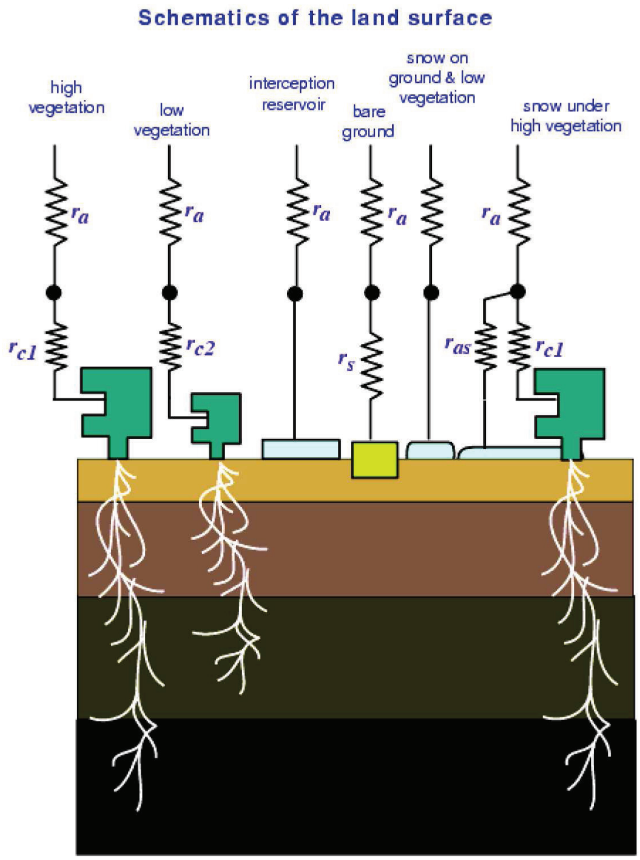

Figure 7.1 *Schematic representation of the structure of TESSEL land-surface scheme.*

law, modified to take into account the thermal effects of soil water phase changes. The energy equation is solved with a net ground heat flux as the top boundary condition and a zero-flux at the bottom.

Snowfall is collected in the snow mantle, which in turn is depleted by snowmelt, contributing to surface runoff and soil infiltration, and evaporation. A fraction of the rainfall is collected by an interception layer, where the remaining fraction (throughfall) is partitioned between surface runoff and infiltration. Subsurface water fluxes are determined by Darcy's law, used in a soil water equation solved with a four-layer discretization shared with the heat budget equation. Top boundary condition is infiltration plus surface evaporation, free drainage is assumed at the bottom; each layer has an additional sink of water in the form of root extraction over vegetated areas.

Finally, open water points have a fixed surface temperature. When present, frozen water occupies a fraction of the grid box, with a prognostic ice temperature evolving in the forecast following the heat budget of a four-layer ice model in thermal contact with an underlying ocean at freezing temperature.

7.2 TILES AND SURFACE FLUXES

7.2.1 Tile and vegetation characteristics

Grid-box surface fluxes are calculated separately for the different subgrid surface fractions (or "tiles"), leading to a separate solution of the surface energy balance equation and skin temperature for each of these tiles. This is an analogue of the "mosaic" approach of Koster and Suarez (1992). Note that the tiles at the interface soil-atmosphere are in energy and hydrological contact with one single atmospheric profile above and one single soil profile below. Each grid box is divided into 8 fractions: two vegetated fractions (high and low vegetation without snow), one bare soil fraction, three snow/ice fractions (snow on bare ground/low vegetation, high vegetation with snow beneath, and sea-ice, respectively), and two water fractions (interception reservoir, ocean/lakes). The tile for "high vegetation with snow beneath" is a combined tile with a separate energy balance and evaporation model for the high vegetation and the underlying snow. A mixture of land and water (ocean/inland water) tiles is not allowed, i.e. a grid box is either 100% land or 100% sea.

In each grid box two vegetation types are present: a high and a low vegetation type. An external climate database, based on the Global Land Cover Characteristics (GLCC) data that has been derived using one year of Advanced Very High Resolution Radiometer (AVHRR) data and ancillary information (Loveland *et al.*, 2000; http://edcdaac.usgs.gov/glcc/glcc.html; see also Chapter 10). The nominal resolution is 1 km. The data used provides for each pixel a biome classification based on the Biosphere-Atmosphere Transfer Scheme (BATS) model (Dickinson *et al.*, 1993), and four parameters have been derived for each grid box: dominant vegetation type, $T_{\rm H}$ and $T_{\rm L}$, and the area fraction, $A_{\rm H}$ and $A_{\rm L}$, for each of the high- and low-vegetation components, respectively.

The coverage C_i for the tile i depends on the type and relative area of low and high vegetation, and the presence of snow and intercepted water. In the absence of snow and interception, the vegetation coverage of high ($c_{\rm H}$) and low ($c_{\rm L}$) vegetation are calculated as $A_{\rm H}c_{\rm veg}(T_{\rm H})$ and $A_{\rm L}c_{\rm veg}(T_{\rm L})$, respectively, with $c_{\rm veg}$ a vegetation type dependent coverage (see Table 10.4). The bare ground fraction $c_{\rm B}$ is the residual.

$$\begin{aligned} c_{\rm H} &= A_{\rm H}c_{\rm veg}(T_{\rm H}) \\ c_{\rm L} &= A_{\rm L}c_{\rm veg}(T_{\rm L}) \\ c_{\rm B} &= (1 - c_{\rm H} - c_{\rm L}) \end{aligned} \tag{7.1}$$

Each vegetation type is characterized by a series of (fixed) parameters as detailed in Table 10.4.

(i) A minimum canopy resistance, $r_{\rm s,min}$.
(ii) A leaf area index, LAI.
(iii) A vegetation coverage, $c_{\rm veg}$.
(iv) A coefficient, $g_{\rm D}$, for the dependence of the canopy resistance, $r_{\rm c}$, on water vapour pressure deficit.
(v) The root distribution over the soil layers, specified by an exponential profile involving attenuation coefficients, $a_{\rm r}$, and $b_{\rm r}$.

The numerical values for the parameters of Table 10.4 are based both on experiments conducted as described in Van den Hurk *et al.* (2000) and on literature review, in particular Mahfouf *et al.* (1995), Manzi and Planton (1994), Giard and Bazile (2000), Dorman and Sellers (1989), Bonan (1994), Pitman *et al.* (1991), and Zeng *et al.* (1998a).

The presence of snow and intercepted water dynamically modifies the coverage fractions. The coverage of snow, $c_{\rm sn}$, is linearly related to the snow mass per unit area (abbreviated to snow mass in the following), S (units 10^3(kg m^{-1}) or m). The interception reservoir fraction, c_1, is given by $W_1/W_{\rm 1m}$, with $W_{\rm 1m}$, the maximum value for the intercepted water in the grid box, defined from the leaf area index contributions from the high and low vegetation tiles. The water contents of the interception reservoir, W_1 (units m), and S are prognostic quantities in the model. Snow cover is assumed to be overlying vegetation and bare ground with the same fraction. The interception reservoir occupies an identical fraction of all snow-free tiles.

$$\begin{aligned} c_{\rm sn} &= \min\left(1, \frac{S}{S_{\rm cr}}\right) \\ W_{\rm 1m} &= W_{\rm lmax}[c_{\rm B} + c_{\rm H}\cdot LAI(T_{\rm H}) + c_{\rm L}\cdot LAI(T_{\rm L})] \\ c_1 &= \min\left(1, \frac{W_1}{W_{\rm lm}}\right) \end{aligned} \tag{7.2}$$

In the expressions above the minimum snow mass that ensures complete coverage of the grid box is $S_{\rm cr} =$ 0.015m and the maximum water over a single layer of leaves or over bare ground is $W_{1\,\rm max} = 0.0002$m. The leaf area index LAI, is specified in Table 10.4 as a function of surface type. The full set of fractional tile coverages is given by (7.3) and (7.4), where the indexing of the tiles is detailed in Table 7.2. Since a

Table 7.1 *Vegetation types and parameter values (see text). H/L refer to the distinction between high and low vegetation.*

Index	Vegetation type	H/L	$r_{s,\min}$ ($\mathrm{sm^{-1}}$)	LAI ($\mathrm{m^2m^{-2}}$)	c_{veg}	g_{D} ($\mathrm{hPa^{-1}}$)	a_r	b_r
1	Crops, mixed farming	L	180	3	0.90	0	5.558	2.614
2	Short grass	L	110	2	0.85	0	10.739	2.608
3	Evergreen needleleaf trees	H	500	5	0.90	0.03	6.706	2.175
4	Deciduous needleleaf trees	H	500	5	0.90	0.03	7.066	1.953
5	Deciduous broadleaf trees	H	175	5	0.90	0.03	5.990	1.955
6	Evergreen broadleaf trees	H	240	6	0.99	0.03	7.344	1.303
7	Tall grass	L	100	2	0.70	0	8.235	1.627
8	Desert	–	250	0.5	0	0	4.372	0.978
9	Tundra	L	80	1	0.50	0	8.992	8.992
10	Irrigated crops	L	180	3	0.90	0	5.558	2.614
11	Semidesert	L	150	0.5	0.10	0	4.372	0.978
12	Ice caps and glaciers	–	–	–	–	–	–	–
13	Bogs and marshes	L	240	4	0.60	0	7.344	1.303
14	Inland water	–	–	–	–	–	–	–
15	Ocean	–	–	–	–	–	–	–
16	Evergreen shrubs	L	225	3	0.50	0	6.326	1.567
17	Deciduous shrubs	L	225	1.5	0.50	0	6.326	1.567
18	Mixed forest/woodland	H	250	5	0.90	0.03	4.453	1.631
19	Interrupted forest	H	175	2.5	0.90	0.03	4.453	1.631
20	Water and land mixtures	L	150	4	0.60	0	–	–

mixture of land and ocean tiles is not allowed, a grid box is either 100% water (open water and ice, with ice fraction c_{i}):

$$\begin{aligned} C_1 &= 1 - c_i \\ C_2 &= c_i \\ C_i &= 0, i \in [3, N_{\mathrm{T}}] \end{aligned} \tag{7.3}$$

or 100% land (tiles 3 to N_{T}, where $N_{\mathrm{T}} = 8$ is the number of tiles):

$$\begin{aligned} C_1 &= C_2 = 0 \\ C_3 &= (1 - c_{\mathrm{sn}}) \cdot c_1 \\ C_4 &= (1 - c_{\mathrm{sn}}) \cdot (1 - c_1) \cdot c_{\mathrm{L}} \\ C_5 &= c_{\mathrm{sn}} \cdot (1 - c_{\mathrm{H}}) \\ C_6 &= (1 - c_{\mathrm{sn}}) \cdot (1 - c_1) \cdot c_{\mathrm{H}} \\ C_7 &= c_{\mathrm{sn}} \cdot c_{\mathrm{H}} \\ C_8 &= (1 - c_{\mathrm{sn}}) \cdot (1 - c_1) \cdot (1 - c_{\mathrm{L}} - c_{\mathrm{H}}) \end{aligned} \tag{7.4}$$

Apart from the fractional gridbox coverage, each tile has a couple of additional parameters (see Table 7.2).

(i) The skin conductivity, Λ_{sk}, provides the thermal connection between the skin level and the soil or snow deck. For high vegetation, Λ_{sk}, is different for a stable and unstable stratification of the temperature gradient between the skin level and the upper soil or snow layer. This difference is considered to represent the asymmetric coupling between the ground surface and the tree canopy layer: an effective convective transport within the tree trunk space for unstable conditions, and a limited turbulent exchange for stable stratification(Bosveld *et al.*, 1999).

(ii) A small fraction $f_{R_{\mathrm{s}}}$ of net short-wave radiation that is transmitted directly to the top soil or snow layer. The remaining fraction of the short-wave radiation $(1 - f_{R_{\mathrm{s}}})$ is absorbed by the skin layer.

Finally, the surface albedo, α_i, is similar for all land tiles within a grid box except for those covered with snow (see the snow scheme description below). The climate database provides the snow-free background

Table 7.2 *Tile specific values.*

Index	Tile	Λ_{sk} unstable ($Wm^{-2}K^{-1}$)	Λ_{sk} stable ($Wm^{-2}K^{-1}$)	f_{R_s}	Resistance scheme
1	Open water	∞	∞	0	Potential
2	Ice water	58	58	0	Potential
3	Interception reservoir	10	10	0.05	Potential
4	Low vegetation	10	10	0.05	Resistance
5	Snow on low vegetation/bare ground	7	7	0	Potential
6	High vegetation	$\Lambda_{a,u}+5$	$\Lambda_{a,s}+5$	0.03	Resistance
7	High vegetation with snow beneath	$\Lambda_{a,u}+5$	$\Lambda_{a,s}+5$	0.03	Canopy and snow resistance
8	Bare ground	15	15	0	Resistance

The resistance scheme describes the way of coupling with the atmosphere: *Potential* denotes atmospheric resistance only; *Resistance* denotes aerodynamic resistance in series with a canopy or soil resistance; *Canopy and snow resistance* denotes a canopy resistance for the vegetation and an extra aerodynamic coupling to the snow surface (see Figs 7.1–7.2 and Subsection 7.2.2). For tiles 6 and 7, $\Lambda_{a,u} = 15\mathrm{W\ m^{-2}K^{-1}}$ and $\Lambda_{a,s} = 10\mathrm{W\ m^{-2}K^{-1}}$ represent the aerodynamic coupling between the canopy and the soil in the unstable and stable cases, respectively, and the factor 5 represents the long-wave radiative exchanges. *Unstable/stable* refers to the temperature gradient between the skin layer and the top soil or snow layer.

albedo on a monthly basis. Long-wave emissivity, ε, outside the window region is equal to 0.99 for all tiles; emissivity in the window region is tile dependent and varies between 0.93 and 0.98 (see Table 2.5 in Section 2.5.5 for more details). The remaining surface characteristics (roughness length for momentum, $z_{0\mathrm{m}}$, and heat, $z_{0\mathrm{h}}$) are similar for all land tiles within a grid box and specified in the climate database (Chapter 10).

7.2.2 Surface heat and evaporation fluxes

A resistance parameterization is used to calculate the turbulent fluxes. Momentum exchange is parameterized with the same roughness length for all tiles, but with a different stability correction for each tile. The resistance scheme for water vapour and heat exchanges is different for different tiles (see Fig. 7.2). For ocean, sea ice and snow on low vegetation, the turbulent fluxes of heat and water vapour are given by

$$H_i = \rho_\mathrm{a} c_p |U_\mathrm{L}| C_{\mathrm{H},i}(T_\mathrm{L} + gz_\mathrm{L} - T_{\mathrm{sk},i}) \tag{7.5}$$

$$E_i = \rho_\mathrm{a} |U_\mathrm{L}| C_{\mathrm{H},i}[q_\mathrm{L} - q_\mathrm{sat}(T_{\mathrm{sk},i})] \tag{7.6}$$

with ρ_a the air density, c_p the heat capacity of moist air, g the acceleration of gravity, $|U_\mathrm{L}|$, T_L, q_L, z_L the wind speed, temperature, humidity and height of the lowest atmospheric model level, and $C_{\mathrm{H},i}$ the turbulent exchange coefficient, that varies from tile to tile because of different atmospheric stabilities. See Chapter 3 for a description of the exchange coefficients where different roughness lengths for heat and momentum are assumed and a Monin–Obukhov formulation is adopted for the stability dependence.

For high and low vegetation, an additional canopy resistance r_c is added with

$$E_i = \frac{\rho_\mathrm{a}}{r_\mathrm{a} + r_\mathrm{c}}[q_\mathrm{L} - q_\mathrm{sat}(T_{\mathrm{sk},i})] \tag{7.7}$$

with $r_\mathrm{a} = (|U_\mathrm{L}|C_{\mathrm{H},i})^{-1}$ and i indicating the high or low vegetation tiles. r_c is a function of downward short-wave radiation R_s, leaf area index LAI, average unfrozen root soil water $\bar{\theta}$, atmospheric water