dry deposition, are considered.

In RTDM, the consideration of large downwind distances may involve a series of terrain obstacles in a given direction. Flow structure on the lee side of terrain obstacles can be more complicated than that on the windward side (Rowe, 1980). Thus, model calculations obtained for receptors on the leeward side of terrain should be interpreted with caution.

2. PHYSICAL PROCESSES MODELED BY RTDM

2.1 Gaussian Dispersion

The fundamental formula used in the model to estimate ground-level pollutant concentrations from a point source is the bi-variate Gaussian plume equation, as presented in the Workbook of Atmospheric Dispersion Estimates (Turner 1969). The general form of the equation is:

$$
\begin{aligned}
\chi(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \cdot \\
\left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] + \right. \qquad (1) \\
\sum_{N=1}^{\infty} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H-2Nz_i}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H-2Nz_i}{\sigma_z}\right)^2\right] \right. \\
\left.\left. + \exp\left[-\frac{1}{2}\left(\frac{z-H+2Nz_i}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H+2Nz_i}{\sigma_z}\right)^2\right] \right\} \right\}
\end{aligned}
$$

where

(x,y,z)	are the (downwind, crosswind, and vertical) coordinates of a receptor point in a Cartesian coordinate system, with the origin at the source location.
$\chi(x,y,z)$	is the pollutant concentration at receptor location (x,y,z) (mass/length^3);
H	is the effective height (stack height plus plume rise) of emission; that is, the centerline height of the plume (length);
Q	is the source strength (mass/time);

σ_y, σ_z are dispersion coefficients that are measures of crosswind and vertical plume spread, respectively. These two parameters are functions of downwind distance and atmospheric stability (length);

u is the average dilution wind speed (length/time); and

z_i is the height of the mixing lid (length).

In the model calculations, the downwind distance (x) and the crosswind distance (y) from the source to the receptor are determined as a function of the hourly wind direction, as well as source and receptor coordinates. The height of receptor points (z) above the ground is assumed to be zero in RTDM. However, non-zero values of z are employed in Equation 1 for the calculation of the maximum crosswind integrated concentration within the plume, which, in general, can occur at any point between the plume centerline height and the ground.

The source base is at z = 0 in the coordinate system. The most important assumptions on which the Gaussian plume formula is based are the following:

1) The mean stack-top wind speed and direction are uniform in space and constant throughout the one-hour period of each concentration calculation.
2) When the effluent plume enters the atmosphere, it rises until it reaches an equilibrium altitude H.
3) At any downwind distance, the distribution of concentration values off the centerline is given by the product of two Gaussian distributions, one in the y direction (crosswind) and one in the z direction (vertical).
4) The concentration profiles described by the Gaussian form are not "instantaneous" plume profiles; instead they represent concentrations averaged over an hour. Consequently, they incorporate the normal variability of wind flow for this time period.
5) In Equation 1, all material in the plume is totally reflected by the ground and the mixing lid. One model option, discussed in Section 2.6, involves a partial

reflection by these surfaces in order to prevent increases in the maximum crosswind-integrated plume concentration as the distance downwind increases.

6) The effluent rate and the meteorological parameters determining plume geometry are constant during the period of interest (that is, the equation represents steady-state conditions).

Equation 1 can be rewritten as

$$\chi(x,y,z) = \frac{Q}{u} \cdot \mathrm{HDF} \cdot \mathrm{VDF}, \tag{2}$$

where HDF, the horizontal distribution factor, is

$$\mathrm{HDF} = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right], \tag{3}$$

and VDF, the vertical distribution factor, is

$$\begin{aligned} \mathrm{VDF} = \frac{1}{\sqrt{2\pi}\sigma_z} \Bigg\{ & \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] + \\ & \sum_{N=1}^{J} \Bigg\{ \exp\left[-\frac{1}{2}\left(\frac{z-H-2Nz_i}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H-2Nz_i}{\sigma_z}\right)^2\right] \\ & + \exp\left[-\frac{1}{2}\left(\frac{z-H+2Nz_i}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H+2Nz_i}{\sigma_z}\right)^2\right] \Bigg\} \Bigg\} \end{aligned} \tag{4}$$

where J is large enough to specify VDF to single precision computer accuracy (about 8 decimal digits). In RTDM, the multiple reflection part of VDF is expressed by a Fourier series, with only 2 terms required in the worst case to provide the desired accuracy.

Equation 3 represents the formulation of HDF for "off-centerline" calculations of the ground-level concentration. If sector averaging is used, HDF becomes 1/SW, where SW is the sector width at the downwind distance of the receptor.

If σ_θ data are to be used for the direct computation of σ_y, then the preferred choice for HDF is the off-centerline option. Sector averaging is an option for use with complex terrain applications. The use of sector averaging (conventionally 22.5 or 45°) accounts for the increased lateral turbulence often observed in the vicinity of high terrain. The horizontal distribution of concentrations is modeled as a top-hat shape rather than a Gaussian shape.

The wind speed, u, used in Equations 1 and 2, represents a dilution factor. Many Gaussian models use the wind speed at stack-top height to dilute the plume, but this practice may be inappropriate for buoyant plumes with a large rise distance. With RTDM, the user has the option to use the wind speed extrapolated to equilibrium plume height for dilution. This option is discussed in Section 2.3.

2.2 Plume Rise

The behavior of an effluent plume in the atmosphere is a complicated process, varying with conditions of release, wind, turbulence and numerous other factors associated with terrain and aerodynamics.

The typical stack plume is warmer than the surrounding air and the plume rise tends to be dominated by buoyancy. In this model, plume rise from point sources is calculated using the Briggs' plume rise equations (Briggs 1969, 1973, 1975). The effects of momentum are ignored because the rise due to momentum is usually small compared to that due to buoyancy. RTDM provides the capability of optionally including stack-tip downwash (see Section 2.8). However, there is no provision for building downwash or the merging of nearby buoyant plumes. Both transitional and equilibrium plume rise values are calculated. To simplify dispersion simulation, it is assumed that dispersion begins from a fictitious height above the actual source. This height, or 'effective stack height' is the sum of the actual stack height (h_s) and the plume rise from emission (Δh). For unstable and neutral conditions (stability classes 1, 2, 3, and 4), plume rise above stack top is computed by:

$$\Delta h = \frac{1.6F^{1/3}x^{2/3}}{u}, \quad x < 3.5x^*$$

$$\Delta h = \frac{1.6F^{1/3}(3.5x^*)^{2/3}}{u}, \quad x \geq 3.5x^* \qquad (5)$$

where

F is the buoyancy flux of stack emissions in m^4/sec^3 = $gv_s d^2(T_s - T_a)/4T_s$,

where

v_s is exit velocity, d is stack diameter,
T_s is stack temperature, T_a is ambient temperature, and
x^* is the downwind distance at which atmospheric turbulence dominates entrainment in plume rise (m), given by,

$$x^* = 34.\ F^{2/5}, \quad \text{if} \quad F > 55\ m^4/sec^3;$$
$$x^* = 14.\ F^{5/8}, \quad \text{if} \quad F \leq 55\ m^4/sec^3;$$

$3.5x^*$ is the approximate downwind distance at which the plume becomes level (m).

For stable conditions (stability class 5 or 6):

$$\Delta h = \frac{1.6F^{1/3}x^{2/3}}{u}, \quad x < 2.07us^{-1/2}$$

$$\Delta h = 2.6\left(\frac{F}{us}\right)^{1/3}, \qquad x \geq 2.07us^{-1/2} \tag{6}$$

where

s is the stability parameter based on atmospheric lapse rate:

$$s = \frac{\partial\theta}{\partial z}\,\frac{g}{T_a} \tag{7}$$

and

$\partial\theta/\partial z$ is the rate of change of potential temperature with height (°Km^{-1}),

g is the acceleration due to gravity (9.8 m s^{-2}), and

T_a is the ambient temperature (°K).

For low wind speeds, the plume rise computed using

$$\Delta h = 5.0F^{1/4}s^{-3/8} \tag{8}$$

is used if the Δh value is lower than that obtained from Equation 6.

For stable conditions RTDM calculates plume rise using both the stable (equations 6 and 8) and the neutral (equation 5) formulas, and the conservative assumption is made (following Briggs, 1975) that the effective plume rise is the smallest value given by the various formulas.

2.3 Wind Speed Determination

The wind speed at stack-top elevation is used in the calculation of plume rise. Since the surface wind speed measurements are commonly taken at lower elevations than stack top, an adjustment is made in the model by the following power law relationship:

$$u(z) = u_r\left(\frac{z}{z_r}\right)^p \tag{9}$$

where

$u(z)$ is the adjusted wind speed at stack height z;
u_r is the wind speed measured at a reference height z_r;
p is the wind profile exponent.

The profile exponent p is a function of stability class and has the default values given in Table 2-1 (DeMarrais, 1959).

In equation 9, the values of z and z_r are specified relative to a height, denoted here as z_a, from which the wind speed profile originates (the wind speed at height z_a is zero). In flat or gently rolling terrain, z_a is at the same height as the stack base elevation. In some rough terrain applications, however, the stack may protrude from a narrow valley or canyon. The wind profile above the canyon walls is often of primary interest for simulating plume transport and dispersion, and is often much different than the wind profile in the valley itself. If all of the model receptors are located on high terrain above the valley walls, use of a wind profile based upon a starting elevation some distance above the stack base elevation may be appropriate if actual wind measurements are taken at an elevation above plant grade. This height, z_a, must be at or above the common stack base used in RTDM, and should not be higher than the elevation of the top of the shortest stack (to prevent an undefined or negative stack-top wind speed). In the RTDM input parameter section, the origin height for the wind speed profile, z_a, is specified relative to its height above stack base. Its default value is zero.

As discussed in Section 2.1, the dilution wind speed can be chosen to be that at stack-top height or at plume height. The user should choose stack-top height if plume rise is typically low compared to the height of the stack. Otherwise, choice of the equilibrium plume height for the dilution wind speed may be more appropriate. RTDM can compute the dilution wind speed at plume height by

TABLE 2-1

WIND SPEED PROFILE EXPONENTS - DEFAULT VALUES

Stability Class	Wind Speed Profile Exponent, p
1	0.09
2	0.11
3	0.12
4	0.14
5	0.20
6	0.30

extrapolating the same wind speed value used to compute the stack-top speed. An alternative wind speed value (located at a height closer to equilibrium rise height, such as on a hill) can be used for extrapolation to plume height for the dilution calculation.

If multiple levels of wind speed on a tower are available, the user can choose to input hourly values of the wind speed profile exponent to RTDM. For many applications, a least-squares fit for the wind speed profile exponent is desired, such that the resulting profile matches the observations with a minimum of error. Of the measurement heights available, one should be selected as a reference height such that it is at or slightly above the stack-top height. If no measurements are taken as high as the stack-top height, the highest available wind speed data level should be designated as the reference level.

It is possible to apply the least-squares fit so as not to alter the wind speed measurement at the reference height. This option should be used if the data are reliable at the reference level and its position relative to other tower levels is superior for use in calculating plume rise. If, however, some data at the reference level are missing or that level is not clearly superior to other levels, then the reference level speed should be determined from all available measurements. The procedures to be used for calculating hourly wind speed profile exponents according to the two methods are explained below.

If the reference level wind speed measurement is to be retained, define p, the wind speed profile exponent, as follows:

$$p = \frac{\sum_{i=1}^{N} \left[\ln\left(\frac{u_i}{u_r}\right) \cdot \ln\left(\frac{z_i}{z_r}\right) \right]}{\sum_{i=1}^{N} \left[\ln\left(\frac{z_i}{z_r}\right) \right]^2} \qquad (10)$$

where

i refers to individual height levels

N is the number of levels,

u_i is the wind speed at the i^{th} level,

z_i is the height of the i^{th} level, relative to height z_a

r refers to the reference level.

If the reference level wind speed measurement is to be estimated from all available data, define p as:

$$p = \frac{N \sum_{i=1}^{N} \left[\ln(u_i) \cdot \ln\left(\frac{z_i}{z_r}\right) \right] - \left[\sum_{i=1}^{N} \ln(u_i) \right] \cdot \left[\sum_{i=1}^{N} \ln\left(\frac{z_i}{z_r}\right) \right]}{N \sum_{i=1}^{N} \left[\ln\left(\frac{z_i}{z_r}\right) \right]^2 - \left[\sum_{i=1}^{N} \ln\left(\frac{z_i}{z_r}\right) \right]^2} \qquad (11)$$

and redefine u_r (used as input to RTDM in the hourly meteorological data) as

$$u_r = \exp\left[\frac{\sum_{i=1}^{N} \ln(u_i) - p \sum_{i=1}^{N} \ln\left(\frac{z_i}{z_r}\right)}{N} \right] \qquad (12)$$

An example of the application of both methods to the same data set is given in Table 2-2.

Several observers (Arya, 1982; Kaimal et al., 1976; Pennell and Le Mone, 1974; Clarke, 1970; Izumi and Barad, 1963) have noted that the wind speed does not obey a power law (Equation 9) throughout the entire boundary layer, whose height is defined by the mixing lid. Instead, the increase of wind speed with height is found to level off or even slightly decrease above a certain height, depending upon the mixing height in unstable conditions or the surface layer friction velocity, u_*, in neutral and stable conditions. The calculation of height limits above which the wind speed is assumed to be constant is a feature that has been incorporated into RTDM. In unstable conditions, the height limit is 0.1 times the mixing height. Arya

TABLE 2-2

EXAMPLE OF LEAST-SQUARE DETERMINATION OF WIND SPEED PROFILE EXPONENT

Wind Speed Measurement Levels (m)	Measured Wind Speeds (m/sec)	Calculated Wind Speeds, Method 1*	Calculated Wind Speeds, Method 2*
10	2.0	1.96	1.97
50	4.0	4.05	4.11
80 (reference level)	5.0	5.00	5.09
150	7.0	6.63	6.79
75**	–	4.86	4.94
		$p=0.4497$	$p=0.4570$

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*Method 1 retains the wind speed measurement at the reference level (80 m), Method 2 does not impose this restriction.

**In this example, 75 m is the stack-top level, for which a calculated wind speed is desired.

(1981) shows that in neutral and stable conditions, the approximate height of the wind speed maximum (H_{max}) is given by

$$H_{max} = 0.142 \frac{u_*}{f}, \tag{13}$$

where u_* is the friction velocity, and f is the Coriolis parameter.

For general application, H_{max} can be specified approximately using a 10-m wind speed with assumptions for typical values of surface roughness length in complex terrain (1 meter) and the Coriolis parameter ($10^{-4} sec^{-1}$). The resulting values of H_{max} as a function of stability are:

$$\begin{aligned} &H_{max} = 0.1 \cdot \text{mixing height for unstable conditions} \\ &H_{max}\ (\text{meters}) = 200 \cdot \text{10-m wind speed (m/sec) for} \\ &\qquad\qquad\qquad \text{neutral and stable conditions} \end{aligned} \tag{14}$$

Equation 9 is therefore modified for RTDM as follows:

$$u(z) = u_r \left(\frac{z_{max}}{z_r} \right)^p, \tag{15}$$

where $z_{max} = z$ if $z < z_r$,
$z_{max} = \min (z, H_{max})$ if $z > z_r$.

Pollutant concentrations estimated by the Gaussian plume equation used in the model are inversely proportional to average wind speed. This relationship implies that concentrations would approach infinity as the wind speed approaches zero, which is clearly not the case. To simulate the effects of very low wind speed cases, hourly wind speeds that are below 1.0 m/sec are set at 1.0 m/sec. This precludes an invalid application of the model. For calm conditions where there is no measured wind direction, the wind direction from the previous non-calm hour persists. This assumption can cause the model to overestimate pollutant concentrations for multiple hour averaging times if calms persist for several hours.

2.4 Stability Category

The user must specify a stability category for each hour of meteorological input. Stability category values range from 1 to 6 and represent the following conditions:

1 - Very unstable
2 - Moderately unstable
3 - Slightly unstable
4 - Neutral
5 - Slightly stable
6 - Moderately to very stable

In RTDM, the stability category can be used for several computations:

1) The formula for plume rise is a function of stability class. Different calculations take place for stable and non-stable hours. However, if on-site vertical temperature difference data exist, the use of stability class can be completely eliminated. In such a case, neutral/unstable rise is assumed for negative or zero vertical potential temperature gradients (VPTG). For positive (stable) values of VPTG, both neutral and stable rise formulas are evaluated, and the lower rise is chosen.
2) The behavior of a plume encountering terrain is a function of the stability class. The choice of the plume path correction factor is usually different for stable versus non-stable conditions. However, if hourly vertical potential temperature gradient values (for determining H_{crit}) are available, these data values can be used to distinguish between stable and nonstable conditions. In stable conditions, the VPTG value is used to calculate

H_{crit}, which is used to determine whether or not the plume is allowed to impinge upon the terrain.

3) Values of σ_y and σ_z are conventionally a function of stability class. This dependence upon stability class can be eliminated (except for selection of a formula for computing the growth of σ_z as a function of distance) by supplying turbulence intensity data (I_y, I_z). The turbulence intensity data (or sigma-theta/ sigma-phi values) can then be used to calculate σ_y and σ_z directly (Hanna et al. 1977).

4) The determination of the wind speed profile exponent is a function of stability class if hourly values are not supplied. The specification of hourly values (Section 2.3) is not a function of stability. However, determination of H_{max} (Equation 14) is weakly dependent upon the stability class.

Depending upon the availability of on-site meteorological measurements and the options selected, the RTDM user may rely heavily or very little upon stability class values in the calculation of ground-level concentrations. The use of as much on-site data as possible in the model computations (Strimaitis et al. 1980) decreases reliance upon the accurate specification of stability class values.

2.5 Dispersion Parameters

The parameters σ_y and σ_z, which represent the crosswind and vertical standard deviations of the dispersing plume, are functions of x and are related to meteorological conditions. These two variables provide the Gaussian equation with some flexibility, as σ_y and σ_z may be obtained by various methods without altering the original computation scheme.

In RTDM, values of σ_y and σ_z may be determined from stability class or from hourly values of the vertical and horizontal components of the turbulence intensity. If the stability class method