CHAPTER 4

HEAT BALANCE OF BARE GROUND

4.1. INTRODUCTION

The basic component in the system we are considering is bare ground. In the daytime, its surface is heated by solar radiation when the weather is fine. The surface also loses heat to the cold sky by long wave radiation. It can be visualized that heat is transferred by conduction to the lower soil layers, neglecting water movement in the soil. At the surface, not only sensible but also latent heat transfer occurs. These heat flows from the surface to the ambient air are by convection. Therefore, three types of heat transfer are at work in a soil-air system, as shown in Fig. 4.1.

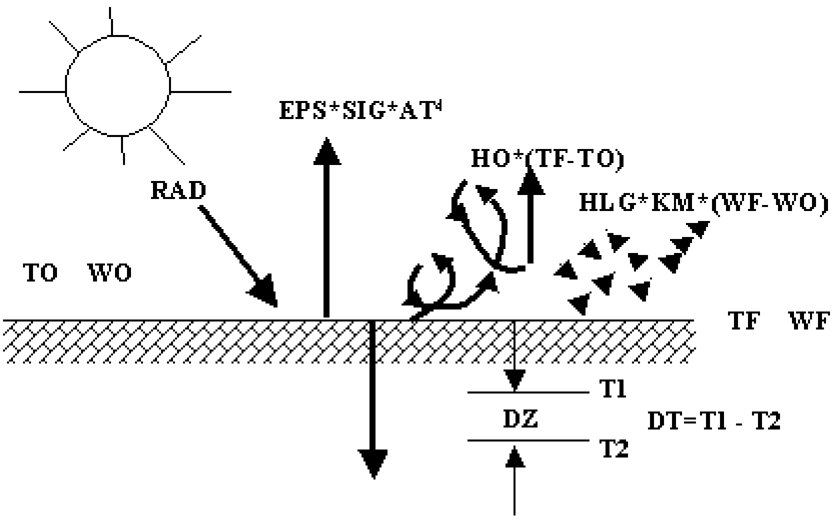


Figure 4.1. Heat balance of bare ground

Heat conduction is heat flow due to molecular movement and is predominant in solid bodies, in which the other two types of heat transfer do not occur. The amount of heat per unit time per unit area is proportional to the product of the thermal conductivity of the material and the temperature difference, and inversely proportional to the distance where the temperature difference occurs:

$$\mathbf{Q = -KS * DT / DZ} \tag{4.1}$$

where **Q** is heat flow (W/m^2), **KS** is thermal conductivity (W/m/^{o}C), **DT** is temperature difference (^{o}C), and **DZ** is a distance (m) short enough that we can neglect heat stored in this thin layer. The negative sign indicates that the direction of heat flow is opposite to the temperature gradient.

Heat transfer due to convection is given by

$$\mathbf{Q} = \mathbf{H} * \mathbf{DT} = \mathbf{H} * (\mathbf{TF} - \mathbf{TO}) \tag{4.2}$$

where **Q** is heat flow (W/m^2), **H** is the heat transfer coefficient due to convection (W/m^2/^{o}C), and **DT** is the temperature difference between the surface **TF** and the ambient fluid, in this case the air **TO** (^{o}C).

Latent heat transfer is based on vapor flow due to the vapor gradient between the surface and the air. The vapor potential is expressed as the actual content of vapor in the air on either a weight or a volume basis. Here, we use the weight basis. Therefore, the vapor content of a unit weight of air is expressed as **W** (kg/kg DA) vapor weight per unit weight of dry air (which does not include vapor), where kg DA means unit weight of dry air. Dry air basis is used because it is not affected by the amount of vapor involved and does not vary. Wet air, therefore, is the total of the dry air and vapor. The equation to express the latent heat flow is then,

$$\mathbf{Q} = \mathbf{HLG} * \mathbf{KM} * \mathbf{DW} / 3.6 = \mathbf{HLG} * \mathbf{KM} * (\mathbf{WF} - \mathbf{WO}) / 3.6 \tag{4.3}$$

where **Q** is heat flow (W/m^2), **HLG** is latent heat due to vaporization (2501.0 kJ/kg), **KM** is mass transfer coefficient (kg/m^2/hr), and **DW** is the difference of humidity ratio between the surface (**WF**) and the air (**WO**) (kg/kg DA). At the soil surface, it is assumed that the air is usually saturated with vapor and that the actual exchange takes place very close to the surface. When the soil surface is dry, a wetness factor coefficient is introduced to express how much **WF** differs from the saturation value.

Radiation heat transfer occurs without any transferring medium such as the air. This means that heat transfers directly from one surface to the other through the air. The ruling relationship of this transfer is given as:

$$\mathbf{Q} = \mathbf{EPS} * \mathbf{SIG} * \mathbf{AT}^4 \tag{4.4}$$

where **Q** is heat flow (W/m^2), **EPS** is a proportional constant between 0 to 1 called emissivity (ND) which is dependent on the material, **SIG** is the Stefan-Boltzmann constant and is 5.67 x 10^{-8} (W/m^2/K^4), and **AT** is absolute temperature of the surface considered (K). Typical values of emissivity for several materials are listed in Table 4.1. From this table it is clear that emissivities for most materials involved in the present systems in this book are in the range between 0.9 and 1.0. Emissivity does not depend on the color of the surface, and lustrous metal surfaces have very small values. Emissivity is not only a constant for emission of radiation but also a constant for absorption. The following two equations hold for most materials:

$$\mathbf{ALF} + \mathbf{RMD} + \mathbf{TAU} = 1 \tag{4.5}$$

$$\mathbf{EPS} = \mathbf{ALF} \tag{4.6}$$

where **EPS** is emissivity, **RMD** is reflectivity, **TAU** is transmissivity, and **ALF** is absorptivity.

Typical values of each type of heat-flux component for the earth are shown in Fig. 4.2 as an annual budget for the earth, and are calculated based on the solar constant 1,360 W/m^2. Radiation exchange is often considered as a single process in which the terms of net radiation and effective radiation are used. Effective radiation on fine days (net in the night) is on the order of 100 W/m^2.

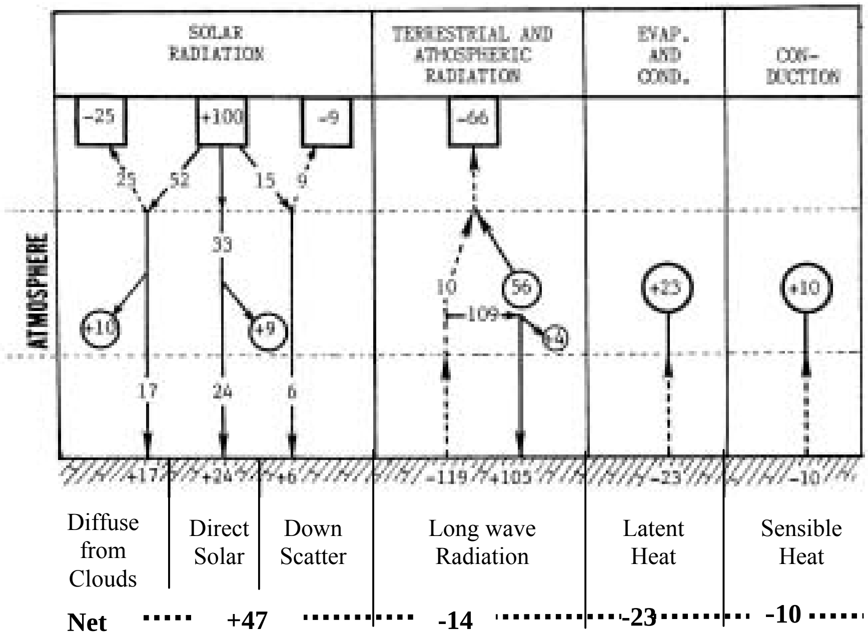


Figure 4.2. Energy exchange of the earth on annual balance (after Gates, 1962).

4.2. CONVECTIVE HEAT TRANSFER

The governing equation for convective heat transfer is shown as eq. 4.2, and eq. 4.3 is the equation for latent heat transfer, which will be described in the next section. The heat transfer coefficient, **H**, in eq. 4.2 is dependent on the movement of the adjacent air. Under outside conditions, wind speed is the primary factor, and the coefficient is expressed as a function of wind.

Wind speed consists of three directional flows -- **x**, **y**, and **z**, and the coefficient is related to the main directional flow, which is horizontal. The main horizontal wind speed changes with the logarithmic distance from the surface. It is rather difficult to determine the height at which wind speed should be taken. However, if the air movement is completely turbulent, change is negligible beyond the boundary layer. There is no rule for determining the height at present, but traditionally, anemometers are set 3 to 5 m above the ground surface.

Quite a number of experimental data have been obtained from wind tunnel experiments, and their results are summarized using non-dimensional numbers such as **Nu**, **Re**, **Gr** and **Pr**. However, the situation in natural fields is different from that in a wind tunnel, and it would be useful to show the final relationship between the coefficient and the wind speed. Figure 4.3a summarizes several of the relationships reported, although they are used mostly for the outside surface of greenhouses.

In the present book, the following relationship is assumed throughout the text:

$$\mathbf{HO} = \mathbf{CONS} * \mathbf{V} \tag{4.7}$$

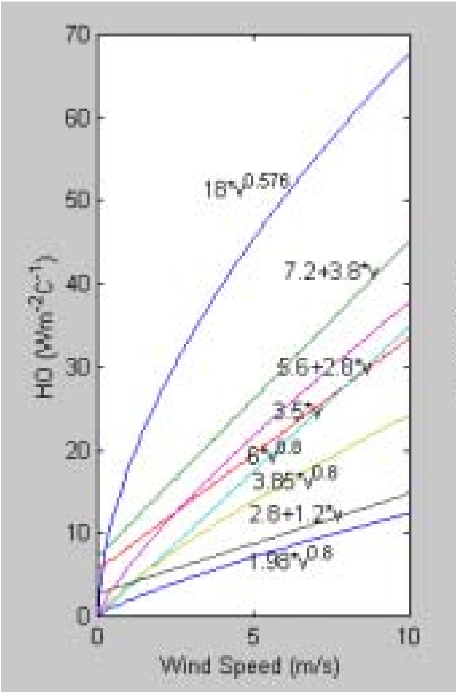
where **HO** is the heat transfer coefficient due to convection at the outside surface (W/m^2/^{o}C), **CONS** is a constant, and **V** is wind speed (m/s).

In the range of free convection -- for example, under the film cover, between the cover and the soil surface, or in the greenhouse - - another expression is applied, where the heat transfer coefficient is a function of the temperature difference between the surface and the air. The relationship between the heat transfer coefficient and temperature differences is summarized in Fig. 4.3b. **MATLAB** scripts to draw Figures 4.3a and 4.3b are listed in Figure 4.4.

Again there are some discrepancies among the data, but in the present text, the following expression is assumed:

$$\mathbf{HI} = \mathbf{CONS} * \mathbf{DT} \tag{4.8}$$

where **HI** is the heat transfer coefficient due to free convection (W/m^2/^{o}C) and **DT** is the temperature difference between the surface and the air (^{o}C).



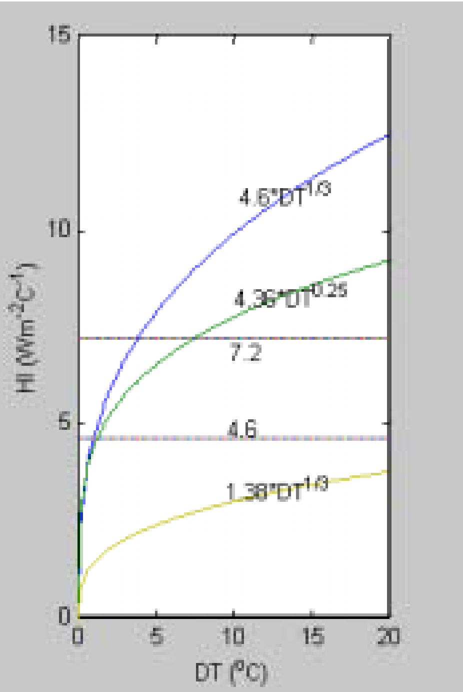


Figure 4.3a. Relationship between heat transfer coefficient and wind speed (after Takakura, 1989).

Figure 4.3b. Relationship between coefficient of free convection and temperature difference between the surface and the air (after Takakura, 1989).

```
%  Progam to draw Figures 4.3a and 4.3b.                          HOHI.m
clear all; clc;
subplot(1,2,1);
v=0:0.1:10;
v1=18*v.^0.576;    v2=7.2+3.8.*v;
v3=5.6+2.8.*v;     v4=3.5.*v;
v5=6*v.^0.8;       v6=3.85*v.^0.8;
v7=2.8+1.2.*v;     v8=1.98*v.^0.8;
plot(v,v1,v,v2,v,v3,v,v4,v,v5,v,v6,v,v7,v,v8);
xlabel('Wind Speed (m/s)');   ylabel('HO (Wm^{-2}C^{-1})');
axis([-inf inf 0 70]);
gtext('18*v^{0.576}');        gtext('7.2+3.8*v');
gtext('5.6+2.8*v');           gtext('3.5*v');
gtext('6*v^{0.8}');           gtext('3.85*v^{0.8}');
gtext('2.8+1.2*v');           gtext('1.98*v^{0.8}');
subplot(1,2,2);
dt=0:0.1:20;
y1=4.6*dt.^(1/3);             y2=4.36*dt.^0.25;
y3=7.2;                       y4=4.6;
y5=1.38*dt.^(1/3);
plot(dt,y1,dt,y2,dt,y3,dt,y4,dt,y5);
```

```
xlabel('DT (^oC)');          ylabel('HI (Wm^{-2}C^{-1})');
axis([-inf inf 0 15]);
gtext('4.6*DT^{1/3}');       gtext('4.36*DT^{0.25}');
gtext('7.2');  gtext('4.6');  gtext('1.38*DT^{1/3}');
```

Figure 4.4. MATLAB scripts to draw Figure 4.3 (**HOHI.m**).

4.3. A MODEL WITH SOLAR RADIATION AND AIR TEMPERATURE BOUNDARY CONDITION (CUC02)

The next model is a more sophisticated one which includes air temperature as a boundary condition and the radiation exchange and convective heat transfer at the soil surface. The outline of the model is shown in Fig. 4.5. In the present model, the soil layers are divided unevenly -- that is, thinnest at the surface and thicker toward the bottom, because the soil temperature does not change so much in deep layers. The top layer is 1 cm thick but is assumed to be a film surface in the balance equation. This assumption is justified because in practice the soil surface is not smooth and the surface temperature is not well defined and extremely difficult to measure correctly. This thickness can be reduced to 1 mm, for example, if necessary.

Three new components of heat transfer, all at the surface, are involved, as shown in Fig. 4.5: direct solar radiation (**RAD**), long wave radiation exchange between the surface and the sky, and convective heat transfer (**HO***(**TF-TO**)). In the present model the atmospheric emissivity (**EPSA**) is assumed to be constant. The model is listed in Fig. 4.6, and its result is given in Fig. 4.7.

In the present model, the simulation model time clock **clk** is calculated by the **mod** function (see Fig. 4.6b). The variable **clk** therefore changes from 0 to 24 hours. Solar radiation (**RAD**) is calculated in '**solar.m'** in Fig. 4.6d.

The result of the simulation is shown in Fig. 4.7. The temperature boundary conditions are the same as in the preceding model except for air temperature. Although air temperature, one of the boundary conditions, ranges from 5 to 15^{o}C in this case, the soil surface temperature is over 23^{o}C because of solar radiation. The soil temperature range is expanded in the daytime and stays more or less the same in the nighttime as in the preceding model. It can be said that the change in soil temperature in the simulation is getting closer to the real pattern. Constants **RP** and **EPSA** can be changed to 100 and 0.71, respectively, in order to simulate severe radiation cooling in the night, and the results are shown in Fig. 4.7. Lower surface temperature than ambient air temperature in the nighttime is clearly shown, although the effect of the initial conditions remains for deeper soil layers.

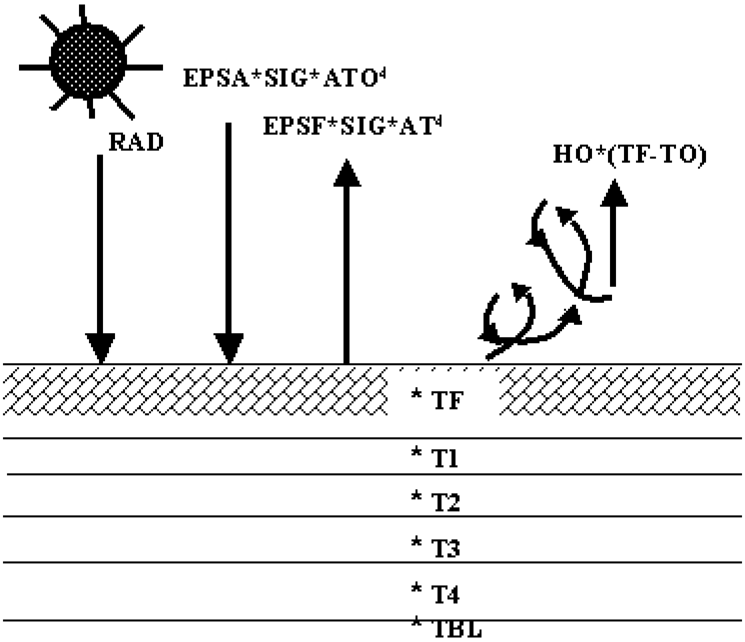


Figure 4.5. Diagram showing heat balance of soil layers.

```
%   Temperature regime in the soil layer                     CUC02.m
%   Boundary condition is air temp.
%   Function required: soil02.m
clear all;  clc
global RP EPSA
tic
RP=2000;   EPSA=0.75; t0=0;   tfinal=48; y0=[10; 10; 10; 10; 10];
[t,y]=ode15s('soil02',[t0 tfinal],y0);   % Calling function 'soil2.m'
h1=findobj('tag','Temperature');close(h1);
figure('tag','Temperature','Resize','on','MenuBar','none',...
   'Name','CUC02.m (T in 5 soil layers given different RP & EPSA)',…
   'NumberTitle','off','Position',[160,80,520,420]);
subplot(2,1,1);
plot(t,y(:,1),'b+-',t,y(:,2),'b:',t,y(:,3),'b-.',t,y(:,4),'b--',...
    t,y(:,5),'b.-');
grid off;  axis([0, inf, 0, 25]);
tit=['RP=' num2str(RP) ' and EPSA=' num2str(EPSA)];  title(tit);
ylabel('Soil temperature, ^oC'); legend('TF','T1','T2','T3','T4',-1);
RP=100; EPSA=0.71;  t0=0;   tfinal=48;  y0=[5; 5; 6; 7; 8];
[t,y]=ode15s('soil02',[t0 tfinal],y0);
subplot(2,1,2);
h=plot(t,y(:,1),'k+-',t,y(:,2),'k:',t,y(:,3),'k-.',t,y(:,4),'k--',...
    t,y(:,5),'k.-');
set(h,'linewidth',2);  grid off;  axis([0, inf, 0, 10]);
tit=['RP=' num2str(RP) ' and EPSA=' num2str(EPSA)];  title(tit);
xlabel('time elapsed, hr');
ylabel('Soil temperature, ^oC'); legend('TF','T1','T2','T3','T4',-1);
toc
disp('Thank you for using');  disp(' ');
```

```
disp('CUC02: Program to calculate Temperatures in soil layers');
disp('      given various RP and EPSA.'); disp(' ');
disp('You can enter ''close'' to close figure window.');
```

Figure 4.6a. Main program to simulate soil temperatures (**CUC02.m**).

Fig. 4.6a shows the main program of the **CUC02** model with the file name of '**cuc02.m**'. The commands listed are nearly the same as those in the main program of the **CUC01** model, and most statements are for setting constants and parameters. Fig. 4.6b shows the function program '**soil02.m**' which performs the main calculations for temperature regime in the soil layer and is similar to the subprogram '**soil01.m**' of **CUC01**. This program includes two more functions '**tabs.m**' and '**solar.m**', of which the scripts are listed in Fig. 4.6c and Fig. 4.6d, respectively. The function '**tabs.m**' calculates (absolute temperature/100)^4 and the function '**solar.m**' gives solar radiation **RAD** as a sine function and starts at 6 am and ends at 6 pm. The maximum value is given as **RP**, as the amplitude, but the negative values of the sine function are cancelled out by the "**if**" statement at the end.

```
%   Subprogram for cuc02 model                                soil02.m
%   Functions required: tabs.m and solar.m
function dy = soil02(t,y)
global RP EPSA
% RP: Solar radiation amp (kJ/m2/hr), EPSA: Emissivity of air layer
Tavg=10.0; TU=5.0; TBL=10.0; % Temp (C)
KS = 5.5; CS= 2.0E+3; HS = 25.2; SIG = 20.4;
% KS (kJ/m/C/hr) and KS/3.6 (W/m/C) also CS (kJ/m3/C)
% HS:Heat transfer coeff. at soil surface (kJ/m2/C/hr) = 7(W/m2/C)
% SIG:Stefan-Boltzmann constant (kJ/m2/K4/hr) = 5.67(W/m2/K4)
%     Please note that the above constant is 5.67e-8, the portion of 1e-8
%     has been performed in function tabs() by (abs.T/100)^4.
Z0=0.01; Z1=0.05; Z2=0.1; Z3=0.2; Z4=0.5; % Depths of soil layer (m)
ALF = 0.7;     % ALF: Absorptivity of solar radiation at soil surface
EPSF = 0.95;   % EPSF:Emissivity of soil surface
clk = mod(t,24);   OMEGA=2.0*pi/24.0;  TO = Tavg + TU*sin(OMEGA*(clk-8));
TF=y(1);T1=y(2);T2=y(3);T3=y(4);T4=y(5);
TO4=tabs(TO);  TF4=tabs(TF);      % calling function tabs()
RAD=solar(RP,OMEGA,clk);          % calling function solar()
ITF = (ALF*RAD+EPSF*SIG*(EPSA*TO4-TF4)+ ...
        HS*(TO-TF)+KS*(T1-TF)*2.0/(Z0+Z1))/CS/Z0;
IT1 = (KS*(TF - T1)*2.0/(Z0+Z1)+KS*(T2 - T1)*2.0/(Z1+Z2))/CS/Z1;
IT2 = (KS*(T1 - T2)*2.0/(Z1+Z2)+KS*(T3 - T2)*2.0/(Z2+Z3))/CS/Z2;
IT3 = (KS*(T2- T3)*2.0/(Z2+Z3)+KS*(T4 - T3)*2.0/(Z3+Z4))/CS/Z3;
IT4 = (KS*(T3 - T4)*2.0/(Z3+Z4)+KS*(TBL - T4)*2.0/Z4)/CS/Z4;
dy=[ITF; IT1; IT2; IT3; IT4];
```

Figure 4.6b. Subprogram to simulate soil temperatures (**soil02.m**).

```
% Calculation for (absolute Temperature/100) to the power of 4   tabs.m
function TT4 = tabs(TT)
  TAA = (TT+273.16)/100.0;    TT4 = TAA*TAA*TAA*TAA;
```

Figure 4.6c. Subprogram to simulate soil temperatures (**tabs.m**).

```
% Subprogram for the calculation of solar radiation              solar.m
function rad = solar(RP,OMEGA,clk)
       rad= RP*sin(OMEGA*(clk-6.0));  % Sunrise at 6 am, sunset at 6 pm
       if rad<=0
          rad=0;
       end
```

Figure 4.6d. Subprogram to simulate soil temperatures (**solar.m**).

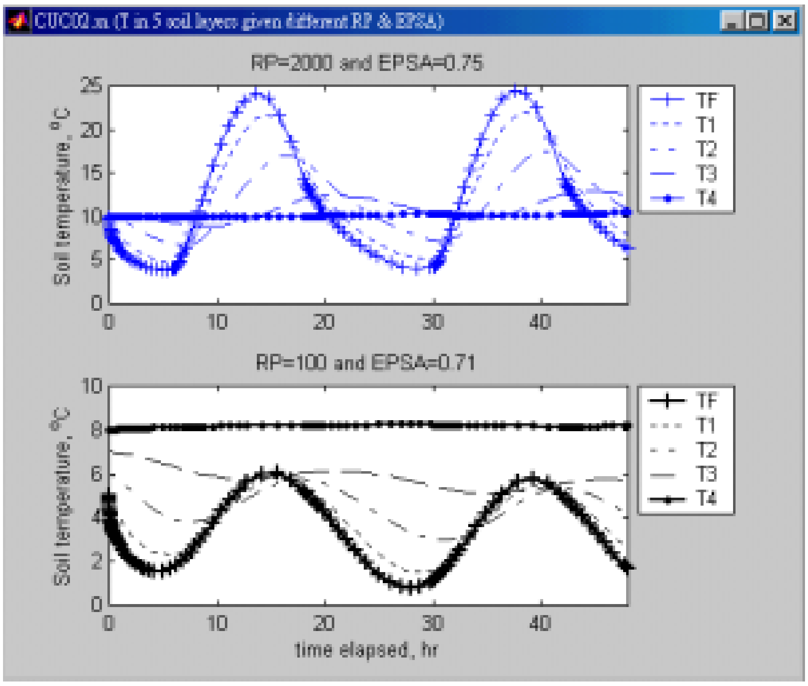


Figure 4.7. Top: Time courses of soil temperatures. Bottom: The effect of radiation cooling on soil temperatures.

4.4. MASS TRANSFER

Mass transfer occurs in the air as well as in the soil. In the soil, not only water in two phases -- water and water vapor -- but also many kinds of salts move. In the air, water vapor and carbon dioxide are two major transport components. As water movement interacts with heat flow, a rather complicated model is required to represent the situation. If the two flows are assumed independent, then modeling the situation is simplified. The movement of salts is beyond the scope of this book. Water vapor and carbon dioxide movement in the air is rather important. Water vapor flow from the soil surface to the adjacent air is always accompanied by energy flow. Vaporization needs energy, as described in eq. 4.3.

Heat flow and water vapor flow can also be related through another number, the Lewis number, which is the ratio of thermal diffusivity and the molecular diffusion coefficient. The Lewis number is almost 0.96 for water vapor and 1.14 for carbon dioxide. Thermal diffusivity (**KAP**, m^2/hr) is expressed as

$$\mathbf{KAP} = \mathbf{K} / (\mathbf{RHO} * \mathbf{CP}) \qquad (4.9)$$

where **K** is thermal conductivity (kJ/m/hr/°C), **RHO** is air density (kg/m^3) and **CP** is specific heat at constant pressure (kJ/kg/°C). If concentrations are expressed on a volumetric basis, the vapor flux is expressed as

$$\mathbf{F} = \mathbf{KMM} * (\ \mathbf{PHII} - \mathbf{PHIS}\ ) \qquad (4.10)$$

where **F** is vapor flux (kg/m^2/hr), **KMM** is the vapor flux coefficient (m/hr), and **PHII** and **PHIS** are the concentrations of vapor (kg/m^3). **KMM** is expressed as

$$\mathbf{KMM} = 1 / \int_{\mathbf{zs}}^{\mathbf{zi}} (1/\mathbf{DD})\ d\mathbf{z} = \mathbf{SH} * \mathbf{DD} / \mathbf{Z} \qquad (4.11)$$

where **zs** and **zi** are distances from the soil surface where the concentrations are **PHIS** and **PHII**, respectively, **DD** is the molecular diffusion coefficient (m^2/hr) and **SH** is the Sherwood number. **zs** can be the soil surface.

The coefficient **KM** in eq. 4.3 presents some problems. In some books, **KM** is related to the molecular diffusion coefficient of the mass through another non-dimensional number, the Sherwood number, but it varies over a wide range due to wind speed. Therefore, in the present book, we will ignore the relationship between the molecular diffusion coefficient and **KM** and define **KM** as an independent constant.

The relationship between **KM** and **KMM** in eq. 4.3 is given as

$$\mathbf{KMM} = \mathbf{KM} / \mathbf{RHO} \qquad (4.12)$$

The Lewis number, which is another non-dimensional number, is defined as

$$\mathbf{Le} = 3.6 * \mathbf{H} / (\mathbf{KM} * \mathbf{CP}) \qquad (4.13)$$

where **H** is the convective heat transfer coefficient and is the same as that used in eq. 4.2. If the Lewis number is equal to 1, the relation between heat flow and mass transfer is expressed as

$$\mathbf{KM} = 3.6 * \mathbf{H} / \mathbf{CP} \qquad (4.14)$$

Since **CP** = 1 (kJ/kg/°C), then **KM** = **H** * 3.6 (kJ/m^2/hr/°C)/(kJ/kg/°C), that is (kg/m^2/hr). This relation is convenient because it is not necessary to give the mass transfer coefficient separately. The problem is to find the condition where **Le** = 1. It is known that **Le** changes with the ratio of relevant diffusivities and air velocity, and as air velocity over a wetted surface becomes low, **Le** decreases from 1 to 0.8 (Threlkeld, 1962). In the present book, **Le** is assumed to be 0.9 in all models. More details can be found in the book written by Threlkeld (1962).

4.5. A MODEL WITH LATENT HEAT TRANSFER (**CUC03**)

In heat transfer under normal conditions, normal air is wet and is defined as the mixed ideal gases of dry air and water vapor. It is not difficult to observe this by putting a glass of cold beer on a desk in the summer. The air around the glass is cooled and water vapor in the air condenses at the surface of the glass. This means that the air temperature at the surface of the glass is cooled below the dew-point temperature of the air at that temperature. This phenomenon can be shown on a psychrometric chart (Fig. 4.8).

The psychrometric chart is a powerful tool for understanding the physical processes of the air. Any condition of normal air can be expressed as a point in the area bounded by three lines: Temperature line (vertical lines), humidity ratio or water vapor pressure line (horizontal lines), and the curved saturation line (which is shifted according to the atmospheric pressure). The process of the air being cooled by a glass of beer is shown in the figure. The starting condition of the air is assumed to be x in the figure, and the cooling process is shown by the horizontal arrow pointed toward the saturation line. The cross point of this arrow and the saturation line is the dew-point, and its temperature is read by projecting it on the horizontal temperature scale. Suppose the surface temperature of the glass is lower than the dew-point indicated by the dot on the saturation line. Then the excess water vapor represented by the difference of the humidity ratio ΔW cannot stay in the air and is condensed. The humidity ratio shows the amount of water vapor per unit weight of dry air.

Fig. 4.9 shows the scripts for calculating temperatures in the soil layer when latent heat transfer is involved.

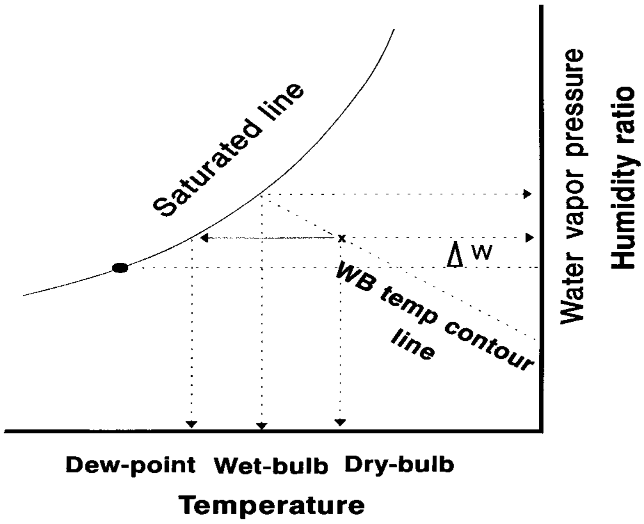


Figure 4.8. Diagrammatic representation of psychrometric chart.

```
%   Temperature regime in the soil layer                       CUC03.m
%   Latent heat transfer is involved
%   Function involved: soil03.m
clear all;clc; tic
t0=0; tfinal=48; tfinal=tfinal*(1+eps);
y0=[10; 10; 10; 10; 10];  % ini. condition of TF, T1,T2,T3,T4
[t,y]=ode15s('soil03',[t0 tfinal],y0);   % Calling function soil3.m
h1=findobj('tag','Temperature'); close(h1);
figure('tag','Temperature','Resize','on','MenuBar','none', ...
   'Name','CUC03.m','NumberTitle','off','Position',[160,80,520,420]);
plot(t,y(:,1),'b^-',t,y(:,2),'gV-',t,y(:,3),'r+-', ...
   t,y(:,4),'c*-',t,y(:,5),'ko-');
grid on;  axis([0, inf, 2, 20]);
title('EPSA=f(TD), also include the latent heat for evaporation');
xlabel('time  elapsed, hr');
ylabel('Soil  temperature, ^oC'); legend('TF','T1','T2','T3','T4',2);
toc; disp('Thank you for using ');  disp(' ');
disp('CUC03: Program to calculate Temperatures in soil layers');
disp('     given EPSA=f(TD), also include the latent heat for evaporation.');
disp(' '); disp('You can enter ''close'' to close figure window.');
```

*Figure 4.9a. Main program to simulate soil temperatures with latent heat exchange (***CUC03.m***).*

```
% Subprogram for cuc03 model                                 soil03.m
% Functions involved: FWS.m, TABS.m, SOLAR.m
% rp=2000, EPSA=f(TD), also include the latent heat for evaporation
% when calculating floor temperature
function dy = soil03(t,y)
Tavg=10.0; TU=5.0; TBL=10.0; % Temp (C)
TD=4.5;              %TD: outside dew point temperature, in degree C
KS = 5.5; CS= 2.0E+3; HS = 25.2;
% KS (kJ/m/C/hr) and KS/3.6 (W/m/C) also CS (kJ/m3/C)
```

```
% HS:Heat transfer coeff at soil surface (kJ/m2/C/hr), HS/3.6= 7 (W/m2/C)
rp=2000;       % rp: Solar radiation amp (kJ/m2/hr)
SIG = 20.4;    % SIG:Stefan-Boltzmann const. (kJ/m2/K4/hr) = 5.67(W/m2/K4)
Z0=0.01; Z1=0.05; Z2=0.1; Z3=0.2; Z4=0.5; % Depths of soil layer (m)
ALF = 0.7;     % ALF: Absorptivity of solar radiation at soil surface
EPSF = 0.95;   % EPSF:Emissivity of soil surface
HLG=2501.0;    LE=0.9;    KM=HS/LE;
WO=FWS(TD);    % calling function fws(), WO: Humidity ratio (outside air)
EPSA=0.711+(TD/100)*(0.56+0.73*(TD/100));% EPSA:Emissivity of air layer
clk = mod(t,24);   OMEGA=2.0*pi/24.0;    % Time (hr)
TO = Tavg + TU*sin(OMEGA*(clk-8));
TF=y(1);T1=y(2);T2=y(3);T3=y(4);T4=y(5);
TO4=tabs(TO);  TF4=tabs(TF);  %calling function tabs()
RAD=solar(rp,OMEGA,clk);  %calling func. solar() for simulated radiation
WF=fws(TF);               %calling function fws()
%WF: Humidity ratio at soil surface (assumed saturated)
ITF=(ALF*RAD+EPSF*SIG*(EPSA*TO4-TF4)+HS*(TO-TF)+HLG*KM*(WO-WF)+...
   KS*(T1-TF)*2.0/(Z0+Z1))/CS/Z0;
IT1 = (KS*(TF-T1)*2.0/(Z0+Z1)+KS*(T2-T1)*2.0/(Z1+Z2))/CS/Z1;
IT2 = (KS*(T1-T2)*2.0/(Z1+Z2)+KS*(T3-T2)*2.0/(Z2+Z3))/CS/Z2;
IT3 = (KS*(T2-T3)*2.0/(Z2+Z3)+KS*(T4-T3)*2.0/(Z3+Z4))/CS/Z3;
IT4 = (KS*(T3-T4)*2.0/(Z3+Z4)+KS*(TBL-T4)*2.0/Z4)/CS/Z4;
dy=[ITF; IT1; IT2; IT3; IT4];
```

Figure 4.9b. Subprogram to simulate soil temperatures with latent heat exchange (**soil03.m**).

```
% Calculate saturated humidity ratio                          FWS.m
function WWW=FWS(TTT)
Patm=101325; TQQ=TTT + 273.16;       T10=TQQ/100.0;
if TTT>0
       A=-5800.2206/TQQ+1.3914993-0.04860239*TQQ;
       B=0.41764768*T10*T10-0.014452093*T10*T10*T10;
       C=6.5459673*log(TQQ);
else
       A=-5674.5359/TQQ+6.3925247-0.9677843*T10;
       B=0.62215701E-2*T10*T10+0.20747825E-2*T10*T10*T10;
       C=-0.9484024E-4*T10*T10*T10*T10+4.1635019*log(TQQ);
end
BETA=A + B + C;       PWS=exp(BETA);        WWW=0.622*PWS/(Patm-PWS);
```

Figure 4.9c. Subprogram to simulate soil temperatures with latent heat exchange (**fws.m**).

In this model (**CUC03**), the boundary condition at the surface was modified to be close to that in reality; that is, latent heat transfer has been included in this model. The rest of the model from section 4.3 is unchanged (see Fig. 4.1). Evaporation from the soil surface is now in the model and the latent heat transfer (**HLG*****KM***(**WF**-**WO**)) has been added. The humidity ratio of the soil surface is assumed saturated at the soil surface temperature and is calculated by using the saturation curve in Fig. 4.8 (see also ASHRAE, 1985).

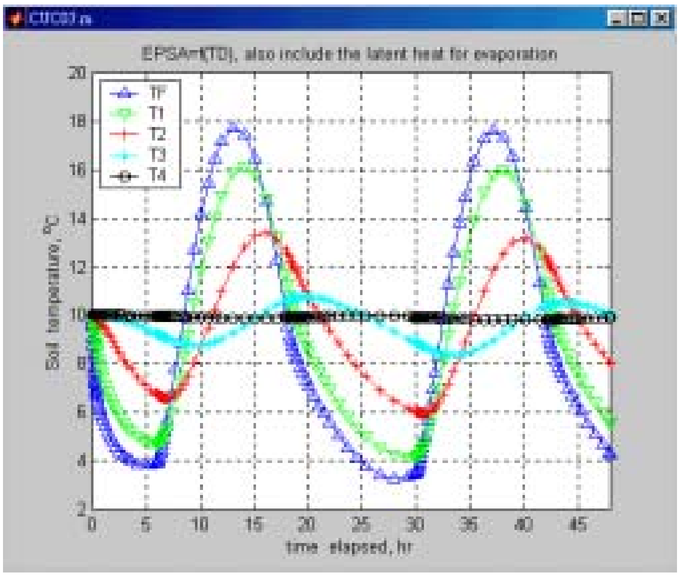


Figure 4.10. Simulated results of CUC03 model.

The structure of the model is similar to the one in section 4.3. In the present program, there are six unknown variables, **TF**, **T1 - T4**, and **WF**; and 6 equations.

TF = f_1(**TF**, **T1**,**Wf**),	**T1** = f_2(**TF**, **T1**, **T2**),	**T2** = f_3(**T1**, **T2**, **T3**)
T3 = f_4(**T2**, **T3**, **T4**),	**T4** = f_5(**T3**, **T4**),	**WF** = f_6(**TF**)

In the present model shown in Fig. 4.9, the new function **FWS** in subprogram **'fws.m'** (see Fig. 4.9c) for calculating the saturated humidity ratio is included. This semi-empirical expression calculates saturated humidity ratio (dummy argument is **WWW**) if a wet-bulb temperature (dummy argument is **TTT**) is given (after ASHRAE, 1988). Other approximations of the curve are also available with less accuracy (see **CUC150**).

One of the new boundary conditions is dew-point temperature (**TD**) of the air. Using **TD**, humidity ratio of the air (**WO**) as well as atmospheric emissivity (**ESPA**) are calculated by eq. 4.18. Humidity ratio at the soil surface (**WF**) is also calculated using the function **FWS**.

The results of the model are given in Fig. 4.10. In the present case, the soil is assumed to be completely wet, that is, saturated at the soil surface. Therefore, potential evaporation takes place and cools down the soil surface temperature. The maximum temperature of the surface is just above 18°C, which is 5°C lower than in the case presented in section 4.3. Deeper soil layers have little effect on the surface.

4.6. RADIATION BALANCE

Radiation is emitted from a body whose temperature is above 0 K; in the present situation, that is, everything emits radiation. Radiation is always considered a balance. For the radiation balance of the bare ground, net radiation is defined as the difference between incoming radiation from the sky and outgoing radiation from the ground. In the daytime, the balance includes solar radiation, of course. The net radiation only for long wave radiation is called effective radiation. In the nighttime, net radiation is equal to effective radiation.

Radiation is like light; it can be considered to travel in a straight line. If two bodies, such as the sky and the ground, are placed face to face without any intermediary, the radiation exchange between these two bodies is one to one. The heat balance systems we have so far considered are of this type -- that is, the bodies involved are the flat soil surface and the sky. These two surfaces can be considered infinite and parallel. Therefore, the radiation emitted from one surface always enters the other.

But when another body such as a building is involved, as shown in Fig. 4.11, part of the radiation from the ground cannot go directly to the sky, and vice versa. This situation can be visualized by looking at the figure from the direction shown by the word 'eye'. Suppose the building is infinite in the direction perpendicular to the page: then half of the sky and half of your perspective are occupied by the face of the building. The ground does receive half of the radiation from the sky, but it also receives half of that from the building surface. In this case, it is said that the view factor of the ground to the sky is 0.5 and the view factor of the ground to the building is 0.5. On the other hand, if you move your eye from the ground to the building surface, it is clear that the view factor of the building to the sky is 0.5. Of the three items being discussed, normally the sky has the lowest temperature and the smallest amount of long wave radiation. On calm clear nights, the soil surface is cooled by radiation because of this fact. However, if half of the sky is blocked by a large building such as shown in Fig. 4.11, the soil surface will be warmer because more radiation will travel from the building surface to the soil surface. Therefore, it is very important to take into account view factor relations when we analyze radiation exchange among surfaces of different surface temperatures.

View factor takes into consideration the area of another body with which the radiation exchange takes place in relation to the total hemisphere of the exchange surface. This relationship is three-dimensional, and the geometric relationship between the two bodies is not simple. A simple way to calculate the view factor is to project all the areas onto the horizontal surface with which the basic surface is involved; then the hemisphere becomes the unit circle and the projected area of the body is the view factor, as shown in Fig. 4.12. The important relationship is that

$$\sum_{\mathbf{j}=1}^{\mathbf{n}} \text{view factor}(\mathbf{i}, \mathbf{j}) = 1 \tag{4.15}$$

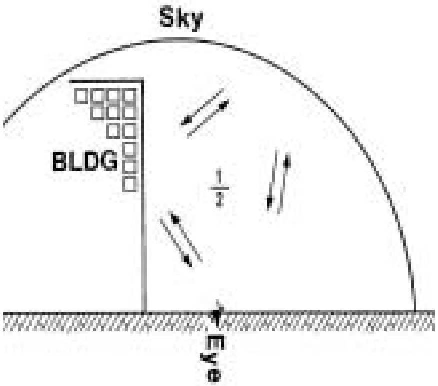


Figure 4.11. Radiation exchange among the sky, the ground and a building.

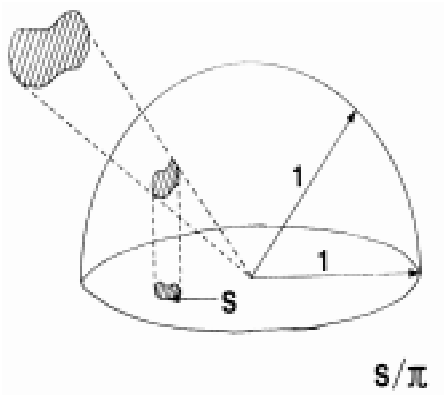


Figure 4.12. Geometrical representation of view factor.

which means that the summation of the view factors of the arbitrary surface **i** to any surface **j** including itself is equal to 1. The self view factor is defined when the surface is concave.

If we look at protected cultivation systems closely, most parts of the systems are not flat surfaces. Rows, tunnels and houses all have curved surfaces of different temperatures. Therefore, it is important to consider view factors in detailed analyses of these systems. However, in the present book, in order to simplify the problem, view factors are not taken into account in any model; it is assumed that all surfaces are infinitely flat. View factor analyses have been conducted in some models (*e.g.*, Takakura *et al*., 1971), which can be consulted when necessary.

Table 4.1. Emissivities of various surfaces (after Seller, 1965).

A. *Water and Soil Surfaces*		C. *Vegetation*	
Water	0.92-0.96	Alfalfa, dark green	0.95
Snow, fresh fallen	0.82-0.995	Oak leaves	0.91-0.95
Ice	0.96	Leaves and plants	
Sand, dry light	0.89-0.90	0.8 μm	0.50-0.53
Sand, wet	0.95	1.0 μm	0.50-0.60
Gravel, coarse	0.91-0.92	2.4 μm	0.70-0.97
Limestone, light gray	0.91-0.92	10.0 μm	0.97-0.98
Concrete, dry	0.71-0.88	D. *Miscellaneous*	
Ground, moist, bare	0.95-0.98	Paper, white	0.89-0.95
B. *Natural Surfaces*		Glass, pane	0.87-0.94
Desert	0.90-0.91	Bricks, red	0.92
Grass, high dry	0.90	Plaster, white	0.91
Fields and shrubs	0.90	Wood, planed oak	0.90
Oak woodland	0.90	Paint, white	0.91-0.95
Pine forest	0.90	Paint, black	0.88-0.95
		Paint, aluminum	0.43-0.55
		Aluminum foil	0.10-0.5
		Iron, galvanized	0.13-0.28
		Silver, highly polished	0.20
		Skin, human	0.95

4.7. LONG WAVE RADIATION

Radiation is emitted from any body whose temperature is above 0 K, including the sky and the earth's surface. Radiation emitted from a body whose temperature is in the ordinary range (0 – 30 °C) has a peak of density in the longer wavelengths shown in Fig. 4.13 called long wave radiation.

Emissivity and temperature of the atmosphere are not simple to determine; neither is long wave radiation from the sky. Within a rather thin layer such as 10 m or so, it can be assumed that the air is transparent to long wave radiation. This assumption, however, cannot be applied to the whole layer of the atmosphere around the earth. Atmospheric radiation is a function of water vapor, carbon dioxide and ozone content, but in most cases, the effects of carbon dioxide and ozone are neglected, mainly because of their thin, very low emissivities.

A large number of radiation charts have been developed for computing atmospheric radiation (*e.g.*, Seller, 1965). They need data that are not available, and the techniques for computing the radiation are not simple. Empirical equations, which are less accurate, are more practical. Brunt's equation (in van Wijk, 1966) is

$$\mathbf{RD = (A + B * sqrt(WO)) * SIG * ATA^4} \tag{4.16}$$

where **RD** is downward long wave radiation (atmospheric radiation) (W/m^2), **A** and **B** are empirical constants related to each location with values of 0.53 and 0.06, respectively, for various locations in U.S.A., **WO** is humidity ratio (kg/kg DA), and **ATA** is absolute air temperature (K) at the screen height. Since **A** and **B** are dependent on temperature and water vapor of the atmosphere, these constants must be determined at the place where this equation is applied.

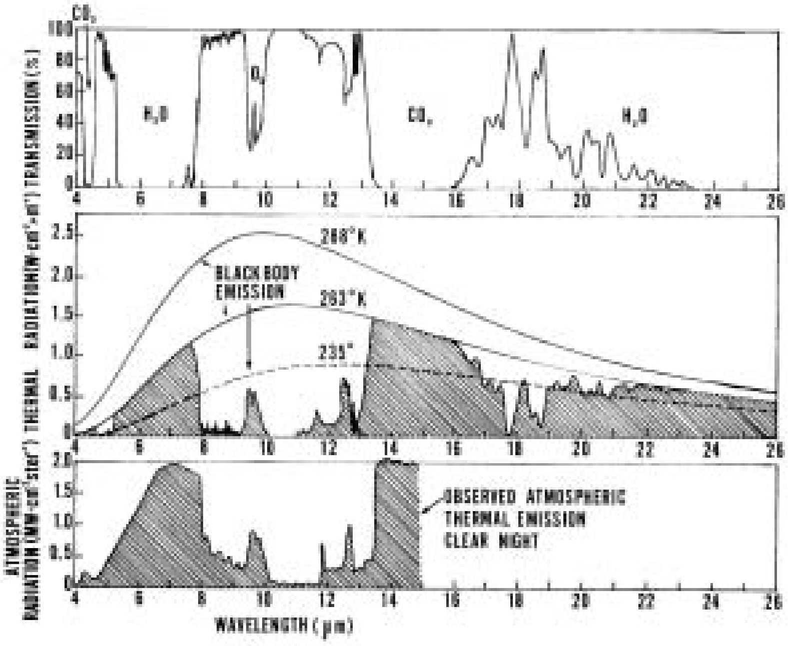


Figure 4.13. Long wave radiation from the sky (after Gates, 1962).

A similar empirical equation was reported based on observation at six locations in the U.S.A. by Martin and Berdahi (1984):

$$\mathbf{RD = EPSA * SIG * ATA^4} \tag{4.17}$$

$$\mathbf{EPSA = 0.711 + 0.56 * TD / 100 + 0.73 * (TD / 100)^2} \tag{4.18}$$

where **EPSA** is atmospheric emissivity and **TD** is dew-point temperature (^{o}C) at the screen height. Emissivities of various materials are summarized in Table 4.1.

MATLAB FUNCTIONS USED

clc	Clear the Command Window and home the cursor.
clear	Clear variables and functions from memory.
clear all	Remove all variables, globals, functions and MEX links.
exp	Exponential. **exp**(X) is the exponential of the elements of X.
for…. end	Repeat statements a specific number of times. The general form is: **for** variable = expr, statement, ..., statement **end**
gtext	Place text with mouse. **gtext**('string') displays the graph window, puts up a cross-hair, and waits for a mouse button or keyboard key to be pressed.
if..else..end	IF statement condition. The general form is: **if** expression statements **elseif** expression statements **else** statements **end**
log	The natural logarithm of the elements of X.

arithmetic operators	+	Plus	-	Minus
	*	Matrix multiply	.*	Array multiply
	^	Matrix power	.^	Array power
	\	Backslash or left matrix divide	/	Slash or right matrix divide
	.\	Left array divide	./	Right array divide
relational operators	==	Equal		
	<	Less than		
	<=	Less than or equal		
	~=	Not equal		
	>	Greater than		
	>=	Greater than or equal		
logical operators	&	Logical AND		
	~	Logical NOT		
	|	Logical OR		
	xor	Logical EXCLUSIVE OR		

PROBLEMS

1. If you look carefully at the periodic changes of the deeper soil layers in Fig. 4.7, a trend of temperature rise or fall is clear. Explain the reason for this, then change the initial conditions for all soil layers to more reasonable values. Note: Two days' run is not enough to check this. Run for a week at least.

2. Modify the program **CUC02**, applying the convective heat transfer coefficient at the soil surface (**HS**) as a function of wind speed. Use the following relationships: **HS** = 2.8 + 1.2 * **V** and **V** = 2.0 + 2.0 * **sin** (**OMEGA** * **clk**).

3. Variable **PWS** (in Pa) in the function **FWS.m** calculates saturated vapor pressure as a function of given temperature (see Fig. 4.9c). Function **VAPRES** (in mb) in the **CUC151** program (see Chapter 10) uses a different approximation. Compare these two methods of calculating saturated vapor pressure in the temperature range of 0 – 40^{o}C.

4. Explain the reason why the front glass of a car facing the sky on a winter night is frosted, while that of a car facing a tall building is not frosted.

5. Calculate **RD** in eqs. 4.16 and 4.17 for the dew-point temperature range 0 – 20^{o}C and air temperature assumed 30 degree C. Program '**FWS.m**' is required to derive humidity ratio from dew-point temperature.

6. Modify the model **CUC01**, assuming the thermal conductivity of soil **KS** is not a constant and is a function of soil temperature (**TEMP**), expressed as: **KS** = 5.5 + 0.1 * **TEMP**.

7. Modify the model **CUC03**, assuming the temperature of the sky follows the Swinkbank model. The expression is: Tsky = 0.0552 * $(TO)^{1.5}$. Both Tsky and TO are expressed in Kelvin. Use Tsky for the calculation of the long wave radiation from the sky.