Model description of the RODOS Meteorological Pre-Processor

Spyros Andronopoulos,

Environmental Research Laboratory, Institute of Nuclear Technology and Radiation Protection, National Centre for Scientific Research "Demokritos"

15310 Aghia Paraskevi, Greece

Email: sandron@ipta.demokritos.gr

John G. Bartzis

University of Western Macedonia, Department of Mechanical Engineering

Bakola & Sialvera Str., 50100, Kozani, Greece

Email: bartzis@uowm.gr

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Management Summary

The RODOS Meteorological Pre-Processor (RMPP) operates as interface between the meteorological data and the atmospheric dispersion models (ADMs) of RODOS. To this purpose RMPP processes the available meteorological data originating from a random or uniform meteorological network. These data may include wind speed and direction, air temperature, humidity, pressure, precipitation intensity, net radiation, surface heat flux, cloud cover, mixing layer height and atmospheric stability. These are then processed to provide more complete and systematic information on a three-dimensional computational grid that can be used by any ADM potentially included in RODOS.

This document describes the computational methods used in the three modules of the RMPP, the geometry module, the main meteorological module and the wind field module. Following an outline of the purpose of the model in Section 1, a description of the geometry-related computational approach is provided in Section 2. The latter includes the configuration of the 3-dimensional domain and grid, the description of the complex topography with the ground slopes and valleys, the assignment of characteristics to the cells according to the land-cover and finally the treatment of the meteorological stations with the methodology for identifying stations that influence a particular cell.

The meteorology-related computational methods are presented in Section 3. The Section starts by listing the input and output meteorological variables and by distinguishing the 2 and 3-dimensional ones. The time-related calculations follow, with a description of the generally applicable computational methods. The approaches for the calculation of the wind field are described next, including the near-ground wind, the synoptic wind and the 3-dimensional wind field. The wind velocity field divergence minimisation module (in brief WFM – wind field module) that is invoked after the main meteorological module of the RMPP is described next. The WFM performs the minimum possible corrections to the first-guess wind velocity field taking into account the ground slopes, so that the final field satisfies the mass conservation. The methods for calculating the other 3-dimensional variables follow: temperature, humidity and pressure fields. The last part of Section 3 describes the approaches for the calculation of the 2-dimensional variables, distinguishing whether there are or not available observations: cloud cover, precipitation, net radiation, sensible heat flux, stability category, mixing layer height, friction velocity, Monin-Obukhov length, convective velocity, eddy diffusivities and Brunt-Vaisala frequency are included in this description.

Contents

1 Introduction

The RODOS Meteorological Pre-Processor (RMPP) operates as interface between the meteorological data and the atmospheric dispersion models (ADMs) of RODOS. To this purpose RMPP processes the available meteorological data originating from a random or uniform meteorological network. These data may include wind speed and direction, air temperature, humidity, pressure, precipitation intensity, net radiation, surface heat flux, cloud cover, mixing layer height and atmospheric stability. These are then processed to provide more complete and systematic information on a three-dimensional computational grid that can be used by any ADM potentially included in RODOS.

In the framework of RODOS, a "Data Pre-Processor" (DPP) provides the input of RMPP. The DPP is in turn connected to the RODOS geographical database and to the sources of the meteorological information. The output of RMPP is connected to the RODOS ADMs and to the RODOS graphics system.

The RMPP has a modular structure. It consists of a geometry module, dealing with the geometrical configuration of the application, a main meteorological processor, calculating all the requested output meteorological variables and a wind field module which corrects the first-guess wind velocity field taking into account the ground slopes, so that the final field satisfies the mass conservation. The modules are based on software previously developed in the Environmental Research Laboratory, adapted for integration in RODOS and updated during the "RODOS MIGRATION" and "EURANOS" projects. In particular, the geometry and main processor modules have evolved from the meteorological pre-processor FILMAKER (Andronopoulos et al. 1999, Davakis et al. 1998). The WFM has been developed during the EURANOS project while the numerical scheme used in it has been developed during Euratom Grant "RODOS /METADM – enhance" (Kovalets, 2006).

2   Geometry and computational domain description

2.1   Computational domain and grid

The computational grid of the RMPP is, three-dimensional. In the horizontal direction the computational domain is Cartesian with the x-axis aligned to the West-East direction and the y-axis aligned to the South-North direction. The computational grid in the horizontal direction can be by uniform or non-uniform in any direction. In the RODOS configuration a uniform grid of 80 × 80 cells with dimensions 2 × 2 km^2 is used.

In the vertical direction the computational grid is non-uniform terrain following. Starting from an "initial" or "undisturbed" configuration, the vertical grid is constructed at each location keeping the domain height and the number of cells in each cells column constant throughout the domain. So in each vertical cells-column the same number of computational cells is "squeezed" between the varying topography and the domain top. This is performed in such a way as to conserve the relative size between adjacent in the vertical direction cells, as in the "undisturbed" configuration.

The height z_k above ground of the centre of the kth cell is computed by the following formula:

$$z_k = z_{und,k} \frac{z_{top} - z_{gr}}{z_{top}} \qquad (1)$$

where $z_{und,k}$ is the "undisturbed" height of the kth cell, z_{top} is the height of the top of the domain and z_{gr} is the ground elevation at the specific location. In the current RODOS configuration, 10 layers of 50, 75, 115, 170, 250, 380, 570, 850, 1300, 1900 m are used in the vertical direction, giving a total domain height of 5660 m.

2.2   Treatment of topography

The topography minimum and maximum elevations are computed. A "reference" topography elevation is computed as the 80% of the difference between the maximum and minimum added to the minimum elevation.

The ground slope in the x- and y-directions is computed for each ground-based cell from the ground elevations at the east and north cells boundaries and the cells dimensions. Then each ground-based cell is classified as "low slope", "medium slope" or "high slope" according to the ground slope and the limit values that the user provides. In the current RODOS configuration the limiting values for low, medium and high ground slope used are 0.05, 0.15 and 0.3 respectively. Ground cells with slope less than "low" and elevation higher than the "reference" elevation are characterised as "comit", while if their elevation is smaller than the "reference" elevation are characterised as "lflat". Furthermore cells with water land cover are assigned a separate category ("seacl").

Next, the module tries to locate more mountain tops in the domain: it considers pairs of cells that are "high slope" or "medium slope" and their distance is less than 5 km. It finds

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whether the directions of their ground slopes are correlated to the direction that connects them. If they are correlated then it finds the intersection point of their ground slopes directions going upslope. It locates this point in the grid. If that cell has a slope less than "medium slope" and elevation higher than the "reference" elevation, it is characterised as "top".

A similar procedure is followed next, to locate valleys in the domain: the code considers pairs of cells that are "high slope" or "medium slope" and their distance is less than 5 km. It finds whether the directions of their ground slopes are correlated to the direction that connects them. If they are correlated then it finds the intersection point of their ground slopes directions going down slope. It locates this point in the grid. If that cell has an elevation higher lower than the "reference" elevation, it is characterised as "valley".

Further checks are performed next concerning the cells characterisation. A cell that has 5 neighbouring cells characterised as "valley" cells is also characterised as "valley", if it has not already been classified as such. Cells that have been characterised as "valley" and are located at the domain boundaries are corrected and they are classified according to their ground slope. Ground cells that have a sea or water surface neighbouring cell are characterized as "coast".

The next step concerns further processing of valleys. The "valley" cells are counted and their numbering is placed in arrays to ease their tracking. Then each group of neighbouring "valley" cells are classified into separate valley regions. The direction of each valley's "back-bone" is computed next. Finally the depth of each valley is calculated by interpolating the elevation difference of each "valley" cell with the non-valley neighbouring cells within a 3-cells radius.

2.3 Ground cover characteristics

Ground-based cells are assigned with values for land-cover related variables: roughness, albedo and moisture content are set according to the 5 types of land-cover used in RODOS (Table 1).

Table 1: Characteristics of land-cover types			
Land-cover types	**Roughness (m)**	**Albedo**	**Moisture content**
Grassland or unidentified areas	0.10	0.2	0.4
Agricultural areas	0.20	0.25	1.0
Wood	1.50	0.15	1.0
Water	0.01	0.20	1.2
Built-up areas	1.50	0.15	0.7

The land-cover type for each cell is provided to the RMPP by the DPP, based on the information included in the geographical database. The moisture content is used for the calculation of the net radiation, and the values are based on those adopted by Hanna and Chang (1993).

2.4   Treatment of input observation points

To process the meteorological stations location data, the stations relative coordinates to the domain origin are calculated first. Stations eventually located outside the domain boundaries are excluded. The ground elevation and slopes in x- and y-direction at the location of each station are calculated by interpolation (Akima's method). The maximum number of stations is eventually reduced based on the actual number of stations present in the domain. The stations are then characterised according the ground slope or land cover at their location: one category includes the stations located on flat, low or medium slopes, another includes stations located on high slopes, a third one stations located over water, and a final category includes stations located in valleys.

Input data from meteorological stations and weather forecasting models are treated the same way: measurement locations and grid points of numerical weather prediction models are considered equally as "meteorological stations" or "stations". A station can have one or more "observation" levels in height: either measurements or grid points at the same location.

The concept of a limited number of stations influencing a computational cell has been adopted to speed up the execution time of the RMPP in cases with large number of stations and grid points, as for example when data from weather forecasting models are used. Two criteria are applied to this purpose. The first criterion is based on the distance between the cell and the station and is mandatory. The second criterion is based on the region type and the topography and is applied only on specific user's request, because it is computationally time consuming.

A maximum of 4 stations has been defined that are allowed to influence a particular computational cell. Obviously, if less than 4 stations are located inside the domain, this number is used as maximum. According to the first (distance) criterion, the user defines an initial and a maximum radius of search to be applied for all cells. The default initial radius is 8 km. If the user does not supply a value for the maximum radius, the entire domain will be searched for stations. The search starts with the initial radius. If more stations than the maximum allowed are found, only the closest 4 are selected. If there are fewer stations, only those are selected. If there is no station, the radius is increased and the search is repeated until stations are found or the maximum radius is reached. If no stations are found for a cell within the maximum radius, the program stops.

The second criterion to exclude stations that can influence a cell is activated only upon specific request by the user. At a first step it is based on the region and concerns the "valley" cells: they can be influenced only by stations located in a valley with the same direction (difference 30º or less). The second step is based on the topography: if between a cell and a station the ground slope changes sign more than 3 times (by default, this can be set by the user) then it is considered that the station cannot influence the cell.

3   Meteorological calculations

3.1   Meteorological variables

3.1.1   Input variables / meteorological stations

The possible input meteorological variables are distinguished to those for which observations in multiple levels in the vertical for each station can be given, and to those for which only one value per station can be given. The variables for which observations in multiple levels in the vertical for each station can be given are the following:

1. Wind speed and direction
2. Air temperature
3. Specific humidity
4. Pressure

The variables for which only one value per station can be given are the following:

1. Precipitation intensity
2. Net radiation
3. Surface heat flux
4. Cloud cover
5. Mixing layer height
6. Atmospheric stability

The available meteorological stations are counted and classified according to the meteorological input variables (listed above) that are available in each one. Then the influencing stations per input variable (wind, temperature, humidity, pressure, precipitation, heat flux, net radiation, cloud cover, stability category) are found for each cell. If for a certain variable there are no observations among the influencing stations already determined by the distance criterion, then the nearest stations with available observations for this variable are considered (up to the maximum allowed number).

3.1.2   Output variables

The calculated output variables by the RMPP are the following:

1. *u*-component (west to east) of the wind velocity vector (3-D)
2. *v*-component (south to north) of the wind velocity vector (3-D)
3. *w*-component (vertical) of the wind velocity vector (3-D)
4. Air temperature (3-D)
5. Specific humidity (3-D)
6. Pressure (3-D)
7. Precipitation intensity (2-D)
8. Cloud cover (2-D)
9. Diffusion coefficient in the x-(west to east)-direction (3-D)
10. Diffusion coefficient in the y-(south to north)-direction (3-D)
11. Diffusion coefficient in the z-(vertical)-direction (3-D)
12. Horizontal wind speed and direction at 10 meters above ground (2-D)
13. Sensible Heat Flux (2-D)

14. Net radiation (2-D)
15. Atmospheric Stability Category (2-D)
16. Atmospheric Stability Class (2-D)
17. Mixing Layer Height (2-D)
18. Monin-Obukhov Length (2-D)
19. Friction Velocity (2-D)
20. Convective Velocity (2-D)
21. Brunt-Väisälä frequency (2-D)
22. Temperature lapse rate (2-D)

It is noted that the "first-guess" values of the horizontal wind components (u and v) are calculated by interpolation in the main part of the RMPP. The topography-adjusted horizontal wind components as well as the vertical wind component (w) are calculated in the WFM.

3.2   Time steps / time-related calculations

The RMPP operates for the times for which the input meteorological variables are provided. These are the "time-steps" of the model. No interpolation in time is performed.

For each time step, the month, day, hour and minute are passed to the RMPP by the DPP. From these, and from the longitude and latitude of the domain (also provided by the DPP), the times of sunrise and sunset as well as the sun's exact position are calculated. This information is taken into account for the empirical calculations of meteorological variables, for which no observations exist.

3.3   Computational methods

The RMPP uses two methods for computing the requested output variables at the cells of the computational grid:

1. Spatial interpolation in two or three dimensions
2. Physical or empirical relations

These methods are used according to the availability or not of meteorological information. Variables, for which observations exist, are interpolated from the stations to the computational grid points. Only the stations influencing a cell are taken into account during the interpolation procedures. Variables, for which observations do not exist, are calculated from physical or empirical relations based on the available information.

The relations used for the calculation of the output meteorological variables will be analysed per case.

3.3.1 Interpolation techniques

Concerning the interpolation techniques, for horizontal-wise interpolation, a two-dimensional $1/r^2$ scheme is used. The "plane" of interpolation can be terrain-following or Cartesian for the wind velocity components, temperature, humidity and pressure. In the current RODOS configuration terrain-following interpolation is used for wind velocity and

Cartesian interpolation for temperature, humidity and pressure. For the rest of the variables, the plane of interpolation is terrain-following.

The general scheme for the interpolation inside each horizontal plane is expressed as following:

$$A_{i,j} = \frac{\sum\limits_{k} \left(A_{\mathrm{obs},k} / R_k^2 \right)}{\sum\limits_{k} \left(1/R_k^2 \right)} \tag{2}$$

$A_{i,j}$ is the calculated variable at the computational cell (i, j), $A_{obs,k}$ is the observed variable at the station k, and R_k is the straight-line distance between the cell (i, j) and the station k. The sums run over the stations that influence the cell (i, j).

The horizontal planes where interpolation is performed are located at "reference heights". The reference heights are calculated from the available observation levels. For each cells column, a number of "reference heights" for each of the variables wind velocity, temperature, humidity and pressure, is determined, based on the levels where observations exist at the sensors that influence the particular cell. To determine the reference heights, the observation levels are grouped according a height range, which can be defined by the user and has a default value of 30 m. The reference heights can be determined in a terrain-following or Cartesian mode, for each variable, depending on the user's choice. The default is terrain-following mode for wind velocity, temperature and humidity, and Cartesian mode for the pressure. In the current RODOS configuration a maximum of 30 "reference heights" has been set. If more such reference heights are calculated based on the existing "observation" levels, then the initial height range of 30 m is increased until the calculated reference height are less than 30.

In the vertical direction, the interpolation/extrapolation scheme for the wind velocity components is logarithmic in the surface layer, power law up to the mixing height and linear between measured values above power law maximum height. In cells located higher than the mixing layer and higher than the highest observation point the wind velocity is set equal to the "synoptic wind" (see below for the definition of the latter). For the rest of the 3-D variables (temperature, pressure and humidity) the interpolation in the vertical direction is linear. The extrapolation (i.e., in cells lower than the lowest of higher than the highest observation levels) is described for each variable in the following sections.

3.3.2 Smoothing

A 2-dimensional smoothing procedure with 2 smoothing passages is applied to the variables mixing layer height and stability category, after they are calculated. This is done to avoid abrupt variations of their values between neighbouring cells. Such variations may be due to changes in land-cover types and roughness heights that are used in the empirical relations.

The smoothing relation applied is the following:

$$A_{\mathrm{smooth},i,j} = 0.5 \cdot A_{i,j} + 0.125 \cdot \left(A_{i+1,j} + A_{i-1,j} + A_{i,j+1} + A_{i,j-1} \right) \tag{3}$$

3.4   Near ground wind field

The wind velocity at 10m above ground is calculated in every ground-based cell, after the horizontal $1/r^2$ interpolation procedure has been completed. It is first determined whether there is a reference level at or near ($\pm$ 1 m) 10 m. If there is such a reference level the velocity at this level is taken as the wind at 10m.

In case of no velocity reference level at the height of 10m, the velocity at this height for each cell is calculated by logarithmic interpolation in the vertical direction between the other existing measurement levels. If the lowest measurement level is above 50m then the result of this method is not considered reliable and a warning message is issued to the user.

The surface wind field is completed at the remaining "empty cells" (i.e., the cells that are not affected by any station with measurements close to 10 m) through a $1/r^2$ horizontal interpolation between the cells where the 10 m wind speed has already been determined.

3.5   Synoptic wind

The synoptic wind is used for the calculation of the wind velocity in cells that are located higher than the highest reference level for the wind velocity. There are three available options in the RMPP to calculate the synoptic wind.

The first option is values provided by the user. Specifically these are the variables USYNOP and DSYNOP with assigned values in DATA statements in the routine mpp_main.f. The second option, applied when no values are supplied by the user, is to set as synoptic wind the wind speed and direction at the highest observation level above the altitude of ZSYNOP meters. The default value of ZSYNOP is 1000 m.

If no values are given by the user and no observation level exists above ZSYNOP, the geostrophic wind is used as an estimation of the synoptic wind. The geostrophic wind is calculated from an empirical relationship based on two forms of the logarithmic wind profile intended to obey both the surface-layer and the upper-layer similarity laws:

$$U_G = \frac{u_*}{\kappa} \sqrt{\left[\ln\left(\frac{h}{z_0}\right) - B_\mu \right]^2 + A_\mu^2} \tag{4}$$

where u_* is the friction velocity, κ is the Von Karman constant, h is the mixing layer height, z_0 is the roughness height, A_μ and B_μ are empirical parameters. The latter are function of the atmospheric stability:

For neutral conditions $A_\mu = 4.5$ and $B_\mu = 0.5$,

For stable conditions $A_\mu = 4.5 + 1.765\sqrt{|\mu|}$ and $B_\mu = 0.5 - 2.55\sqrt{|\mu|}$,

For unstable conditions $A_\mu = 4.5 \big/ \left(1 + 1.581\sqrt{|\mu|}\right)$ and $B_\mu = 10 - 9.5 \big/ \left(1 + 0.27\sqrt{|\mu|}\right)$,

where the parameter $\mu = \kappa u_* / z_0 L$, with L the Monin-Obukhov length.

The angle between the geostrophic wind and the surface wind is calculated by the following relation:

$$\alpha_0 = \arcsin\left(A_\mu \frac{u_*}{\kappa U_G}\right)$$

The absolute direction of the geostrophic wind is calculated by adding α_0 to the direction of the surface wind. The west-east and south-north components of the geostrophic wind are calculated by projecting U_G on these directions.

3.6   Three-dimensional wind field

3.6.1   Interpolation

The first step for the calculation of the 3-D wind field is the $1/r^2$ interpolation in the horizontal direction for each velocity-reference height. At the end of this step, the wind horizontal components u and v have been evaluated at each cells column, at the velocity reference heights. No vertical component is calculated at this stage.

The second step is the interpolation in the vertical direction to calculate the horizontal velocity components at all cells in each cell column from the values at the reference heights. The general case concerns cells located between two reference heights. For the cells located inside the surface layer, a logarithmic interpolation is applied. For the cells located above the surface layer, but below the mixing layer height, a power law interpolation is applied. For cells located above the mixing layer height, a linear interpolation is applied. Special cases are the cells located below the lowest reference level and the cells located higher than the highest reference level. For these, the rules of logarithmic or power law stated above are also applied, depending on whether they are located in the surface or mixing layer. The velocity at 10 m above ground and the synoptic wind are also used in the interpolations. If the highest observation lies above the mixing height, then for cells above that, the synoptic wind is imposed.

3.6.2   Smoothing

After the 3-dimensional fields of horizontal wind velocities are calculated by interpolation, a smoothing procedure is applied per horizontal level, with 2 smoothing passages for each component (u and v).

3.6.3   Wind field divergence minimizing procedure

The divergence minimizing procedure is performed in the Wind Field Module (WFM). The WFM is invoked after the RMPP has calculated by spatial interpolation the 3-dimensional horizontal wind velocity field. Since this "first-guess" wind velocity field is generated by spatial interpolation, it is not influenced by the topography features and therefore it does not satisfy the mass-conservation principle. The role of the WFM is to perform the minimum possible corrections to the first-guess wind velocity field taking into account the ground slopes, so that the final field satisfies the mass conservation. In mathematical terms, the WFM minimises the divergence of the wind velocity field.

The WFM uses the variational approach originally developed by Sasaki (1958, 1970) and described also by Kitada et al. (1983).

Let x and y represent the horizontal directions (west-east and south-north respectively) and z represent the vertical direction in the computational domain $\Omega(x,y,z)$. Let $u_0(x,y,z)$, $v_0(x,y,z)$ and $w_0(x,y,z)$ be the components of the wind velocity field (in the directions x, y, z respectively) initially calculated by the MPP by spatial interpolation (also called "first guess" field). Actually in the RMPP no vertical velocity is calculated by spatial interpolation, i.e., $w_0 = 0$, but nevertheless it is included here for generality purposes. The (u_0,v_0,w_0) field does not satisfy the continuity (mass conservation) equation. Therefore the aim is to perform the minimum possible correction to the initial field in order that the final (or "adjusted") wind field (u,v,w) satisfy the continuity equation.

In mathematical terms, the problem is expressed as the minimization of the following integral

$$E = \int_\Omega F \, d\Omega ,$$

(5.a)

where

$$F(u,v,w) = \alpha_H^2 (u - u_0)^2 + \alpha_H^2 (v - v_0)^2 + \alpha_V^2 (w - w_0)^2$$

(5.b)

subject to the constraint of the continuity equation:

$$g \equiv u' + v' + w' = 0$$

(6)

where $u' = \partial u / \partial x$, $v' = \partial v / \partial y$ and $w' = \partial w / \partial z$. The coefficients α_H and α_V are weighting parameters in the horizontal and vertical directions respectively. Some authors relate them to the standard deviation of the respective velocity components (e.g., $\alpha_H^2 = 1/\sigma_H^2$, $\alpha_V^2 = 1/\sigma_V^2$, Ratto et al., 1994).

To solve the minimization problem (5) and (6) the Lagrange's method of undetermined multipliers suggests forming the function (Daley, 1991)

$$F_1 = F + \lambda g$$

(7)

where $\lambda(x,y,z)$ is the Lagrange multiplier, and minimizing the integral

$$J = \int_\Omega F_1 \, d\Omega \tag{8}$$

It can be proved that for $\delta J = 0$ the Euler-Lagrange equations must hold:

$$\frac{\partial F_1}{\partial u} + \frac{d}{dx}\frac{\partial F_1}{\partial u'} = 0$$

$$\frac{\partial F_1}{\partial v} + \frac{d}{dy}\frac{\partial F_1}{\partial v'} = 0 \tag{9}$$

$$\frac{\partial F_1}{\partial w} + \frac{d}{dz}\frac{\partial F_1}{\partial w'} = 0$$

By substituting (7) into (9), taking into account (5.b) and (6) the following equations are obtained for the adjusted wind velocity components:

$$u = u_0 + \frac{1}{2\alpha_H^2}\frac{\partial \lambda}{\partial x}$$

$$v = v_0 + \frac{1}{2\alpha_H^2}\frac{\partial \lambda}{\partial y} \tag{10}$$

$$w = w_0 + \frac{1}{2\alpha_V^2}\frac{\partial \lambda}{\partial z}$$

To calculate λ the derivative of (10) is taken and it is substituted in the continuity equation (6). In this way the following elliptic differential equation is obtained:

$$\frac{\partial^2 \lambda}{\partial x^2} + \frac{\partial^2 \lambda}{\partial y^2} + \alpha\frac{\partial^2 \lambda}{\partial z^2} = -2\alpha_1^2\left(\frac{\partial u_0}{\partial x} + \frac{\partial v_0}{\partial y} + \frac{\partial w_0}{\partial z}\right) \tag{11}$$

where $\alpha = \alpha_H^2 / \alpha_V^2$.

Equation (11) is solved in the WFM for λ and then the adjusted velocity components are calculated by (10).

Two groups of numerical solution schemes are currently available in the WFM for solving the differential equation for λ (11): the point- or line-iterations method and the conjugate gradient (CG) method (Kovalets, 2006). The default method in the current RODOS configuration is the CG.

3.7   Near-ground temperature

The near ground temperature is the temperature at the ground-based computational cells. It is used by the code for the calculation of several meteorological parameters: net radiation, sensible heat flux, friction velocity, Monin-Obukhov length. Furthermore, it can be used in combination with the temperature lapse rate for the calculation of the 3-dimensional temperature field, if no temperature observations in height exist.

The near-ground temperature is normally calculated at the ground-based cells by interpolation from the available near-ground observations. If no temperature observations exist, then the near-ground temperature is calculated from a sinusoidal function of time in the day. For this function, a maximum and minimum temperature is required. The user can specify these; otherwise default values are used by the code (20 and 10 degrees Celsius respectively in the current RODOS configuration).

3.8   Temperature lapse rate

The temperature lapse rate is used in the calculation of the 3-dimentional temperature field, for the cells that are above the highest available observations. It is also used in one of the methods for calculating of the atmospheric stability.

RMPP attempts to calculate the temperature lapse rate for the stations with more than two measurements in height. The first measurement level should be below 50m and the height difference between the two levels that will be considered for the calculation of the temperature lapse rate must be between 50m and 150m. If the above conditions are satisfied, the temperature lapse rate is calculated and then a $1/r^2$ horizontal interpolation is performed between the stations where the lapse rate is calculated, to evaluate the temperature lapse rate in all the cells of the domain.

If the above methodology cannot be applied, then the temperature lapse rate is calculated after the atmospheric stability has been calculated. In that case, typical temperature lapse rate is assigned to each cell column corresponding to the already available Pasquill stability class, according to the Table 2 (IAEA, 1980, Seinfeld, 1986).

Table 2: Relationship between Pasquill stability class and temperature lapse rate						
Stability class	A	B	C	D	E	F
$\Delta T/\Delta z$ (K/100m)	-2.0	-1.8	-1.6	-1.0	0.5	1.6

3.9   Three-dimensional temperature field

3.9.1   Horizontal interpolation

If temperature measurements exist, a $1/r^2$ interpolation in the horizontal direction is performed between the stations and the cell columns, at the existing reference levels.

3.9.2   Vertical interpolation

In the vertical direction, up to the highest measurement, a linear interpolation is performed between the reference levels and the cell heights. For the cells above the highest measurement, the calculated temperature lapse rate is used up to the mixing height and the Standard Atmosphere's lapse rate 6.5K/km (Holton, 1979) is used above the mixing height.

3.9.3   Special case: no temperature observations in the vertical

If no temperature measurements in height exist, then the 3-dimensional temperature field is calculated from the near-ground temperatures and the temperature lapse rates.

3.10   Surface pressure

3.10.1 General case

The pressure at the ground-based computational cells is normally calculated by interpolation from the available observations.

3.10.2 Special case: no pressure observations

If no pressure observations exist, or for cells not influenced by any pressure observation, the pressure is calculated by a fitting function relating the Standard Atmosphere (Holton, 1979) with the elevation. The ground pressure is calculated as function of the ground elevation as follows:

$$P_{surf} = 406.5 z_{ground} - 11507 z_{ground} + 101325 \qquad (12)$$

where the ground elevation z_{ground} is given in km.

3.11   Three-dimensional pressure field

3.11.1 Horizontal interpolation

The first step for the calculation of the 3-D pressure field is the $1/r^2$ interpolation in the horizontal direction for each pressure-reference height. At the end of this step, the pressure has been evaluated at each cells column, at the pressure reference heights.

3.11.2 Vertical interpolation

The second step is the interpolation in the vertical direction to calculate the pressure at all cells in each cell column from the values at the reference heights. The general case concerns cells located between two reference heights. For such cells linear interpolation is applied.

3.11.3 Vertical extrapolation

In special cases of cells located below the lowest reference level or higher than the highest reference level, the following exponential variation, based on the hydrostatic approximation is used:

$$P = P_{ref} \exp\left[\frac{(z_{ref} - z)g}{RT}\right] \qquad (13)$$

where P_{ref} is the pressure at the height z_{ref} of the reference level above or below the cell in question, g is the acceleration of gravity, R is the gas constant and T is the temperature of the cell in question.

In cases where no pressure observations in the vertical exist, fitting functions expressing the pressure variation with height for the Standard Atmosphere (Holton, 1979) are employed:

$$P = 406.5z^2 - 11507z + 101325, \text{ for } z < 11\,\text{km}$$
$$P = 123666\exp(-0.1554z), \text{ for } z > 11\,\text{km}$$

(14)

where z is expressed in km.

3.12   Three-dimensional humidity field

3.12.1 Horizontal interpolation

The first step for the calculation of the 3-D humidity field is the $1/r^2$ interpolation in the horizontal direction for each humidity-reference height. At the end of this step, the humidity has been evaluated at each cells column, at the humidity reference heights.

3.12.2 Vertical interpolation

The second step is the interpolation in the vertical direction to calculate the humidity at all cells in each cell column from the values at the reference heights. The general case concerns cells located between two reference heights. For such cells linear interpolation is applied.

3.12.3 Vertical extrapolation

For cells located below the lowest reference level, the humidity value at the lowest level is used. For those located above the highest level, the following exponential variation is used:

$$q_w = q_{w,\text{top}} \exp\left[-\left(w_L - \frac{g}{RT}\right)\left(z - z_\text{top}\right)\right], \text{ where}$$
$$w_L = 0.09205 \cdot 10^{-4}\left(z - z_\text{top}\right)^{0.453117}$$

(15)

3.13   Cloud cover

If cloud cover observations exist, then RMPP calculates the values at all cells by $1/r^2$ interpolation. If no observations exist, the default value that is assigned is 4 oktas.

3.14   Precipitation intensity

If precipitation intensity observations exist, then RMPP calculates the values at all cells by $1/r^2$ interpolation. If no observations exist, the default value that is assigned is 0 mm/h.

3.15   Net radiation

3.15.1 Case 1: observations exist

If net radiation observations exist, then the values at the ground-based cells are computed by $1/r^2$ interpolation.

3.15.2 Case 2: no observations exist

The net radiation flux (including shortwave and longwave components) is calculated by the methodology proposed by Hanna and Chang (1993):

$$Q^* = \frac{(1-A)Q_{sw} + c_1 T^6 - \sigma T^4 + c_2 N}{1 + c_3} \tag{16}$$

where Q^* is the net radiation flux, A is the surface albedo (provided by the user), T is the surface temperature, σ is the Stefan-Boltzmann constant, $5.67 \times 10^{-8} Wm^{-2} K^{-4}$, $c_1 = 5.31 \times 10^{-13} Wm^{-2} K^{-4}$ and $c_2 = 60 Wm^{-2}$ are constants, N is the fractional cloud cover (eighths). The parameter c_3 is calculated by the formula:

$$c_3 = 0.38 \frac{(1-\alpha)S + 1}{S + 1}$$

where α is a "surface moisture availability factor" which depends on the land use and is provided by the user and S is related to the slope of the saturation specific humidity curve (Clausius-Clapeyron).

Hanna and Chang (1993) propose the following values for α

$\alpha = 0.0 - 0.2$ (dry desert with no rain for months)
$\alpha = 0.2 - 0.4$ (arid rural area)
$\alpha = 0.4 - 0.6$ (crops and fields, mid-summer during periods when rain has not fallen for several days)
$\alpha = 0.5 - 1.0$ (urban environment, some parks)
$\alpha = 0.8 - 1.2$ (crops, fields, and forests with sufficient soil moisture)
$\alpha = 1.2 - 1.4$ (large lake or ocean with land more than 10km distant)

The parameter S is calculated by

$$S = 6.45225 \times 10^6 \exp(-0.0561201 \cdot T)$$

The shortwave solar radiation $Q_{sw} (Wm^{-2})$ is calculated as function of the sun's zenith angle Z

$$Q_{sw} = 990 \cos Z - 30$$

3.15.3 Consistency of net radiation with atmospheric stability

In case that there are atmospheric stability input data (from measurements or model), these are considered reliable and therefore the calculated net radiation is checked and eventually corrected to be consistent with the atmospheric stability. This checks and corrections are made according to Table 3 (Tercier, 1995)

Table 3: Stability categories related to net radiation and wind speed at 10m							
Q (Wm^{-2})	**> 390**	**390 – 240**	**240 – 80**	**80 – 5**	**5 – -7**	**-7 – -28**	**≤ -28**
u: 0.0 – 0.9	A	A	B	C	E	F	F
1.0 – 1.9	A	B	B	C	E	E	F
2.0 – 2.9	A	B	C	C	D	D	E
3.0 – 4.9	A	B	C	C	D	D	D
5.0 – 6.9	B	C	D	D	D	D	D
≥ 7.0 (ms^{-1})	D	D	D	D	D	D	D

3.16 Sensible heat flux

By convention the heat flux is considered positive when it is directed from the ground to the air, and negative in the opposite sense.

3.16.1 Case 1: observations exist

If heat flux observations exist, then the values at the ground-based cells are computed by $1/r^2$ interpolation.

3.16.2 Case 2: no observations exist

If no observations exist, or for cells not influenced by sensible heat flux measurements, the sensible heat flux is calculated following Hanna and Chang (1993) by:

$$Q_H = Q^*(1-\alpha)\left[\frac{(1-\alpha)+S}{1+S}\right] - 20\alpha \qquad (17)$$

where all the parameters have been defined in §3.15.2.

If there are no sensible heat flux observations but there are atmospheric stability input data (from measurements or model), then the sensible heat flux is calculated from:

$$Q_H = -\frac{u_*^3 \rho c_p T}{L_* \kappa g}$$

where u_* is the friction velocity, ρ is the air density, c_p is the air specific heat under constant pressure, T is the air temperature, L_* is the Monin-Obukhov length, κ is the von Karman constant and g is the gravity acceleration.

3.17 Stability category

3.17.1 Case 1: observations exist

If stability category observations exist, then the values at the ground-based cells are computed by $1/r^2$ interpolation.

3.17.2 Case 2: no observations exist

If no observations exist, or for cells not influenced by stability category observations, the stability is calculated by alternative methodologies, according to the available data.

The first option is to use the wind speed at 10 m height and the net radiation, if the latter is calculated from observations. The evaluation is based on Table 4 (IAEA, 1980).

The second option is to use the wind speed at 10m height and the temperature lapse rate, if the latter has been already evaluated. The evaluation is based on Table 5 (IAEA, 1980).

The third option is to use the wind speed at 10m, the solar zenith angle and the cloud cover. The zenith angle is calculated by the hour of the day (see Section 3.2). The insolation is characterised as "strong" if the zenith angle is less than 30°, "medium" if the zenith angle is greater than 30° and less than 55° and "slight" if the zenith angle is greater than 55°. This characterisation is modified if the cloud cover is available. Then the stability class is determined from Table 6 (IAEA, 1980).

Finally, RMPP performs quality checks to ensure that there are no inconsistencies between the calculated sensible heat flux and stability categories. If the sensible heat flux is negative (i.e., downward) then the stability is not allowed to be 'A', 'B' or 'C' (unstable). If the sensible heat flux is positive (i.e., upward) then the stability is not allowed to be 'E' or 'F' (stable). Furthermore unstable conditions ('A', 'B', and 'C') are not permitted during the night and over the sea. If any inconsistencies are spotted then the stability class is set to neutral ('D').

Table 4: Stability classification using net radiation and wind speed		
Wind	Day with solar radiation $R_D\left(Wm^{-2}\right)$	Night with net radiation $R_N\left(Wm^{-2}\right)$

speed U (ms^{-1}) at 10m	$R_D \geq 581.5$	$581.5 > R_D \geq 290.8$	$290.8 > R_D \geq 145.4$	$145.4 > R_D$	$R_N > -20.9$	$20.9 \geq R_N > -41.9$	$-41.9 \geq R_N$
U<2	A	B	B	D	D	E	F
2≤U<3	B	B	C	D	D	E	F
3≤U<4	B	C	C	D	D	D	E
4≤U<6	C	D	D	D	D	D	D
6≤U	C	D	D	D	D	D	D

Table 5: Stability class from temperature lapse rate and wind speed							
Wind speed U (ms^{-1}	Stability class with $\Delta T/\Delta z$ (K/100m)						
	$\frac{\Delta T}{\Delta z} \leq -1.5$	$-1.5 < \frac{\Delta T}{\Delta z} \leq -1.2$	$-1.2 < \frac{\Delta T}{\Delta z} \leq -0.9$	$-0.9 < \frac{\Delta T}{\Delta z} \leq 0.7$	$-0.7 < \frac{\Delta T}{\Delta z} \leq 0$	$0 < \frac{\Delta T}{\Delta z} \leq 2$	$\frac{\Delta T}{\Delta z} > 2$
U<1	A	A	B	C	D	F	F
1≤U<2	A	B	B	C	D	F	F
2≤U<3	A	B	C	D	D	E	F
3≤U<5	B	B	C	D	D	D	E
5≤U<7	C	C	D	D	D	D	E
7≤U	D	D	D	D	D	D	D

Table 6: Stability class from insolation and wind speed					
Wind speed U(m/s) at 10m	Stability class, day, with insolation			Stability class, night with sky conditions:	
	Strong	Moderate	Slight	Thinly over-cast or ≥ 4/8 cloud cover	≤ 3/8 cloud cover
U<2	A	B	B	F	F
2≤U<3	B	B	C	E	F
3≤U<5	B	C	C	D	E
5≤U<6	C	D	D	D	D
6≤U	C	D	D	D	D

3.18 Mixing layer height

3.18.1 Case 1: Observations exist, or vertical temperature profiles can be used

If mixing layer height observations exist, RMPP uses them to perform $1/r^2$ interpolation to calculate the mixing height at all cells.

If mixing layer height information is not available, RMPP attempts to estimate the mixing layer height from observed temperature profiles. This option is invoked upon user's request by setting the value to the variable TPRMLH = 'Y' in the DATA statement in routine mpp_main.f. If TPRMLH = 'N' the procedure is not used. The methodology is based on the "COST ACTION 710" Final Report (Seibert et al., 1997). Only the stations with more than 3 temperature measurement levels in the vertical direction are considered. Stations located in valleys or high slopes are excluded. The code checks for the presence of temperature inversions. If temperature inversions are located, then their heights are assigned as mixing layer heights at the stations locations. Then a $1/r^2$ interpolation between affecting stations is performed to obtain the mixing layer height at all cells.

3.18.2 Case 2: No observations exist, no temperature profiles can be used

If no mixing layer height observations exist and no temperature profiles can be exploited, RMPP has two alternative approaches. The selection of the approach is made according to the value of the variable MLHMTD in DATA statement in the routine mpp_main.f.

The first approach (MLHMTD = 'D') is to assign pre-fixed values of the mixing layer height according to the stability category. The default values are:

A   1600 m
B   1200 m
C   800 m
D   600 m
E   300 m
F   200 m

The above values can be modified by the user. The values are set in the variables AMLH, BMLH, CMLH, DMLH, EMLH, FMLH in DATA statement in routine mpp_main.f.

The second approach (MLHMTD = 'H') is to use the empirical relation based on sensible heat flux and friction velocity provided graphically by Desiato and Palmieri (1988).
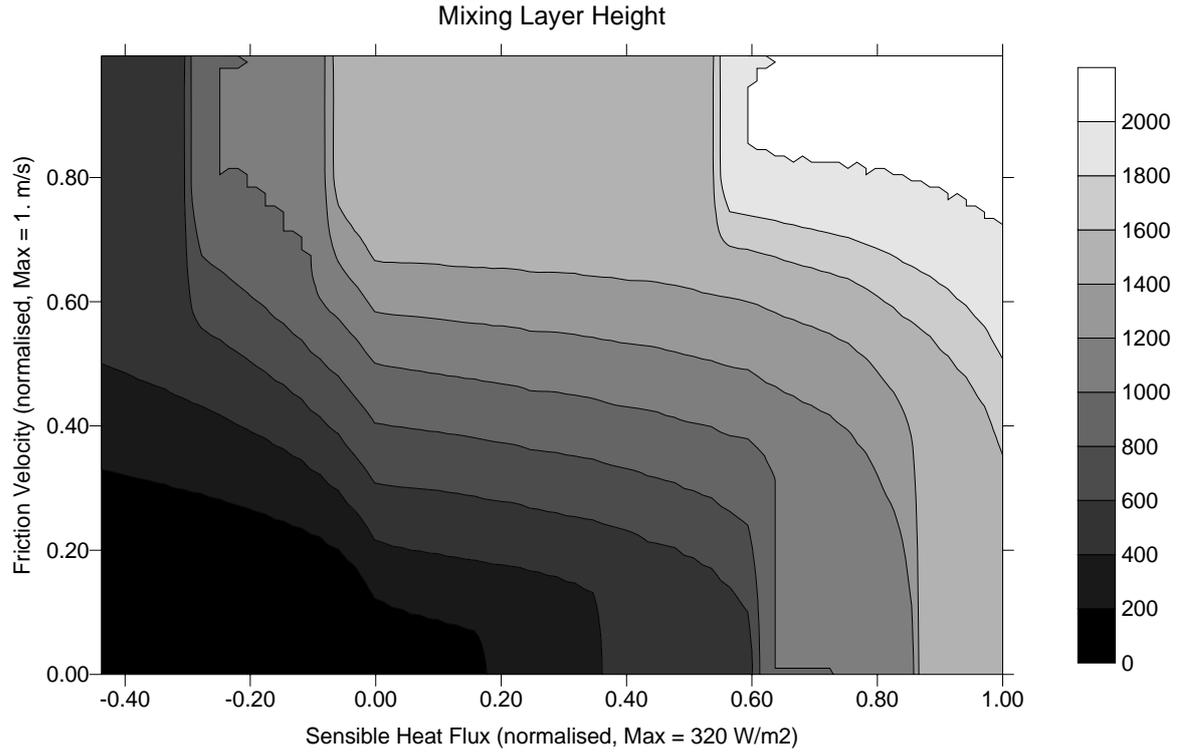
Mixing Layer Height

Figure 1: Variation of mixing layer height in relation to sensible heat flux and friction velocity.

3.19 Friction velocity

RMPP estimates the friction velocity u_* from empirical relations following the methodology of Hanna and Chang (1993).

For neutral conditions:

$$u_* = \frac{\kappa u_{10}}{\ln((z-d)/z_0)} \tag{18}$$

where κ is the von Karman constant (=0.4), u_{10} is the wind speed at 10 m height, $z = 10$ m, z_0 is the roughness and $d = 5z_0$ is the displacement length.

For stable conditions:

$$u_* = \frac{0.2u_{10}}{\ln((z-d)/z_0)}\left\{1+\left[1-4\left(\frac{4.7gz\theta_* \ln((z-d)/z_0)}{0.4Tu_{10}^2}\right)\right]^{1/2}\right\} \tag{19}$$

where g is the gravity acceleration, T is the near-ground temperature and θ_* is a scaling temperature, calculated as the minimum of the following 2 empirical equations:

$$\theta_{*1} = 0.09(1-0.5N^2)$$

$$\theta_{*2} = \frac{0.4 T u_{10}^2}{18.8 gz \ln((z-d)/z_0)}$$

where N is the cloud cover in eighths. Clear sky is assumed if no cloud cover data are available. A further upper limit $u_* = 0.05/\theta_*$ is imposed.

For unstable conditions:

$$u_* = \frac{0.4 u_{10}}{\ln((z-d)/z_0)}[1 + d_1 \ln(1 + d_2 d_3)] \qquad (20)$$

Where

$$d_1 = 0.128 + 0.005 \ln(z_0/(z-d)) \quad \text{if} \quad z_0/(z-d) \leq 0.01$$
$$\quad\;\; = 0.107 \qquad\qquad\qquad\qquad\;\; \text{if} \quad z_0/(z-d) > 0.01$$

$$d_2 = 1.95 + 32.6(z_0/(z-d))^{0.45}$$

$$d_3 = \frac{Q_H}{\rho c_p} \frac{0.4 g(z-d)}{T} \left(\frac{\ln((z-d)/z_0)}{0.4 u_{10}} \right)^3$$

where Q_H is the sensible heat flux.

3.20   Monin-Obukhov length

RMPP includes two options for calculating the Monin-Obukhov length L_*, selected through the value of the variable MOLMTD in DATA statement in the routine mpp_main.f.

The first (MOLMTD = 'R') is to use the relation:

$$L_* = \frac{u_*^3 \rho c_p T}{Q_H \kappa g} \qquad (21)$$

The second option (MOLMTD = 'S') is to derive L_* from the Pasquill stability category and the roughness z_0, as follows:

- Neutral stability ('D'): $L_* \rightarrow \infty$

- Other categories ('A', 'B', 'C', 'E', 'F'): $L_* = (\alpha + \beta \log_{10} z_0)^{-1}$

where the coefficients α and β depend on the stability category (Table 7).

Table 7: Coefficients for the calculation of the Monin-Obukhov length

Coefficient	Stability category				
	A	B	C	E	F
α	-0.0875	-0.03849	-0.00807	0.00807	0.03849
β	-0.1029	-0.1714	-0.3049	-0.3049	-0.1714

3.21   Convective velocity scale

RMPP calculates the convective velocity scale w_* from:

$$
\begin{aligned}
w_* &= u_*\left(\frac{-h}{\kappa L_*}\right)^{1/3} && \text{if} \quad L_* < 0 \\
w_* &= 0 && \text{if} \quad L_* \geq 0
\end{aligned}
\tag{22}
$$

where h is the mixing layer height, u_* is the friction velocity, $\kappa = 0.4$ is the Von Karman constant and L_* is the Monin-Obukhov length.

3.22   Eddy diffusivities

RMPP uses the following relations (Zannetti, 1990) for the calculation of the vertical diffusivity K_z:

Unstable conditions: $\qquad K_z = w_* h f\left(z/h\right)$ (23)

where w_* is the convective velocity scale, h is the mixing layer height and the function $f\left(z/h\right)$ is given by:

$$
f\left(\frac{z}{h}\right) = 2.5\left(\kappa\frac{z}{h}\right)^{4/3}\left(1-15\frac{z}{L_*}\right)^{1/4}, \text{ for } 0 \leq \frac{z}{h} < 0.05 \text{ (i.e., surface layer)}
$$

$$
f\left(\frac{z}{h}\right) = 0.021 + 0.408\left(\frac{z}{h}\right) + 1.351\left(\frac{z}{h}\right)^2 - 4.096\left(\frac{z}{h}\right)^3 + 2.560\left(\frac{z}{h}\right)^4, \text{ for } 0.05 \leq \frac{z}{h} \leq 0.6
$$

$$
f\left(\frac{z}{h}\right) = 0.2\exp\left(6-10\frac{z}{h}\right), \text{ for } 0.6 < \frac{z}{h} \leq 1.1
$$

$$
f\left(\frac{z}{h}\right) = 0.0013, \text{ for } 1.1 < \frac{z}{h}
$$

Stable conditions: $\qquad K_z = \dfrac{\kappa u_* z}{0.74 + 4.7\left(z/L_*\right)}\exp\left(-\dfrac{8 f_C z}{u_*}\right)$ (24)

where u_* is the friction velocity, κ is the Von Karman constant, L_* is the Monin-Obukhov length, and f_C is the Coriolis parameter ($f_C = 2\omega \sin\lambda$, $\omega = 7.292 \times 10^{-5}$ rad s^{-1} is the angular speed of rotation of the earth and λ is the geographic latitude).

Neutral conditions:

$$K_z = \kappa u_* z \quad \text{for} \quad 0 < z \le z_{sl}$$

$$K_z = K_{eff} + \frac{(h-z)^2}{(h-z_{sl})}\left[K_{sl} - K_{eff} + (z - z_{sl})\kappa u_* + 2(z - z_{sl})\frac{K_{sl} - K_{eff}}{h - z_{sl}} \right], \text{for } z_{sl} < z \le h \quad (25)$$

where K_{eff} is the diffusivity above the mixing height h, and $z_{sl} = 0.01 u_* / f_C$ is the height of the surface layer.

The horizontal diffusivities K_x and K_y are calculated as multiples of the vertical one:

$$K_x = K_y = cK_z \qquad (26)$$

The value of the factor c can be either provided by the user (variable `RDIFFH` in `DATA` statement in routine `mpp_main.f`) or calculated by `RMPP` (if the user sets `RDIFFH` < 0 in `mpp_main.f`) as function of the stability category (c = 0.1, 0.5, 1.5, 6.0, 19.0, 65.0 for stability categories 'A', 'B', 'C', 'D', 'E', 'F' respectively).

3.23   Brunt-Vaisala frequency

The Brunt-Vaisala frequency is calculated in connection to the temperature lapse rate (see Section 3.8). For those stations with multiple measurement levels for which temperature lapse rate can be calculated from the observations only, the Brunt-Vaisala frequency is calculated by the relation:

$$N = \left(g\frac{\partial T / \partial z}{T_{\text{aver}}} \right)^{1/2} \qquad (27)$$

where T_{aver} is the average temperature of the layer for which $\partial T / \partial z$ is calculated.

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