Turbulence Parameterizations for the Random Displacement Method (RDM) Version of ADPIC

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1. Introduction

This document describes the algorithms that are used in the new random displacement method (RDM) option in the ADPIC model to parameterize atmospheric boundary layer turbulence through an eddy diffusivity, K . Both the new RDM version and previous gradient version of ADPIC use eddy diffusivities, and, as before, several parameterization options are available. The options used in the RDM are similar to the options for the existing Gradient method in ADPIC (Taylor et al., 1993), but with some changes. Preferred parameterizations are based on boundary layer turbulence scaling parameters and measured turbulent velocity statistics. Simpler parameterizations, based solely on Pasquill stability class, are also available.

When eddy diffusivities are based on boundary layer turbulence scaling parameters (i.e., u_* , h , z and L)*, "turbulence parameterization" is an appropriate term. In other cases, this term is used loosely to describe "sigma curves". These are semi-empirical relationships between the standard deviations, $\sigma_z(x)$ and $\sigma_y(x)$, of concentration from a point source and downwind distance. Separate sigma curves are used for each of six Pasquill stability classes, which are used to categorize the diffusive properties of the atmospheric surface layer. Consequently, sigma curves are more than parameterizations of turbulence since they also prescribe the final concentration distribution (for a point source) given a Pasquill stability class.

In the ADPIC model, sigma curves can be used to calculate the eddy diffusivities, K_z and K_H . Thus, they can be used to "back out" parameterizations for K which are consistent with the dispersion associated with the particular sigma curve. This results in eddy diffusivities which are spatially homogeneous, but travel time dependent. A vertically homogeneous K_z is a poor assumption in the atmospheric boundary layer. A horizontally homogeneous K_H is a better assumption because quasi-horizontally-homogeneous turbulence is more common in the atmospheric boundary layer. The use of these time-dependent eddy diffusivities is an empirical approach to calculating diffusion at short times when the assumptions implicit in the advection-diffusion equation (on which the RDM is based) are less valid.

An improvement to the overly-broad, site-dependent stability class/sigma curve approach is the use of direct statistical measures of turbulent fluctuations (i.e., σ_θ) along with a horizontal turbulence time scale, τ_H , to determine a time-dependent horizontal concentration standard deviation, $\sigma_y(t)$. These are used in the RDM as a semi-empirical method of parameterizing a time-dependent, horizontally-homogeneous K_H .

* See section 4 below for definitions of symbols.

A new feature to the operation of the ADPIC code is that the input parameter "turb_param_type" has been split into two parameters in the RDM option: one which controls the turbulence parameterizations to be used for *vertical* turbulence (turb_param_vert) and a second which controls the parameterization to be used for *horizontal* turbulence (turb_param_horz). Another new feature allows the user to override the default values for the constant coefficients used in the turbulence parameterizations.

A major advantage of the RDM over the gradient method is the use of consistent turbulence parameterizations at all times during the calculation. The gradient method required a grid for the diffusion calculation and used turbulence parameterizations for near-in sub-grid diffusion that could be inconsistent with the gradient diffusion portions of the calculation. In addition, unlike the gradient diffusion option, the RDM does not need to approximate travel time using cell-average particle ages for use in time-dependent K_H formulations.

The RDM turbulence parameterization options are described in Section 2. This is followed in Section 3 by a discussion of the differences between the RDM turbulence parameterization options and the old gradient method options. Within the RDM option, improvements and extensions have been made to several parameterizations used in the gradient method option. Two parameterizations used in the gradient diffusion option are not included in the RDM option, because more highly recommended parameterizations are now available.

2. Turbulence parameterizations in the RDM

Tables 1 and 2 summarize the options available for both vertical and horizontal turbulence, respectively, in the RDM. An important note is that the new turbulence parameters work only for the RDM, and not in the gradient diffusion option in ADPIC. For the gradient diffusion option the old parameterizations *and* old input parameters are still used.

2.1 Vertical turbulence options

turb_param_vert = "kz_simthry" and "kz_simthry_user"

These options use K_z profiles based on surface layer and boundary layer scaling parameters (Lange, 1989). For the boundary layer ($z < h$), K_z^{bl} is a function of z , L , h , and u_* as follows:

$$K_z^{bl}(z) = \frac{ku_*z}{\phi_z} e^{-cz/h}, \quad (1)$$

Table 1. Vertical turbulence options in the *RDM*

TURB_PARAM_VERT=	Description
'KZ_SIMTHRY'	K_z as a function of z ; calculated from boundary layer similarity theory as a function of u_* , h , z and L for $z < h$. Constant, K_z^{tropo} , used for $z > h$.
'KZ_SIMTHRY_USER'	K_z as a function of z ; calculated from boundary layer similarity theory as function of u_* , h , z and L , but with <i>user-specified</i> coefficients a , b , and c .
'SIGZ_PWRLAWX_PG'	K_z as a function of downwind distance, x ; calculated from <i>Pasquill-Gifford</i> $\sigma_z(x)$ in a power law form ($\sigma_z = \gamma x^\rho$).
'SIGZ_PWRLAWX_USER'	K_z as a function of x ; calculated from the power-law form of $\sigma_z = \gamma x^\rho$ and <i>user-specified</i> coefficients γ and ρ .
'KZ_LINEARZ'	K_z calculated from a linear function of height: $K_z = K_{z_{\text{ref}}}(z/z_{\text{ref}})$, where $K_{z_{\text{ref}}}$ and z_{ref} are specified by the user.
'KZ_CONSTANTZ'	K_z fixed at constant value.

Table 2. Horizontal turbulence options in the *RDM*

TURB_PARAM_HORZ=	Description
'SIGH_SIGTHETA'	K_H as a function of particle age (time) t ; calculated from <i>Draxler's</i> $\sigma_y(t)$ using input σ_θ data and internal-default τ_H .
'SIGH_SIGTHETA_USER'	K_H as a function of particle age (time) t ; calculated from <i>Draxler's</i> $\sigma_y(t)$ using input σ_θ data and <i>user-specified</i> τ_H .
'SIGH_PWRLAWX_PG'	K_H as a function of downwind distance x ; calculated from <i>Pasquill-Gifford</i> $\sigma_y(x)$ in a power law form ($\sigma_y = \alpha x^\beta$).
'SIGH_PWRLAWX_MESO'	K_H as a function of x ; calculated from <i>MESODIF</i> $\sigma_y(x)$.
'SIGH_PWRLAWX_LONGRANGE'	K_H as a function of x ; calculated from <i>Rodriguez's long-range</i> $\sigma_y(x)$.
'SIGH_PWRLAWX_USER'	K_H as function of x ; calculated from power law form of $\sigma_y = \alpha x^\beta$ and <i>user-specified</i> coefficients α and β .

where

$$\phi_z = \left(1 + a \frac{z}{L}\right)^b, \quad (2)$$

$$a = \begin{cases} -15, & \text{if } 1/L < 0 \\ 0, & \text{if } 1/L = 0 \\ 4.5, & \text{if } 1/L > 0 \end{cases},$$

$$b = \begin{cases} -0.25, & \text{if } 1/L < 0 \\ 1, & \text{if } 1/L \geq 0 \end{cases},$$

and

$$c = 4.$$

These default values for a , b , and c can be overridden by user input.

For the free troposphere ($z > h$), K_z is constant with height with a value of

$$K_z = K_z^{\text{tropo}}. \quad (3)$$

In order to obtain a single K_z function for all z which is a smooth, differentiable function of z and which provides a quick transition from K_z^{bl} to K_z^{tropo} above $z=h$, a function $H(z)$ proposed by Ermak (1994, private communication) is used as follows:

$$K_z = H(z)K_z^{\text{bl}}(z) + [1 - H(z)]K_z^{\text{tropo}}, \quad (4)$$

where

$$H(z) = e^{-\left(z/c_2 h\right)^8}, \text{ and} \quad (5)$$

$$c_2 = 1.5.$$

K_z^{tropo} may be larger or smaller than the value of K_z^{bl} at the mixed layer height, h . Therefore, especially under stable conditions, K_z may increase with height above $z \approx h$. The user may override the default value of K_z^{tropo} , which is currently $1 \text{ m}^2/\text{s}$. Figs. 1-3 show example K_z profiles for unstable, neutral and stable cases. Appendix A gives the vertical derivative of K_z , which is also required by the RDM.

Since this turbulence parameterization uses fundamental boundary layer turbulence scaling parameters and accounts for vertical inhomogeneity of K_z , it is the preferred option for vertical turbulence parameterization.

Fig. 1. Example K_z profile (solid line) for an unstable case ($u_* = 0.3$ m/s, $h/L = -9$). For reference, dashed line shows K_z^{trpo} value ($= 1$ m²/s).

Fig. 2. Example K_z profile (solid line) for a neutral stability case ($u_* = 0.4$ m/s, $h/L = 0$). For reference, dashed line shows K_z^{tropo} value ($= 1 \text{ m}^2/\text{s}$).

Fig. 3. Example K_z profile (solid line) for a stable case ($u_* = 0.3$ m/s, $h/L = 6$). For reference, dashed line shows K_z^{tropo} value ($= 1$ m²/s).

turb param vert = 'sigz pwrlawx pg'

In this option K_z is determined from Pasquill-Gifford $\sigma_z(x)$ using only stability class. K_z is calculated from $\sigma_z(x)$ in the following form:

$$\sigma_z = \gamma x^\rho. \quad (6)$$

There are different coefficients γ and ρ for each of six Pasquill stability classes, A, B, C, D, E, and F, corresponding in the ADPIC code to `stab_class` = 1, 2, 3, 4, 5 and 6, respectively. Values for these coefficients were determined by Lange (1993, private communication) by fitting sigma curves developed by Pasquill, adapted by Gifford, and published in Fig. 3.11 of *Meteorology and Atomic Energy* (Slade, 1968). These curves are based on data from experiments on surface releases with release durations and averaging times of 3-15 min. Therefore, it is recommended for calculations of near-surface sources with release durations, concentration averaging times and wind data temporal resolution close to this 3-15 min time period, and when only stability class is available.

Using the relationship between the variance of the concentration distribution and the eddy diffusivity*,

$$K = \frac{1}{2} \frac{d\sigma^2}{dt}, \quad (7)$$

and the relationship between mean wind speed (assumed to be constant) and downwind distance,

$$x = \bar{u} t \quad (8)$$

a relationship for K_z can be obtained[#]:

$$K_z = \gamma^2 \rho \bar{u} x^{(2\rho-1)}. \quad (9)$$

Values of the γ and ρ coefficients were determined by Lange (1993, private communication) by fitting the close-in portions of the Pasquill-Gifford curves and are as

* This relationship assumes K is spatially homogeneous. However, this assumption is not generally valid in the vertical direction in the boundary layer, especially under unstable conditions. Correspondingly, vertical concentration distributions are not Gaussian in the vertical direction, as is assumed in this option.

[#] In calculating K , the time t is the age of the particle since it was emitted from the source, and $\bar{u}$ is the mean wind at the particle location.

follows:

stab class	γ	ρ
1	0.013	1.5
2	0.039	1.2
3	0.222	0.81
4	0.382	0.64
5	0.418	0.58
6	0.288	0.55

A new parameter, $x_{\max}$, specifies the downwind distance beyond which the value of K_z is held constant at its value at that maximum distance. The default values are as follows:

stab class	$x_{\max}$ (m)
1	5.E+3
2	1.E+4
3	1.E+4
4	1.E+4
5	1.E+4
6	1.E+4

turb param vert = 'kz linearz'

This new option allows K_z to be calculated as a function of height from the linear equation:

$$K_z = K_{z_{\text{ref}}} (z/z_{\text{ref}}), \quad (10)$$

where $K_{z_{\text{ref}}}$ is the value of K_z at reference height z_{ref} . $K_{z_{\text{ref}}}$ and z_{ref} must be input by the user, and do *not* have any internal default values. When used with the wind speed power law option, this linear K_z option allows RDM calculations to be compared to analytical solutions to the advection-diffusion equation.

turb param vert = 'kz constantz'

This new option allows K_z to be fixed at a constant value, unchanging with height, time or downwind distance:

$$K_z = K_{z_{\text{constant}}}.$$

When used with the constant wind speed option, this constant K option allows RDM calculations to be compared to a Gaussian solution to the advection-diffusion equation.

2.2 Horizontal turbulence options

turb param horz='sigh sigtheta' and 'sigh sigtheta user'

K_H for this option is based on Draxler's (1976) semi-empirical relationship for σ_y as a function of time and the standard deviation of cross-wind velocity component (σ_v). Draxler used an equation of the following form for σ_y :

$$\sigma_y = \sigma_v t f(t/\tau_H) \quad (11)$$

where

$$f(t/\tau_H) = \frac{1}{1 + d(t/\tau_H)^{1/2}}.$$

This formulation results in $\sigma_y \propto t$ for $t \ll \tau_H$ and $\sigma_y \propto t^{1/2}$ for $t \gg \tau_H$. The constant d is a combination of constants used by Draxler. A value of $d = 0.36$ resulted in Draxler's best fit to close-in diffusion data, and is similar to the value of 0.4 recommended by Hanna et al. (1982). Assuming $d = 0.36$, Draxler recommended values of $\tau_H = 50$ sec for surface releases and 160 sec for elevated releases (note: Draxler's T_i is equal to $6.36\tau_H$). The default values in the RDM are

$$d = 0.36 \text{ and}$$

$$\tau_H = 50 \text{ sec.}$$

The value of τ_H can be overridden by user input. Using eq. (7), assuming $K_H = K_y$, and using the approximation $\sigma_v \approx \sigma_\theta \bar{u}$, the following equation for K_H can be derived:

$$K_H = \frac{\bar{u}^2 \sigma_\theta^2 t \left[1 + \frac{d}{2} \left(\frac{t}{\tau_H} \right)^{1/2} \right]}{\left[1 + d \left(\frac{t}{\tau_H} \right)^{1/2} \right]^3}. \quad (12)$$

(Note: σ_θ is in radians).

Since this turbulence parameterization uses measured wind direction fluctuations, it is the preferred option for horizontal turbulence parameterization.

turb_param horz='sigh pwrlawx pg', 'sigh pwrlawx meso', 'sigh pwrlawx longrange', and 'sigh pwrlawx user'.

For these options, K_H is based only on stability class and is calculated using $\sigma_y(x)$ in the following form:

$$\sigma_y = \alpha x^\beta. \quad (13)$$

Using eqs. (7) and (8), and assuming again that $K_H = K_y$, the following relationship for K_H can be obtained:

$$K_H = \alpha^2 \beta \bar{u} x^{(2\beta-1)}. \quad (14)$$

For values of $x \geq x_{\max}$, the value of K_H is held constant at its value at that maximum distance.

The constants α and β depend on the turb_param_horz option used and are described below:

α and β for turb_param_horz = 'sigh pwrlawx pg':

The α and β coefficients for $\sigma_y(x)$ used in this option are based on a least-squares fit (Lange, 1993, private communication) to the sigma curves developed by Pasquill, adapted by Gifford, and published in Fig. 3.10 of *Meteorology and Atomic Energy* (Slade, 1968). These curves are based on data from experiments involving surface releases with release durations and averaging times of 3-15 min. Therefore, this turbulence parameterization option is recommended for calculations of near-surface releases with release durations, concentration averaging times and wind data temporal resolution close to this 3-15 min time period, and when only stability class is available.

There are separate curves for each of six Pasquill stability classes (A, B, C, D, E, and F, corresponding to stab_class = 1, 2, 3, 4, 5 and 6, respectively). The $\sigma_y(x)$ equation coefficients for this option are

$$\beta = 0.92 \text{ and}$$

α , depending on stability class, as follows:

stab class	Pasquill-Gifford α
1	0.42
2	0.30
3	0.22
4	0.15
5	0.09
6	0.06

Default values of $x_{\max}$ for this option are as follows:

stab class	Pasquill-Gifford $x_{\max}$ (m)
1	2.E+4
2	2.E+4
3	2.E+4
4	2.E+4
5	2.E+4
6	2.E+4

α and β for `turb_param_horz = 'sigh_pwrlawx_meso'`:

The equations for $\sigma_y(x)$ in this parameterization option are based on a fit to experimental data from near-surface releases from the Idaho National Reactor Testing Station (NRTS) (Yanskey et al., 1966) which were subsequently used in the MESODIF model (Start and Wendell, 1974) for the NRTS. These data show increased horizontal diffusion when compared to the Pasquill-Gifford values above, especially under stable conditions. This is due to both (a) the longer release durations (and, therefore, longer averaging times) used in the NRTS data (15-60 min) compared to the release durations in the Pasquill-Gifford data (3-15 min), and (b) the presence of meandering conditions during stable conditions. Therefore, this option is recommended for calculations of near-surface releases with release durations, concentration averaging times and wind data temporal resolution close to this 15-60 min time period, and when only stability class is available. The $\sigma_y(x)$ equation coefficient values are

$$\beta = 0.85 \text{ and}$$

α , depending on stability class, as follows:

stab class	MESODIF α
1	0.72
2	0.42
3	0.35
4	0.27
5	0.30
6	0.40

Default values of $x_{\max}$ for this parameterization are as follows:

stab class	MESODIF $x_{\max}$ (m)
1	2.E+4
2	2.E+4
3	2.E+4
4	2.E+4
5	2.E+4
6	2.E+4

α and β for `turb_param_horz = 'sigh_pwrlawx_longrange'`:

In this option, the equations for $\sigma_y(x)$ are based on a fit by Rodriguez *et al.* (1995) to long-range dispersion data. The $\sigma_y(x)$ equation coefficient values are

$$\beta = 1.0,$$

$$\alpha = 0.056, \text{ and}$$

$$x_{\max} = 4.E+7 \text{ m}$$

The large default value of 40,000 km for $x_{\max}$ is used to assure that these α and β coefficients are, for practical purposes, always used, and, therefore, $\sigma_y \propto t$ essentially for all time. This parameterization reflects the effect of processes other than turbulent diffusion, i.e., spatial and temporal variation in the mean wind. Therefore, this parameterization is recommend for large-scale calculations using wind fields with low spatial resolution (in particular, low vertical resolution so that vertical wind shear in the lowest kilometer is unresolved) and/or low temporal resolution (e.g., 12 hour resolution).

3. Differences between RDM and gradient ADPIC turbulence parameterizations

The RDM turbulence parameterization options reflect some of the significant differences between the RDM and the gradient diffusion method. In the gradient diffusion option in ADPIC one parameter, *turb_param_type*, controls the turbulence parameterization for 4 distinct parts of the calculation: (1) *vertical* turbulence for *sub-grid* diffusion, (2) *horizontal* turbulence for *sub-grid* diffusion, (3) *vertical* turbulence for *gradient* diffusion, and (4) *horizontal* turbulence for *gradient* diffusion. As mentioned above, in the RDM there is no need for a separate method of calculating sub-grid diffusion, and, in addition, the flexibility of controlling the parameterization of vertical and horizontal turbulence separately has been included. Discussed below are differences between the parameterizations used by the RDM and gradient diffusion methods in ADPIC.

One option for gradient diffusion turbulence parameterization that was not included in the RDM is the *gradient* diffusion *vertical* turbulence parameterization used when *turb_param_type* = 1 or 2. This parameterization was based on a more complicated second-order polynomial fit to the Pasquill-Gifford $\sigma_z(x)$ curves, and had potentially erroneous behavior, i.e., negative K_z and K_z decreasing with time for certain stability classes at short or long times.

The second option for gradient diffusion method turbulence parameterization that was not included in the RDM is the *gradient* diffusion *horizontal* turbulence parameterization used when *turb_param_type* = 5. This option was based on similarity theory for relative diffusion of puffs using the turbulent kinetic energy dissipation rate, ϵ , as the key turbulence parameter. This option was not included in the RDM because the recommended option based on measured or defaulted sigma theta values is now readily usable.

The *gradient* diffusion *vertical* turbulence parameterization based on similarity theory and used when *turb_param_type* = 4 or 5 has been modified for use in the RDM. The formulation for K_z has been restored to the form in the referenced journal articles. In addition it now uses a single formulation for the surface layer and outer boundary layer and, correspondingly, has a continuous first derivative with respect to height. The new formulation used by the RDM corrects some problems with low values of K_z above the surface layer in unstable conditions.

The *gradient* diffusion *horizontal* turbulence parameterization based on σ_θ and used when *turb_param_type* = 4 or 5 has been modified for use in the RDM. This parameterization no longer uses an approximation to Draxler's (1976) expression; it now uses the exact expression.

The *gradient diffusion horizontal* turbulence parameterization based on a power law form for $\sigma_y(x)$ and used when *turb_param_type* = 1 or 2 and *hemi_scale* = 'y' used a constant K_H (with a value dependent on stability class) beyond 20 km downwind distance. For this long-range diffusion parameterization, the RDM (by default) uses a K_H that is a linear function of travel distance for all distances of interest.

4. Nomenclature

h	mixed layer height (m)
k	von Karman constant (= 0.4)
K_x	along-wind eddy diffusivity (m^2/s)
K_y	cross-wind eddy diffusivity (m^2/s)
K_z	vertical eddy diffusivity (m^2/s)
K_H	horizontal eddy diffusivity (m^2/s) (Note: It is assumed that $K_H = K_x = K_y$)
L	Obukhov length (m)
t	particle age; time since material released (s).
$\bar{u}$	mean wind speed (m/s)
u_*	friction velocity (m/s)
x	downwind travel distance (m) (Note: This is approximated as $\bar{u} t$)
y	crosswind distance (m)
z	height above ground level (m)
σ_H	horizontal standard deviation of spatial distribution of concentration (m) (Note: It is assumed that $\sigma_y = \sigma_x = \sigma_H$)
σ_y	crosswind standard deviation of spatial distribution of concentration (m)
σ_z	vertical standard deviation of spatial distribution of concentration (m)
σ_θ	standard deviation of wind direction (radians)
σ_v	standard deviation of cross-wind speed component (m/s)
τ_H	horizontal Lagrangian time scale of turbulence (s)

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Appendix A: Vertical derivative of similarity theory K_z

$$\frac{\partial K_z}{\partial z} = H(z) \frac{\partial K_z^{\text{bl}}}{\partial z} + K_z^{\text{bl}}(z) \frac{\partial H(z)}{\partial z} - K_z^{\text{tropo}} \frac{\partial H(z)}{\partial z} \quad (\text{A1})$$

where

$$H(z) = e^{-\left(z/c_2 h\right)^8}, \quad (\text{A2})$$

$$\frac{\partial H(z)}{\partial z} = \frac{-8z^7}{(c_2 h)^8} H(z), \quad (\text{A3})$$

$$\frac{\partial K_z^{\text{bl}}}{\partial z} = \frac{ku_*}{\phi_z} e^{-cz/h} \left(1 - \frac{cz}{h} - \frac{z}{\phi_z} \frac{\partial \phi_z}{\partial z} \right), \text{ and} \quad (\text{A4})$$

$$\frac{\partial \phi_z}{\partial z} = \frac{ab}{L} \left(1 + a \frac{z}{L} \right)^{b-1}. \quad (\text{A5})$$

Appendix B: Namelist input parameters for RDM turbulence parameterizations (and wind speed power law option)

NOTE: Namelist parameters controlling the RDM numerical calculation and time step are not listed below. See UCRL-ID, "Implementation of a Random Displacement Method (RDM) in the ADPIC Model Framework", Appendix II, by Ermak et al. for descriptions of these namelist input parameters.

ADPIC_CONTROL namelist

DIFF METHOD

New option:

DIFF_METHOD = 'RDM'

Diffusion is calculated with the Random Displacement Method (RDM). For this method, the types of horizontal and vertical turbulence parameterizations to be used for K_z and K_H respectively, by the RDM must be specified using the parameters TURB_PARAM_VERT and TURB_PARAM_HORZ.

REFLECT AT MLHGT

A character variable ('y' / 'n') which selects whether or not a particle reflection algorithm at the mixing layer height, mlhgt, is to be used. If selected, a particle approaching the mixing layer height from below will be reflected downward if the computed motion would otherwise take the particle above the mixing layer height. Particles approaching from above the mixing layer height are not affected until their motion drops them below the mixing layer height. Then, such a particle is treated as if it had been created below the mixing layer height. With this algorithm in effect, a particle can only be above the mixing layer height if it was released there. (Default: 'y'). Note: This parameter used *only* with DIFF_METHOD = 'RDM'.

WIND_TYPE

New option:

'POWER_LAW'

Produces a vertical power law wind field in ADPIC which is purely analytical and not gridded. No input wind field files are needed for this option. Power law winds are controlled by input parameters U_MEAN_REF, U_MEAN_REF_HGT, PWRLAW_EXPNT_U, and U_MEAN_DIR, which must be entered for this option.

Winds vary with power law in the vertical, but do not vary in the horizontal directions at any given height.

WARNING: Use only with flat terrain.

ADPIC_METPARAMS namelist

TURB PARAM VERT

Character string identifying *vertical* turbulence parameterization option to be used. The parameter applies only if DIFF_METHOD = 'RDM' in the ADPIC_CONTROL namelist. Possible values are as follows:

TURB_PARAM_VERT= 'KZ_SIMTHRY'

K_z as function of z calculated from boundary layer similarity theory as function of u_* , h , z and L . A constant value of K_z^{tropo} is used above $z = h$.

TURB_PARAM_VERT= 'KZ_SIMTHRY_USER'

$K_z(z)$ as function of z calculated from boundary layer similarity theory as function of u_* , h , z and L , but with *user-specified* coefficients a , b , c , and K_z^{tropo} (KZ_SIMTHRY_PHI_A, KZ_SIMTHRY_PHI_B, KZ_SIMTHRY_C, and KZ_SIMTHRY_TROPO)

TURB_PARAM_VERT= 'SIGZ_PWRLAWX_PG'

K_z as function of downwind distance, x , calculated from *Pasquill-Gifford* $\sigma_z(x)$ in a power law form.

TURB_PARAM_VERT= 'SIGZ_PWRLAWX_USER'

K_z as function of downwind distance x (in meters) calculated from $\sigma_z(x)$ (in meters) using *user-specified* power law coefficients γ and ρ (SIGZ_PWRLAWX_GAMMA and SIGZ_PWRLAWX_RHO) in the power law equation: $\sigma_z = \gamma x^\rho$.

TURB_PARAM_VERT= 'KZ_LINEARZ'

K_z calculated from power law equation, $K_z = K_{z\text{ref}}(z/z_{\text{ref}})$, where $K_{z\text{ref}}$ and z_{ref} (KZ_LINEARZ_REF and KZ_LINEARZ_REF_HGT) are specified by the user.

TURB_PARAM_VERT= 'KZ_CONSTANTZ'

K_z fixed at constant value = KZ_CONSTANTZ, specified by the user.

TURB_PARAM_HORZ

Character string identifying *horizontal* turbulence parameterization option to be used. This parameter applies only if DIFF_METHOD = 'RDM'. Possible values are as follows:

TURB_PARAM_HORZ = 'SIGH_SIGTHETA'

K_H as function of t calculated from Draxler $\sigma_y(t)$ using input σ_θ data (see SIGMA_THETA_DATA namelist) and internal-default value of HORZ_TIME_SCALE, τ_H .

TURB_PARAM_HORZ = 'SIGH_SIGTHETA_USER'

K_H as function of t calculated from Draxler $\sigma_y(t)$ using input σ_θ data (see SIGMA_THETA_DATA namelist) and *user-input* value of HORZ_TIME_SCALE, τ_H .

TURB_PARAM_HORZ = 'SIGH_PWRLAWX_PG'

K_H as function of downwind distance x calculated from *Pasquill-Gifford* $\sigma_y(x)$ in a power law form ($\sigma_H = \sigma_y = \alpha x^\beta$)

TURB_PARAM_HORZ = 'SIGH_PWRLAWX_MESO'

K_H as function of downwind distance x calculated from *MESODIF* $\sigma_y(x)$

TURB_PARAM_HORZ = 'SIGH_PWRLAWX_LONGRANGE'

K_H as function of downwind distance x calculated from *Dan Rodriguez's long-range* $\sigma_y(x)$

TURB_PARAM_HORZ = 'SIGH_PWRLAWX_USER'

K_H as function of downwind distance x (in meters) calculated from $\sigma_y(x)$ (in meters) using *user-specified* power law coefficients SIGH_PWRLAWX_ALPHA, α , and SIGH_PWRLAWX_BETA, β in the power equation: $\sigma_H = \alpha x^\beta$.

HORZ TIME SCALE

Horizontal turbulence time scale, τ_H (seconds). Applies to TURB_PARAM_VERT = 'KH_SIGTHETA_USER' option only, and must be input for that option. (Default: 50 s for TURB_PARAM_VERT = 'KH_SIGTHETA')

K VON KARMAN

Optional input parameter to override default value of the von Karman constant, k . (Default: K_VON_KARMAN = 0.4)

KZ CONSTANTZ

Constant K_z value used when TURB_PARAM_VERT = 'KZ_CONSTANTZ'. Must be input by the user. No internal default value.

KZ_LINEARZ_REF

Reference value K_{zref} (m^2/s) for linear vertical eddy diffusivity profile, $K_z = K_{zref}(z/z_{ref})$. Applies to TURB_PARAM_VERT = 'KZ_LINEARZ' option only, and must be input for that option.

KZ_LINEARZ_REF_HGT

Reference height z_{ref} (m) for power law vertical eddy diffusivity reference value. Applies to TURB_PARAM_VERT = 'KZ_LINEARZ' only, and must be input for that option.

KZ_SIMTHRY_PHI_A

Constant, a , for similarity theory vertical eddy diffusivity profile phi function. Applies to TURB_PARAM_VERT = 'KZ_SIMTHRY_USER' option only, and must be input for that option.

KZ_SIMTHRY_PHI_B

Constant, b , for similarity theory vertical eddy diffusivity profile phi function. Applies to TURB_PARAM_VERT = 'KZ_SIMTHRY_USER' option only, and must be input for that option.

KZ_SIMTHRY_C

Constant, c , for similarity theory vertical eddy diffusivity profile. Applies to TURB_PARAM_VERT = 'KZ_SIMTHRY_USER' option only, and must be input for that option.

KZ_SIMTHRY_TROPO

Constant value of K_z^{tropo} used above $z > h$. when TURB_PARAM_VERT = 'KZ_SIMTHRY_USER'.

SIGH_PWRLAWX_ALPHA

Constant α in power-law equation for horizontal concentration standard deviation versus downwind distance, $\sigma_H = \alpha x^\beta$, used to calculate horizontal eddy diffusivity. Applies to TURB_PARAM_HORZ = 'SIGH_PWRLAWX_USER' option only, and must be input for that option.

SIGH_PWRLAWX_BETA

Constant β in power-law equation for horizontal concentration standard deviation versus downwind distance, $\sigma_H = \alpha x^\beta$, used to calculate horizontal eddy diffusivity. Applies to TURB_PARAM_HORZ = 'SIGH_PWRLAWX_USER' option only, and must be input for that option.

SIGH_PWRLAWX_XMAX

Maximum downwind distance which the power law equation for horizontal concentration standard deviation versus downwind distance is to be used. After this distance the value of horizontal diffusivity, K_H , is held constant at its value at this distance. Applies to

TURB_PARAM_HORZ = 'SIGH_PWRLAWX_USER' option only, and must be input for that option.

SIGZ PWRLAWX GAMMA

Constant γ in power-law equation for vertical concentration standard deviation versus downwind distance, $\sigma_z = \gamma x^\rho$, used to calculate vertical eddy diffusivity. Applies to TURB_PARAM_VERT = 'SIGZ_PWRLAWX_USER' option only, and must be input for that option.

SIGZ PWRLAWX RHO

Constant ρ in power-law equation for vertical concentration standard deviation versus downwind distance, $\sigma_z = \gamma x^\rho$, used to calculate vertical eddy diffusivity. Applies to TURB_PARAM_VERT = 'SIGZ_PWRLAWX_USER' option only, and must be input for that option.

SIGZ PWRLAWX XMAX

Maximum downwind distance (m) which the power law equation for vertical concentration standard deviation versus downwind distance is to be used. After this distance the value of vertical diffusivity, K_z , is held constant at its value at this distance. Applies to TURB_PARAM_HORZ = 'SIGH_PWRLAWX_USER' option only, and must be input for that option.

U MEAN REF

Reference wind speed value $\bar{u}_1$ (m/s) for power law wind profile:

$$\bar{u}(z) = \bar{u}_1 \left(\frac{z}{z_1} \right)^m.$$

Applies to WIND_TYPE= 'POWER_LAW' option only, and must be input for that option.

PWRLAW EXPNT U

Exponent m for power law wind profile. Applies to WIND_TYPE= 'POWER_LAW' option only, and must be input for that option.

U MEAN REF HGT

Reference height z_1 (m) for power law wind profile reference wind speed, U_MEAN_REF. Applies to WIND_TYPE= 'POWER_LAW' option only, and must be input for that option.

U MEAN DIR

Mean horizontal wind direction (in degrees) using standard meteorological convention (clockwise from north for direction wind is blowing from). Applies to WIND_TYPE= 'POWER_LAW' option only, and must be input for that option.