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
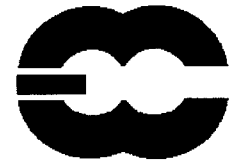# for NWP and Climate: the ECMWF Experience

Lecture 3

<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**
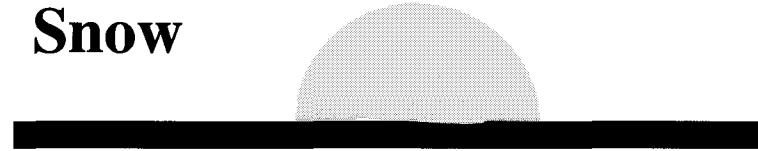- **Initial conditions**
- **Snow**
- **Conclusions and a look ahead**
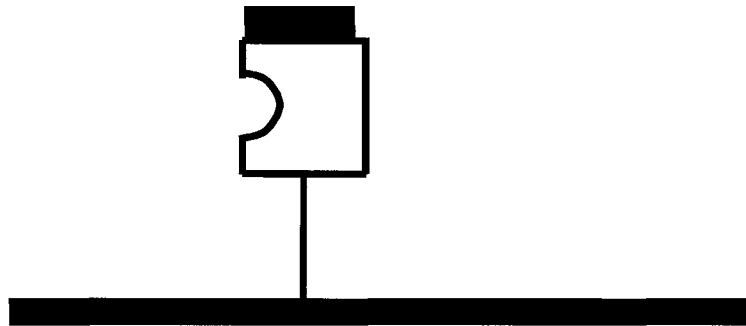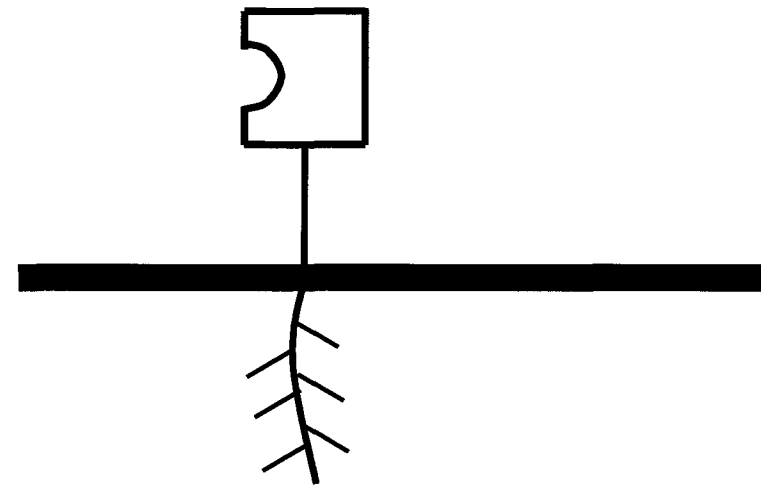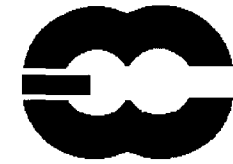
Evaporation: Idealized surfaces
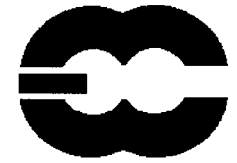
Lake

Snow

Wet vegetation

Dry vegetation

Bare ground

Potential evaporation, bucket model

- **Potential evaporation**
  - The evaporation of a large uniform surface, sufficiently moist or wet (the air in contact to it is fully saturated)

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

- **Evaporation efficiency** $E = \beta E_{pot}$
  - Ratio of evaporation to potential evaporation $0 < \beta < 1$
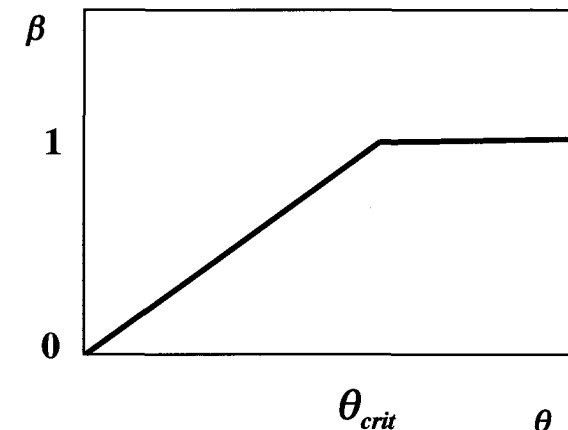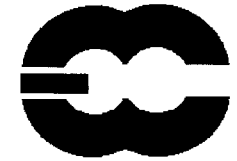
- **Bucket model   Budyko 1963, 1974 Manabe 1969**

$$\beta = \begin{cases} 1 & \theta > \theta_{crit} \\ \dfrac{\theta}{\theta_{crit}} & \theta > \theta_{crit} \end{cases}$$

Ideally, β should be a well defined function of soil cover (vegetation type vs. bare ground) and soil properties

A general, algebraic formulation

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

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

- **Two limit behaviours**
  - Bare soil: Evaporation dependent on soil water (and trapped water vapour) in a top shallow layer of soil (~ 20 mm).
  - Vegetated surfaces: Evaporation controlled by a canopy resistance, dependent on shortwave radiation, water on the root zone (~ 1-5 m deep) and other physical/physiological effects.
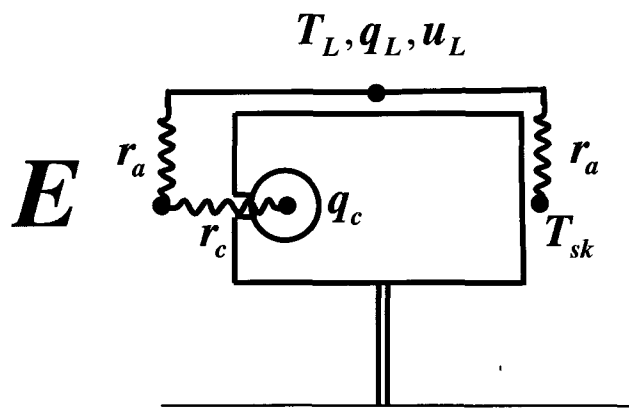
Transipiration: The big leaf approximation
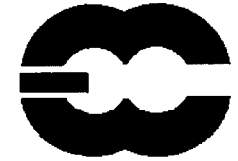
- ## Sensible heat (H), the resistance formulation

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

r_a aerodynamic resistance, $[r_a] = sm^{-1}$

$$r_a = \frac{1}{C_h u_L}$$

- ## Evaporation (E), the resistance formulation (the big leaf approximation, Deardorff 1978, Monteith 1965)
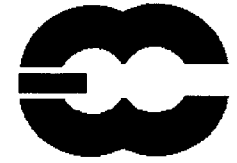
$$T_L, q_L, u_L$$

E

H

$$E = \rho \frac{q_L - q_c}{r_a + r_c} = \rho \frac{q_L - q_{sat}(T_{sk})}{r_a + r_c}$$

$q_c = q_{sat}(T_{sk})$ Specific humidity for the interior of the stomata, ie, for saturated conditions

r_c canopy resistance

Some plant science

$$r_c = \frac{\langle r_s \rangle}{L}$$

$$\langle (\ ) \rangle = \frac{L}{\int dL/(\ )}$$

L Leaf area index (see later for a definition)

- r_s, the stomatal resistance of a single leaf. Physiological control of water loss by the vegetation. Stomata (valve-like openings) regulate the outflow of water vapour (assumed to be saturated in the stomata cells) and the intake of CO_2 from photosynthesis. The energy required for the opening is provided by radiation (Photosynthetically Active Radiation, PAR). In many environments the system appears to be operate in such a way to maximize the CO_2 intake for a minimum water vapour loss. When soil moisture is scarce the stomatal apertures close to prevent wilt and dessication of the plant.

Jarvis approach(1)
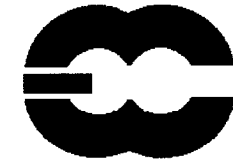
$$r_c = r_{c\min} f_1(PAR) f_2(T_s) f_3(D_a) f_4(\theta)$$

T_s soil temperature

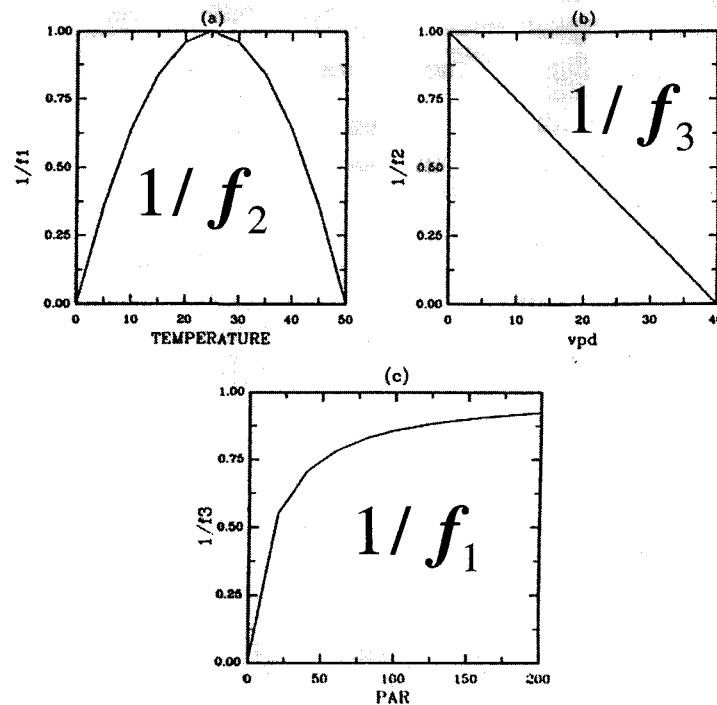$D_a = e_{sat}(T_a) - e$ near - surface saturation deficit

$f_i > 1$

Fig. 4. Environmental dependencies of the inverse of stomatal resistances (i.e. conductance) in BATS model: (a) dependence of conductance on temperature; (b) dependence of conductance on vapor pressure deficit; (c) dependence of conductance on PAR.

Dickinson et al 1991
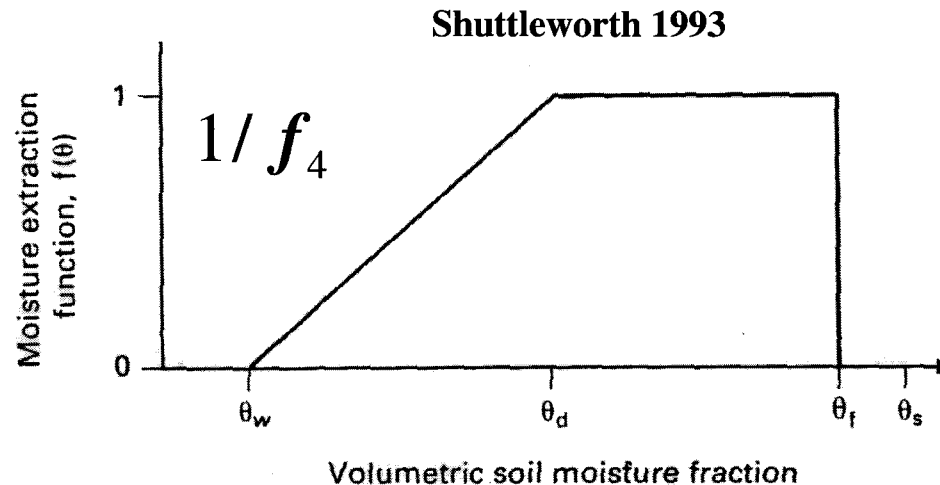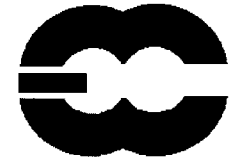
Jarvis approach(2)

FIGURE 4.4.3 Typical variation of the moisture extraction function $f(\theta)$ which modifies the potential crop coefficient in response to changes in the volumetric soil moisture content θ in (portions of) the plants' rooting zone. θ_s, θ_f, and θ_w are the values of θ at saturation, field capacity, and wilting point, respectively, and (θ_d/θ_f) is typically 0.5 to 0.8. These values are determined by soil type.
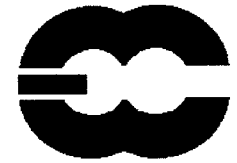
θ soil water in the root zone

$\theta_d = \theta_{cap}$ in many models (ECMWF)

$\theta_{ava} = \theta_d - \theta_{pwp}$ availability

$\theta_{ava} \cdot d$ available soil water (water holding capacity)

Bare ground evaporation

- **Soil (bare ground) evaporation is due to:**
  - Molecular diffusion from the water in the pores of the soil matrix up to the interface soil atmosphere (z_{0q})
  - Laminar and turbulent diffusion in the air between z_{0q} and screen level height

- **All methods are sensitive to the water in the first few cm of the soil (where the water vapour gradient is large). In very dry conditions, water vapour inside the soil becomes dominant**
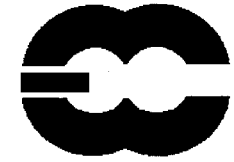
α method

$$E = \rho \frac{q_L - \alpha q_{sat}(T_{sk})}{r_a}$$

$\alpha = f(\theta_1)$ "Relative humidity of the soil"

θ_1 Top soil layer (a few cm) water

TESSEL transpiration

i is the high/low vegetation tile

$$E_i = \frac{\rho_a}{r_{c,i} + r_{a,i}} \left[q_a - q_{sat}(T_{sk,i})\right]$$

$$r_c = \frac{r_{s,min}}{LAI} f_1\left(R_S^\downarrow\right) f_3\left(\overline{\theta}\right) f_4(D_a)$$
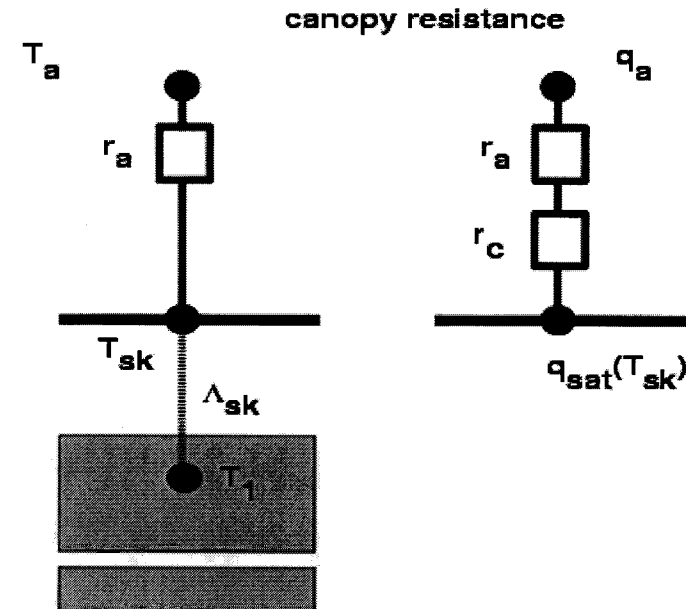
$$f_1\left(R_S^\downarrow\right)^{-1} = \min\left[1, \frac{a\left(1 + bR_S^\downarrow\right)}{bR_S^\downarrow + c}\right]$$

$$f_4(D_a)^{-1} = \exp(-g_D D_a)$$

$g_D = 0$ for low vegetation

$$f_3\left(\overline{\theta}\right)^{-1} = \begin{cases} 0 & \overline{\theta} < \theta_{pwp} \\ \dfrac{\overline{\theta} - \theta_{pwp}}{\theta_{cap} - \theta_{pwp}} & \theta_{pwp} < \overline{\theta} < \theta_{cap} \\ 1 & \overline{\theta} > \theta_{cap} \end{cases}$$
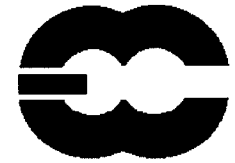
$\overline{\theta}$ is a root weighted average of the liquid soil water

canopy resistance

T_a q_a

r_a r_a

r_c

T_{sk} $q_{sat}(T_{sk})$

Λ_{sk}

T_1

TESSEL root profile

Integrated root fraction

1–19 BATS+Zeng et al. Solid: low veg Dash: High veg

Legend:
- 1 Crops, mixed farming
- 2 Short grass
- 3 Evergreen Needleleaf Trees
- 4 Deciduous Needleleaf Trees
- 5 Deciduous Broadleaf Trees
- 6 Evergreen Broadleaf Trees
- 7 Tall Grass
- 8 Desert
- 9 Tundra
- 10 Irrigated Crops
- 11 Semidesert
- 16 Evergreen Shrubs
- 17 Deciduous Shrubs
- 18 Mixed Forest
- 19 Interrupted Forest

Y-axis: Root fraction (0–1)
X-axis: Depth (m)
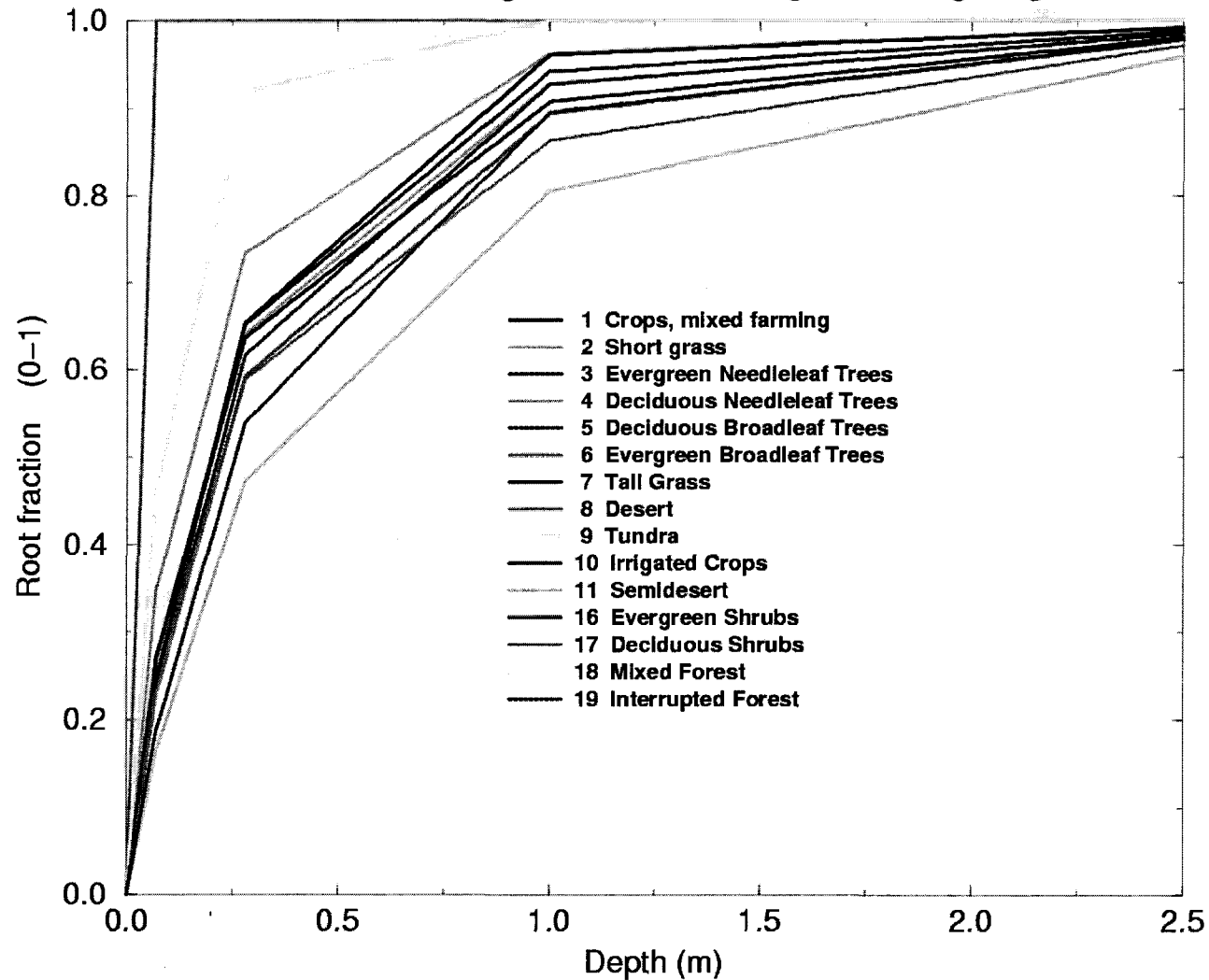
# TESSEL evaporation: shaded snow

i   is the shaded snow tile

$$E = E_{veg} + E_{snow}$$

$$E_{snow} = \frac{\rho_a}{r_{a,s} + r_a} \left[q_a - q_{sat}(T_{sn}) \right]$$
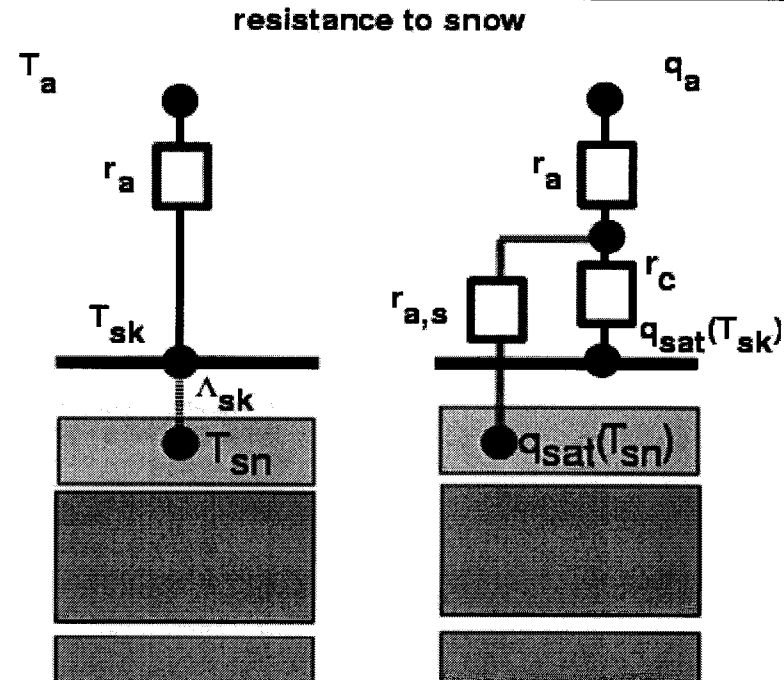
- **Evaporation is the sum of the contribution of the snow underneath (with an additional resistance, $r_{a,s}$,to simulate the lower within canopy wind speed) and the exposed canopy. The former is dominant in early spring (frozen soils) and the latter is dominant in late spring.**
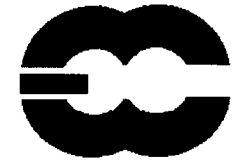
TESSEL bare ground evaporation
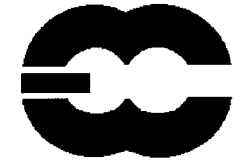
i is the bare ground tile

$$E_i = \frac{\rho_a}{r_{soil} + r_{a,i}} \left[q_a - q_{sat}(T_{sk,i}) \right]$$

$$r_{soil} = r_{soil,min} f_3(\theta_1)$$

$$f_3(\theta_1)^{-1} = \begin{cases} 0 & \theta_{1,liq} < \theta_{pwp} \\ \dfrac{\theta_{1,liq} - \theta_{pwp}}{\theta_{cap} - \theta_{pwp}} & \theta_{pwp} < \theta_{1,liq} < \theta_{cap} \\ 1 & \theta_{1,liq} > \theta_{cap} \end{cases}$$

Interception (1)

- Interception layer represents the water collected by interception of precipitation and dew deposition on the canopy leaves (and stems)

- Interception (I) is the amount of precipitation (P) collected by the interception layer and available for "direct" (potential) evaporation. I/P ranges over 0.15-0.30 in the tropics and 0.25-0.50 in mid-latitudes.

- Leaf Area Index (LAI) is (total area of leaf surface)/(projected area) $0.1 < LAI < 6$

- Two issues
  - Size of the reservoir
  - C_l, fraction of a gridbox covered by the interception layer

- T=P-I; Throughfall (T) is precipitation minus interception

Interception: Canopy water budget
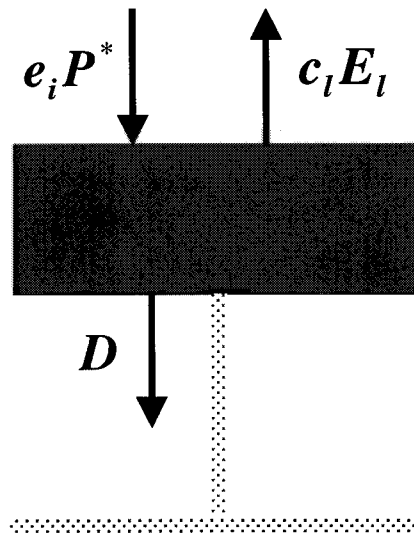
$$\frac{\partial w_l}{\partial t} = e_i P^* + c_l E_l + D = I + c_l E_l$$
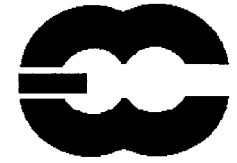
w_l Intercepted water

e_i efficiency of interception

P^* modified precipitation

$c_l E_l$ evaporation of intercepted water

D rate of drainage at the bottom of the canopy

TESSEL: interception

- **Interception layer for rainfall and dew deposition**
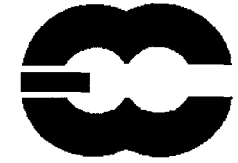
$$\frac{\partial w_l}{\partial t} = I + c_l E_l$$

$$I = max\left(e_i c_l P^*, \frac{w_{lmx} - w_l^n}{\Delta t} \right)$$

$P^* = P / k$ modified precipitation

k fraction of grid - box covered by precipitation

$T = P - I$ Throughfall (input to top soil)

Example: Deep tropics interception

a) Arme 1983-1985 One column simulation
Time integrated quantities

Interception

Interception
CY48
CY47

Evaporation
CY48
PMR
CY47

Evaporation

DAY
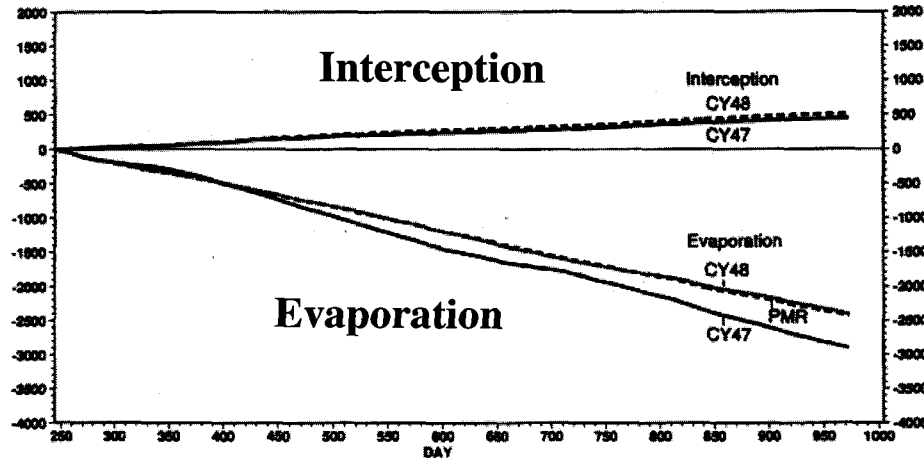
ARME, 1983-1985, Amazon forest
Accumulated water fluxes

b) Arme 1983-1985 One column simulation
Time integrated quantities

Interception

CY48
CY47

DAY
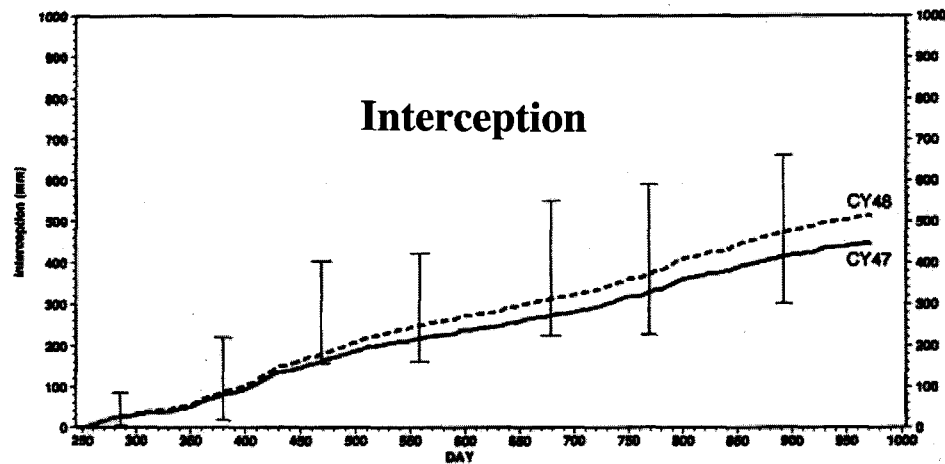
FIG. 17. Accumulated interception and evaporation for ARME with model cycles 47 and 48. Curve PMR is an estimation of evaporation from the Penman-Monteith-Rutter model as described by Shuttleworth (1988) with some improvements by Dolman et al. (1991). The accumulated interception is repeated in panel (b), notice the different scale, in comparison with the range of observations (error bars) as published by Sellers et al. (1989).
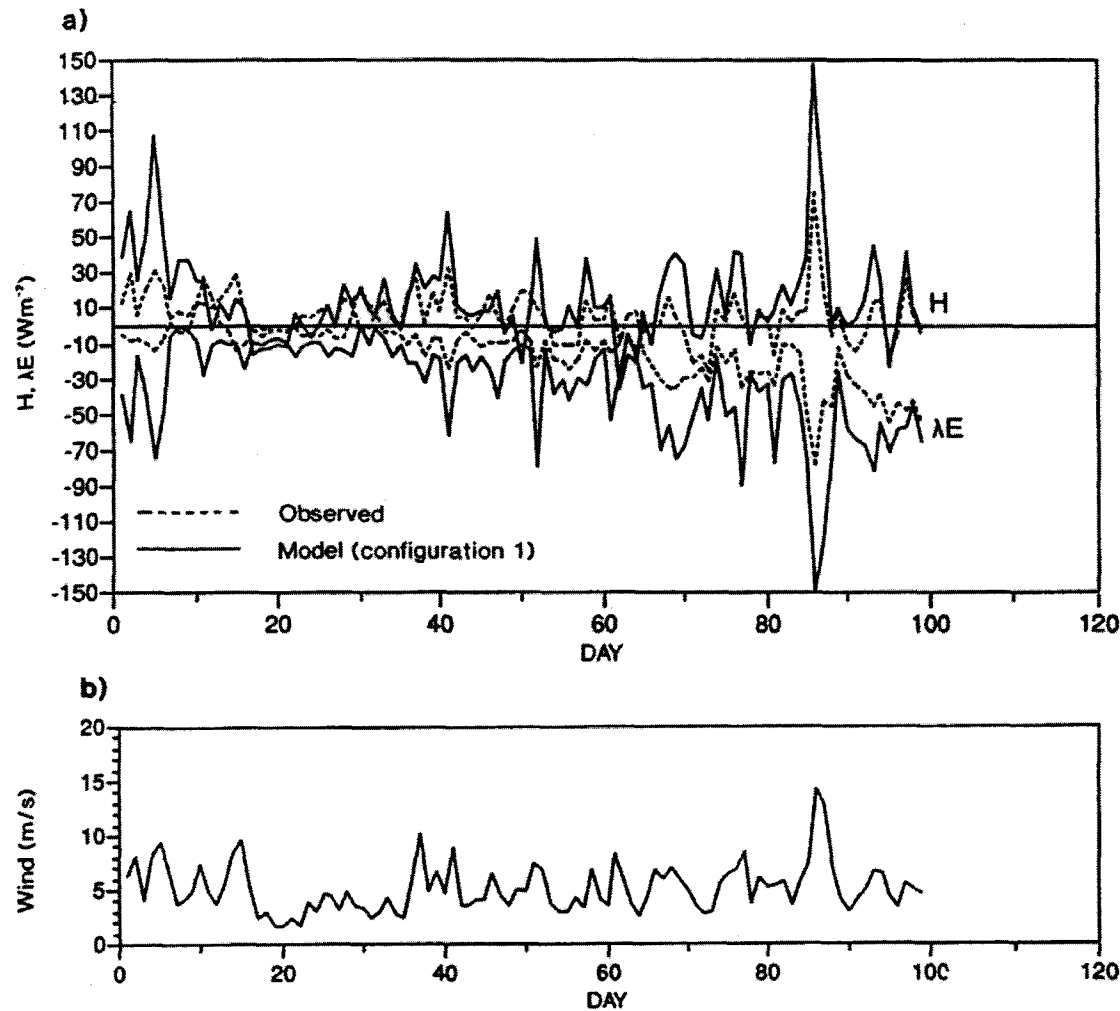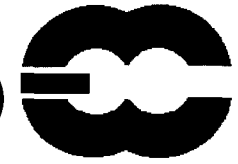
Viterbo and Beljaars 1995

Case study: Aerodynamic resistance (1)
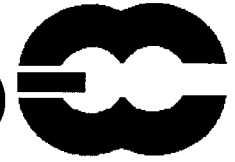
- Cabauw (Netherlands), is a grass covered area, where multi-year detailed boundary layer measurements have been taken
- Observations were used to force a stand-alone version of the surface model for 1987
- The first model configuration tried had $z_{0h}=z_{0m}$

Case study: Aerodynamic resistance (2)

a)

Beljaars and Viterbo 1994

b)

Fig. 2. Observed (dashed) and simulated (solid) diurnal averages of sensible and latent heat (Figure 2a). The wind speed is shown in Fig 2b.
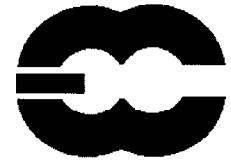
Case study: Aerodynamic resistance (3)
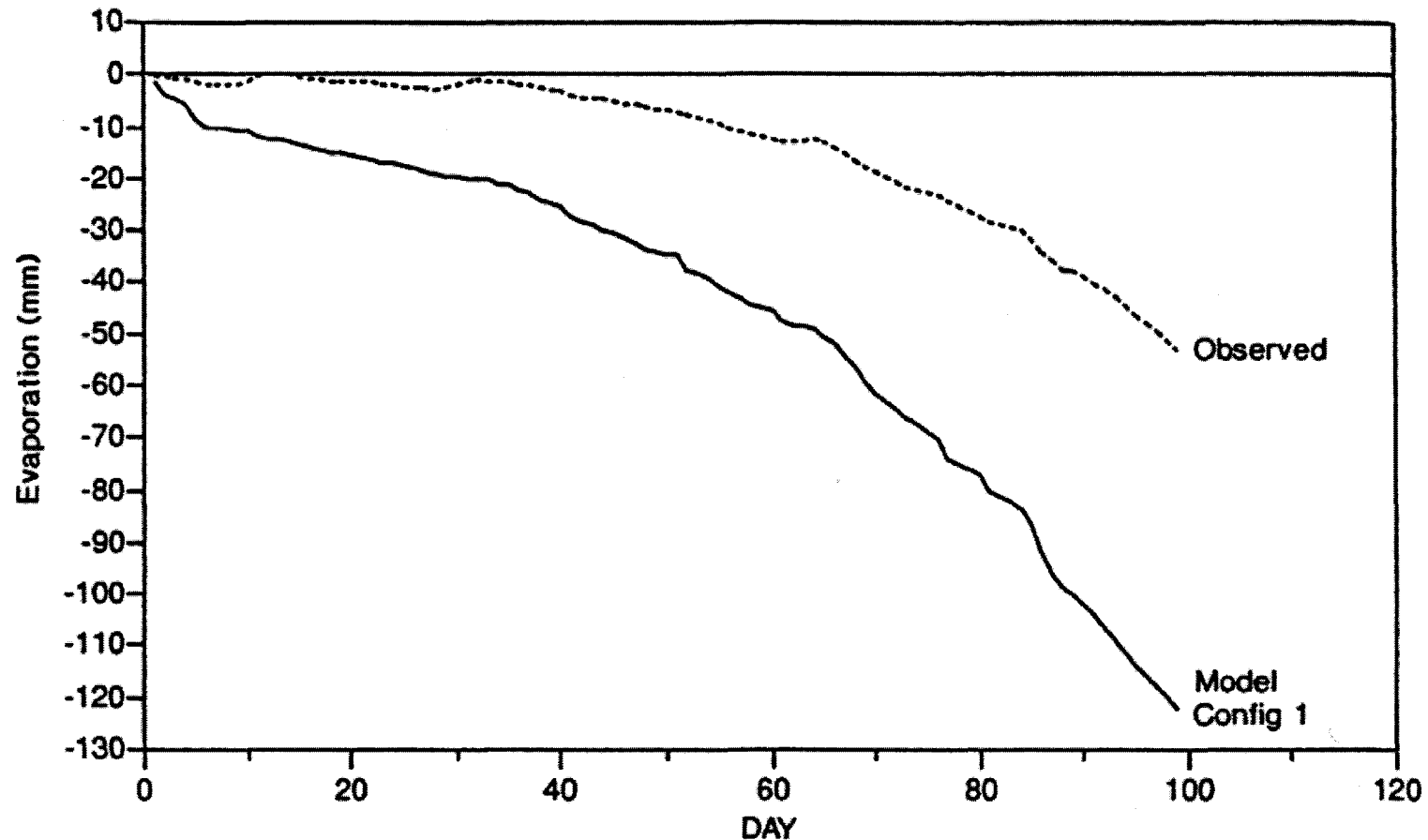
Fig. 3. Time-integrated evaporation (in mm water; upward flux is negative), observed (dashed) and simulated (configuration 1, solid) for the first 100 days of 1987 of the Cabauw data set.

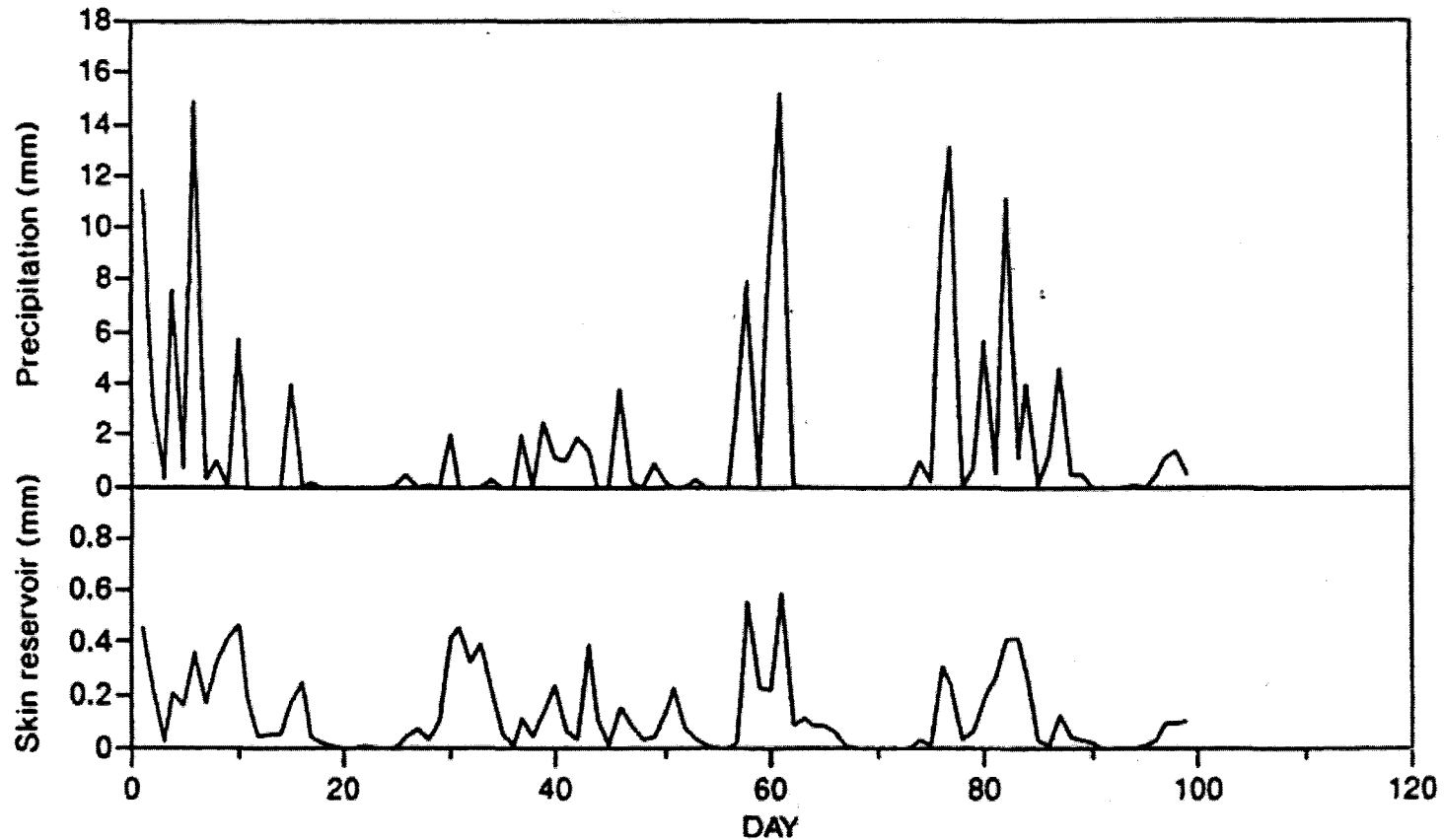# Case study: Aerodynamic resistance (4)

Fig. 4. Day sums of precipitation (observed, a) and diurnal average of skin reservoir content as simulated by the model in configuration 1 (b).
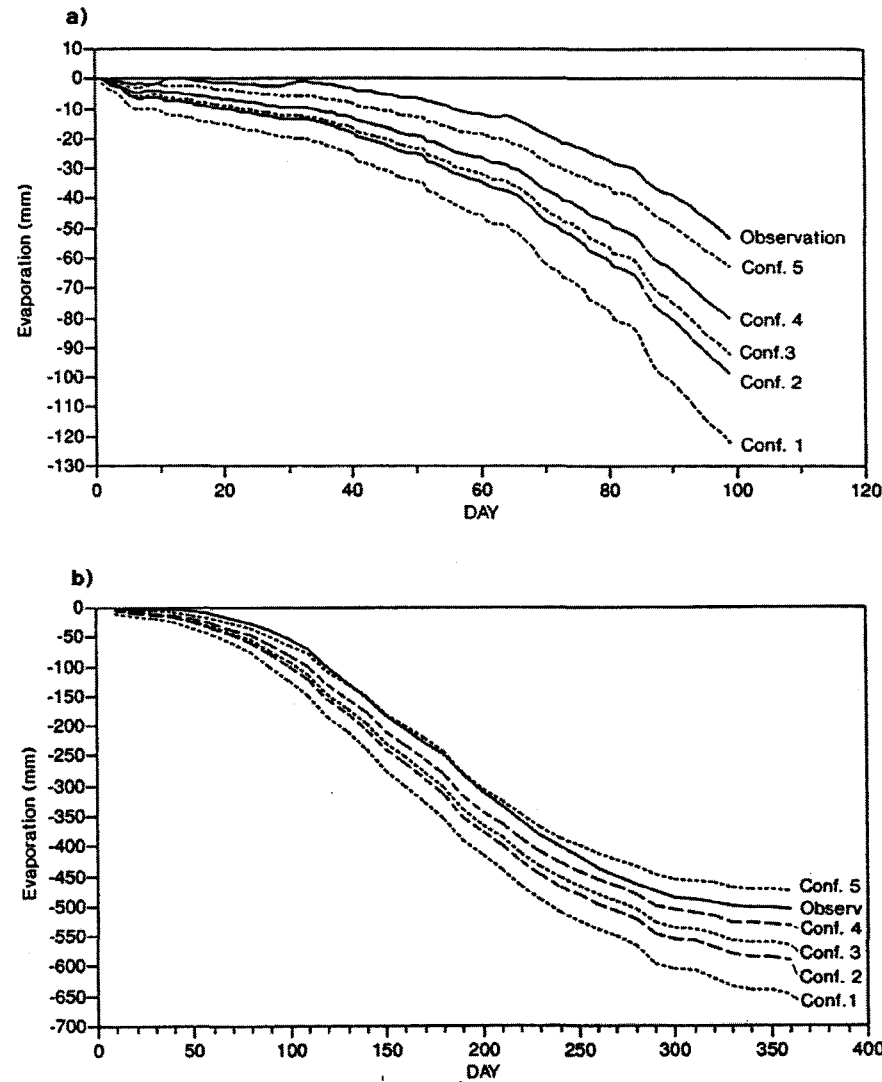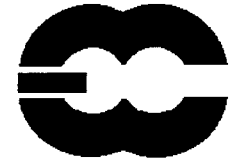
Case study: Aerodynamic resistance (5)

a)

b)

TABLE I

Parameters in the different model simulations

Model configuration	z_{0m} (m)	z_{0h} (m)
1	0.4	0.4
2	0.4	0.033
3	0.1	0.1
4	0.1	0.01
5	0.1	0.0001

Fig. 5. Accumulated evaporation as observed and simulated with different model configurations (see Table 1) for the first 100 days of 1987 (a) and for the entire year (b).
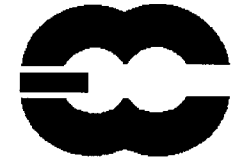
Runoff and infiltration

$$I_f = T - Y$$

I_f infiltration

T throughfall

Y runoff

- **Infiltration is that part of the precipitation flux that contributes to wet the soil**
- **Runoff occurs in**
  - Parts of the watershed where hydraulic conductivities are lowest (Horton mechanism, in upslope areas)
  - Parts of the watershed where the water table is shallowest (Dunne mechanism, in near channel wetlands)
- **Runoff depends on orography, nature and moisture state of the soil, precipitation intensity, and sub-grid scale variations of all these parameters**
- **Runoff in NWP/climate models should be called runoff generation (upon application of a routeing algorithm, it becomes "runoff")**

TESSEL: runoff generation

- Surface runoff is based on a maximum infiltration limit concept, but with no sub-grid scale variability of either the precipitation flux or the top soil water content. Physically, it is the Hortonian concept, but applied at the wrong spatial scales (the model grid-box)

- Deep runoff is free drainage at the bottom

- All computations are performed with soil liquid water only. The frozen fraction of the surface is impervious to vertical water fluxes

Layout
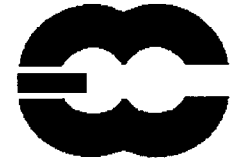
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- **Initial conditions**
- **Snow**
- **Conclusions and a look ahead**

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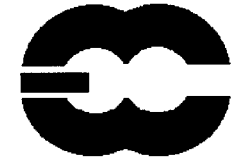
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Snow
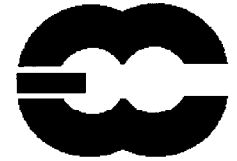
- Snow insulates the ground (30% to 90% of the snow mantle is air)

- A snow covered surface has a higher albedo than any other natural surface (0.2-0.3 in the presence of forests, 0.5-0.8 for bare ground/low vegetation)

- Snow melting keeps the surface temperature at 0 C for a long period in spring

Snow energy budget
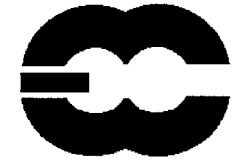
$$(\rho C)_{sn} D \frac{\partial T_{sn}}{\partial t} = R_n + L_s E + H - G - Q_m$$
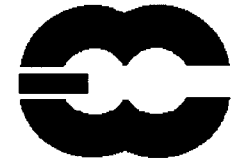
L_s **Latent heat of sublimation**

Q_m **Heat of melting**

G **Basal heat flux**

$$Q_m = L_f M = L_f \frac{\rho_w}{C_{sn}} \frac{\partial S}{\partial t}\bigg|_m$$

L_f Latent heat of fusion

M Meltwater

C_{sn} Snow fraction

Snow mass budget

$$\rho_w \frac{\partial S}{\partial t} = F + C_{sn}(E - M)$$

F **Snowfall**

S **Snow water equivalent (snow mass)**

- **Snow mass (S) and snow depth (D)**

$$D = \frac{\rho_w}{\rho_{sn}} \frac{S}{C_{sn}}$$
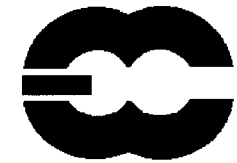
ρ_{sn} Snow density

D Snow depth for the snow - covered area, m
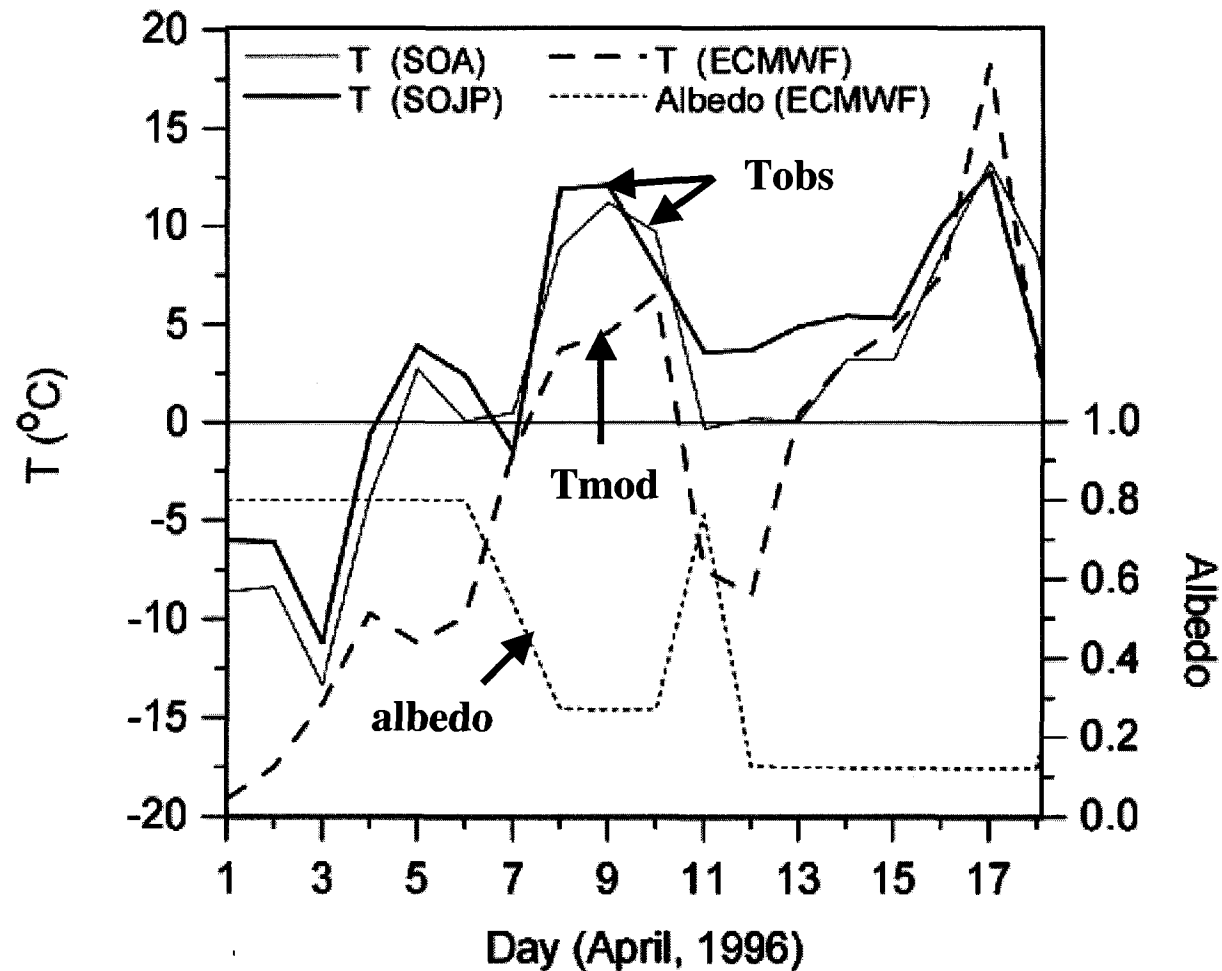
Metamorphism, density and albedo
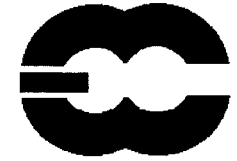
- **Density**
  - Weighted average between current density and the density of fresh snow, in case of snowfall
  - Exponential relaxation

- **Albedo**
  - Exponential relaxation with different time scales for melting and non-melting snow
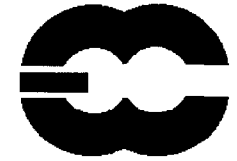
Case study: Boreal forest albedo (1)

2m temperature at BOREAS, Canada, 18 LT

Observations vs 48 h forecast

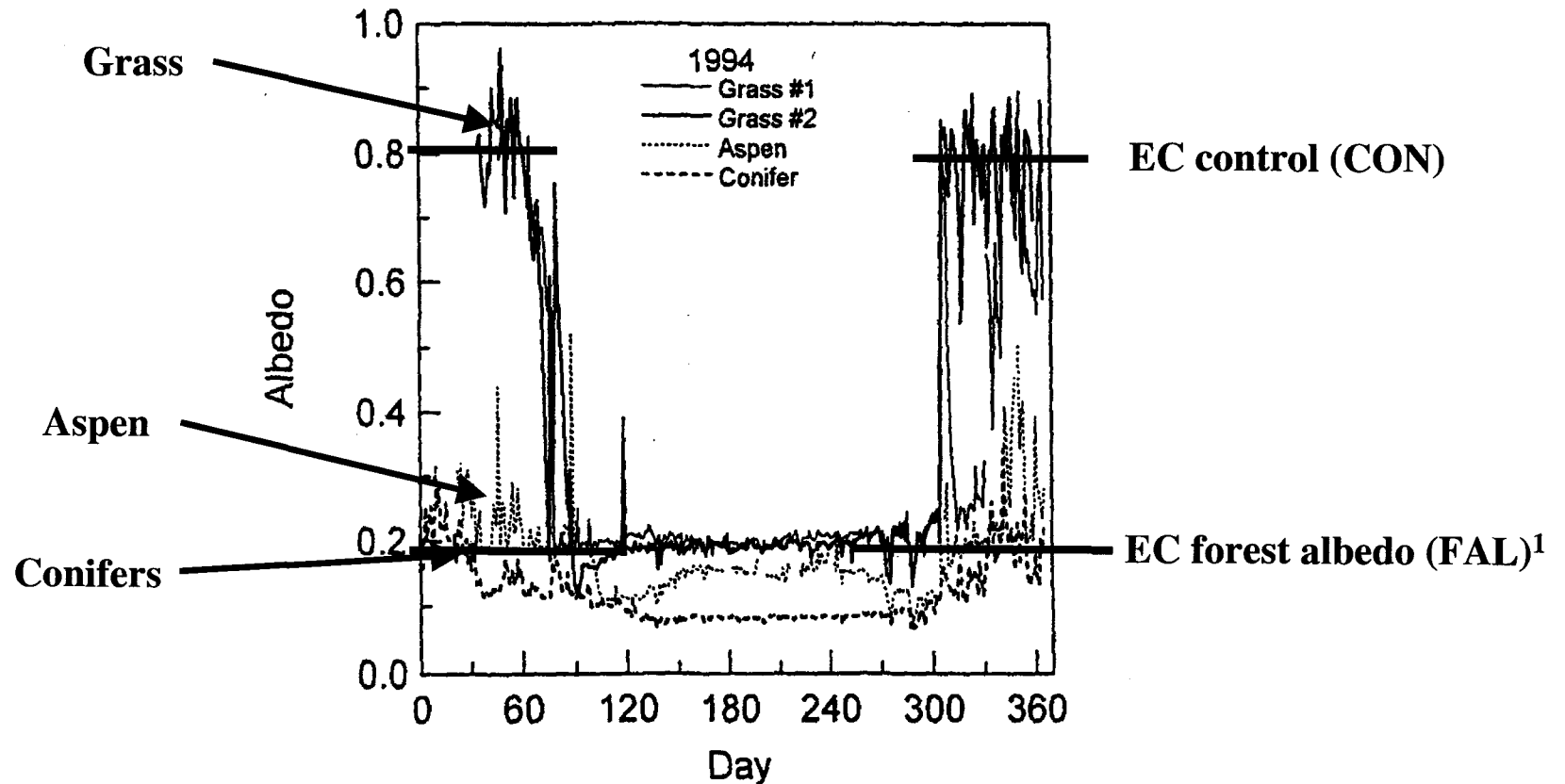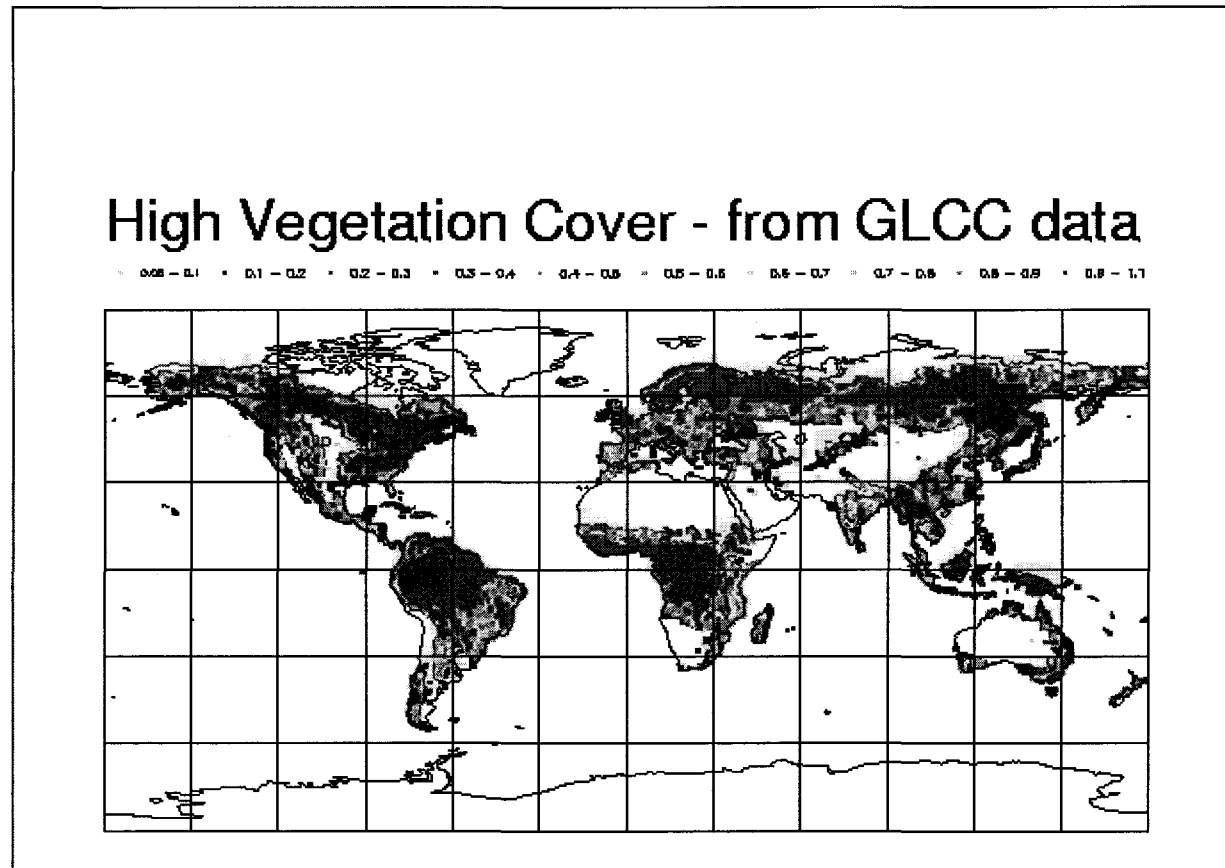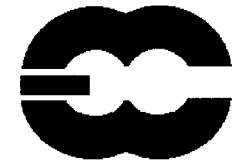# Case study: Boreal forest albedo (2)

Observed albedo BOREAS 1994

Figure 4. Daily average albedo for 10 BOREAS mesonet sites for 1994; showing two grass sites, the aspen site, and an average of the seven conifer sites.
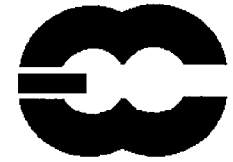
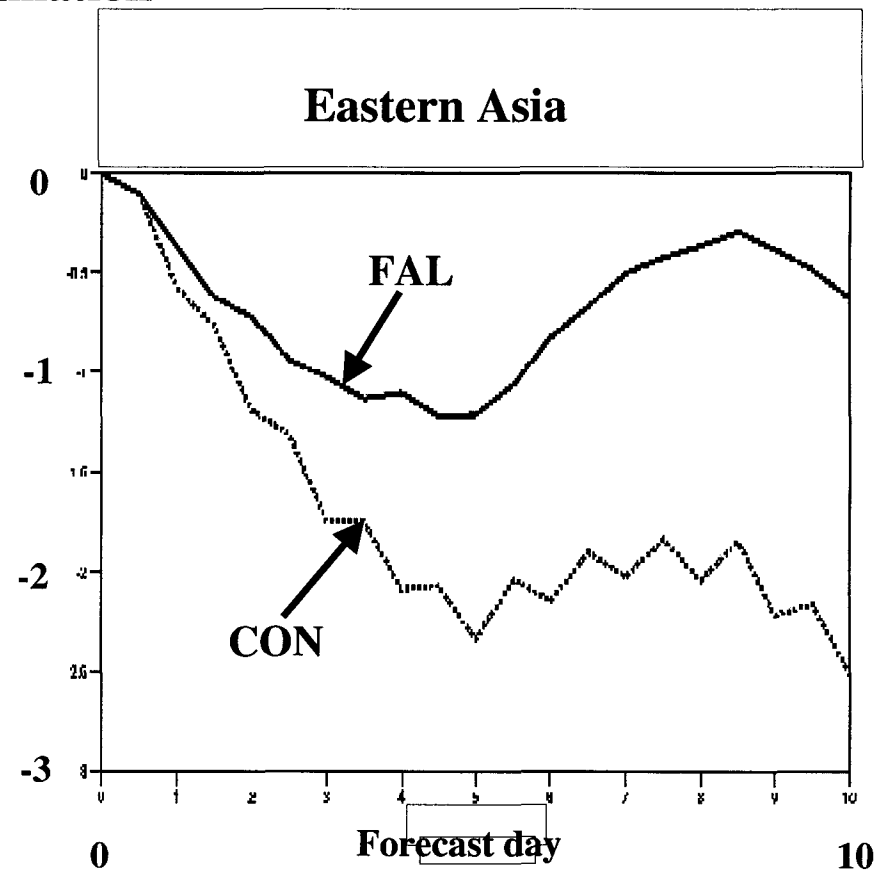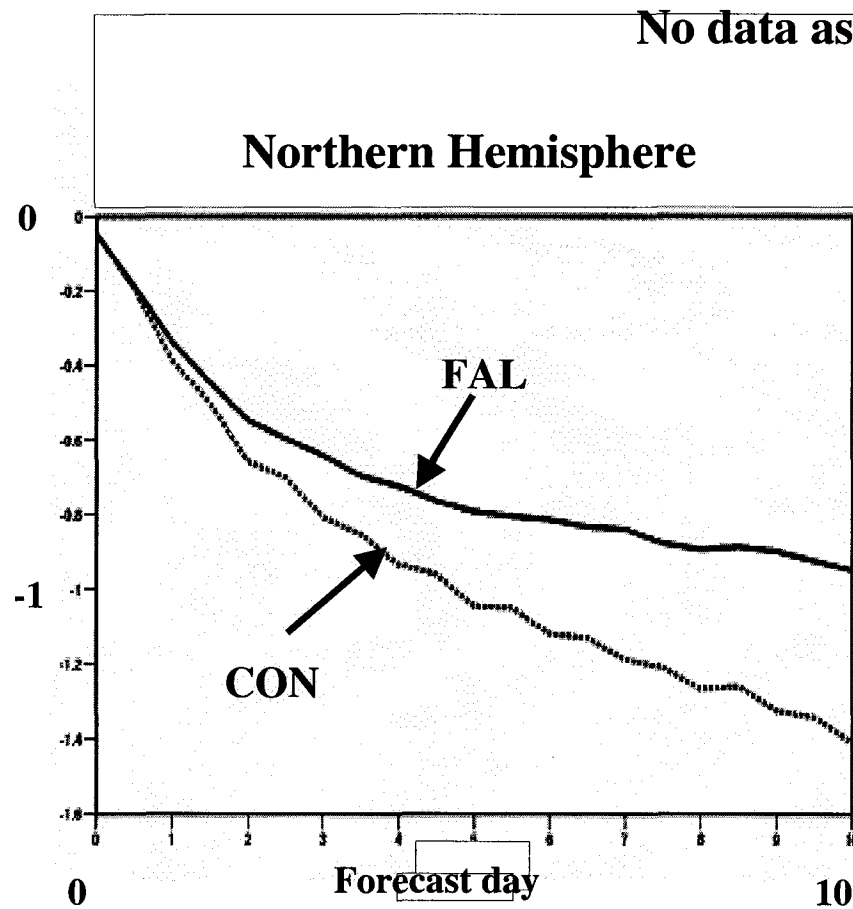**Viterbo and Betts, 1999: J. Geophys. Res., 104D, 27,803-27,810.**

Case study: Boreal forest albedo (3)

High Vegetation Cover - from GLCC data

Case study: Boreal forest albedo (4)

850 hPa temperature bias
20 forecasts every 3 days, March-April 1996
No data assimilation

Case study: Boreal forest albedo (5)

March-April 1997 850 hPa T day 5 error

-3 - -2   -2 - -1   1 - 2

1997
Operational
Bias
(FAL)

March-April 1996 850 hPa T day 5 error

-7 - -6 -6 - -5 -5 - -4 -4 - -3 -3 - -2 -2 - -1 1 - 2
2 - 3 3 - 4 4 - 5 5 - 6
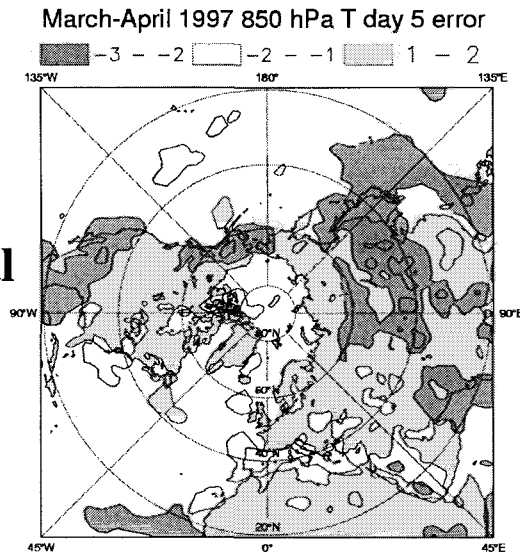
1996
Operational
Bias
(CON)
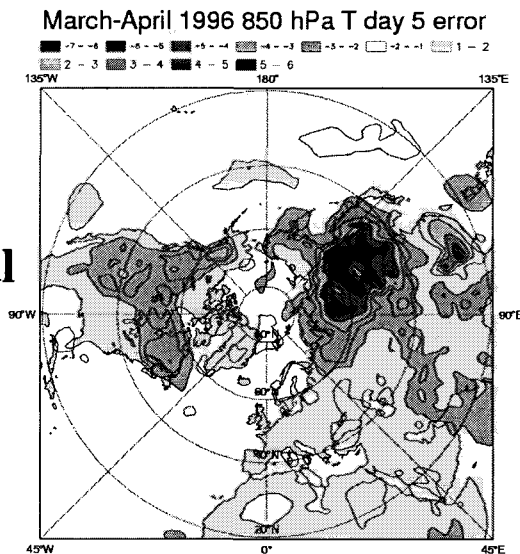
- **The surface albedo is the direct regulator of the energy available to the surface. The albedo of natural surfaces has a limited range (0.1-0.3), but in non-forested snow covered areas can reach values up to 0.8.**

- **Snow covered boreal forests have a much lower albedo than grassland to their south and tundra to their north; the presence of boreal forests has a direct control on the climate of high-latitudes.**

Evaporation: "The sting in the tail" (1)

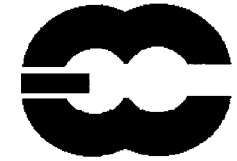**BOREAS evaporation: One-column integration**
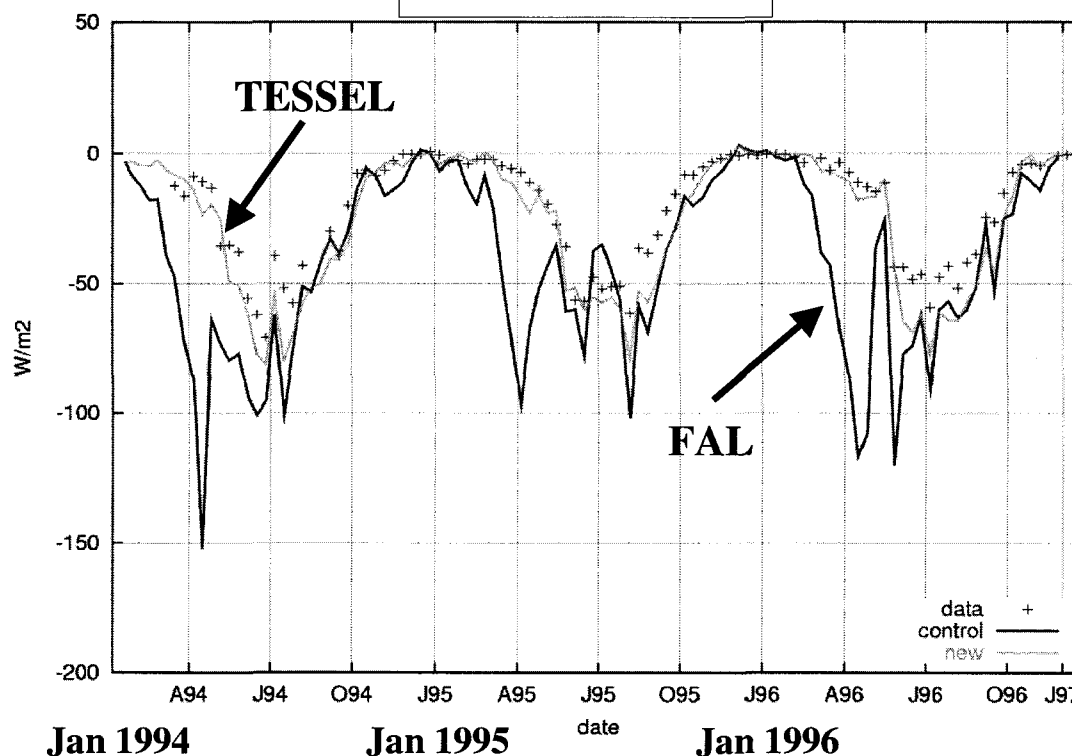
van den Hurk et al 2000

- The model FAL erroneously transform the available energy into evaporation. However, plants have limited transpiration in winter/spring, when the roots are frozen.

- The TESSEL model (operational at ECMWF July 2000) simulates that behaviour.

Evaporation: "The sting in the tail" (2)
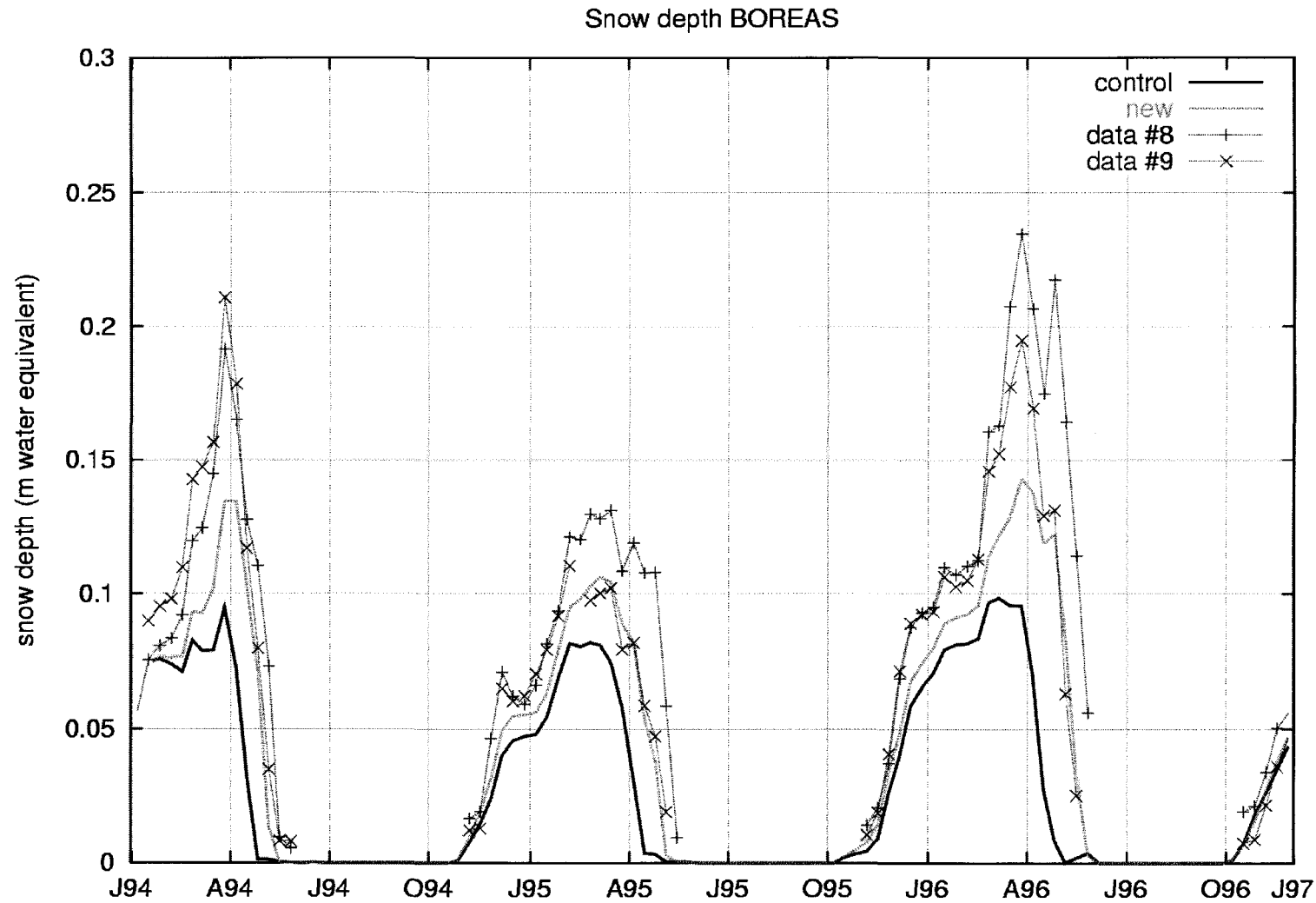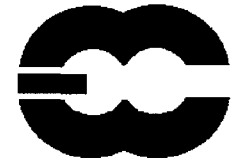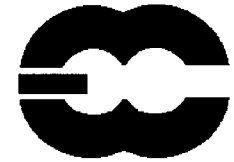

Snow depth BOREAS

Layout

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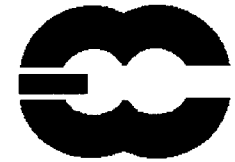- **Snow**
- **Conclusions and a look ahead**

Conclusions

- The land surface can have a significant impact on the atmosphere at the synoptic/continental time scale when it affects the partitioning of the net radiation into sensible/latent heat, via the soil water content. This effect can be local or non-local.

- The land surface has a significant impact on the atmosphere at a synoptic/continental scale when it affects the net radiation at the surface, such as a change of the albedo in spring.

- In winter, stable, situations the land surface is decoupled from the atmosphere: Large variations in surface temperature affect only the lowest hundred metres of the atmosphere with no impact on the circulation.

- Forecast systems are sensitive to mis-representation of longer time scales in the land-surface/atmosphere interaction.

- Data assimilation systems are ideal tools to validate parameterisations because of their constant confrontation with observations and the customers' needs for accurate diurnal cycles of weather parameters.

History of ECMWF 2m T errors

ICTP, May 2001

40
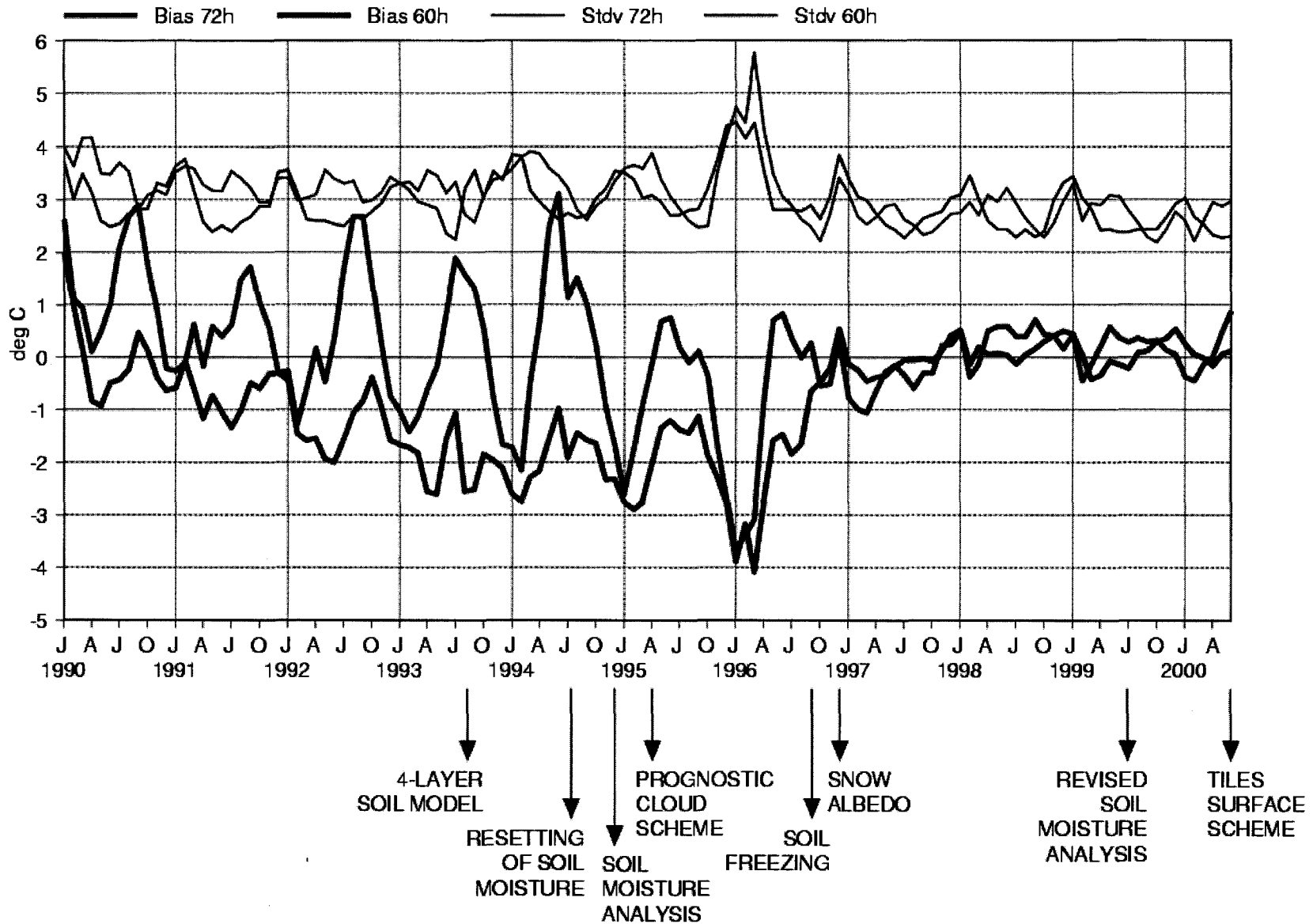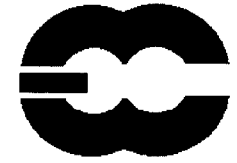
3-5 years ahead

- **Model**
  - Surface runoff taking into account sub-grid scale heterogeneity
  - Distribution of soil types
  - Alternative formulation for hydraulic conductivity/diffusivity
  - Handling of fractional lake/sea cover
  - Urban tile
  - Snow cover and orography
  - Monthly climatology of LAI and biome vegetation fractions
  - Snow over ice
  - Daily production of basin averaged runoff and precipitation
- **Data assimilation**
  - Use tile skin temperature, assisting on satellite retrievals over land
  - Cloudy and clear sky tiles for satellite retrievals
  - Use of satellite data for snow data assimilation
  - Prototype scheme for surface data assimilation

5-10 years ahead
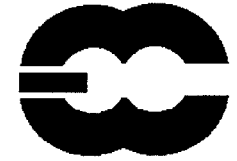
- **Model**
  - Near-real time (weekly) input of satellite derived LAI and vegetation fractions
  - CO_2 model and NPP production
  - Crop yield forecasts
  - Lake model
  - Runoff routeing

- **Data assimilation**
  - Studies on assimilation of microwave L-band data to initialise soil water