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SMR.1313 - 5

Summer Colloquium on the Physics of Weather and Climate

Workshop on Land-Atmosphere Interactions in Climate Models

(28 May - 8 June 2001)

Land-surface Modeling of Intermediate Complexity for NWP and Climate: the ECMWF Experience

Lecture 2

<u>REVISED</u>

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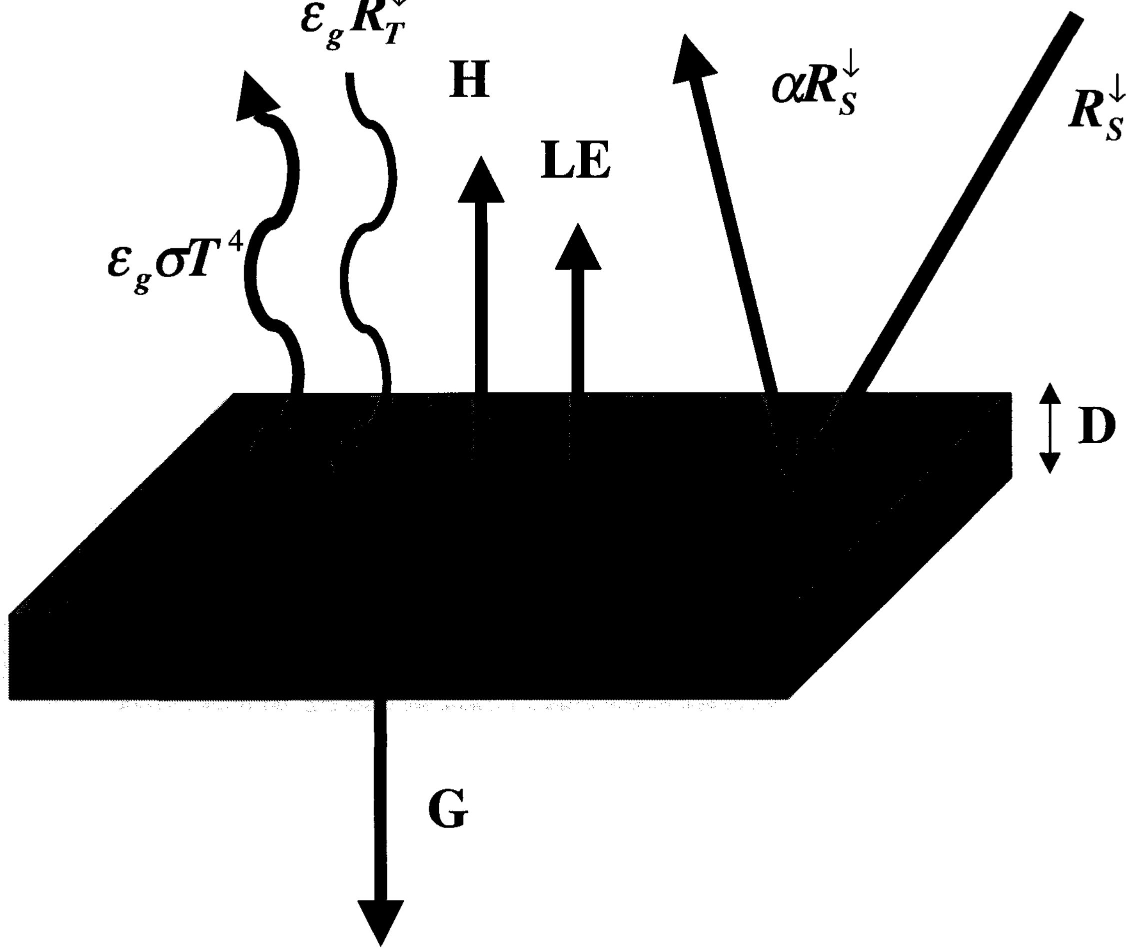
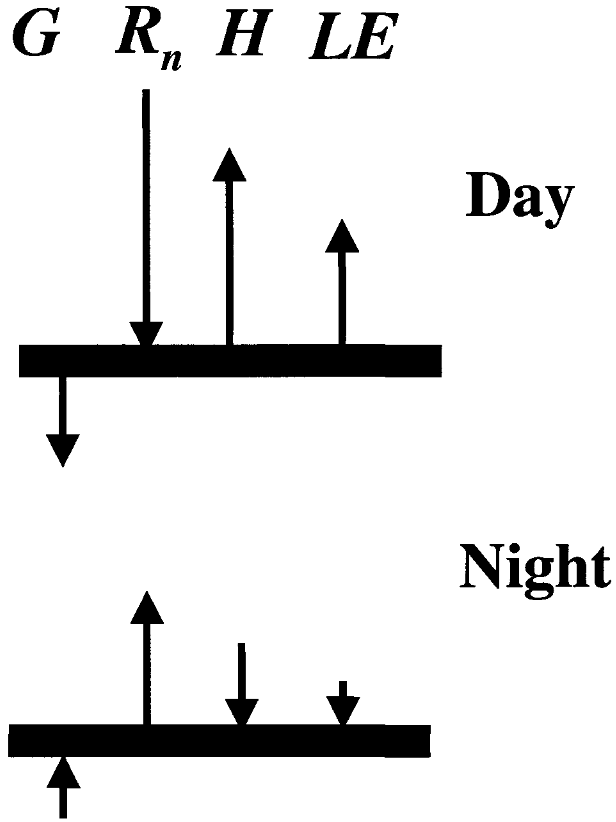
These are preliminary lecture notes, intended only for distribution to participants

Layout

- Introduction
- General remarks
- Model development and validation
- The surface energy budget
- Soil heat transfer
- Soil water transfer
- Surface fluxes
- Initial conditions
- Snow
- Conclusions and a look ahead

Thermal budget of a ground layer at the surface





$$R_n + H + L \cdot E + G = (\rho C)_g D \frac{\partial \overline{T}_s}{\partial t}$$

Energy budget: Summer examples

Dry

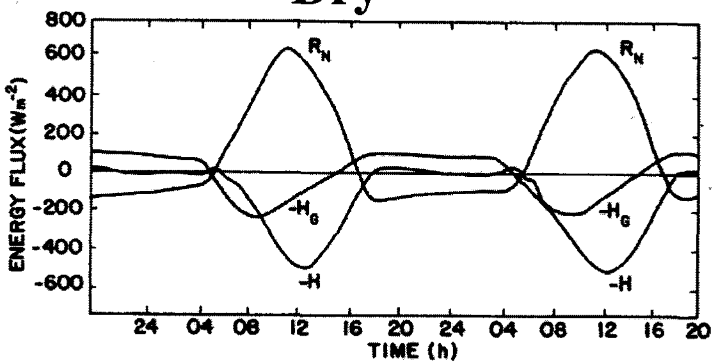


Fig. 2.3 Observed diurnal energy balance over a dry lake bed at El Mirage, California, on June 10 and 11, 1950. [After Vehrencamp (1953).]

Fir canopy

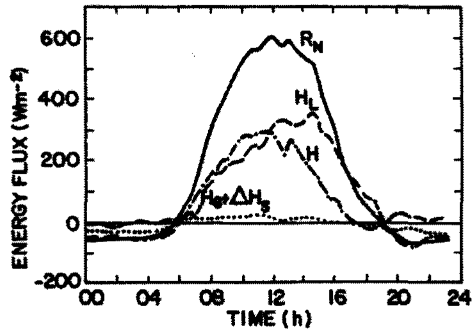


Fig. 2.5 Observed energy budget of a Douglas fir canopy at Haney, British Columbia, on July 23, 1970. [From Oke (1987); after McNaughton and Black (1973).]

Barley field

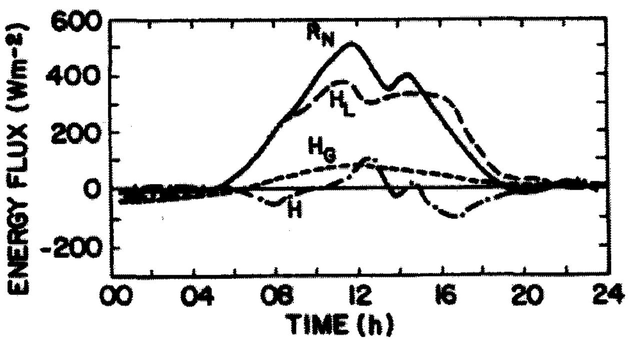


Fig. 2.4 Observed diurnal energy budget of a barley field at Rothamsted, England, on July 23, 1963. [From Oke (1987); after Long *et al.* (1964).]

$$R_N = R_n$$
$$-H_G = G$$
$$-H = H$$
$$-H_L = LE$$

Arya, 1988

The surface radiation

$$R_n = (1-\alpha)R_S^{\downarrow} + \varepsilon_g R_T^{\downarrow} - \varepsilon_g \sigma T_{sk}^4$$

α Surface albedo

ε_g Surface emissivity

T_{sk} Skin temperature

$\overline{T}_s \neq T_{sk}$

- In some cases (snow, sea ice, dense canopies) the impinging solar radiations penetrates the "ground" layer and is absorbed at a variable depth. In those cases, an extinction coefficient is needed.

Table 3.1

Radiative Properties of Natural Surfaces[a]

Surface type	Other specifications	Albedo (a)	Emissivity (ε)
Water	Small zenith angle	0.03–0.10	0.92–0.97
	Large zenith angle	0.10–0.50	0.92–0.97
Snow	Old	0.40–0.70	0.82–0.89
	Fresh	0.45–0.95	0.90–0.99
Ice	Sea	0.30–0.40	0.92–0.97
	Glacier	0.20–0.40	
Bare sand	Dry	0.35–0.45	0.84–0.90
	Wet	0.20–0.30	0.91–0.95
Bare soil	Dry clay	0.20–0.35	0.95
	Moist clay	0.10–0.20	0.97
	Wet fallow field	0.05–0.07	
Paved	Concrete	0.17–0.27	0.71–0.88
	Black gravel road	0.05–0.10	0.88–0.95
Grass	Long (1 m) Short (0.02 m)	0.16–0.26	0.90–0.95
Agricultural	Wheat, rice, etc.	0.10–0.25	0.90–0.99
	Orchards	0.15–0.20	0.90–0.95
Forests	Deciduous	0.10–0.20	0.97–0.98
	Coniferous	0.05–0.15	0.97–0.99

[a] Compiled from Sellers (1965), Kondratyev (1969), and Oke (1978).

Arya, 1988

The other terms

Sensible heat flux

$$H = \rho C_h u_L (C_p T_L + gz - C_p T_{sk})$$

$$C_h = f(Ri_B, z_{oh}, z_{om})$$

z_{oh}, z_{om} **specify the surface**

Evaporation

$$E = \rho C_h u_L \left[a_L q_L - a_s q_{sat}(T_{sk}, p_s) \right]$$

$$a_{L,s} = f(q_L, T_s, \text{state and nature of the soil, soil cover})$$

Ground heat flux

$$(\rho C)_g \frac{\partial T_s}{\partial t} = -\frac{\partial G}{\partial z} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z}$$

$$(\rho C)_g, \lambda_T = f(\textbf{soil type, other soil characteristics})$$

Recap: The surface energy equation

$$(1-\alpha)R_S^{\downarrow} + \varepsilon_g R_T^{\downarrow} - \varepsilon_g \sigma T_{sk}^4 + \rho C_h u_L (C_p T_L + gz - C_p T_{sk}) +$$

$$\rho C_h u_L \left[a_L q_L - a_s q_{sat}(T_{sk}, p_s) \right] + G(T_s, T_{sk}) = (\rho C)_g D \frac{\partial T_s}{\partial t}$$

- **Equation for** T_s, T_{sk}
- **For:**
  - **a thin soil layer at the top** $(\rho C)_g D \frac{\partial T_s}{\partial t} \approx 0$
  - **G (T_s,T_{sk}) is known, or parameterized or G << R_n**

we have a non-linear equation defining the skin temperature

TESSEL

- **Skin layer at the interface between soil (snow) and atmosphere; no thermal inertia, instantaneous energy balance**
- **At the interface soil/atmosphere, each grid-box is divided into fractions (tiles), each fraction with a different functional behaviour. The different tiles see the same atmospheric column above and the same soil column below.**

$$G_i = \Lambda_{sk,i}\left(T_s - T_{sk,i}\right)$$

i index for tile

$i = 1,\ldots,N$

- **If there are N tiles, there will be N fluxes, N skin temperatures per grid-box**
- **There are currently up to 6 tiles over land (N=6)**

TESSEL skin temperature equation

$$(1-\alpha_i)R_S^{\downarrow} + \varepsilon_g R_T^{\downarrow} - \varepsilon_g \sigma T_{sk,i}^4 +$$
$$\rho C_{h,i} u_L (C_p T_L + gz - C_p T_{sk,i}) +$$
$$\rho C_{h,i} u_L \left[a_{L,i} q_L - a_{s,i} q_{sat}(T_{sk,i}, p_s)\right] +$$
$$\Lambda_{sk,i}(T_s - T_{sk,i}) = 0$$

- **Grid-box quantities**

$$H = \sum_i C_i H_i$$

$$E = \sum_i C_i E_i$$

$$T_{sk} = \sum_i C_i T_{sk,i}$$

C_i Tile fraction

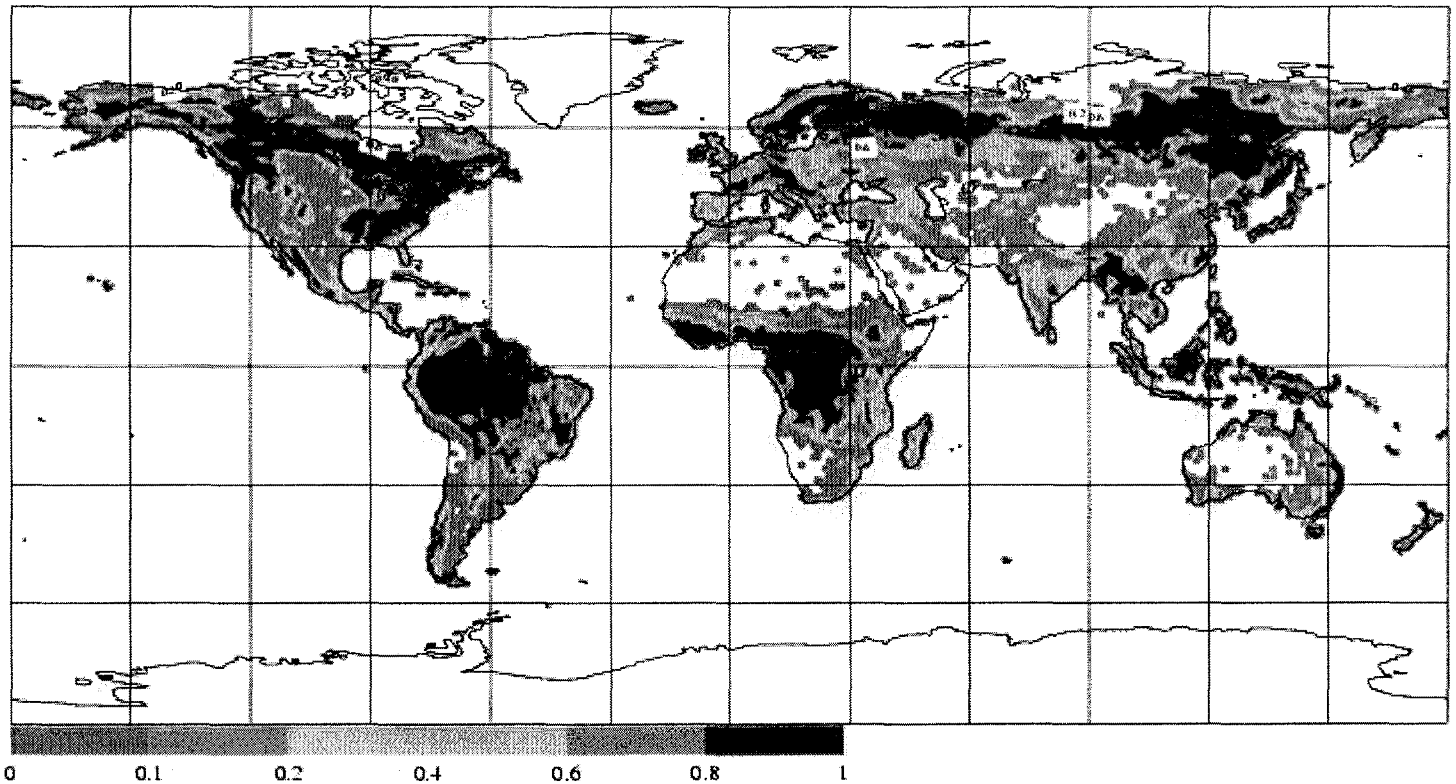
Tiles

Land	Sea and ice
High vegetation	Open sea / unfrozen lakes
Low vegetation	Sea ice / frozen lakes
High vegetation with snow beneath	
Snow on low vegetation	
Bare ground	
Interception layer	

TESSEL geographic characteristics

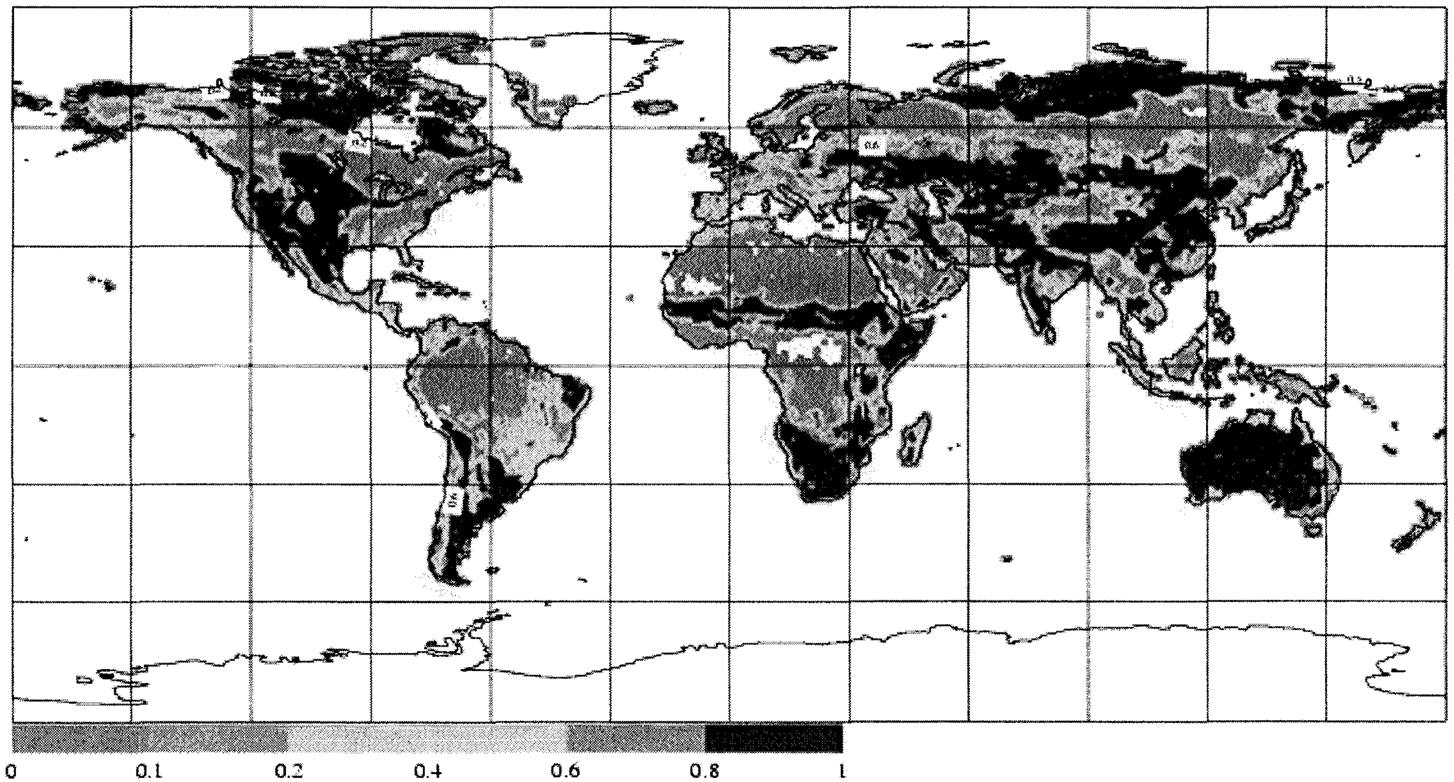
Fields	ERA15	TESSEL
Vegetation	Fraction	Fraction of low Fraction of high
Vegetation type	Global constant (grass)	Dominant low type Dominant high type
Albedo	Annual	Monthly
LAI r_{smin}	Global constants	Dependent on vegetation type
Root depth Root profile	1 m Global constant	Dependent on vegetation type

High vegetation fraction at T511



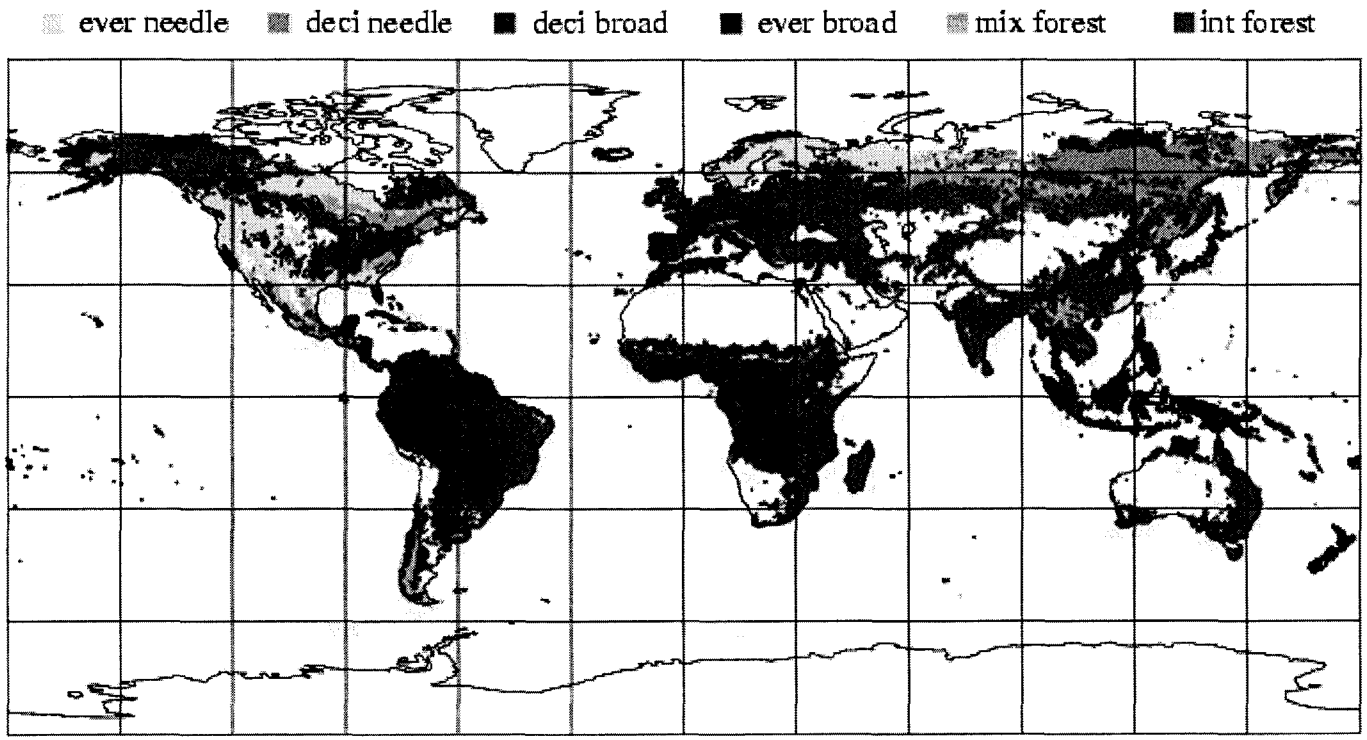
Aggregated from GLCC 1km

Low vegetation fraction at T511



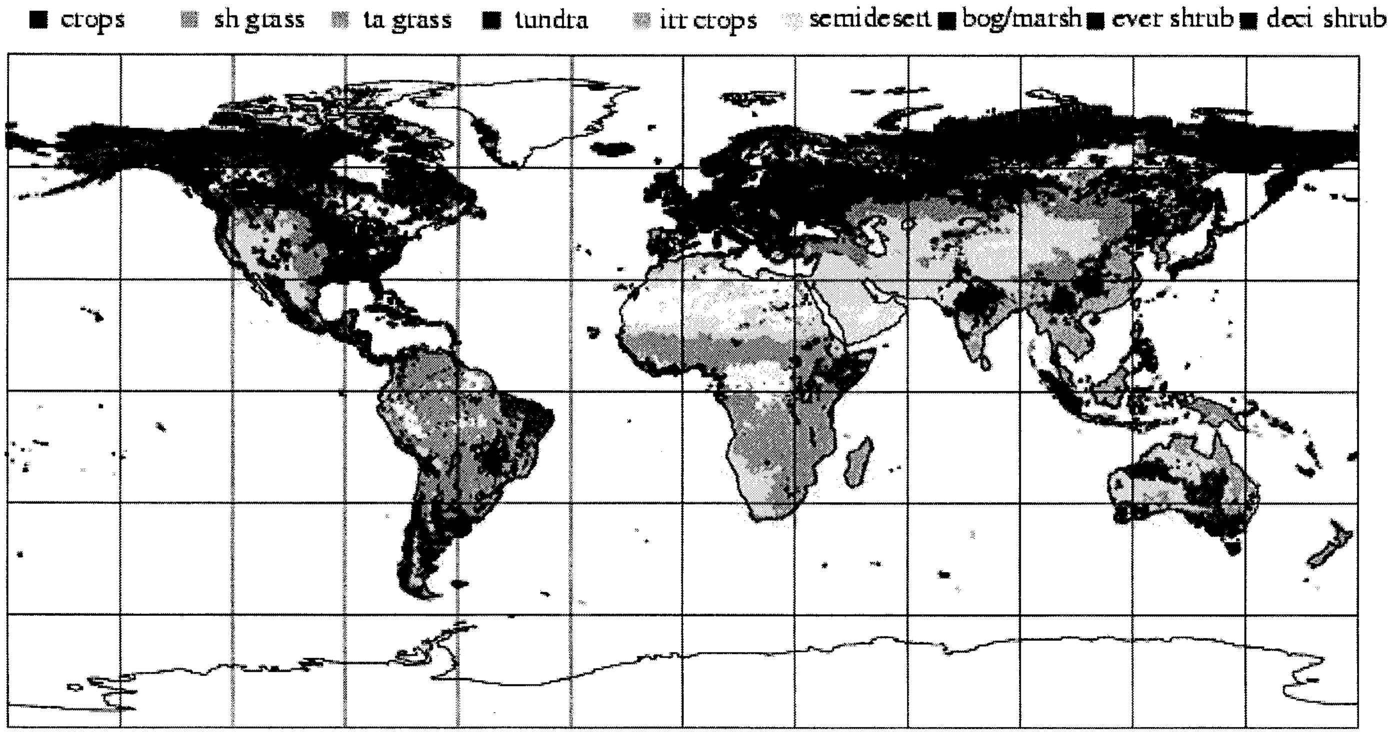
Aggregated from GLCC 1km

High vegetation type at T511



Aggregated from GLCC 1km

Low vegetation type at T511



Aggregated from GLCC 1km

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Ground heat flux

In the absence of phase changes, heat conduction in the soil obeys a Fourier law

$$(\rho C)_g \frac{\partial T_s}{\partial t} = -\frac{\partial G}{\partial z} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z}$$

$(\rho C)_g$ **Soil volumetric heat capacity**

λ_T **Thermal conductivity**

$k = \frac{\lambda_T}{(\rho C)_g}$ **Thermal diffusivity**

For an homogeneous soil,

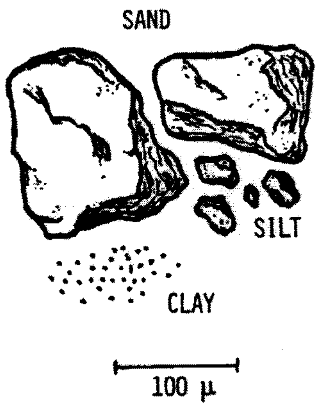
$$\frac{\partial T_s}{\partial t} = k \frac{\partial^2 T}{\partial z^2}$$

Boundary conditions:

- **Top** **Net surface heat flux**
- **Bottom** **No heat flux OR prescribed climate**

Soil science miscellany (1)

- **The soil is a 3-phase system, consisting of**
  - **minerals and organic matter** — **soil matrix**
  - **water** — **condensate (liquid/solid) phase**
  - **moist air trapped** — **gaseous phase**
- **Texture - the size distribution of soil particles**



Hillel 1982

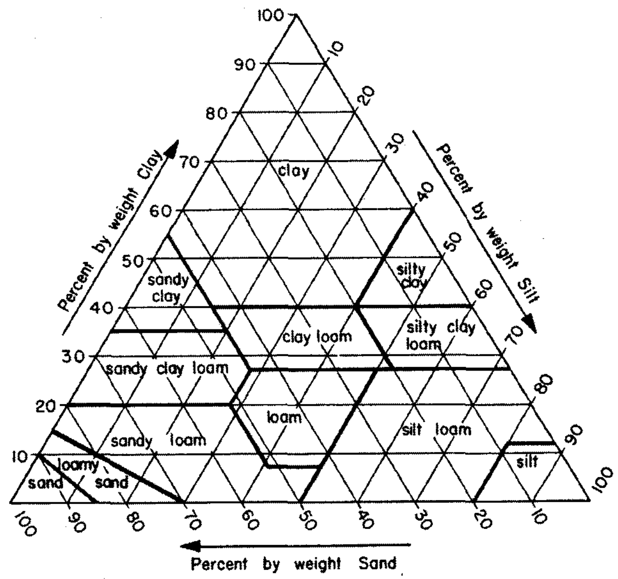


Fig. 3.5. Textural triangle, showing the percentages of clay (below 0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2.0 mm) in the basic soil textural classes.

Soil science miscellany (2)

- **Structure - The spatial organization of the soil particles**
- **Porosity - (volume of maximum air trapped)/(total volume)**

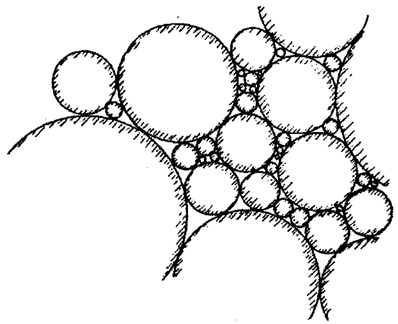
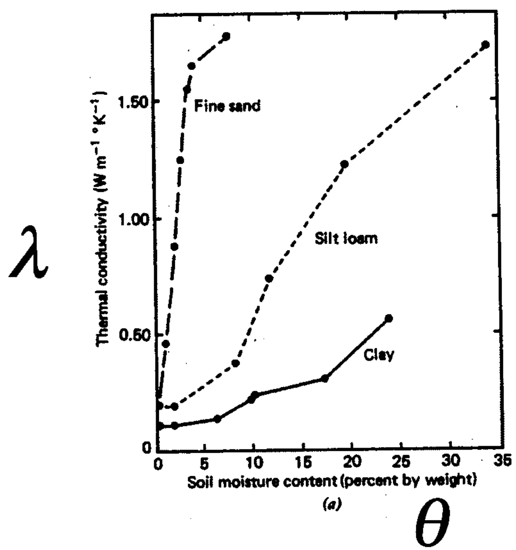


Fig. 4.1. Packing of polydisperse particles (hypothetical).

Hillel 1982

- **Composition**
- **Water content**

Soil properties



Rosenberg et al 1983

Table 4.1
Molecular Thermal Properties of Natural Materials[a]

Material	Condition	Mass density ρ ($kg\ m^{-3} \times 10^3$)	Specific heat c ($J\ kg^{-1}\ K^{-1} \times 10^3$)	Heat capacity C ($J\ m^{-3}\ K^{-1} \times 10^6$)	Thermal conductivity k ($W\ m^{-1}\ K^{-1}$)	Thermal diffusivity α_h ($m^2\ sec^{-1} \times 10^{-6}$)
Air	20°C, Still	0.0012	1.00	0.0012	0.026	21.5
Water	20°C, Still	1.00	4.19	4.19	0.58	0.14
Ice	0°C, Pure	0.92	2.10	1.93	2.24	1.16
Snow	Fresh	0.10	2.09	0.21	0.08	0.38
Sandy soil	Dry	1.60	0.80	1.28	0.30	0.24
(40% pore space)	Saturated	2.00	1.48	2.98	2.20	0.74
Clay soil	Dry	1.60	0.89	1.42	0.25	0.18
(40% pore space)	Saturated	2.00	1.55	3.10	1.58	0.51
Peat soil	Dry	0.30	1.92	0.58	0.06	0.10
(80% pore space)	Saturated	1.10	3.65	4.02	0.50	0.12

[a] After Oke (1987).

Arya 1988

Diurnal cycle of soil temperature

winter

summer

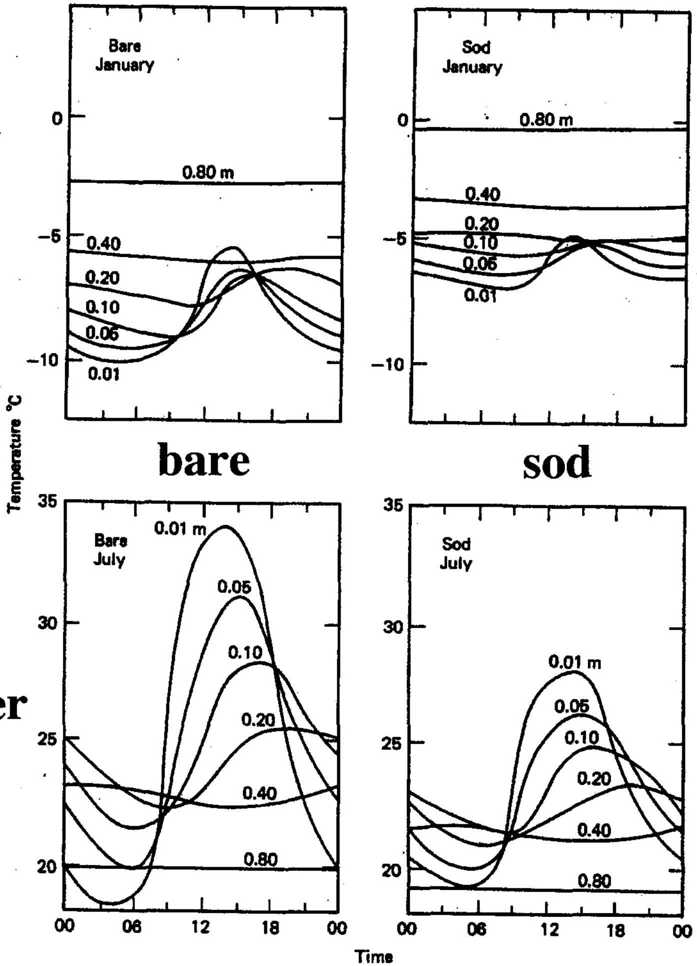
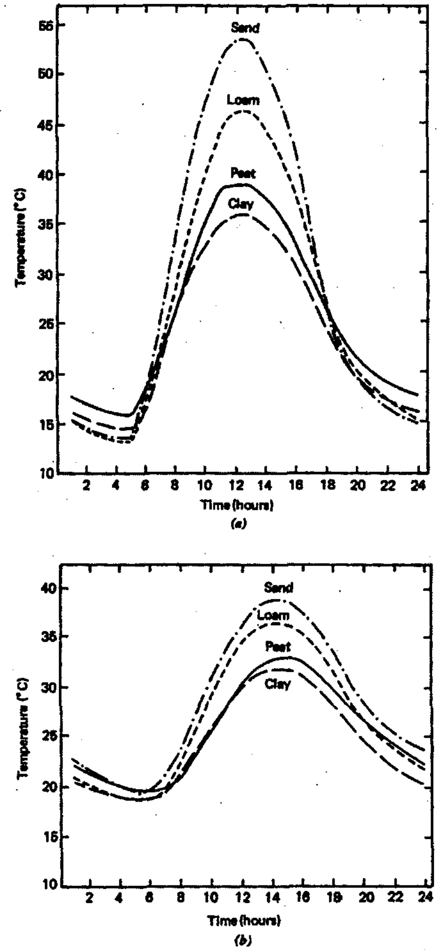


Fig. 2.2 Average hourly soil temperature under bare and sod-covered soil at St. Paul, Minnesota in January (top) and July (bottom). Soil depth is shown in m (after Baker, 1965).

summer



surface

50 cm depth

Fig. 2.6 Daily course of temperature (*a*) at the surface and (*b*) at a depth of 50 mm on clear summer days at Sapporo, Japan (after Yakuwa, 1946).

Rosenberg et al 1983

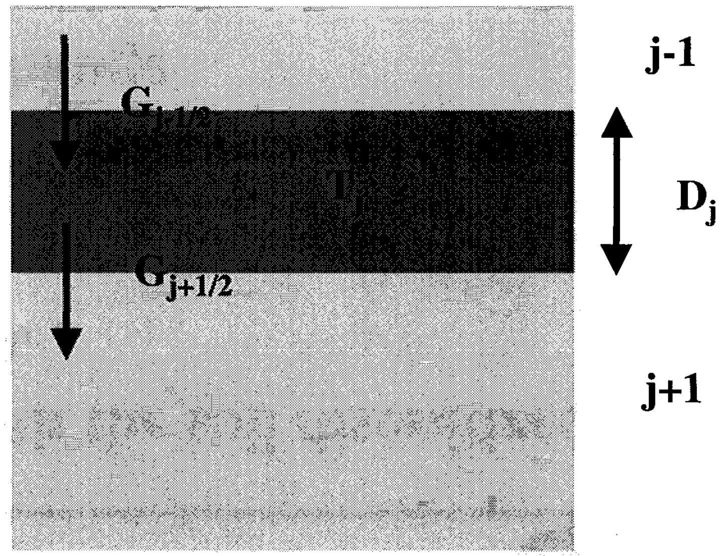
TESSEL

- Solution of heat transfer equation with the soil discretized in 4 layers, depths 7, 21, 72, and 189 cm.
- No-flux bottom boundary condition
- Heat conductivity dependent on soil water
- Thermal effects of soil water phase change

TESSEL soil energy equations

$$\frac{(\rho C)_j}{\Delta t}\left(T_j^{n+1} - T_j^{n}\right) = -\frac{\left(G_{j+1/2}^{n+1} - G_{j-1/2}^{n+1}\right)}{D_j} \qquad j = 1,\ldots,4$$

$$G_{j+1/2}^{n+1} = -\lambda_{T,j+1/2}\,\frac{T_{j+1}^{n+1} - T_j^{n+1}}{0.5\left(D_j + D_{j+1}\right)}$$



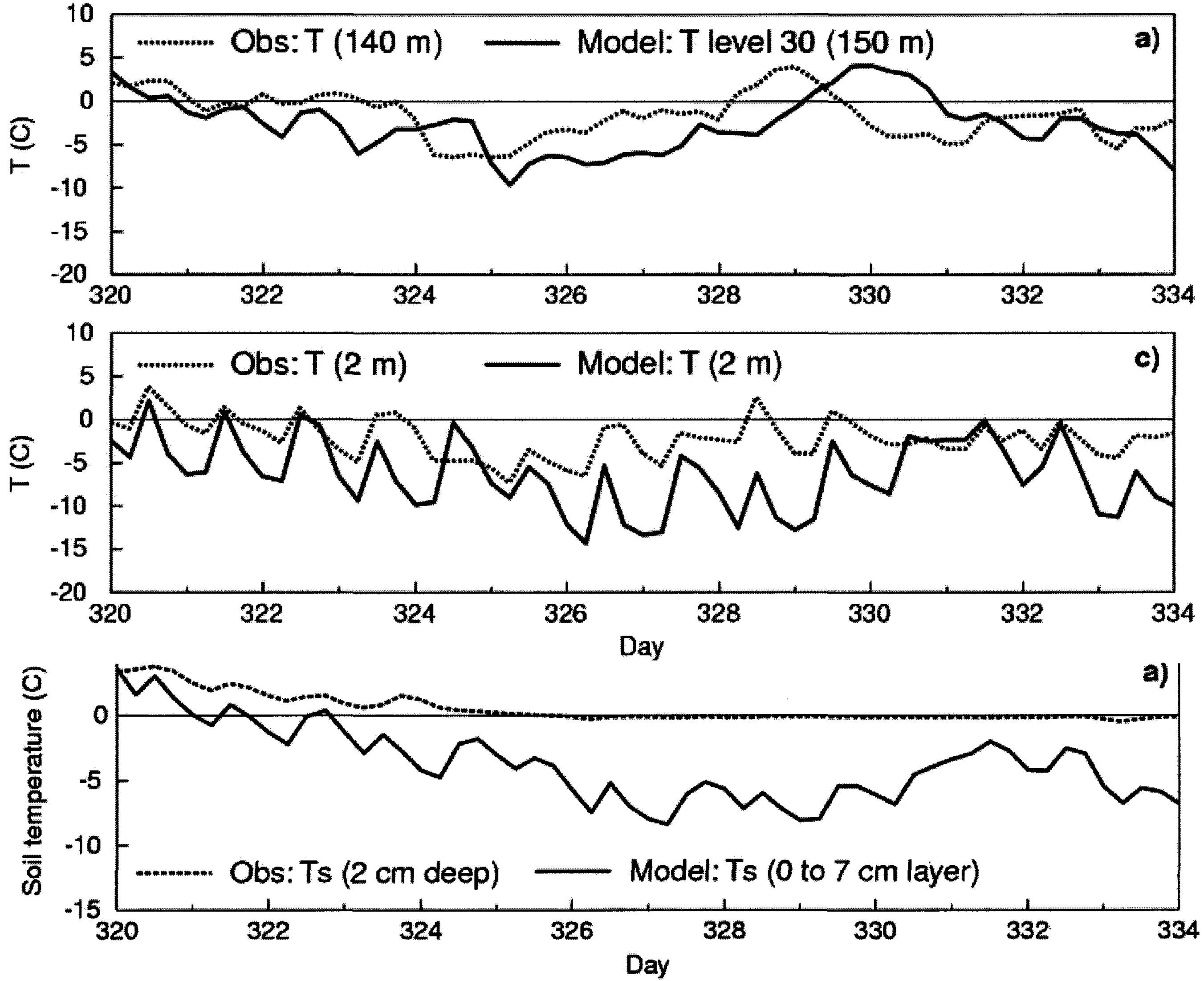
Boundary conditions

$$G_{1/2} = \sum_i \Lambda_{sk,i}\left(T_{sk,i} - T_1\right)$$

$$G_{41/2} = 0$$

Case study: winter (1)

Model vs observations, Cabauw, The Netherlands, 2nd half of November 1994



140 m

2 m

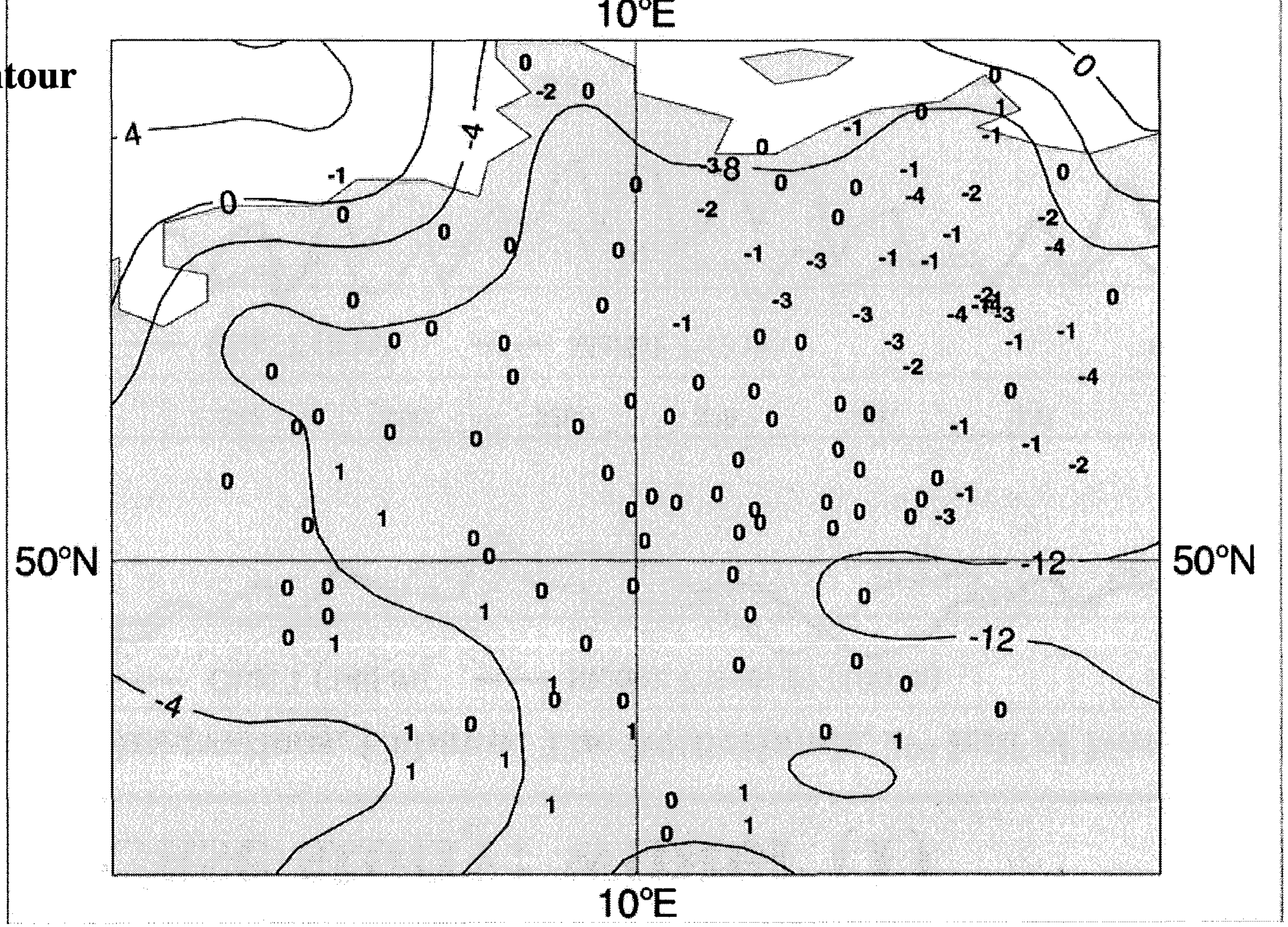
Soil

Case study: winter (2)

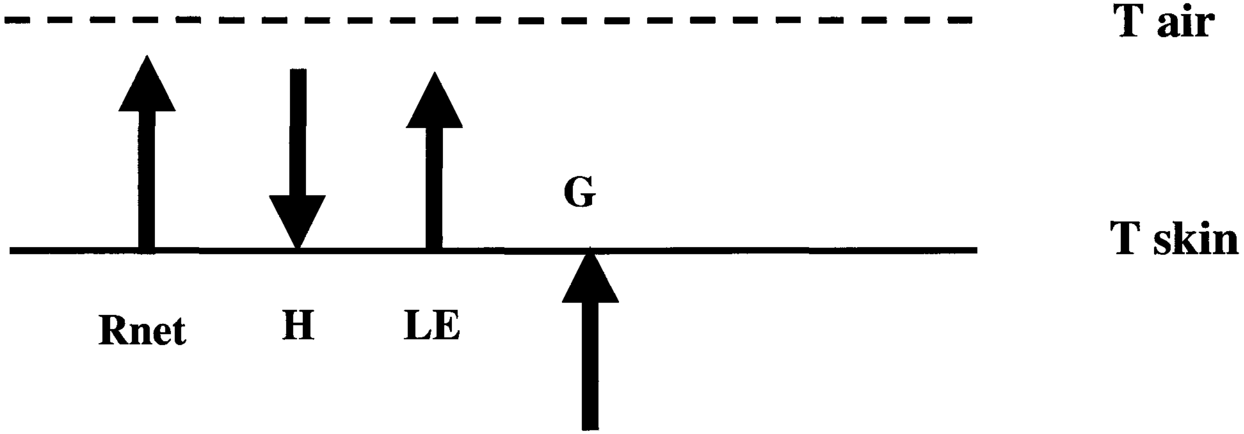
Soil Temperature, North Germany, Feb 1996: Model (28-100 cm) vs OBS 50 cm

Observations: Numbers

Model: Contour



Case study: winter (3)



$$H = \rho C_p \left| U_{air} \right| C_{Hn} f(Ri)(T_{air} - T_{sk})$$

- **Model bias:**
  - Net radiation (Rnet) too large
  - Sensible heat (H) too small
    - But (Tair-Tsk) too large (too large diurnal cycle)
    - Therefore f(Ri) problem
  - Soil does not freeze (soil temperature drops too quickly seasonally)

Stability functions

Soil water freezing

Viterbo, Beljaars, Mahfouf, and Teixeira, 1999: Q.J. Roy. Met. Soc., 125,2401-2426.

Winter: Soil water freezing

Soil heat transfer equation

$$(\rho C)_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z}$$

Winter: Soil water freezing

Soil heat transfer equation

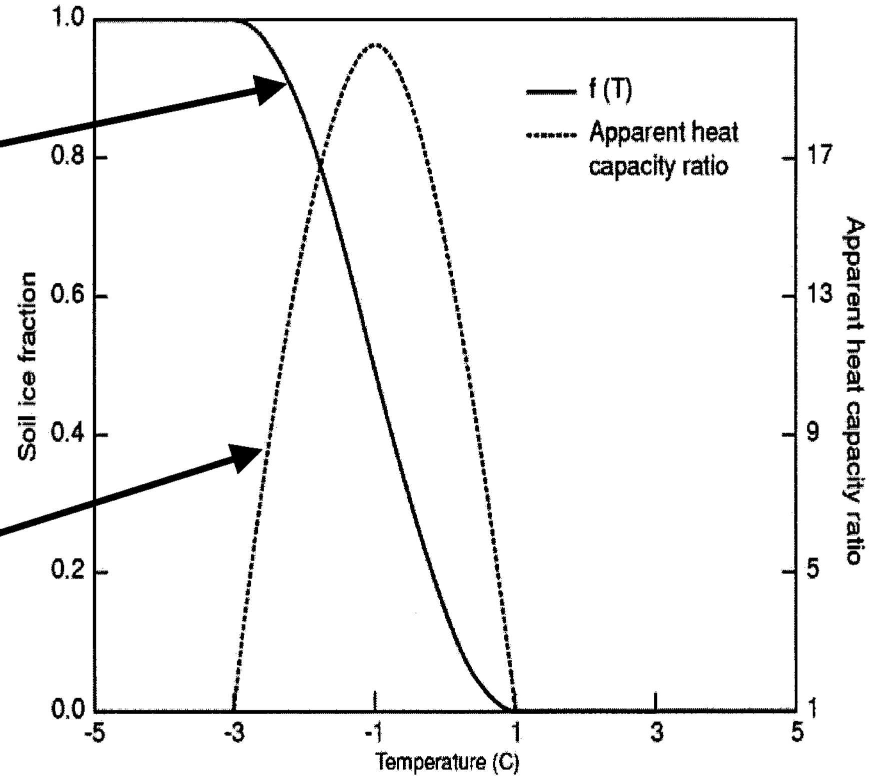
$$(\rho C)_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z} + L_f \rho_w \frac{\partial \theta_I}{\partial t}$$

θ_I **Soil frozen water**

$$\theta_I = \theta_I(T) = f(T)\theta$$

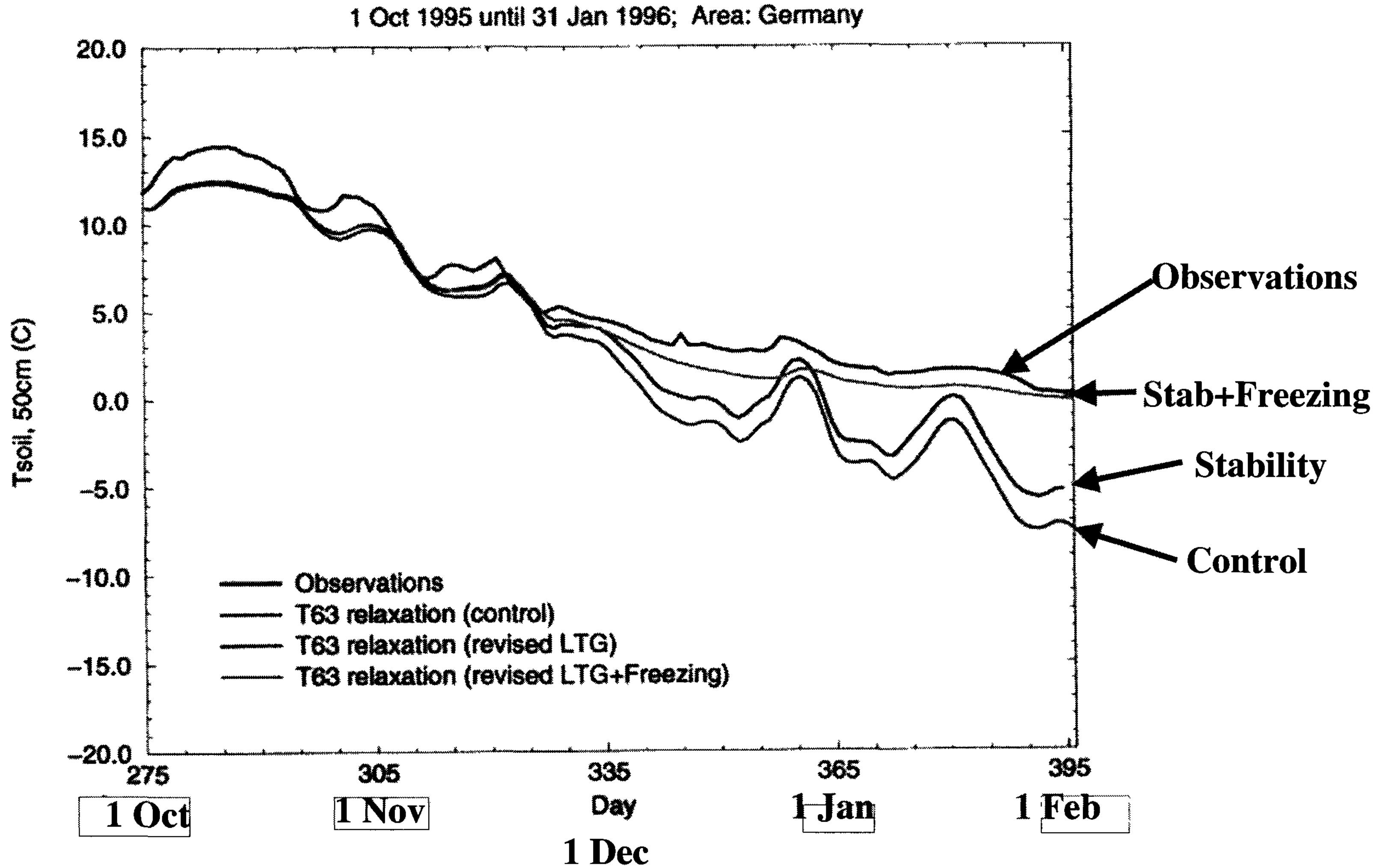
$$\left[(\rho C)_s - L_f \rho_w \theta \frac{\partial f}{\partial T} \right] \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z}$$

Apparent heat capacity

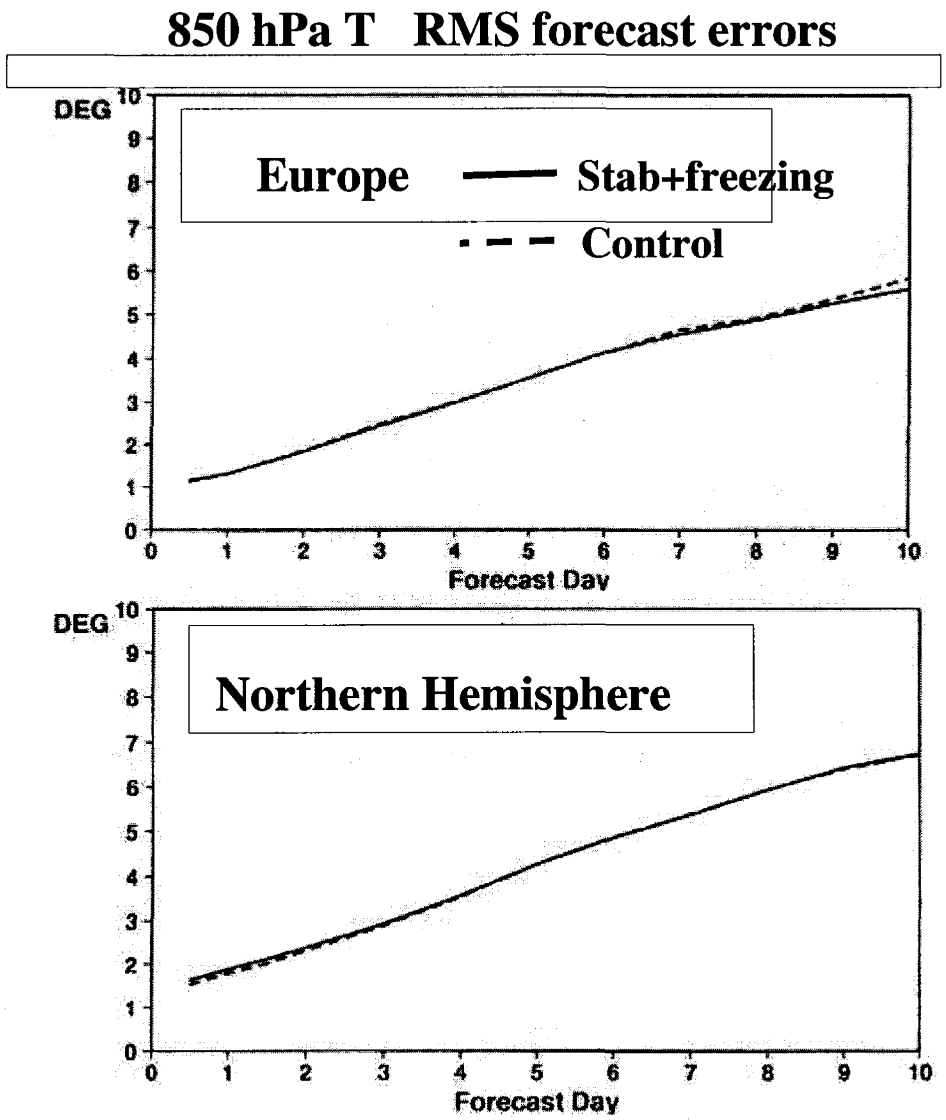


Case study: winter (4)

Germany soil temperature: Observations vs Long model relaxation integrations



Case study: winter (5)



- Soil water freezing acts as a thermal regulator in winter, creating a large thermal inertia around 0 C.
- Simulations with soil water freezing have a near-surface air temperature 5 to 8 K larger than control.
- In winter, stable, situations the atmosphere is decoupled from the surface: large variations in surface temperature affect only the lowest hundred metres and do NOT have a significant impact on the atmosphere.

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Schematics

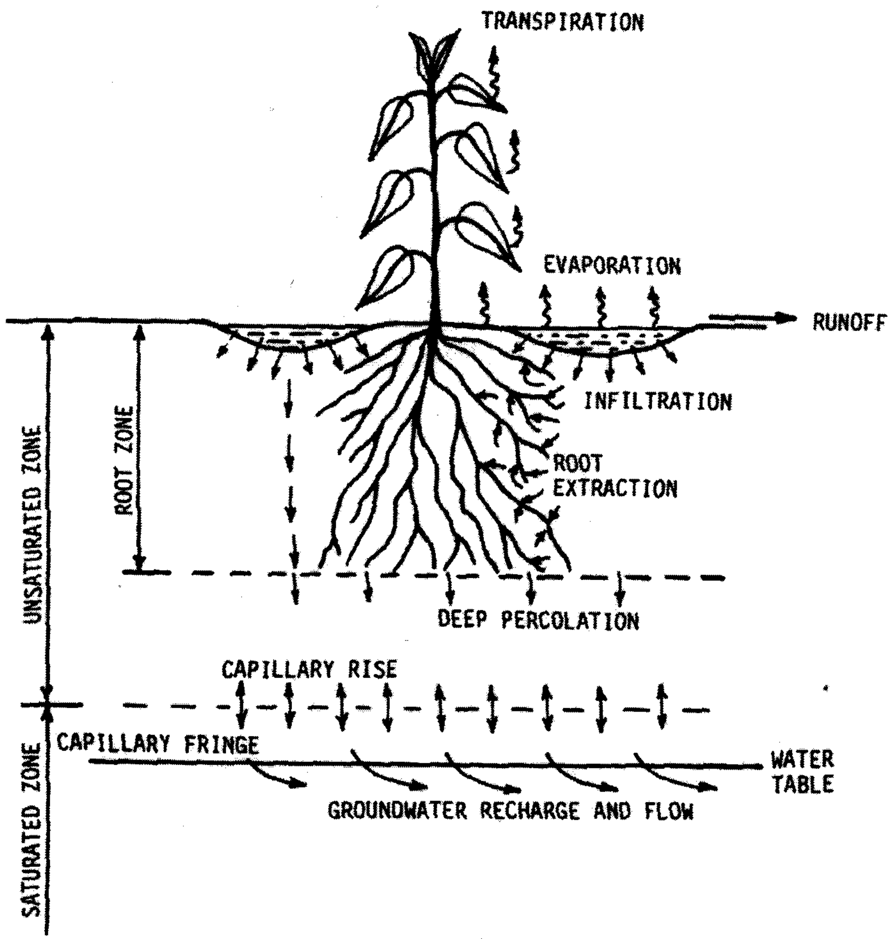


Fig. 17.1. The water balance of a root zone (schematic).

Hillel 1982

$$\rho_w \frac{\partial \theta}{\partial t} = -\frac{\partial F}{\partial z} + \rho_w S_\theta$$

θ soil water $[\;] = m^3 m^{-3}$

F Soil water flux $[\;] = kgm^{-2}s^{-1}$

S_θ Soil water source/sink, ie root extraction

Boundary conditions:

Top See later

Bottom Free drainage or bed rock

Root extraction

The amount of water transported from the root system up to the stomata (due to the difference in the osmotic pressure) and then available for transpiration

Soil water flux

$$F = -\rho_w \left(\lambda \frac{\partial \theta}{\partial z} - \gamma\right)$$

Darcy's law

λ hydraulic diffusivity $[\lambda] = m^2 s^{-1}$

γ hydraulic conductivity $[\gamma] = m s^{-1}$

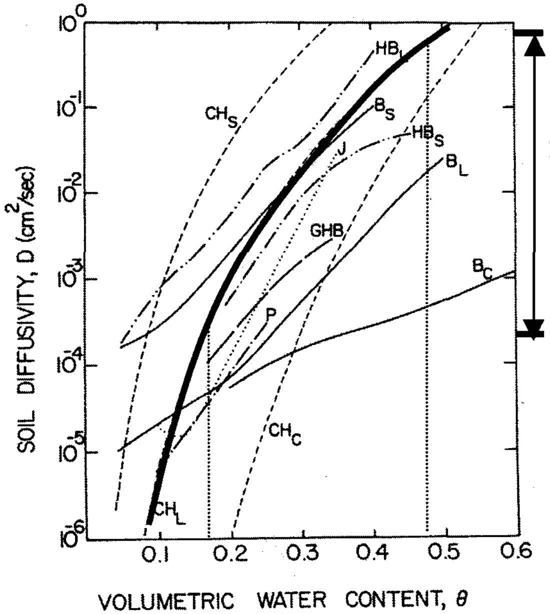


Fig. 2. Examples of the dependence of soil hydraulic diffusivity on volumetric soil water content for loam (HB_L, Hanks and Bowers, 1962); (J, Jackson, 1973); (GHB, Gardner *et al.*, 1970); silt loam (HB_S, Hanks and Bowers, 1962); clay (P, Passioura and Cowan, 1968); results approximated from Gardner (1960) for sand (B_S), loam (B_L), and clay (B_C); relationship from Clapp and Hornberger (1978) for sand (CH_S), loam (CH_L), and clay (CH_C).

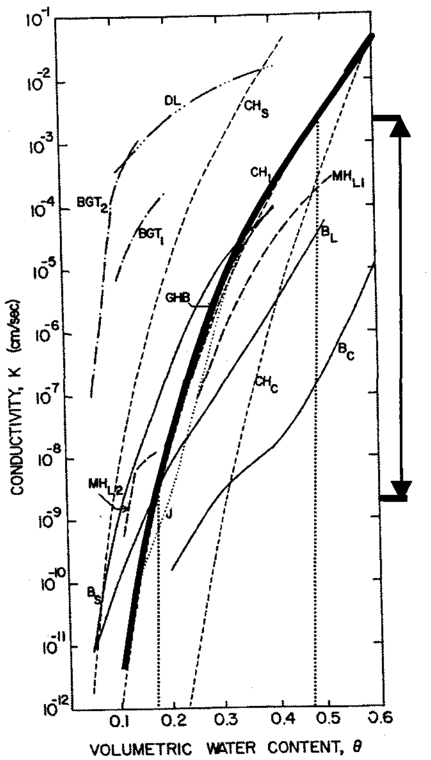


Fig. 3. Examples of the dependence of hydraulic conductivity on volumetric soil water content for sand (DL, Day and Luthin, 1956); (Black *et al.*, 1970, 0–50 cm-BGT_1, 50–150 cm-BGT_2); loam (J, Jackson, 1973); (MH_{L1} and MH_{L2}, Marshall and Holmes, 1979); (GHB, Gardner *et al.*, 1970); results approximated from Gardner (1960) for sand (B_S), loam (B_L), and clay (B_C); relationship from Clapp and Hornberger (1978) for sand (CH_S), loam (CH_L), and clay (CH_C).

Mahrt and Pan 1984

More soil science miscellany

Hillel 1982

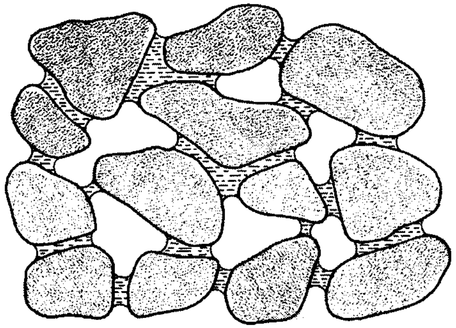


Fig. 7.1. Water in an unsaturated coarse-textured soil.

TABLE I **Jacquemin and Noilhan 1990**

Critical water contents of soils derived from the classification of Clapp and Hornberger (1978): saturated moisture w_{sat}, field capacity w_{fl}, wilting point w_{wilt}. The field capacity is associated with a hydric conductivity of 0.1 mm/day. The wilting point corresponds to a moisture potential of −15 bar

Soil type	w_{sat} (m^3/m^3)	w_{fc} (m^3/m^3)	w_{wilt} (m^3/m^3)
Sand	0.395	0.135	0.068
Loamy sand	0.410	0.150	0.075
Sandy loam	0.435	0.195	0.114
Silt loam	0.485	0.255	0.179
Loam	0.451	0.240	0.155
Sandy clay loam	0.420	0.255	0.175
Silty clay loam	0.477	0.322	0.218
Clay loam	0.476	0.325	0.250
Sandy clay	0.426	0.310	0.219
Silty clay	0.482	0.370	0.283
Clay	0.482	0.367	0.286

- **3 numbers defining soil water properties**
  - **Saturation (soil porosity) Maximum amount of water that the soil can hold when all pores are filled 0.472 m^{3}m^{-3}**
  - **Field capacity "Maximum amount of water an entire column of soil can hold against gravity" 0.323 m^{3}m^{-3}**
  - **Permanent wilting point Limiting value below which the plant system cannot extract any water 0.171 m^{3}m^{-3}**

TESSEL: soil water budget

- Solution of Richards equation on the same grid as for energy
- Clapp and Hornberger (1978) diffusivity and conductivity dependent on soil liquid water
- Free drainage bottom boundary condition
- Surface runoff, but no subgrid-scale variability; It is based on infiltration limit at the top
- One soil type for the whole globe: “loam”

TESSEL soil water equations (1)

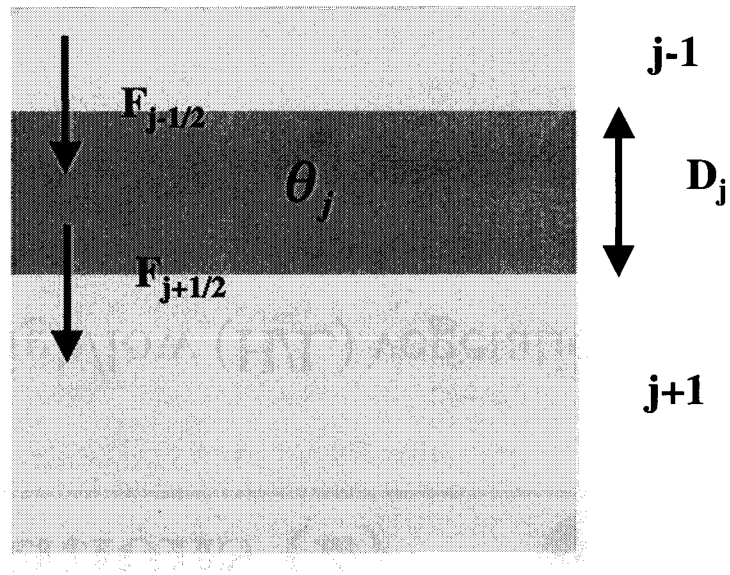
$$\rho_w \frac{\left(\theta_j^{n+1} - \theta_j^n\right)}{\Delta t} = -\frac{\left(F_{j+1/2}^{n+1} - F_{j-1/2}^{n+1}\right)}{D_j} + \rho_w S_{\theta,j} \qquad \mathrm{j}=1,\ldots,4$$

$$F_{j+1/2}^{n+1} = -\rho_w \left(\lambda_{j+1/2} \frac{\theta_{j+1}^{n+1} - \theta_j^{n+1}}{0.5\left(D_j + D_{j+1}\right)} - \gamma_{j+1/2} \right)$$

Boundary conditions

$$F_{1/2} = T - Y_s + E_{1/2}$$

$$F_{41/2} = \rho_w \gamma_{41/2}$$



TESSEL soil water equations (2)

Root extraction at layer j, separate for high/low (H/L) vegetation

$$\left[\rho_w S_{\theta,j}\right]_{H/L} = C_{H/L} \frac{R_{j,H/L}\theta_{j,liq}D_j}{\sum_j R_{j,H/L}\theta_{j,liq}D_j} \qquad j=1,\ldots,4$$

Hydraulic coefficients

$$\gamma = \gamma_{sat}\left(\frac{\theta}{\theta_{sat}}\right)^{2b+3}$$

$$\lambda = \frac{b\gamma_{sat}(-\psi_{sat})}{\theta_{sat}}\left(\frac{\theta}{\theta_{sat}}\right)^{b+2}$$

FIFE: Time evolution of soil moisture

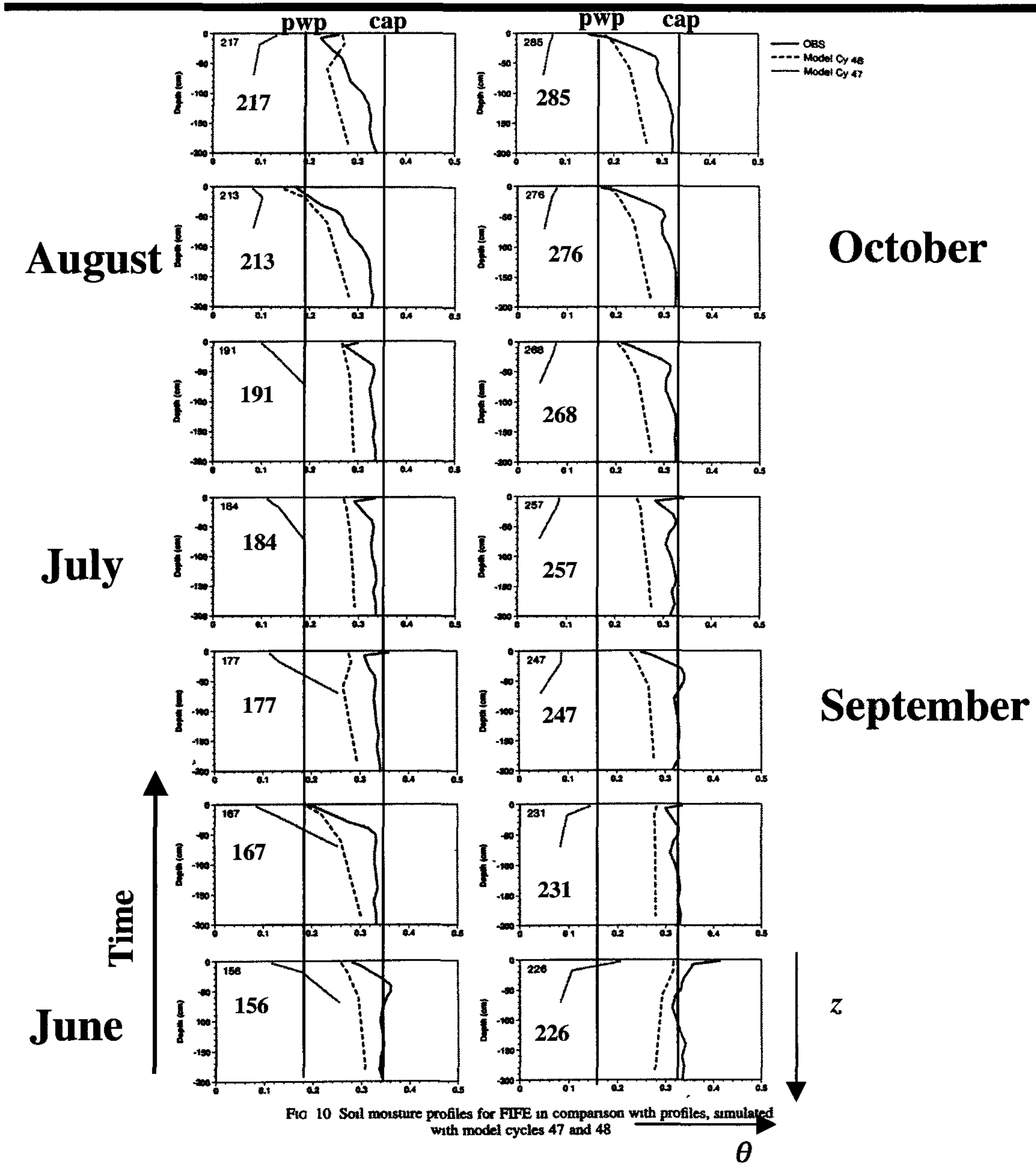


Fig 10 Soil moisture profiles for FIFE in comparison with profiles, simulated with model cycles 47 and 48

Viterbo and Beljaars 1995