A PROGRAM FOR GROUND TEMPERATURE DATA GENERATION BASED ON THE EXPANDED AMeDAS WEATHER DATA CD-ROMS

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ABSTRACT

The Expanded AMeDAS Weather Data CD-ROMs would be available and may be utilized to conduct building simulations. However, the CD-ROMs do not include temperature data for thermally undisturbed ground. Considering that such data constitute important information for thermal design, a program having graphical user interface is developed for generatation of hourly ground temperatures based on the CD-ROMs' data. This paper describes the numerical methods applied for the data generation, the scheme of the program, and the database of soil thermal properties that works with the program. The accuracy of the generated data is also discussed. The evaluation result tells that the daily mean ground temperatures can be generated with the accuracy of 2.5K at the maximum. The program is designed to be a useful thermal design tool by incorporating user friendly interfaces and accurate numerical methods, and is planned to be bundled with the release of the CD-ROMs.

INTRODUCTION

The most popular dense array system for weather data acquisition in Japan is known as AMeDAS, which is the abbreviation for the Automated Meteorological Data Acquisition System. The observatories are located in about 840 points all around Japan. This works out to be one observatory every 21km^2 area on the average. The detail hourly data obtained by the AMeDAS are to be made open to the public, but several important data items for building simulations, such as horizontal global irradiance, are not measured. For wider application of the data for building simulations, Nimiya et al. (1989, 1996a and 1996b) developed the estimation methods for three kinds of data items: horizontal global irradiance; long-wave sky radiation; and vapor pressure. The original AMeDAS weather data for the period of 15 years from 1981 to 1995 and the estimated weather data for the same period have already been compiled as CD-ROM disks. The set of disks is named "The Expanded AMeDAS Weather Data CD-ROMs" and is now ready to be published.

The CD-ROMs may be sufficient as input data for building simulations but may be considered insufficient for direct design applications. For example, when earth tubes or ground-coupled heat pump systems are designed for a building, the designer/engineer needs to know the effective depth based on the ground temperature distributions. Unfortunately, the CD-ROMs do not cover such secondary weather data. The ground temperatures seem to be one of the widely used secondary weather data.

An hourly data generation program for undisturbed/ natural ground temperatures using the finite element method is developed by the authors for this purpose. This paper describes and discusses the followings:

1) Scope of the program development;
2) Numerical model applied for heat transfer in ground;
3) Scheme of the program;
4) Database of soil thermal properties to ease data input;
5) Confirmation of the accuracy by comparison with measured data to ensure that the program is useful as thermal design tool.

SCOPE OF THE PROGRAM DEVELOPMENT

Generally, the objective of a simulation program is to solve some phenomena as accurate as possible and the simulation requires large main frame system, such as a super computer. Because the program described here is a tool for designers, it has quite different objectives as follows:

1) The program should be work with the Expanded AMeDAS Weather Data CD-ROMs on Windows 95® /98®/NT® Operation Systems in personal computers;
2) Graphical user interface, database and auto-mesh generator should be prepared to ease data input;
3) The program should generate the data within a few minutes;
4) Daily mean temperature data should be as accurate as possible but less accuracy may be allowed for the hourly data;
5) If a user wants to generate more accurate data, the optional settings may be changed accordingly.

APPLIED NUMERICAL MODEL

Basic Equation and Boundary Conditions

Hayashi et al. have described two numerical models: one is a model considering heat and moisture-coupled transfer; and the other is a simpler model only considering heat transfer (Hayashi et al. 1987 and Hayashi 1990). They solved the two models by the finite difference method and compared with the measured ground temperatures. The comparison result shows that the latter simple model, which considers latent heat loss by evaporation at the ground surface as a function of the ground surface temperature and evaporation ratio, gives good estimation for daily mean ground temperatures but the estimation of the fluctuation hour by hour is not very accurate. In view of the objectives mentioned above, the simpler model in Hayashi et al. (Hayashi et al. 1987 and Hayashi 1990) is utilized in the program. The relevant equations applicable to the method are given below.

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\lambda}{C_e}\frac{\partial T}{\partial z}\right), \qquad (1)$$

$$-\lambda \left.\frac{\partial T}{\partial z}\right|_{z=\infty} = 0, \qquad (2)$$

$$\begin{cases} T_s = 273.16, & \text{case w/ snow cover} \quad (3) \\ -\lambda \left.\dfrac{\partial T}{\partial z}\right|_{z=0} = \alpha_c\left(\Theta_o - T_s\right), & \text{case w/o snow cover} \quad (4) \end{cases}$$

$$\Theta_o = \frac{aI + \varepsilon L^{\downarrow} - \varepsilon\sigma_b T_s^4}{\alpha_c} + \frac{kH}{C_o}\left(x_o - X_s\right). \qquad (5)$$

The meaning of the symbols and notations used in Equations (1)-(5) are given in the nomenclature.

The basic partial differential equation of Equation (1) is applied for a semi-infinite domain. Boundary at the point of $z = \infty$ is considered as having adiabatic condition as shown in Equartion (2). Boundary condition at the ground surface is separated into two cases: one is the snow-covered ground surface given by Equation (3); and the other is the ground surface without snow cover given by Equation (4). Equation (4) includes a sol-air temperature of Θ_o, defined in Equation (5), in which the latent heat loss by evaporation is also considered.

Numerical Solution Techniques

Several methods, including the finite difference, finite element and boundary element schemes are available for the solution of Equation (1). The finite element method using one-dimensional quadratic element is applied here. Several assumptions and techniques, described below, are also applied.

Boundary condition at the ground surface I, $L^{\downarrow}$, x_o, C_o in the right side of Equation (5) are given by the data in CD-ROMs and all symbols except Stefan-Boltzmann constant σ_b are considered as time-depended variables. But the equation includes the ground surface temperature, T_s, which is required to be solved and also the latent heat of water, H, which again is a function of T_s. Thus, some iteration procedure needs to be applied for the solution. However, the value of T_s at the previous calculation step is used directly to avoid the iteration and to save the CPU time. The constants related on the surface thermal properties, *i.e.*, a, ε and k are constant with default values assigned previously. However, a user can change these constants to time-series values using optional switches and user-defined data files. The film coefficient α_c is a function of the reference wind velocity (Kimura 1977). Because of time-dependence of the film coefficient, Cauchy's boundary condition must be assembled just before the time when the matrix equation is solved for each step. It requires more CPU time compared to the case of constant film coefficient, but user can avoid to use the variable film coefficient and apply some suitable constant coefficient by checking the optional switch.

Heat transfer in snow-covered soil must be very difficult phenomenon to be solved. However, several reports indicate that the temperature of snow-covered ground surface is nearly equal to the temperature of frozen point of water (Kondo 1987, for example). Equation (3) is based on such experience. Nimiya et al. suggest a procedure to judge whether the ground surface is covered with snow or not (Nimiya et al. 1989) and their procedure is adopted in the program. Equation (3) means that Dirichlet's boundary condition should be taken instead of Cauchy's one of Equation (4) when the ground surface is covered with snow.

Boundary condition in the infinite distance Adiabatic boundary condition is applied as expressed by Equation (2). The inifinite distance should be modified when the finite element method is applied because the method is basically developed for a limited domain. The infinite element technique (Dhatt and Touzat 1984, for example) is one of the suitable modification method and is applied here. Generally, the interpolation function for a reference element can be expressed by Equation (6) for one-dimensional quadratic element. When T_3 is eliminated by considering $dT/d\zeta|_{\zeta=1} = 0$, Equation (7) is obtained. When z_1 is defined as the actual coordinate for node 1, a mapping function of $z = 2z_1/(1-\zeta)$ is suitable for coordinate mapping between the actual and the reference infinite elements. The program defines z_1=10m as a default. It means normal elements are used for the range between the ground surface and the point of 10m in depth, with infinite element at the point.

$$T(\zeta) = \left\langle \frac{-\zeta(1-\zeta)}{2};\ (1-\zeta)(1+\zeta);\ \frac{\zeta(1+\zeta)}{2} \right\rangle \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \end{Bmatrix} \qquad (6)$$

$$T(\zeta) = \left\langle \frac{-\zeta(2-\zeta)}{3}\ \ \frac{(3-\zeta)(1+\zeta)}{3} \right\rangle \begin{Bmatrix} T_1 \\ T_2 \end{Bmatrix} \qquad (7)$$

Initial temperatures and the approach run Considering the initial temperatures and the approach run is also important for the accuracy of calculation results. The program gives a value calculated by Equation (8) for all nodal points as the initial temperatures and the calculation with four-months approach run is automatically started.

$$T(z) = 0.89\overline{T_o} + 33.45 \tag{8}$$

SCHEME OF THE PROGRAM

Developing Environment

The program was written by one of the authors with C++Builder3™ using Visual Class Library™. A personal computer with 166MHz single Pentium™ chip was utilized. Unfortunately, multi-language is not supported completely at this stage and only Japanese/US English options are available. Using the computer mentioned above, the program can generate hourly ground temperature data for five soil points within 12sec/yr.

Flow of the Program

A brief flow chart is shown in Figure 1. After reading the database of soil thermal properties, the user is prompted to select the desired location and the year to be simulated. Though the program has a default single layer soil model, which contains a 10m deep homogeneous loam layer with five soil points for generation of temperature data, the user can select soil layering as desired by referring to the soil database. Because the program has automatic meshing routine as mentioned above, there is no need to generate the mesh in the soil model. Only thing the user needs to do is to select a switch to assign the desired course of meshing, fine or coarse. The fine and coarse meshing corespond to elements with 10cm width and elements with 20cm width, respectively. Thermal properties of the ground surface can also be changed with a graphical user interface. Even the consideration of snow cover can be turned off by a graphical switch. When the user clicks the run button or select the run menu, the program begins to read the related weather data from the CD-ROMs and to prepare an index to identify the day the ground surface is covered with snow. After this preparation, the FEM solution begins. If the approach run is finished, the required data are written on the user's hard disk as a binary file.

Database of Soil Thermal Properties

A literature survey is carried out to construct the database. Table 1 lists the main reference material. There are 142 data registered in the database file of 144kbytes. The database records can be accessed, modified and added with Borland Database Engine™.

The database is expected to be helpful in finding the suitable data when the user knows the soil quality at the desired location. However, the users of the program may not always be familiar with the soil quality. Thus, the possibility of a set of default soil thermal properties for all Japan was studied. See the appendix at the end of this paper for information on the study. The heat conductivity of 1.5W/mK and the volumetric heat capacity of 3.0MJ/m^{3}K were obtained as the default thermal properties for loam type of soil.

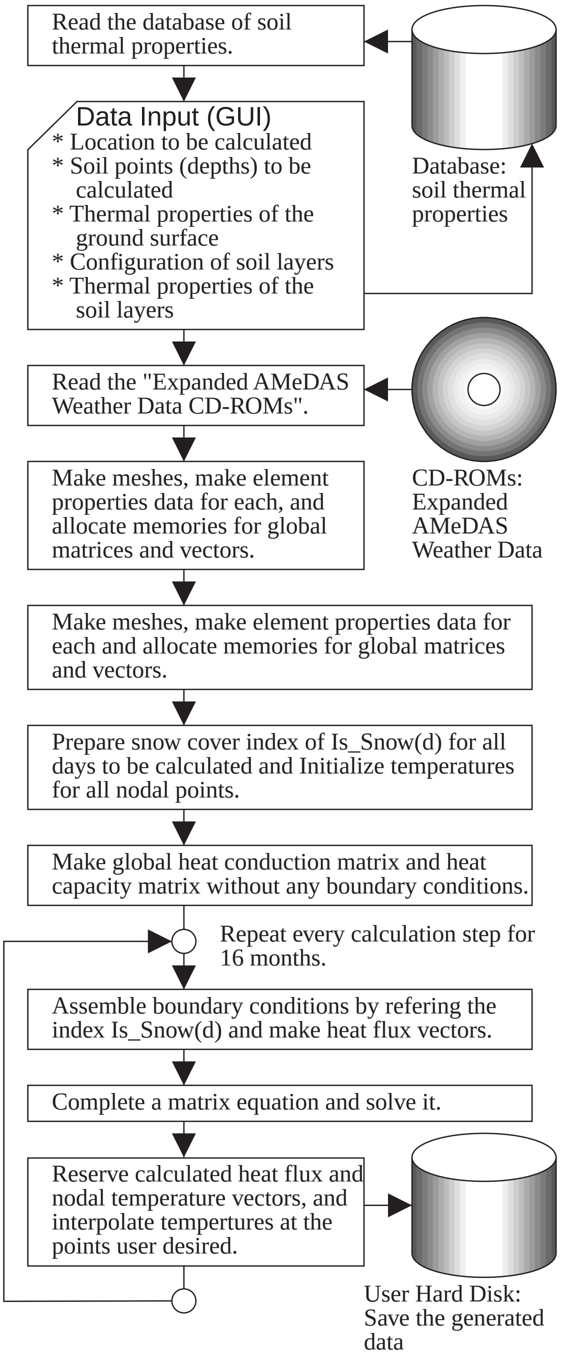


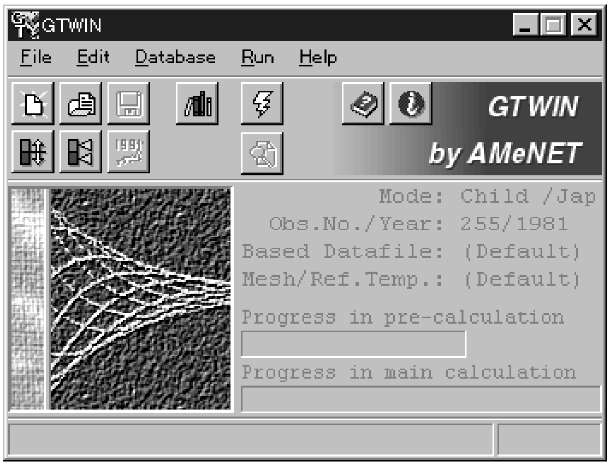
Figure 1 *Brief flow chart of the developed program*

Table 1 *Refered literatures to construct the database of soil thermal properties*

[1] ASHRAE, "1982/1985/1993 ASHRAE Fundamentals Handbooks", ASHRAE, Atlanta GA, 1982/1985/1993.
[2] CEN/TC89, "Thermal Performance of Buildings - Heat Transfer via the ground - Calculation Method", Revision of prEN1190 (ISO/DIS 13370), CEN, 1995.
[3] Bose, J. E. et al., "Design/Data Manual for Closed-Loop Ground Coupled Heat Pump Systems", ASHRAE, Atlanta GA, 1985.
[4] Carslaw, H. S. and Jaeger, J. C., "Conduction of Heat in Solids", 2nd Ed., Oxford at the Clarendon Press, London UK, 1959.
[5] Welty, J.R. et al., "Fundamentals of Momentum, Heat, and Mass Transfer", 3rd Ed., John Wiley and Sons, N.Y., 1984.
(and five literatures in Japanese)

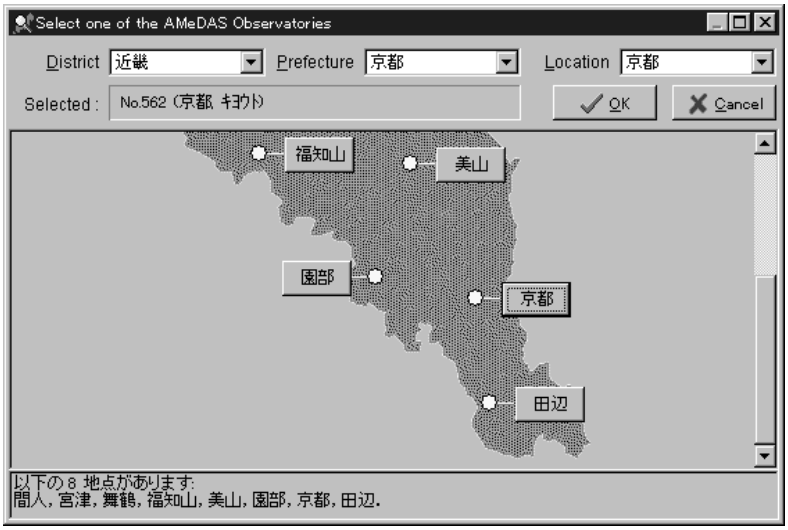
Graphical User Interfaces

The program has various graphical user interfaces. Most of them are prepared as modal dialog windows. Figures 2-6 are shown as examples of them. Figure 2 is the main window of the program. Speed buttons are designed to take shortcuts by clicking menus/sub-menus. As the data generation may sometime take long time, animation of a picture on the left hand and progress bars tells the user that the program is at work. When the user clicks a button or selects a menu for a desired location, a dialog window shown in Figure 3 appears to help the selection. Figures 4, 5 and 6 are dialog windows to set properties of the ground surface, to set points in soil for generation of temperature data, and to configure model of soil layers, respectively. When a soil layer or a grid cell is clicked, a dialog window shown in Figure 7 appears to facilitate selection of the suitable data set of soil thermal properties from the database. In these figures, some portions are seen to be written in Japanese but English version is also available if prefered. Unfortunately, a help file written in WinHelp 4™ style (Deaton and Zubak 1996, for example) doesn't support English. This inconvenience will be improved in the next version.



Mode: Child /Jap
Obs.No./Year: 255/1981
Based Datafile: (Default)
Mesh/Ref.Temp.: (Default)
Progress in pre-calculation
Progress in main calculation

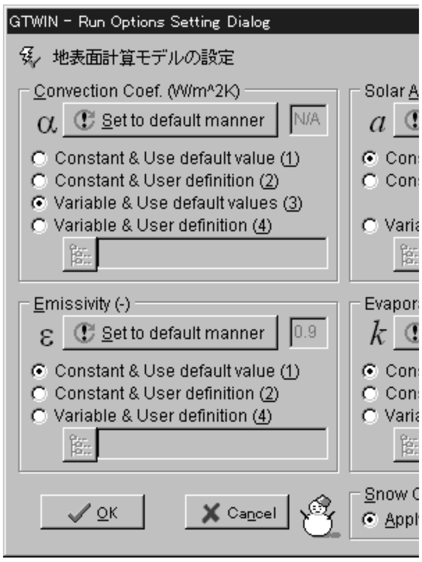
Figure 2 *Main window of the developed program*



District: 近畿
Prefecture: 京都
Location: 京都
Selected : No.562 (京都 ｷｮｳﾄ)

以下の8 地点があります:
間人, 宮津, 舞鶴, 福知山, 美山, 園部, 京都, 田辺.

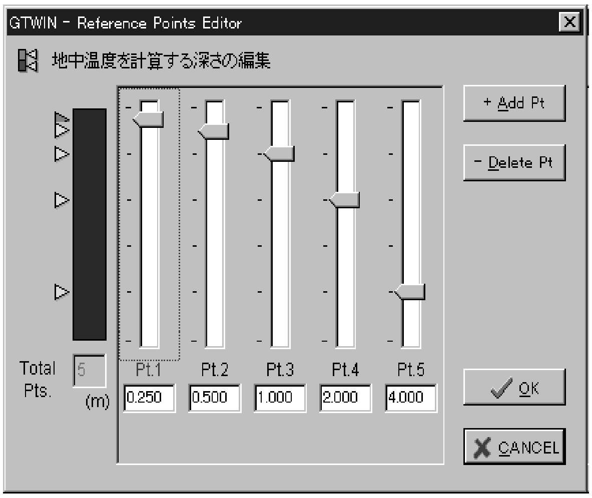
Figure 3 *Dialog window to select desired location*



Convection Coef. (W/m^2K): N/A
○ Constant & Use default value (1)
○ Constant & User definition (2)
● Variable & Use default values (3)
○ Variable & User definition (4)

Emissivity (-): 0.9
● Constant & Use default value (1)
○ Constant & User definition (2)
○ Variable & User definition (4)

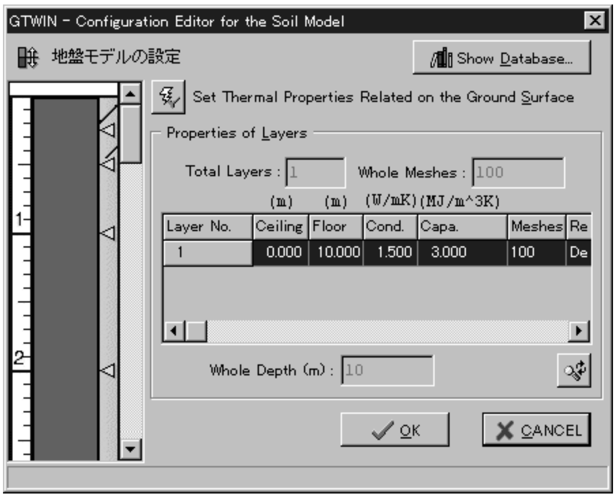
Figure 4 *Dialog window (part)to set thermal properties of the ground surface*



Total Pts. 5

	Pt.1	Pt.2	Pt.3	Pt.4	Pt.5
(m)	0.250	0.500	1.000	2.000	4.000

Figure 5 *Dialog window to desired soil points at which the temperature data are generated.*

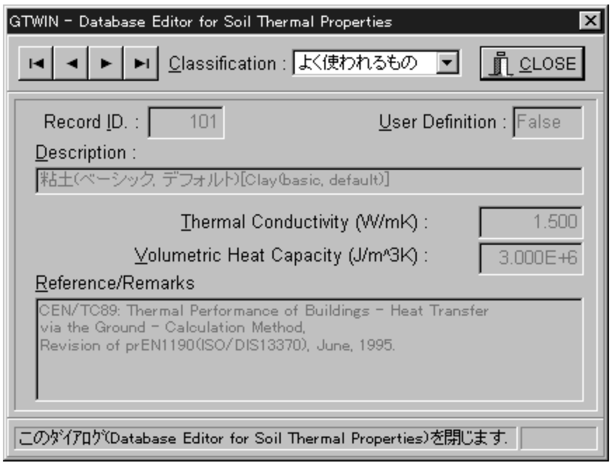


Total Layers : 1
Whole Meshes : 100

Layer No.	Ceiling (m)	Floor (m)	Cond. (W/mK)	Capa. (MJ/m^3K)	Meshes	Re
1	0.000	10.000	1.500	3.000	100	De

Whole Depth (m) : 10

Figure 6 *Dialog window to configurate soil model*



Classification : よく使われるもの

Record ID. : 101

User Definition : False

Description :

粘土(ベーシック, デフォルト)[Clay(basic, default)]

Thermal Conductivity (W/mK) : 1.500

Volumetric Heat Capacity (J/m^3K) : 3.000E+6

Reference/Remarks

CEN/TC89: Thermal Performance of Buildings - Heat Transfer
via the Ground - Calculation Method,
Revision of prEN1190(ISO/DIS13370), June, 1995.

このダイアログ(Database Editor for Soil Thermal Properties)を閉じます.

Figure 7 *Dialog window to view the database of soil thermal properties*

EVALUATION OF THE ACCURACY

Method of the Evaluation

Comparison with the measured ground temperatures is necessary to confirm that the program works well and to evaluate the accuracy. Because the program will be made public, the evaluation result must also be open and clearly understood. The evaluation is based on the the comparison between measured and simulated results as follows.

Two of the authors have good database from measurement of ground temperatures. The measurement was made every hour during the year in 1987 at the campus of Tohoku University in Sendai, Japan, using Copper-Constantan thermocouples with ±0.1K accuracy (Matsumoto et al. 1994). These data are used for the comparison. Though weather data measured on the site are also available, some weather items used for the simulation are not available. Thus all of the input weather data are taken from CD-ROMs of the Expanded AMeDAS Weather Data.

The soil thermal properties of the measurement site had been clarified already (Matsumoto et al. 1994) as shown in Table 2. These properties are applied for the simulation using the program. However, solar absorptivity, emissivity and evaporation ratio of the ground surface are unknown, and the data available in the literature (Hayashi 1990) are utilized. The values are also shown in Table 2. Snow cover for the ground surface is considered.

Table 2 *Input data for the calculation to evaluate the precision (*: assumed values)*

Ground Surface	Solar Abs.(-)	Emissivity (-)	Evap.Ratio (-)
	0.7*	0.9*	0.6*

Soil Layers Range (m)	Heat Conductivity (W/mK)	Vol. Heat Capacity (MJ/m^{3}K)
0.00-0.70	0.62	3.32
0.70-1.30	0.67	1.51
1.30-1.80	0.80	2.44
1.80-2.50	0.71	2.44
2.50-3.50	1.12	1.76
3.50-	1.16	2.90

As mentioned above, the accuracy of the data generation is limited to daily mean values, the daily mean values generated are compared with the daily mean measured values.

Result and Discussion

Profiles for the simulated and the measured daily mean temperatures at the points of 0.0m, 1.0m and 3.0m in depth from the ground are shown in Figure 8, together with a profile of the measured outdoor air temperature. The difference between the simulated and the measured temperatures becomes narrower with the depth. This is because the values for thermal properties of the ground surface and for soil thermal properties are considered to be time-independent for the simulation and the values affect mainly shallow part of the ground. The root mean square errors were 2.2K, 0.6K and 0.3K for the soil points of 0.0m, 1.0m and 3.0m in depth, respectively. Thus, it can be said that the program can generate the ground temperature data having the accuracy within about 2.5K if the soil thermal properties are modeled carefully. This accuracy seems to be enough for the

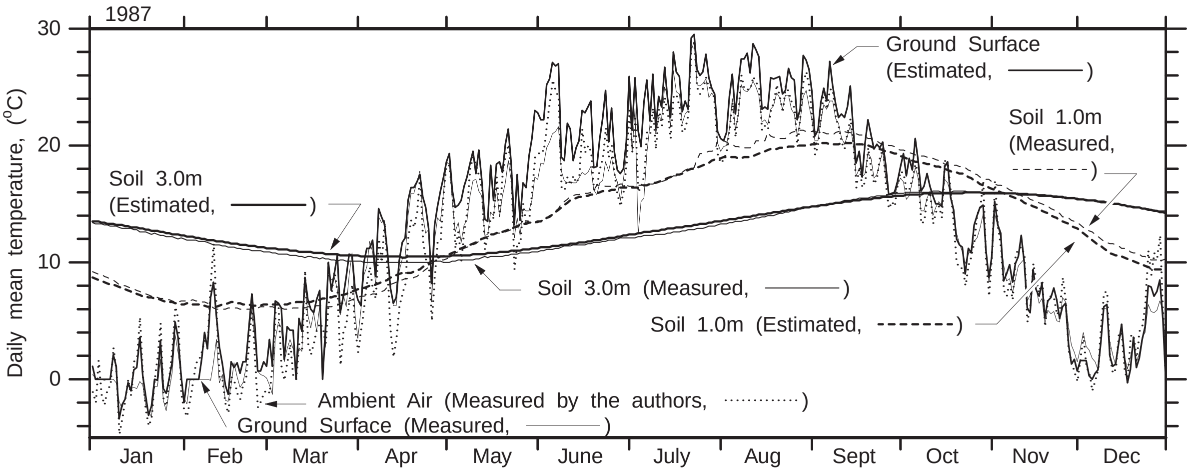


Figure 8 *Comparison of daily mean ground temperature data between the measurement (Matsumoto et al. 1994) and the calculation by this program*

development purpose of the program. However, it may be recommended to the user that the program should be used for data generation at soil points about one meter or greater in depth.

When looking carefully at the profile for the measured ground surface temperature, it is found that the temperature is stable at around 0°C during the winter. It is affected by the snow cover on the ground surface. The profile of the simulated surface temperature also shows the same tendency during the similar period. Although the modeling of the snow cover utilized in the program is very simple, it gives good estimation of the daily mean ground surface temperature. However, it would be dangerous to use the program for finding the frost line in connection with design of building foundation. Such application of the program shoud not be attempted.

Figure 9 compares the temperature distributions with and without considering the snow cover, which is obtained based on the weather data of Aomori, one of the typical northern cities in Japan. The input thermal properties are also noted in the figure. The danger mentioned above appears clearly in the figure.

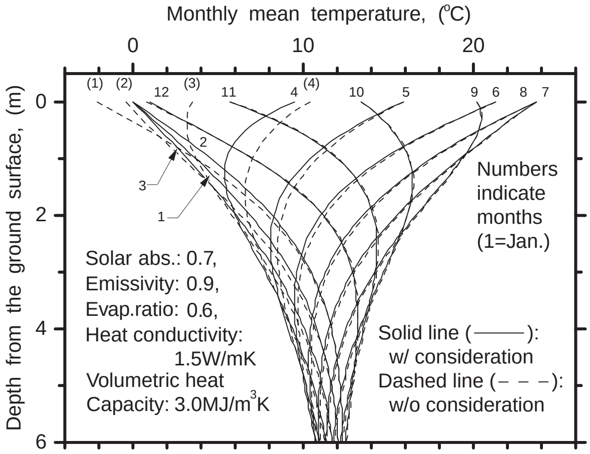


Figure 9 *Comparison of monthly temperature distributions between the cases with and without snow cover consideration*

CONCLUSIONS

A program for generation of hourly data for undisturbed/natural ground temperatures, using the finite element method, is developed as a design tool. The program has the following features:

1) Target users of the program are designers rather than researchers, *i.e.*, the program is aimed to be a design tool to generate accurate daily mean ground temperature data.
2) As a design tool, various graphical user interfaces and database of soil thermal properties are compiled to ease the data input procedures. The program also includes well-considered default initial values to simplify data input. Thus, the users can arrive at the desired data by simply clicking several buttons.
3) Latent heat loss by evaporation at the ground surface and snow cover on the surface are considered in the program to improve the accuracy of the generated data. Simpler algorithms are carefully selected to save the CPU time.
4) The program can generate data of daily mean ground temperatures at any soil points with accuracy of ±2.5K if the soil thermal properties are suitable for the desired location. But it is recommended that the program be used for data generation at soil points about one meter or greater in depth to assure the accuracy.
5) Modeling of snow cover on the ground surface applied in the program is too simple for it to be useful in finding the frost line needed in the buidling foundation design. The switch for the consideration of snow cover should be turned off if the application to frost line evaluation is to be attempted.

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NOMENCLATURE

a = Solar absorptivity [-]
α_c = Convective film coefficient [W/m^{2}K]
C_o = Specific heat of the outdoor air [J/kg]
= $1004.6+1.846x_o$
ε = Radiation emissivity [-]
H = Latent heat of water [J/g]
= $1996.04664+1.846T_s$
I = Horizontal global irradiance [W/m^2]
k = Evaporation ratio [-]
$L^{\downarrow}$ = Downward atmospheric radiance [W/m^2]
σ_b = Stefan-Bolzmann’s constant [W/m^{2}K^4]
= 5.67×10^{-8}
T = Ground temperature [K]
$T(\zeta)$ = Interpolated temperature of a reference element at a point of ζ [K]
T_n = Nodal temperature of a reference element [K] (n=1, 2 or 3)
$\overline{T}_o$ = Annual mean outdoor air temperature [K]
T_s = Ground surface temperature [K]
Θ_o = Sol-air temperature for the ground surface [K]
x_o = Humidity ratio of the outdoor air [g/kgDA]
X_s = Saturated humidity ratio of the air at the ground surface of the temperature T_s [g/kgDA]
z = Downward one-dimensional coordinate along a vertical line across a horizontal ground surface [m] (z=0 means a point at the ground surface)
ζ = one-dimensional coordinate for a reference element [-] ($-1\leq\zeta\leq1$)

APPENDIX

Determination of Default Soil Thermal Properties

As mentioned above, determination of a default set of soil thermal properties is important to ease the data input. A study is carried out for this purpose as follows.

Method of the determination Fortunately, averaged monthly mean data of ground temperatures measured for 10 years at nine observatories (Asahikawa, Sapporo, Sendai, Tokyo, Osaka, Hiroshima, Tokushima, Fukuoka and Kumamoto) are available in a literature (Watanabe 1965). Although the data seem to be old, they must be good reference to compare with the simulated data by the program. Thus, a series of parametric calculations is carried out with changing the input data of soil thermal diffusivity for each location. The results are compared with the reference data in the literature. The reference data were measured before the year of 1942 that the annual mean values of the outdoor air temperatures are very different from the values in the Expanded AMeDAS Weather Data CD-ROMs, because the climate at the each city is changed by the heat island and the global warming phenomenon. To neglect the difference, monthly mean swings of the outdoor air for each city, which are 12 data for each city obtained by subtracting the annual mean outdoor air temperature from every monthly mean temperatures of the outdoor air, are calculated for the referred and the simulated data and are compared each other. The evaluation is made by basis on the root mean square errors (RMSEs) to find an optimum thermal diffusivity. The input thermal diffusivity of soil is varied from 0.20 mm^2/s to 0.80mm^2/s with a step of 0.05mm^2/s.

Result of the determination Figure 10 shows the RMSEs for various thermal diffusivities. The curved

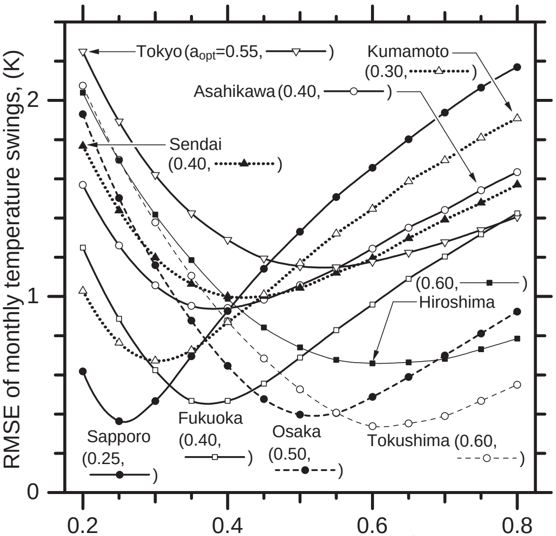


Figure 10 *Identification of the thermal diffusivity of soil by RMSE of the difference of monthly temperature swings between the measured and the calculated data*

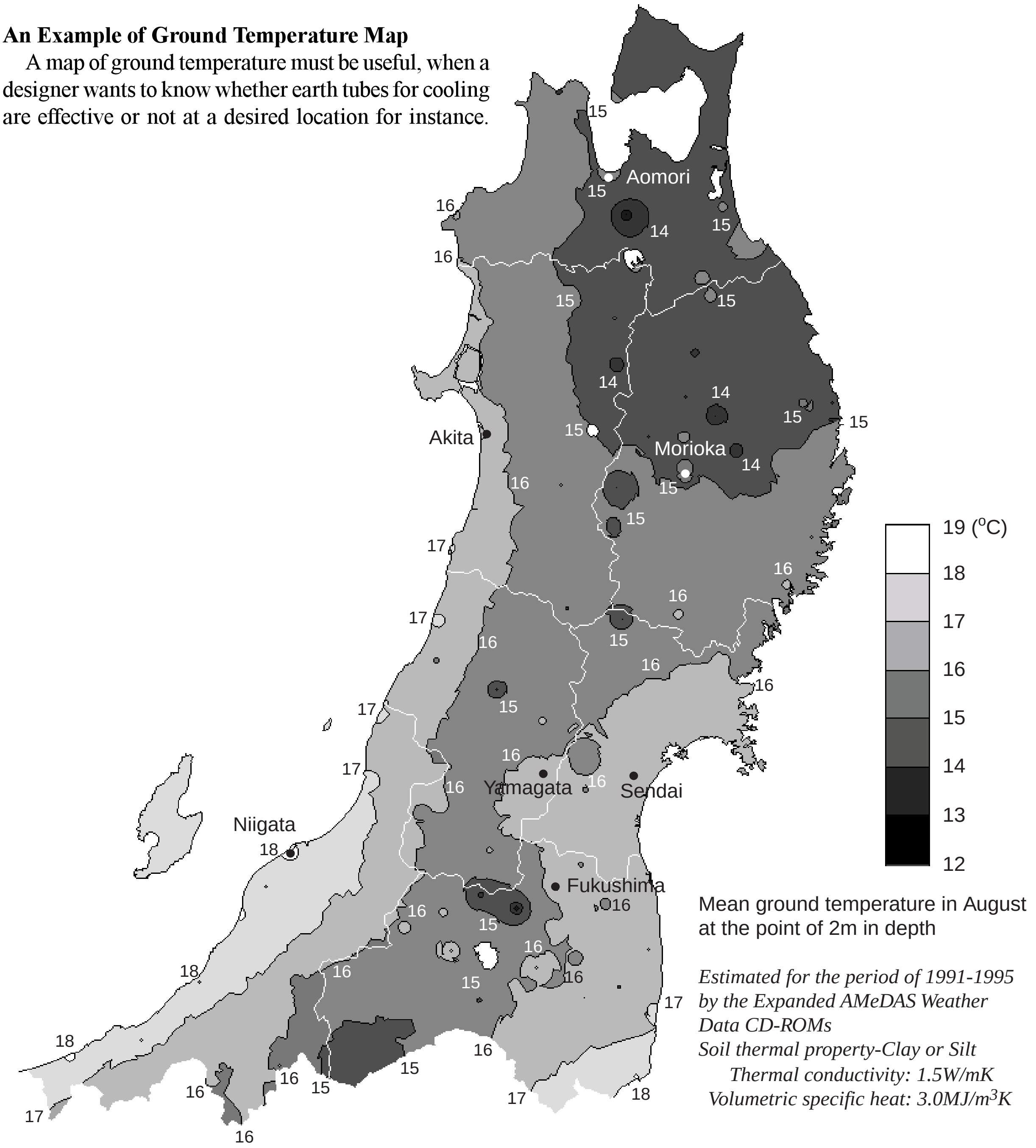
line of RMSEs for each city has a minimum point. In the figure, the value noted beside the label of each city's name indicates the x-coordinate of the minimum point. The diffusivity of 0.45mm^2/s seems to be a reasonable selection for all cities. Kim and Matsuo (Kim et al. 1986) made the similar study and found the closer diffusivity. CEN's calculation method for basement heat losses (CEN/TC89 1995) recommends three soil thermal properties and one of them has also the similar diffusivity (the heat conductivity of 1.5W/mK and the volumetric heat capacity of 3.0MJ/m^{3}K for clay or silt, *i.e.*, the thermal diffusivity of 0.5mm^2/s). These values are finally determined as a default data set because the CEN's method may become the international standard.

An Example of Ground Temperature Map

A map of ground temperature must be useful, when a designer wants to know whether earth tubes for cooling are effective or not at a desired location for instance.

As an application example of the program, monthly mean ground temperature in August at the point of two meters in depth is simulated for every location having an AMeDAS observatory in Tohoku District. A color contour map based on the result is illustrated by an original windows program developed by one of the author, which will also be bundled with the Expanded AMeDAS Weather Data CD-ROMs.

The map is shown as Figure 11. This kind of illustrated design data would be provided more and more after the release of the CD-ROMs. Designers must be more interested in "climatic building design" procedures. That is a wish of the authors.



Mean ground temperature in August at the point of 2m in depth

Estimated for the period of 1991-1995 by the Expanded AMeDAS Weather Data CD-ROMs
Soil thermal property-Clay or Silt
Thermal conductivity: 1.5W/mK
Volumetric specific heat: 3.0MJ/m^{3}K

Figure 11 *Map of estimated mean ground temperatures in August at the point of 2m in depth*