10. Ground hydrology and thermodynamics*

10.1 Types of the earth's surface and related constants

In the model, the earth's surface is prescribed either as open ocean, sea ice, glacial ice, lake or land. The prescribed surface type is dependent on the model simulated time. The distribution of open ocean, sea ice and lake is determined once a month according to climatological data. Snow on the ground is a prognostic variable. The model predicts the surface temperature of either sea ice, glacial ice, land or snow. The sea ice has a depth of 3 m at both the Arctic and the Antarctic. The model also predicts intersticial moisture (so-called ground wetness) and intersticial ice. The lake is treated as land which is always saturated. The parameterization is based on Katayama (see AM).

10.1.1 Roughness

Surface roughness (z_0) is specified as follows according to the types of the surface;

$$
\begin{aligned}
z_0 &= 0.0002\text{m, for ocean} \\
&= 0.0001\text{m, for sea ice} \\
&= 0.005\text{m, for glacial ice} \\
&= 0.45\text{m, otherwise.}
\end{aligned}
\tag{10.1}
$$

10.1.2 Thermal conductivity

The thermal conductivities for ice, snow and soil are

$$
\begin{aligned}
k_{ice} &= 2.2 \ \text{J/m/sec/deg}, \\
k_{snow} &= 0.34 \ \text{J/m/sec/deg}, \\
k_{soil} &= 4.16 \times 0.2 \times (1 + w' + 0.25 w_i) \ \text{J/m/sec/deg},
\end{aligned}
\tag{10.2}
$$

respectively, where w' is the intersticial moisture (or ground wetness) and is given by

$$w' = W / W_m \tag{10.3}$$

where W is the amount of water stored in the ground and W_m is the prescribed maximum amount of W which the ground can absorb (the prescribed maximum amount of water per unit area, ρW_m h, is assumed to be 1.5 kg m^{-2}); and w_i is the intersticial ice, *i.e.*, the part of w' which is in the ice phase.

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* This chagter is prepared by A. Kitoh.

10.1.3 Heat capacity

The heat capacities for ice, snow and soil are

$$c_{ice} = 4.16 \times 10^6 \times 0.51 \ \mathrm{J/m^3/deg},$$
$$c_{snow} = 4.16 \times 10^6 \times 0.23 \ \mathrm{J/m^3/deg}, \tag{10.4}$$
$$c_{soil} = 4.16 \times 10^6 \times \{0.276 + (0.11 + 0.15w')(1. - 0.5w_i/w')\} \ \mathrm{J/m^3/deg},$$

respectively. Here the heat capacity of soil depends on intersticial moisture and ice.

10.1.4 Bulk heat capacity

Bulk heat capacity of the ground depends on the ground condition and is given by

$$C = ch, \tag{10.5}$$

where h is the characteristic decay depth. For both ice and snow, h is assigned to the value 0.1 m, and thus

$$C_{ice} = 5.1 \times 4.16 \times 10^4 \ \mathrm{J/m^2/deg},$$
$$C_{snow} = 2.3 \times 4.16 \times 10^4 \ \mathrm{J/m^2/deg}. \tag{10.6}$$

The bulk heat capacity of snow is assumed to be independent of the depth of the snow. For the soil, the characteristic depth of the diurnal variation is given by

$$h = \sqrt{D/\omega}. \tag{10.7}$$

where $D = k/c$ is the thermal diffusivity and $\omega = 2\pi$ radians/day. From (10.5) and (10.7)

$$C = ch = c\sqrt{D/\omega} = c\sqrt{k/c\omega} = \sqrt{ck/\omega}. \tag{10.8}$$

From above relations the bulk heat capacity for the soil is given by

$$C_{soil} = 4.16 \times 10^4 \times \sqrt{\{0.276 + (0.11 + 0.15w')(1. - 0.5w_i/w')\}}$$
$$\times \sqrt{(1. + w' + 0.25w_i) \times 0.002/\omega}. \tag{10.9}$$

10.2 Land surface temperature and heat balance

The ground temperature is obtained from

$$C\frac{\partial T_g}{\partial t} = H_A, \tag{10.10}$$

where T_g is the ground temperature, C is the bulk heat capacity and H_A is the net surface heating rate. The net surface heating rate is given by

$$H_A = -(F_h)_s - R_6 + S_6 + H_l, \tag{10.11}$$

where $(F_h)_s$ is the heat flux (sensible plus latent heat flux) from the ground to the atmosphere, R_6 is the net long wave flux from the ground to the atmosphere, S_6 is the solar flux absorbed at the earth's surface, and H_i is the heat conduction from below to the ground surface. For both land and glacial ice, we assume $H_i=0$. For sea ice, whether covered by snow or not,

$$H_i = k_{ice}(T_i - T_g)/h_i, \tag{10.12}$$

where T_i is the melting (or freezing) temperature of sea ice (=273.1K in the model), and h_i is the thickness of the sea ice. At present, we assume h_i to be constant (=3m) regardless of the season.

In the implementation of (10.10), R_6 is treated implicitly. Thus,

$$C\frac{\Delta T_g}{\Delta t} = S_6 + H_i - (F_h)_s - R_6(T_g + \Delta T_g). \tag{10.13}$$

Using the first-order approximation

$$R_6(T_g + \Delta T_g)^4 \simeq \sigma T_g^4 + 4\sigma T_g^3 \Delta T_g, \tag{10.14}$$

the change of the ground temperature is given by

$$T_{g,new} - T_{g,old} = \Delta T_g = \frac{\Delta t \{S_6 - R_6(T_{g,old}) + H_i - (F_h)_s\}}{C + 4\sigma T_{g,old}^3 \Delta t}. \tag{10.15}$$

10.3 Surface hydrology and soil water budget

See Fig. 10.1 for the flow of the computation of ground hydrology.

10.3.1 Surface evapotranspiration

The surface evapotranspiration is given by

$$E_s = \varkappa (q_g - q_m)_e, \tag{10.16}$$

where $(q_g - q_m)_e = \beta (q_g^* - q_m)$ is the effective ground-air total mixing ratio difference, and q is the mixing ratio, subscript g indicates a ground value, and subscript m indicates a mean value in the PBL and is defined by

$$(\quad)_m = \frac{1}{p_s - p_B}\int_{p_B}^{p_s} (\quad) dp, \tag{10.17}$$

and asterisk denotes the saturated value. The quantity β is the efficiency factor of evapotranspiration and is given by

$$\begin{aligned} \beta &= 1 && \text{when } w' \geq 0.5 \\ &= 2. \times w' && \text{when } w' \leq 0.5. \end{aligned} \tag{10.18}$$

When $q_g < q_m$ (dew is being deposited), or if fog occurs, we assume that the ground has been wetted and $\beta = 1$.

$\varkappa$ is the ventillation factor and is given by

$$\kappa = \rho \mid v_m \mid C_D C_H, \qquad (10.19)$$

where ρ is the density, v_m is the representative velocity within the PBL and C_D, C_H are transfer coefficients (see Fig. 8. 3). Negative evapotranspiration is able to occur, representing the condensation on the surface.

10.3.2 Snow

Precipitation results from large-scale supersaturation of the lowest model layer and/or from cumulus convection (middle level and penetrative). When precipitation occurs, it is counted either for rainfall (P_r) or for snowfall (P_s) depending upon the surface air temperature T_s, *i.e.*,

i) when $T_s > T_i$, rainfall occurs and

$$P_r = P, \ P_s = 0, \qquad (10.20a)$$

ii) when $T_s \leq T_i$, snowfall occurs and

$$P_s = P, \ P_r = 0, \qquad (10.20b)$$

where P is the rate of precipitation.

The snow mass is a prognostic variable in the model except for open ocean and is given by

$$\frac{\partial S}{\partial t} = P_s - E_s[1 - \delta(S)] - M_s, \qquad (10.21)$$

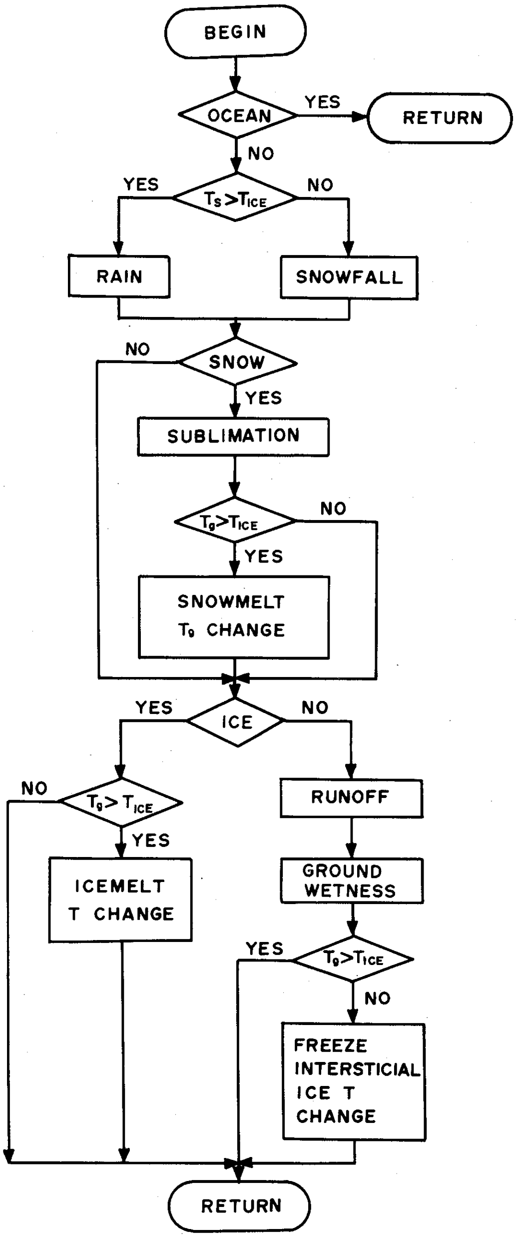

Fig. 10.1 Flow diagram of ground hydrology process.

where S is snow mass per unit area, E_s is evapotranspiration, M_s is snowmelt per unit area and

$$\delta(S) = 1 \text{ if } S = 0, \quad = 0 \text{ if } S \neq 0. \qquad (10.22)$$

Snowmelt occurs when model computed ground temperature T_g is greater than T_i

$$\begin{aligned} &\text{i) } T_g \leq T_i,\ M_s = 0, \\ &\text{ii) } T_g > T_i,\ M_s \Delta t = \min\left(\frac{C_s}{L_i}(T_g - T_i),\ S\right), \end{aligned} \tag{10.23}$$

where C_s is bulk heat capacity of snow and L_i is latent heat of melting.

10.3.3 Intersticial moisture and intersticial ice

The intersticial moisture (w′) and the intersticial ice (w_i) are governed by

$$W_m \rho h \frac{\partial w'}{\partial t} = P_r - R - E_s \delta(S) + M_s + C_T, \tag{10.24}$$

$$W_m \rho h \frac{\partial w_i}{\partial t} = F_i \delta(S), \tag{10.25}$$

where ρ is the density of the ground, R is runoff, C_T is capillary transport of water into the soil layer, and F_i is the mass of intersticial moisture which freezes or melts per unit area and time. We assume that the maximum available water, per unit area of the soil layer, $W_m \rho h$, is a constant (15 gr/cm^2).

Usually we assume $C_T = 0$, but when the predicted intersticial moisture without capillary pumping becomes either negative or greater than unity, we allow a value of C_T such that it restores the intersticial moisture to zero or unity, respectively.

10.3.4 Runoff

The rainfall-runoff relation we are using is

$$R = (P_r^3 + D^3)^{1/3} - D, \tag{10.26}$$

where the deficiency of water, D, is defined by

$$D = (1 - w') W_m \rho h. \tag{10.27}$$

If rainfall amount is zero, runoff is also zero. When $D \neq 0$, runoff increases with rainfall. When soil is saturated ($D = 0$), all the rainfall becomes runoff. The runoff is discarded instantly out of the model.