Land surface model

palmgroup

Institute of Meteorology and Climatology, Leibniz Universität Hannover

Content

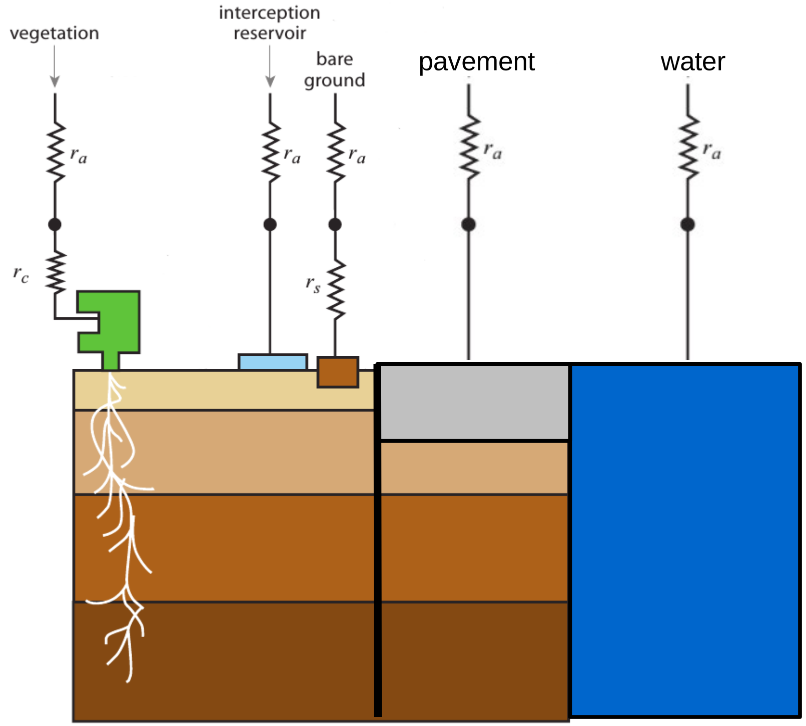
- Energy balance solver
- Soil model
- 3D vegetation
- Treatment of pavements and water bodies
- Technical aspects & usage
- Example applications

Why using a land surface model (LSM)?

- Traditional surface boundary conditions in LES:
  - Prescribed surface fluxes of sensible (H) and latent heat (LE)
  - Prescribed surface temperature and humidity
- Problems:
  - Requires accurate measurement data (incorporating reaction of plants)
  - No forecasting
  - Feedback processes are neglected (vegetation-soil, turbulence, clouds)
- Solution:
  - Interactive LSM that calculates surface fluxes
  - Advantage: Only information on vegetation, soil and radiation is needed
  - Disadvantage: Information on vegetation, soil, and radiation is needed

LSM in PALM

- Land surface parameterization based on the TESSEL scheme (IFS)
- Energy balance solver for the skin/surface temperature
- Multi-layer soil model (default: 8 layers, 6 types)
- Interception reservoir on plants
- Liquid water reservoir on pavements and bare soil
- Surface types:
  - Vegetation (18 types)
  - Pavement (15 types)
  - Water (5 types)
- Limitations:
  - No frozen water / snow (coming soon
  - No lateral transport
  - Vegetation is flat



Surface energy balance

- Prognostic equation for the (skin-layer) radiative temperature:

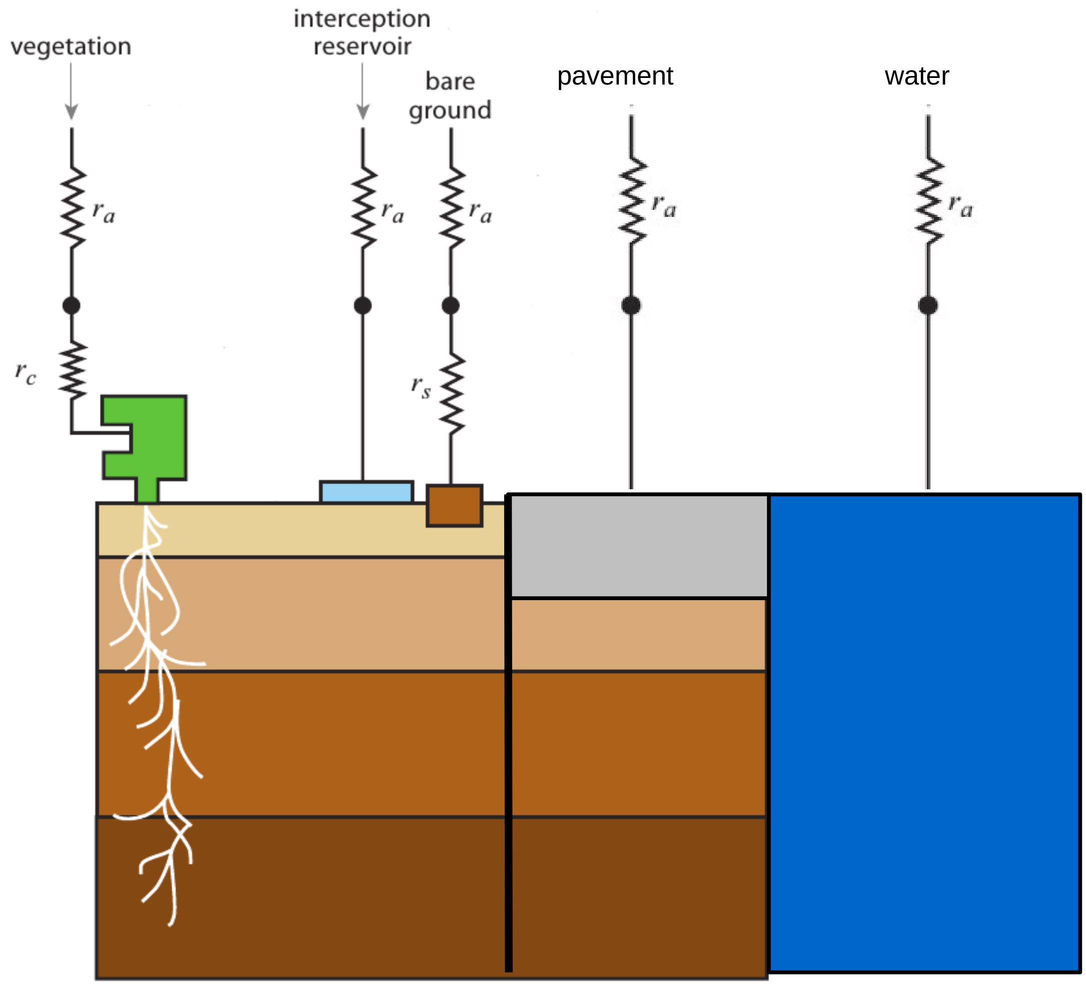
$$C_0 \frac{dT_0}{dt} = R_\mathrm{n} - H - LE - G$$

- C_0: Heat capacity of the skin layer (J m^{-2} K^{-1})
- T_0: Radiative temperature of the skin layer (K)
- R_n: Net radiation at the surface (W m^{-2})
- H: Sensible heat flux at the surface (W m^{-2})
- LE: Latent heat flux at the surface (W m^{-2})
- G: Ground heat flux (W m^{-2})

Resistance parameterization

- Exchange of sensible heat:
  r_a: aerodynamic resistance

- Exchange of latent heat:
- r_a: aerodynamic resistance
- r_c: canopy resistance
- r_s: bare soil resistance
- (r_l = 0 : liquid water resistance)



Parameterization of turbulent surface heat fluxes

$$H = -\rho\ c_{\mathrm{p}}\ \frac{1}{r_{\mathrm{a}}}(\theta_1 - \theta_0)$$

- θ_1: potential temperature at 1st grid level (K)
- θ_0: potential temperature at surface (K)

$$LE = -\rho\ l_{\mathrm{v}}\ \frac{1}{r_{\mathrm{a}} + r_{\mathrm{s}}}(q_{\mathrm{v,1}} - q_{\mathrm{v,sat}}(T_0))$$

- $q_{v,1}$: water vapor mixing ratio at 1st grid level (kg kg^{-1})
- $q_{v,sat}(T_0)$: water vapor mixing ratio at saturation (kg kg^{-1}) at Temperature T_0

Parameterization of soil heat flux

- Vegetated surfaces (skin layer):

$$G = \Lambda(T_0 - T_{\mathrm{soil},1})$$

- with

$$\Lambda = \frac{\Lambda_{\mathrm{skin}}\Lambda_{\mathrm{soil}}}{\Lambda_{\mathrm{skin}} + \Lambda_{\mathrm{soil}}}$$

- Λ_{skin}: Heat conductivity of the vegetation canopy (W m^{-2} K^{-1})
- $\Lambda_{soil} = \lambda / dz$: Total heat conductivity of the uppermost soil layer (W m^{-2} K^{-1})
  with λ: heat conductivity of the uppermost soil layer (W m^{-1} K^{-1})
- $T_{soil,1}$: Temperature of uppermost soil layer (K)

Parameterization of soil heat flux

- Bare soil:

$$G = \Lambda_{\mathrm{soil}}(T_0 - T_{\mathrm{soil},1})$$

- $\Lambda_{soil} = \lambda / dz$: Total heat conductivity of the uppermost soil layer (W m^{-2} K^{-1})
- $T_{soil,1}$: Temperature of 1st soil layer (K)

Parameterization of soil heat flux

- Pavement:

$$G = \Lambda_{\mathrm{pavement}}(T_0 - T_{\mathrm{pavement},1})$$

- $\Lambda_{\mathrm{pavement}} = \lambda / dz$: Total heat conductivity of the uppermost pavement layer (W m^{-2} K^{-1})
- $T_{\mathrm{pavement},1}$: Temperature of 1st pavement layer (K)

Parameterization of soil heat flux

- Water surfaces:

$$G = 10e^{10}(T_0 - T_{\mathrm{water}})$$

- T_0 is always equal to the water temperature!
- T_{water}: Water temperature (K) – fixed value at the moment! (see parameter water_temperature)

Heat capacity of the surface

$$C_0 \frac{dT_0}{dt} = R_\mathrm{n} - H - LE - G$$

- Vegetation surfaces (skin layer):
  - $C_0 = 0$ (skin layer has no heat capacity!)
- Bare soil (no skin layer):
  - $C_0 \neq 0$: heat capacity of the uppermost soil layer
- Pavement (no skin layer):
  - $C_0 \neq 0$: heat capacity of the uppermost pavement layer
- Water:
  - $C_0 = 0$ (surface temperature equals water temperature)

Surface energy balance

$$C_0 \frac{dT_0}{dt} = R_\mathrm{n} - H - LE - G$$

$$= R_\mathrm{n} + \rho\ c_\mathrm{p}\ \frac{1}{r_\mathrm{a}}(\theta_1 - \theta_0) + \rho\ l_\mathrm{v}\ \frac{1}{r_\mathrm{a} + r_\mathrm{s}}(q_{\mathrm{v},1} - q_{\mathrm{v,sat}}(T_0)) - \Lambda(T_0 - T_{\mathrm{soil},1})$$

- Land surface parameterization
- Input from soil model
- Input from atmosphere model
- Input from radiation model

Land surface parameterization (I): calculation of r_a

- r_a is the aerodynamic resistance due to roughness and stability:

$$
\begin{aligned}
H &= -\rho\ c_\mathrm{p}\ \frac{1}{r_\mathrm{a}}(\theta_1 - \theta_0) \\
&= \rho\ c_\mathrm{p}\ \overline{w'\theta'}_0 \\
&= -\rho\ c_\mathrm{p}\ u_*\ \theta_*
\end{aligned}
$$

$$
u_*\ \theta_* = \frac{1}{r_\mathrm{a}}(\theta_1 - \theta_0)
$$

$$
\boxed{\rightarrow r_\mathrm{a} = \frac{\theta_1 - \theta_0}{u_*\ \theta_*}}
$$

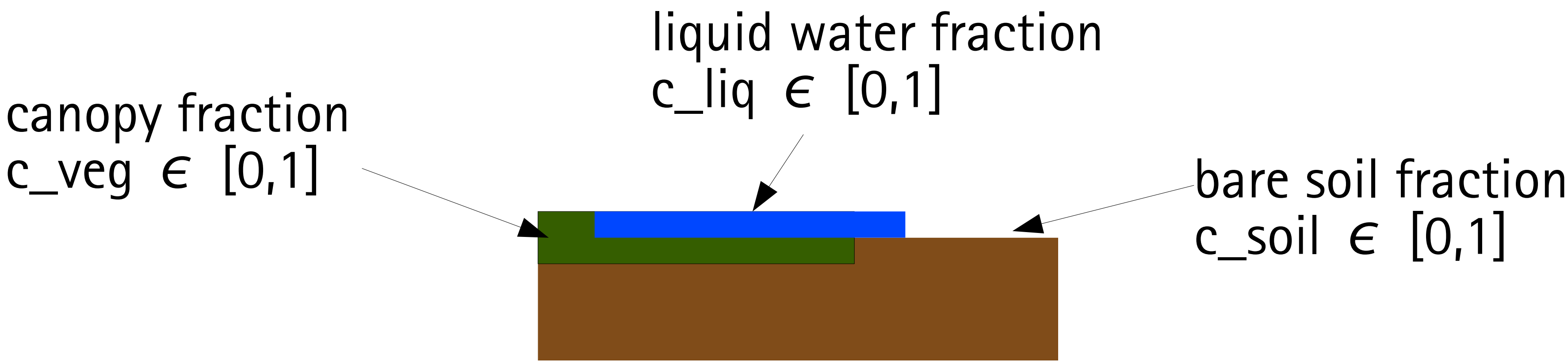
- u^* and θ^* are calculated based on Monin-Obukhov similarity theory

Land surface parameterization (II): calculation of r_s

- r_s is the surface resistance due to plant canopy or bare soil:

$$r_s = \begin{cases} r_c & \text{plants} \\ r_{soil} & \text{soil} \\ 0 & \text{interception water} \end{cases}$$

- Surface coverage:



Land surface parameterization (III): calculation r_c

- r_c is the stomatal resistance of plants ($m\ s^{-1}$)
- Parameterization after Jarvis (1976):

$$r_{\mathrm{c}} = \frac{r_{\mathrm{c,min}}}{LAI}\ f_1(R_{\mathrm{sw,in}})\ f_2(\widetilde{m})\ f_3(e_{\mathrm{def}})$$

$r_{\mathrm{c,min}}$: Minimum stomatal resistance ($\mathrm{ms^{-1}}$)
LAI: Leaf area index ($\mathrm{m^2\ m^{-2}}$)
f_i: Correction functions ($f_i \geq 1$)
$R_{\mathrm{sw,in}}$: Incoming shortwave radiation ($\mathrm{W\ m^{-2}}$)
$\widetilde{m}$: Layer-averaged soil moisture ($\mathrm{m^3\ m^{-3}}$)
e_{def}: Water-vapor pressure deficit (hPa)

Land surface parameterization (III): calculation of r_c

- r_{soil} is the bare soil resistance (m s^{-1})
- Parameterization after Jarvis (1976):

$$r_{\mathrm{soil}} = r_{\mathrm{soil,min}}\ f_{2b}(m_{\mathrm{soil,1}})$$

$r_{\mathrm{soil,min}}$: Minimum soil resistance $(\mathrm{m\ s^{-1}})$
f_{2b}: Correction function $(f_i \geq 1)$
$m_{\mathrm{soil,1}}$: Soil moisture of the uppermost layer $(\mathrm{m^3 m^{-3}})$

Land surface parameterization (IV): calculation of LE

- LE is calculated separately for all fractions:

$$LE_{\mathrm{veg}} = -\rho\ l_{\mathrm{v}}\ \frac{1}{r_{\mathrm{a}} + r_{\mathrm{c}}}(q_{\mathrm{v},1} - q_{\mathrm{v,sat}}(T_0))$$

$$LE_{\mathrm{soil}} = -\rho\ l_{\mathrm{v}}\ \frac{1}{r_{\mathrm{a}} + r_{\mathrm{soil}}}(q_{\mathrm{v},1} - q_{\mathrm{v,sat}}(T_0))$$

$$LE_{\mathrm{liq}} = -\rho\ l_{\mathrm{v}}\ \frac{1}{r_{\mathrm{a}}}(q_{\mathrm{v},1} - q_{\mathrm{v,sat}}(T_0))$$

- Prognostic equation for liquid water reservoir:

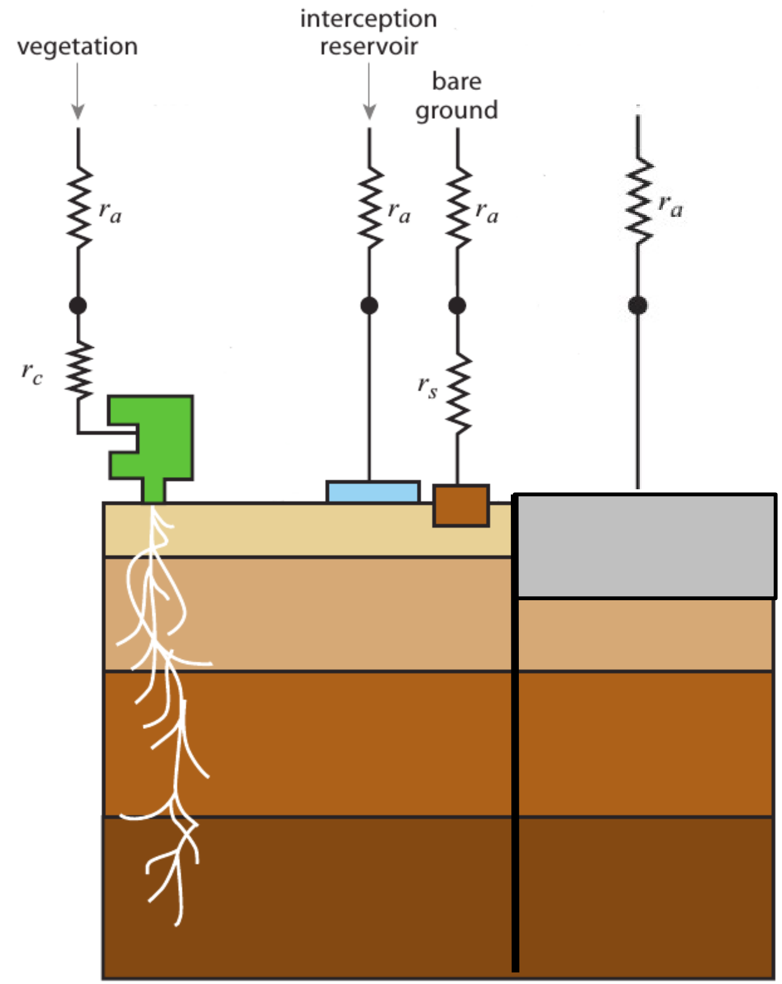
$$\frac{dm_{\mathrm{liq}}}{dt} = \frac{LE_{\mathrm{liq}}}{\rho_{\mathrm{l}}\ l_{\mathrm{v}}}$$

- Total LE (Evapotranspiration):

$$LE = c_{\mathrm{veg}}(1 - c_{\mathrm{liq}})\ LE_{\mathrm{veg}} + c_{\mathrm{liq}}\ LE_{\mathrm{liq}} + (1 - c_{\mathrm{veg}})(1 - c_{\mathrm{liq}})\ LE_{\mathrm{soil}}$$

Soil model basics

- Multiple (8) layers with varying depth
- Vertical transport of heat and water
- Preferential withdrawal from different soil layers with root extraction



Heat diffusion: Fourier's law

- Prognostic equation for T_{soil}

$$(\rho C)_{\mathrm{soil}} \frac{\partial T_{\mathrm{soil}}}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_T \frac{\partial T_{\mathrm{soil}}}{\partial z}\right)$$

$(\rho C)_{\mathrm{soil}}$: depends on porosity and the water content of the soil

λ_T: depends on the soil type and the water content

$(\rho C)_{\mathrm{soil}}$: Volumetric heat capacity $(\mathrm{J\ m^{-3}\ K^{-1}})$
λ_T: Thermal heat conductivity $(\mathrm{W\ m^{-1}\ K^{-1}})$

Soil water transport: Richard's equation

- Prognostic equation for m_{soil} (m^3 m^{-3})

$$\frac{\partial m_{\rm soil}}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_m \frac{\partial m_{\rm soil}}{\partial z} - \gamma\right) + S_m$$

Parameterized after Clapp & Hornberger (1978) (λ_m)

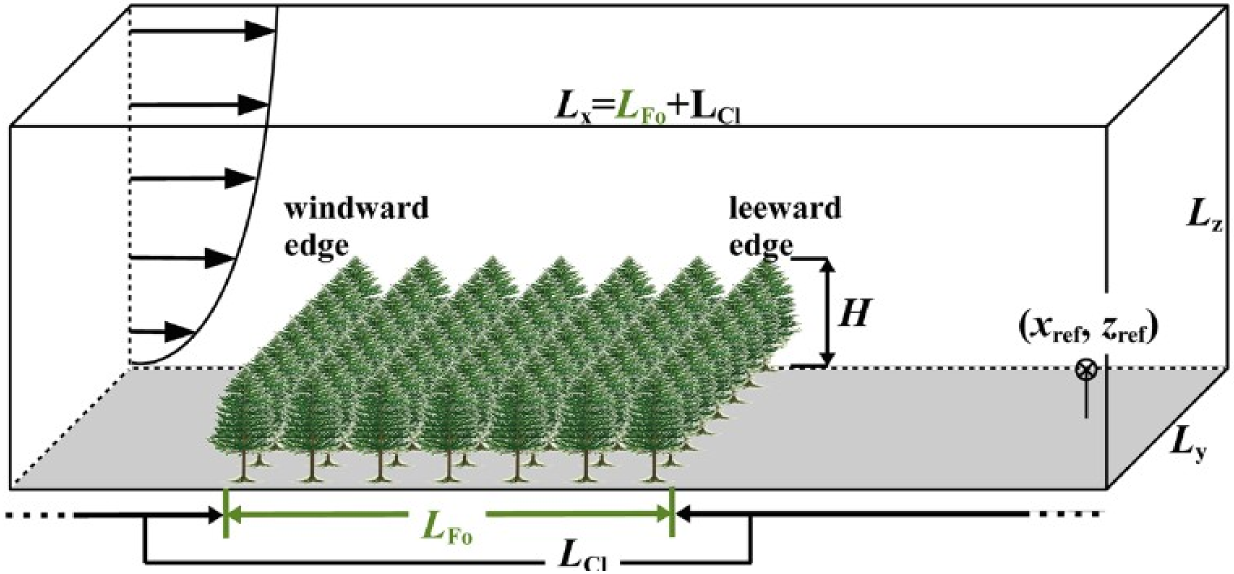
Parameterized after Van Genuchten (1980) (γ)

Transpiration by plants (S_m)

λ_m: Hydraulic diffusivity $(\mathrm{m^2\ s^{-1}})$
γ: Hydraulic conductivity $(\mathrm{m\ s^{-1}})$
S_m: Sink term due to root extraction $(\mathrm{m^3\ m^{-3}\ s^{-1}})$

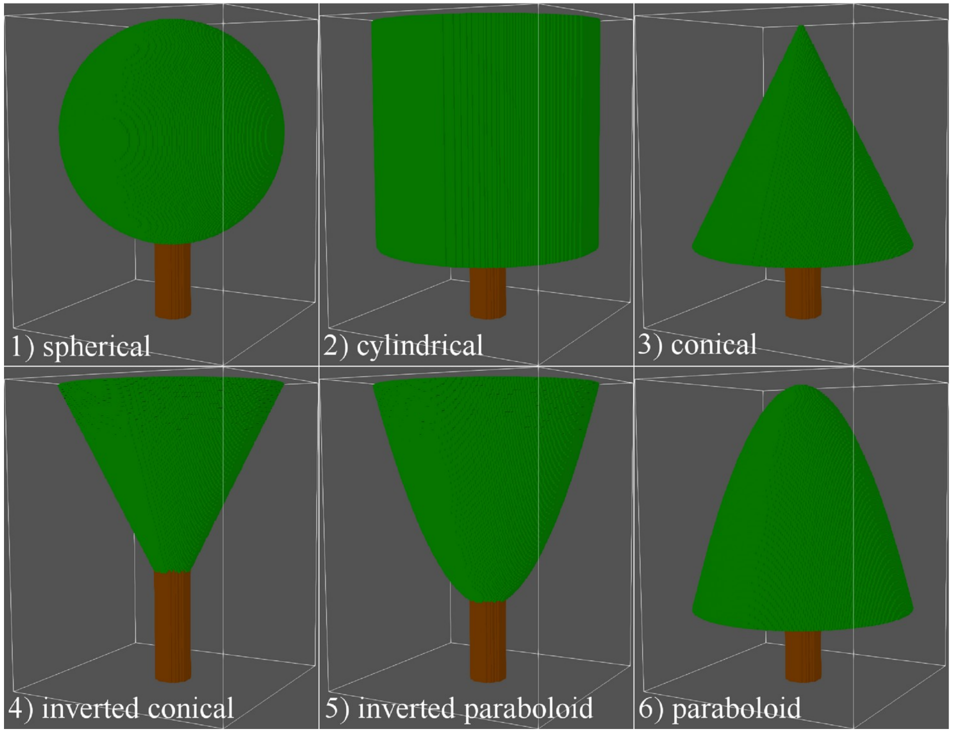
3D Vegetation

- Interactions of 3D vegetation objects with the atmosphere are treated in the plant canopy model:
  - Plants are represented by Leaf area density (LAD) and Basal area density (BAD) fields



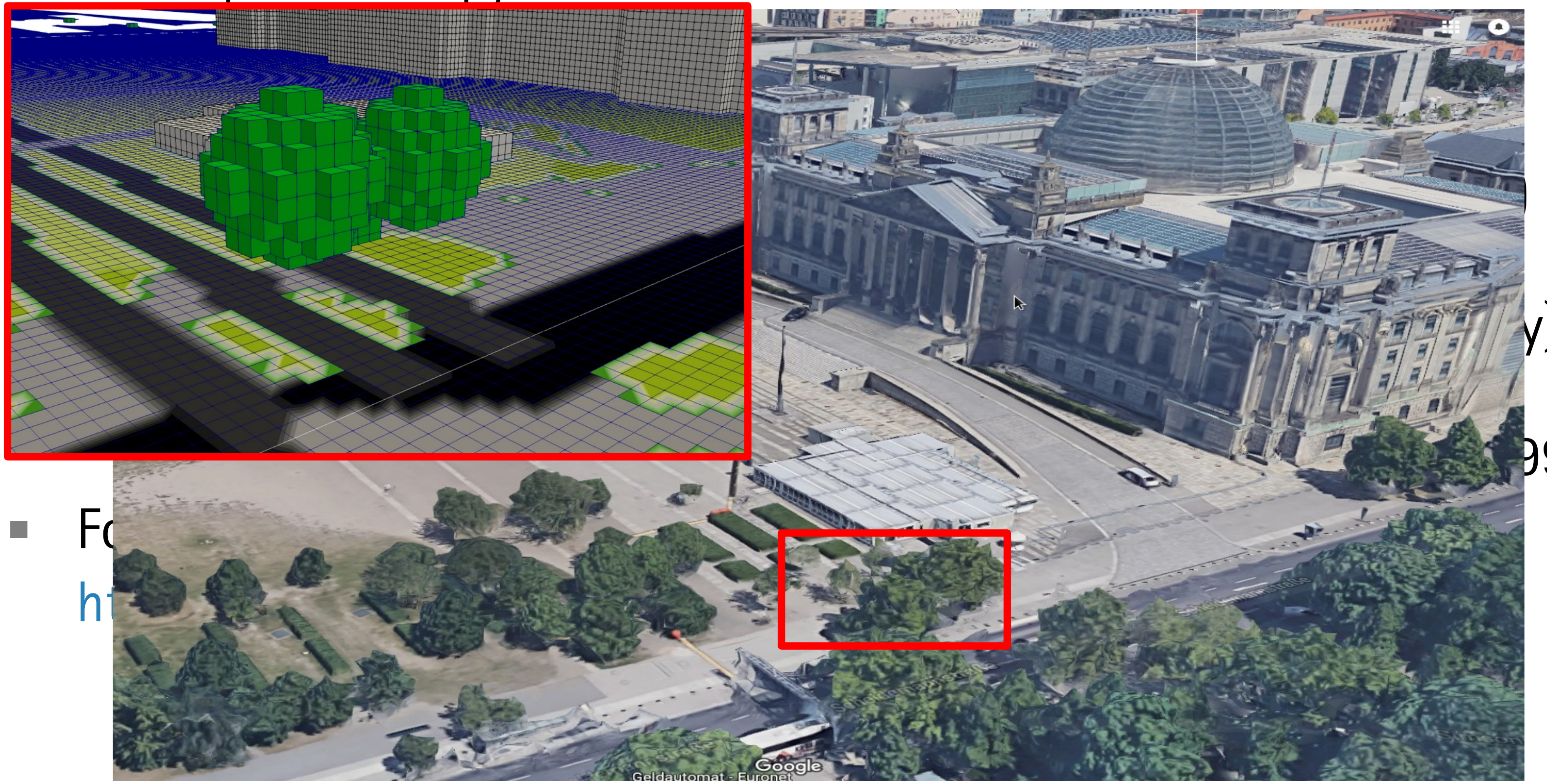
3D Vegetation

- Interactions of 3D vegetation objects with the atmosphere are treated in the plant canopy model:
  - Plants are represented by Leaf area density (LAD) and Basal area density (BAD) fields



Plant canopy model: Outline

- Interactions of 3D vegetation objects with the atmosphere are treated in the plant canopy model:



) is

y) and

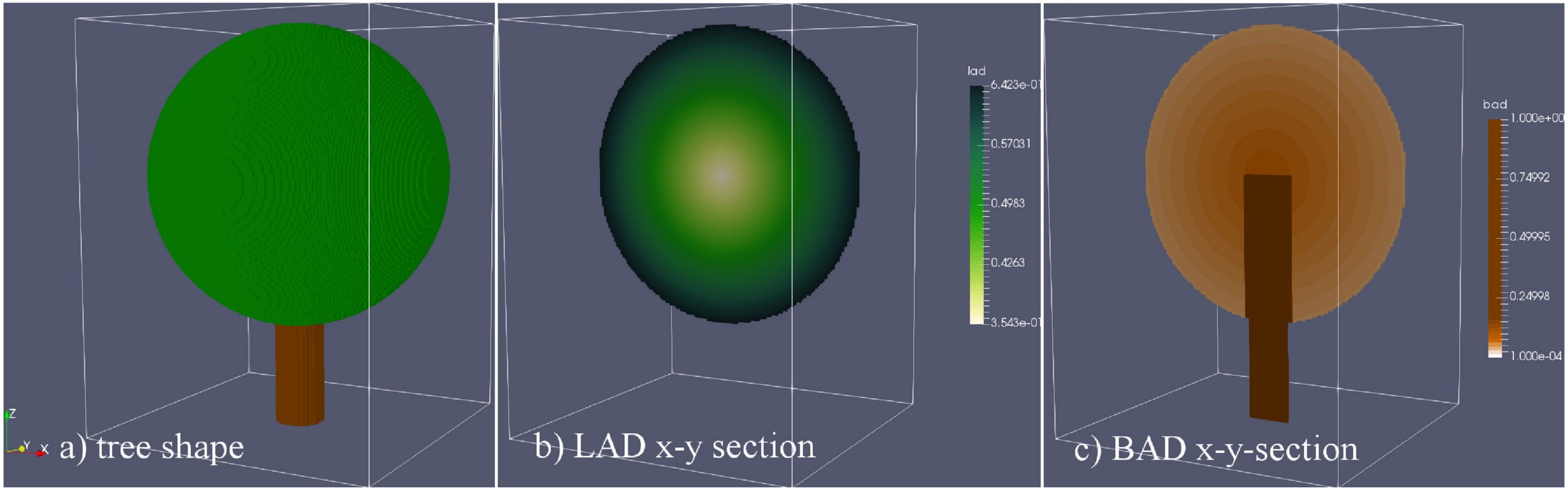
99)

- Fo

  ht

3D Vegetation

- Interactions of 3D vegetation objects with the atmosphere are treated in the plant canopy model:
  - Plants are represented by Leaf area density (LAD) and Basal area density (BAD) fields



3D Vegetation

- Interactions of 3D vegetation objects with the atmosphere are treated in the plant canopy model:
  - Plants are represented by LAD+BAD fields
  - Sink for momentum based on drag force approach
  - Interaction with radiation (absorption of energy, shading) is done in RTM (see next lecture)
  - Absorbed energy goes into sensible heat (no heat capacity) and transpiration
  - Transpiration via Jarvis-Steward model (Daudet et al., 1999)

- For details, see:
  https://palm.muk.uni-hannover.de/trac/wiki/doc/tec/canopy

Summary of prognostic equations

- Four prognostic equations:
  - (Skin layer) radiative temperature T_0
  - Liquid water in interception reservoir m_{liq} (for vegetation and pavement)
  - Soil temperature at all depths (except water surfaces)
  - Soil moisture at all depths (except water surfaces)

Numerical solution of the energy balance I

- Solving for T_0:

$$C_0 \frac{T_0}{dt} = S_0 \; \tau \; \sin(\Psi) - \alpha \; S_0 \; \tau \; \sin(\Psi) + \epsilon_\mathrm{atm} \; \sigma \; T_1^4 - \epsilon \; \sigma \; T_0^4 + \rho \; c_\mathrm{p} \; \frac{1}{r_\mathrm{a}}(\theta_1 - \theta_0) + \rho \; l_\mathrm{v} \; \frac{1}{r_\mathrm{a} + r_\mathrm{s}}(q_{\mathrm{v},1} - q_{\mathrm{v,sat}}(T_0)) - \Lambda(T_0 - T_{\mathrm{soil},1})$$

- Problem: non-linear terms, requires iteration method
- Solution: Taylor series expansion at T_0^{t-1}:

$$T_0^{4,t} = T_0^{4,t-1} + 4 \; T_0^{3,t-1}(T_0^t - T_0^{4,t-1})$$

$$q_{\mathrm{v,sat}}(T_0^t) = q_{\mathrm{v,sat}}(T_0^{t-1}) + \frac{dq_{\mathrm{v,sat}}}{dT}(T_0^t - T_0^{t-1})$$

Numerical solution of the energy balance II

- Prognostic-diagnostic equation for T_0:

$$T_0 = \frac{A \cdot \Delta t + C_0 \cdot T_0^{t-1}}{C_0 + B \cdot \Delta t}$$

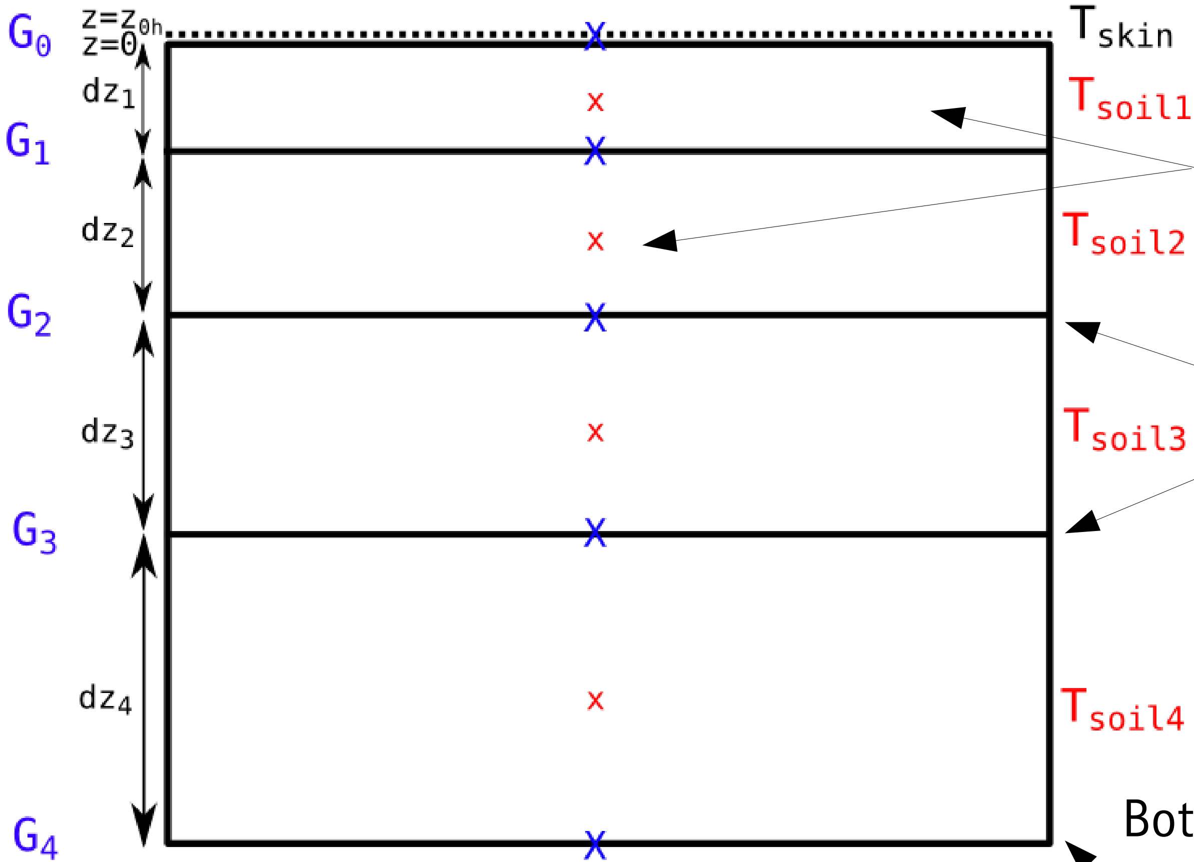
with coefficients A, B

- Equation can be solved with the standard time-stepping scheme in PALM (e.g. Runge-Kutta-3) – no iteration needed!
- Special case: $C_0 = 0$: diagnostic equation

$$T_0 = \frac{A}{B}$$

Discretization of the soil (4-layer example)

Type 1: natural land surfaces with vegetation



T_{soil} defined at the center of the soil layers

Fluxes are calculated at the edges of the layers

Bottom can be closed (bedrock) or open (free drainage)

LSM constants

- 8 fixed parameters:

$$\beta_{\mathrm{CH}} = 6.04 \quad : \quad \text{Clapp \& Hornberger exponent}$$

$$\lambda_{\mathrm{h,dry}} = 0.19\,\mathrm{W\ m^{-1}\ K^{-1}} \quad : \quad \text{Heat conductivity of dry soil}$$

$$\lambda_{\mathrm{h,sm}} = 3.44\,\mathrm{W\ m^{-1}\ K^{-1}} \quad : \quad \text{Heat conductivity of soil matrix}$$

$$\lambda_{\mathrm{h,water}} = 0.57\,\mathrm{W\ m^{-1}\ K^{-1}} \quad : \quad \text{Heat conductivity of water}$$

$$\psi_{\mathrm{sat}} = -0.388 \quad : \quad \text{Soil matrix potential at saturation}$$

$$(\rho C)_{\mathrm{soil}}) = 2.19e^{6}\,\mathrm{J\ m^{-3}\ K^{-1}} \quad : \quad \text{Volumetric heat capacity of soil}$$

$$(\rho C)_{\mathrm{water}}) = 4.20e^{6}\,\mathrm{J\ m^{-3}\ K^{-1}} \quad : \quad \text{Volumetric heat capacity of water}$$

$$m_{\mathrm{max}} = 0.2\,\mathrm{mm} \quad : \quad \text{Maximum water column on vegetation}$$

Input parameters

- Required input parameters:
  - about 20 parameters to be specified by the user
  - Initial soil profiles of T_{soil} and m_{soil}
  - List of all parameters:

  https://docs.palm-model.org/23.04/Reference/LES_Model/Namelists/#land-surface-parameters

- Simplified setup:
  - Specification of a surface type ('vegetation', 'water', 'pavement') and a default class (e.g. `vegetation_type = 1-18`)
  - Specification of a soil type (`soil_type = 1-6`)
  - Initial profiles of T_{soil} and m_{soil}
  - Specification of a deep soil temperature
  - All parameters can be changed individually!

Land surface model

Usage & special features

Predefined vegetation types

- Classification according to land cover
- 12 parameters are set

vegetation_type	Description
0	user defined
1	bare soil
2	crops, mixed farming
3	short grass
4	evergreen needleleaf trees
5	deciduous needleleaf trees
6	evergreen broadleaf trees
7	deciduous broadleaf trees
8	tall grass
9	desert
10	tundra
11	irrigated crops
12	semidesert
13*	ice caps and glaciers
14	bogs and marshes
15	evergreen shrubs
16	deciduous shrubs
17	mixed forest/woodland
18	interrupted forest

vegetation_type	r_c_min (s/m)	LAI (m²/m²)	c_veg	gD (1/hPa)	z0_vegetation (m)	z0h_vegetation	lambda_s (W/m²/K)	lambda_u (W/m²/K)	f_sw_in	c_surface	albedo_type	emissivity
1	180.0	3.00	1.00	0.00	0.005	0.5E-4	10.0	10.0	0.05	0.0	0	0.94
2	180.0	3.00	1.00	0.00	0.10	0.0001	10.0	10.0	0.05	0.0	2	0.95
3	110.0	2.00	1.00	0.00	0.03	0.30E-4	10.0	10.0	0.05	0.0	2	0.95
4	500.0	5.00	1.00	0.03	2.00	2.00	20.0	15.0	0.03	0.0	5	0.97
5	500.0	5.00	1.00	0.03	2.00	2.00	20.0	15.0	0.03	0.0	6	0.97
6	175.0	5.00	1.00	0.03	2.00	2.00	20.0	15.0	0.03	0.0	8	0.97
7	240.0	6.00	0.99	0.13	2.00	2.00	20.0	15.0	0.03	0.0	9	0.97
8	100.0	2.00	0.70	0.00	0.47	0.47E-2	10.0	10.0	0.05	0.0	8	0.97
9	250.0	0.05	0.00	0.00	0.013	0.013E-2	15.0	15.0	0.00	0.0	3	0.94
10	80.0	1.00	0.50	0.00	0.034	0.034E-2	10.0	10.0	0.05	0.0	11	0.97
11	180.0	3.00	1.00	0.00	0.5	0.50E-2	10.0	10.0	0.05	0.0	13	0.97
12	150.0	0.50	0.10	0.00	0.17	0.17E-2	10.0	10.0	0.05	0.0	2	0.97
13*	0.0	0.00	0.00	0.00	1.3E-3	1.3E-4	58.0	58.0	0.00	0.0	11	0.97
14	240.0	4.00	0.60	0.00	0.83	0.83E-2	10.0	10.0	0.05	0.0	4	0.97
15	225.0	3.00	0.50	0.00	0.10	0.10E-2	10.0	10.0	0.05	0.0	4	0.97
16	225.0	1.50	0.50	0.00	0.25	0.25E-2	10.0	10.0	0.05	0.0	4	0.97
17	250.0	5.00	1.00	0.03	2.00	2.00E-2	20.0	15.0	0.03	0.0	7	0.97
18	175.0	2.50	1.00	0.03	1.10	1.10E-2	20.0	15.0	0.03	0.0	8	0.97

Predefined soil types

- Soil classification according to porosity
- 8 parameters are set

soil_type	Description
0	user defined
1	coarse
2	medium
3	medium-fine
4	fine
5	very fine
6	organic

soil_type	alpha_vg	l_vg	n_vg	gamma_w_sat (m/s)	m_sat (m³/m³)	m_fc (m³/m³)	m_wilt (m³/m³)	m_res (m³/m³)
1	3.83	1.150	1.38	6.94E-6	0.403	0.244	0.059	0.025
2	3.14	-2.342	1.28	1.16E-6	0.439	0.347	0.151	0.010
3	0.83	-0.588	1.25	0.26E-6	0.430	0.383	0.133	0.010
4	3.67	-1.977	1.10	2.87E-6	0.520	0.448	0.279	0.010
5	2.65	2.500	1.10	1.74E-6	0.614	0.541	0.335	0.010
6	1.30	0.400	1.20	1.20E-6	0.766	0.663	0.267	0.010

Special case: inland water / ocean

- No soil model
- One layer water body
- Roughness lengths can be parameterized after Charnock (1955) and Beljaars (1994):

$$z_0 = \frac{0.11\mu}{u_*} + \frac{\alpha_{\mathrm{Ch}} u_*^2}{g}$$

← increasing roughness for increasing wind due to waves

$$z_{0,\mathrm{h}} = \frac{0.40\mu}{u_*}$$

$$z_{0,\mathrm{q}} = \frac{0.62\mu}{u_*}$$

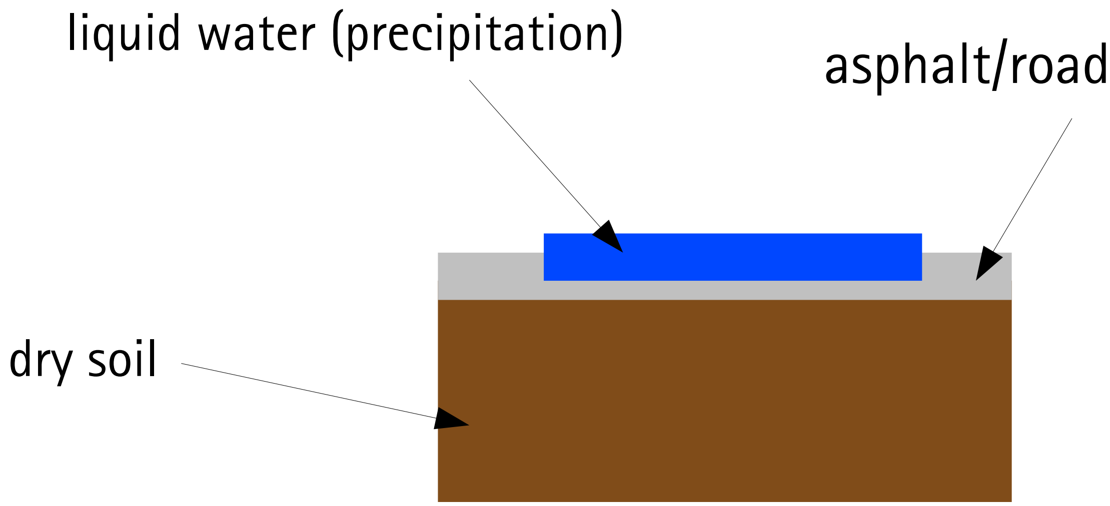
Only set constant_roughness =.T. only for ocean!

$\alpha_{\mathrm{Ch}} = 0.018$: Charnock constant
μ: Molecular viscosity ($\mathrm{m}^2\ \mathrm{s}^{-1}$)
g: Gravitational acceleration ($\mathrm{m\ s}^{-2}$)

Special case: pavement/roads

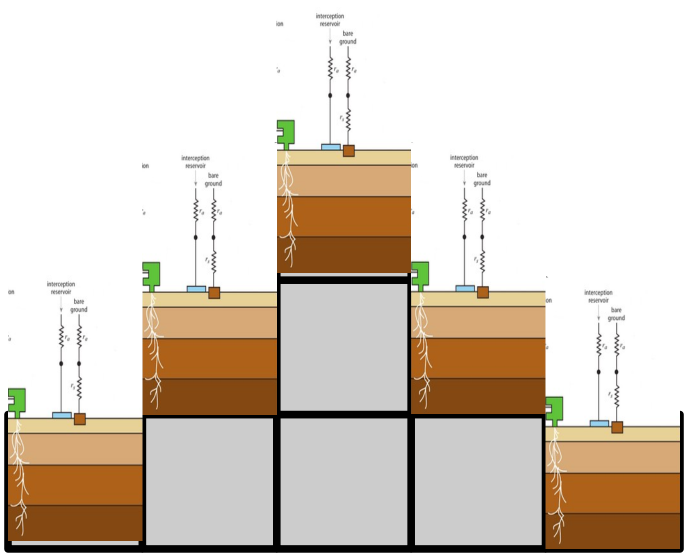
- Impervious surface (asphalt/concrete etc.)
- Dry soil below (no moisture transport)
- Thermal diffusion between pavement and soil is considered
- Interception reservoir
- Variable depth of the impervious surface

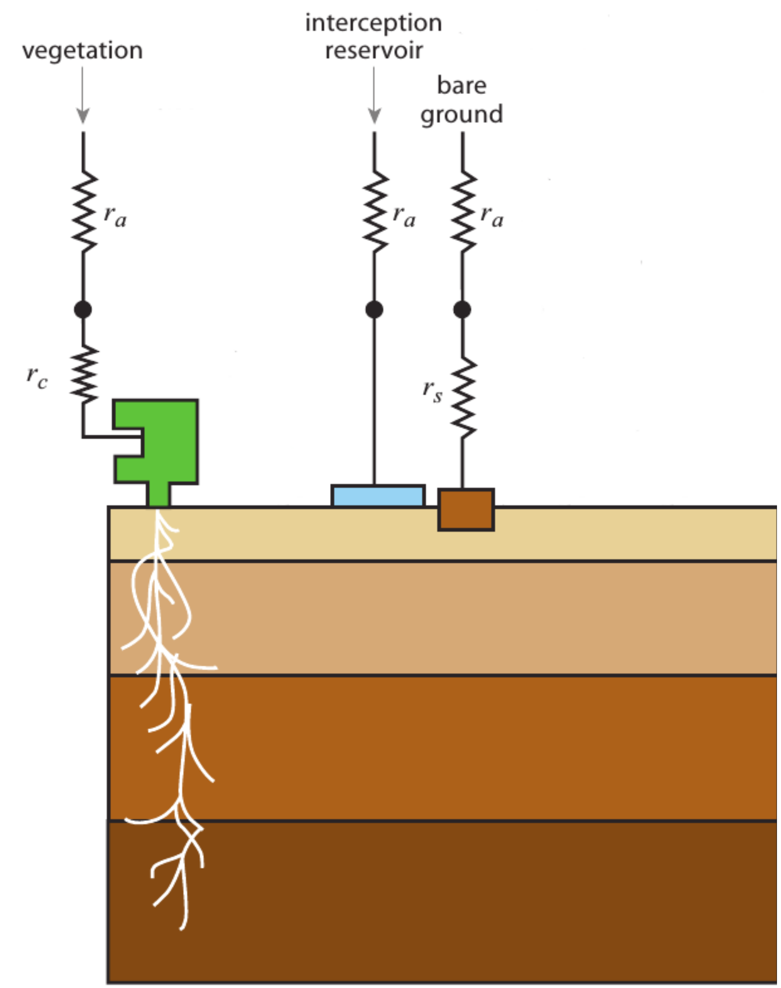
0	user defined
1	asphalt/concrete mix
2	asphalt (asphalt concrete)
3	concrete (Portland concrete)
4	sett
5	paving stones
6	cobblestone
7	metal
8	wood
9	gravel
10	fine gravel
11	pebblestone
12	woodchips
13	tartan (sports)
14	artifical turf (sports)
15	clay (sports)



Special case: complex terrain

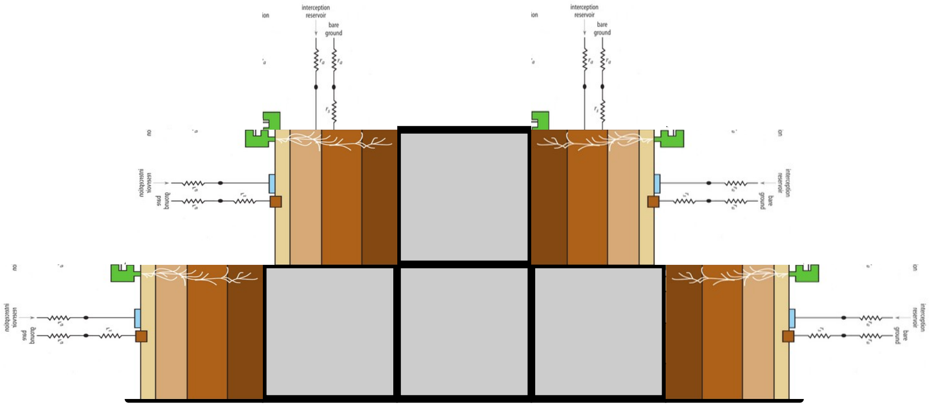
- How to treat vertically-oriented surfaces?
- For now: apply LSM and integrate in horizontal direction
- Each surface element is independent
- Requires special radiation code

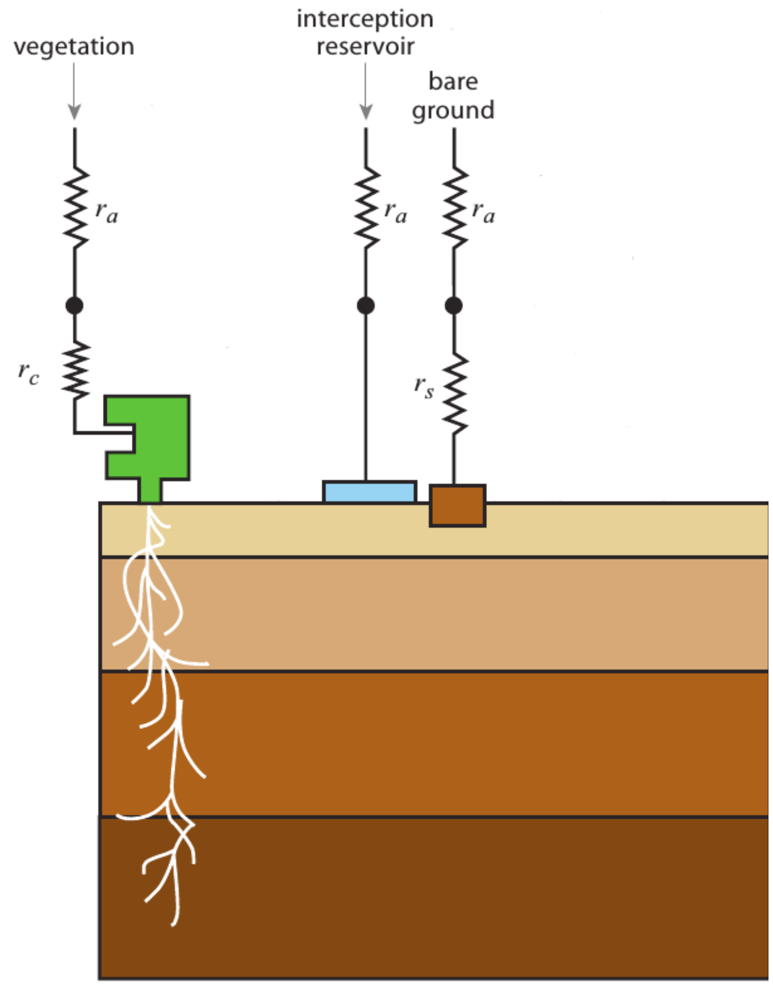




Special case: complex terrain

- How to treat vertically-oriented surfaces?
- For now: apply LSM and integrate in horizontal direction
- Each surface element is independent
- Requires special radiation code





&land_surface_parameters NAMELIST

- Minimum configuration in _p3d file:

```
&land_surface_parameters
          surface_type      = 'vegetation',
          vegetation_type   = 3,            ! short grassland
          soil_type         = 3             ! medium-fine
          soil_temperature = 290.0, 289.0, 288.0, 286.0, ! levels 1-4
                             285.0, 285.0, 285.0, 285.0, ! levels 5-8
          dz_soil           = 0.01, 0.02, 0.04, 0.07,    ! levels 1-4
                             0.15, 0.21, 0.72, 1.89,     ! levels 5-8
          root_fraction     = 0.10, 0.20, 0.30, 0.10,    ! levels 1-4
                             0.05, 0.00, 0.00, 0.00,     ! levels 5-8
          deep_soil_temperature = 285.0                  ! deep soil
/
```

- For a list of all available parameters, see https://docs.palm-model.org/23.04/Reference/LES_Model/Namelists/#land-surface-parameters
- Note: the LSM always requires a radiation model (next talk...)!

Limitations & Challenges

- LSM Vegetation is always flat
- 3D plant canopy is available but not coupled to soil water (trees have enough water for transpiration)
- Combine 3D canopy + LSM for the under-tree surface
- Very simply water body treatment
- Intense precipitation cannot be treated (no run-off model)
- Partial absorption of shortwave radiation by the canopy is not considered yet
- Ice phase (snow pack, frozen soil) not implemented yet
  (→ some vegetation types will not work)

Coming soon

- Snow pack will be available in the next PALM release
- Sea and land ice will be available in the next PALM release
- Slanted surfaces (immersed boundary condition) available soonish

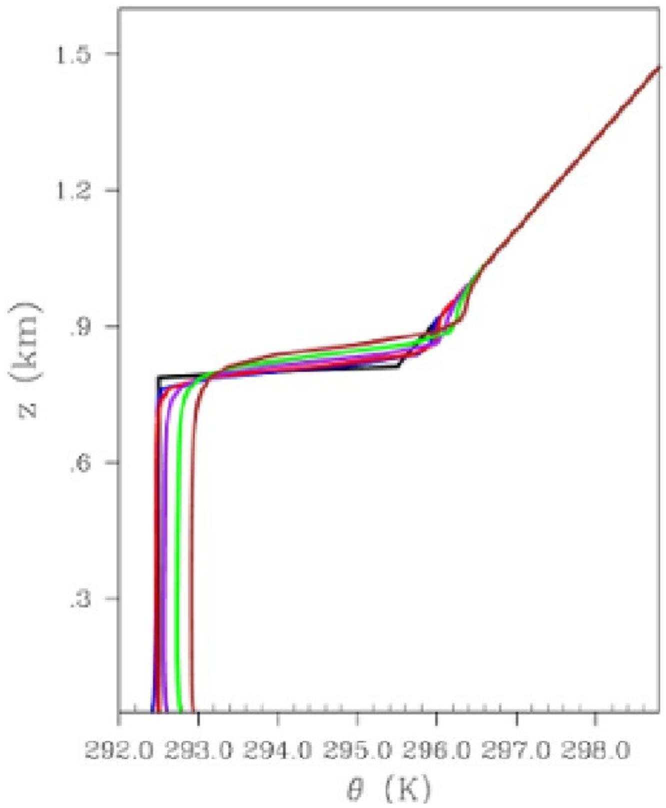
Application scenarios for the LSM

- **Scenario 1:** Interaction between land surface and turbulence in the convective boundary layer
  - Two-way feedback between the turbulent eddies and the land surface
  - Forecasting requires the surface to develop dynamically

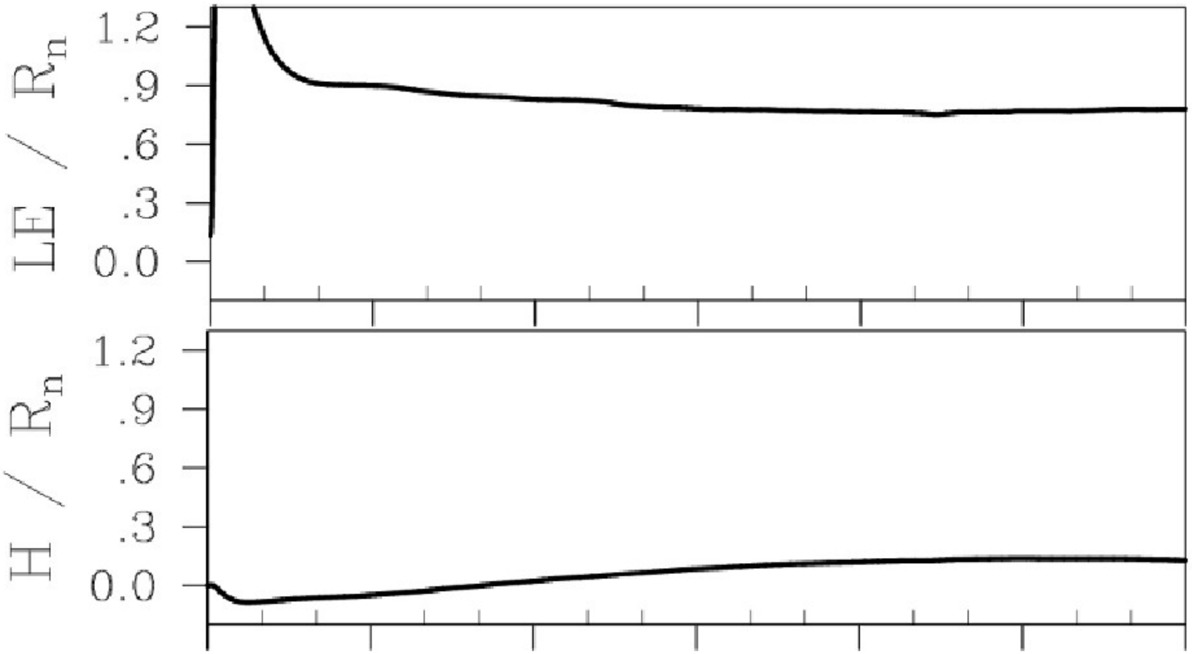
- **Scenario 2:** Nocturnal boundary layer
  - Surface fluxes are difficult to measure during nighttime
  - Low clouds (fog) can have a large impact on the energy balance (longwave radiation)
  - Highly unstationary conditions

Example 1: Convective boundary layer

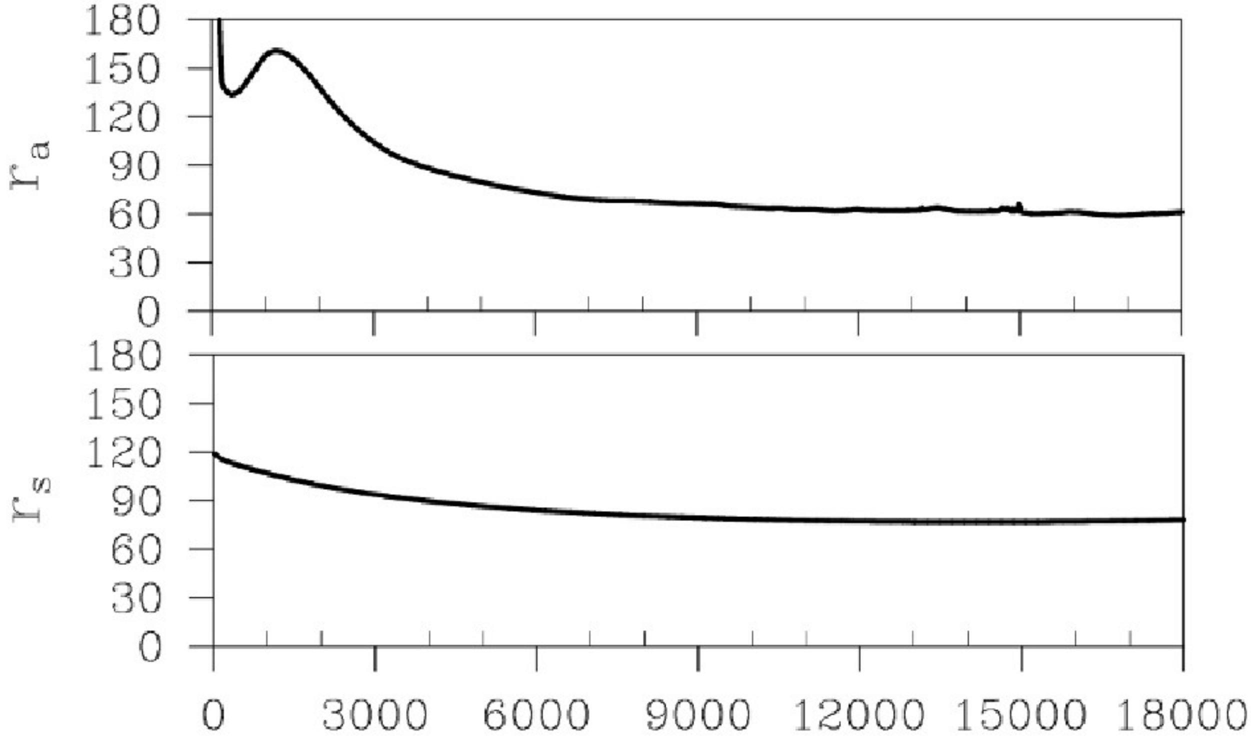
- Setup:
  - Grassland
  - Summer day radiative forcing (0800 – 1300 UTC)
  - 2.5 m/s geostrophic wind
  - Grid: dx = dy = 50 m, dz = 25 m
  - 4 layers in soil
  - Initial conditions: neutral with capping inversion



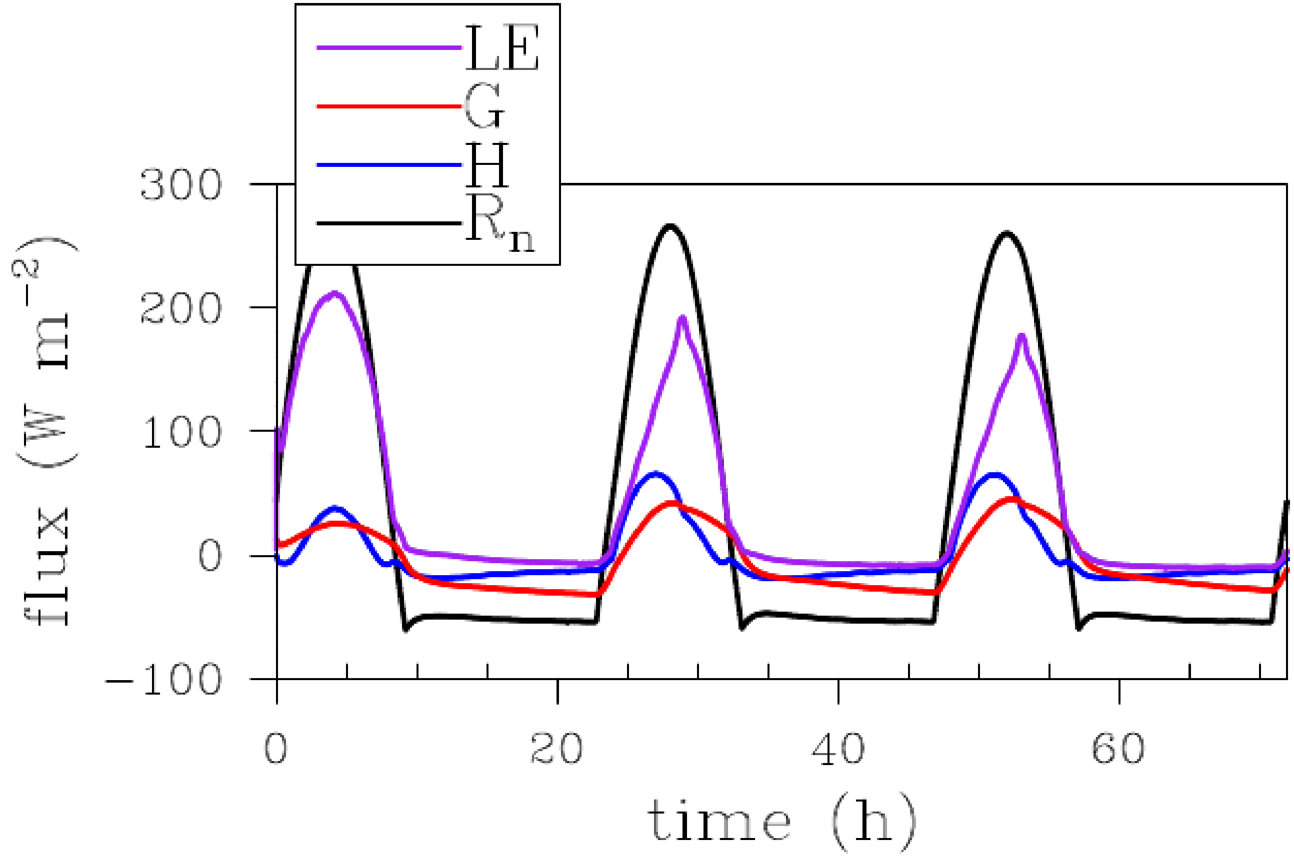
Example 1: Convective boundary layer



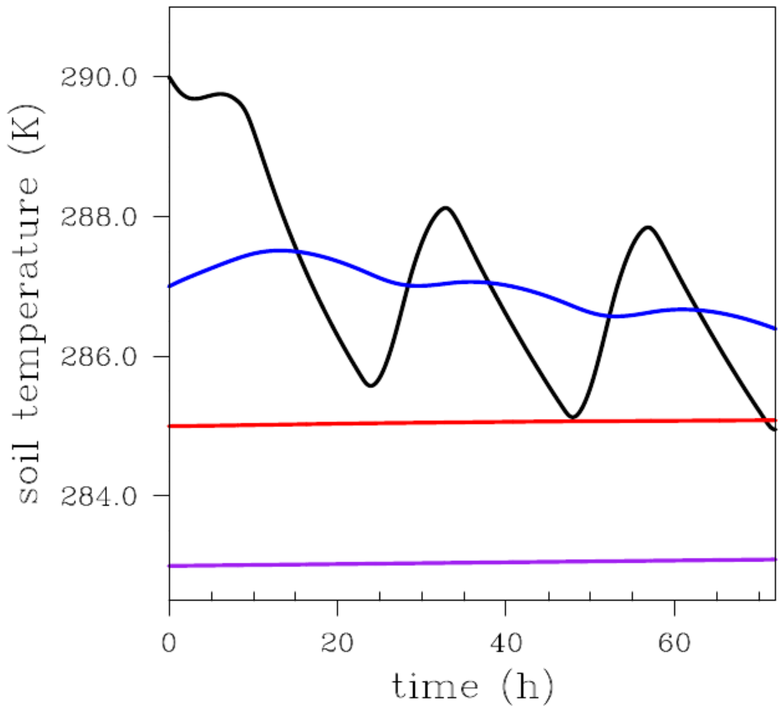
Example 1: Convective boundary layer

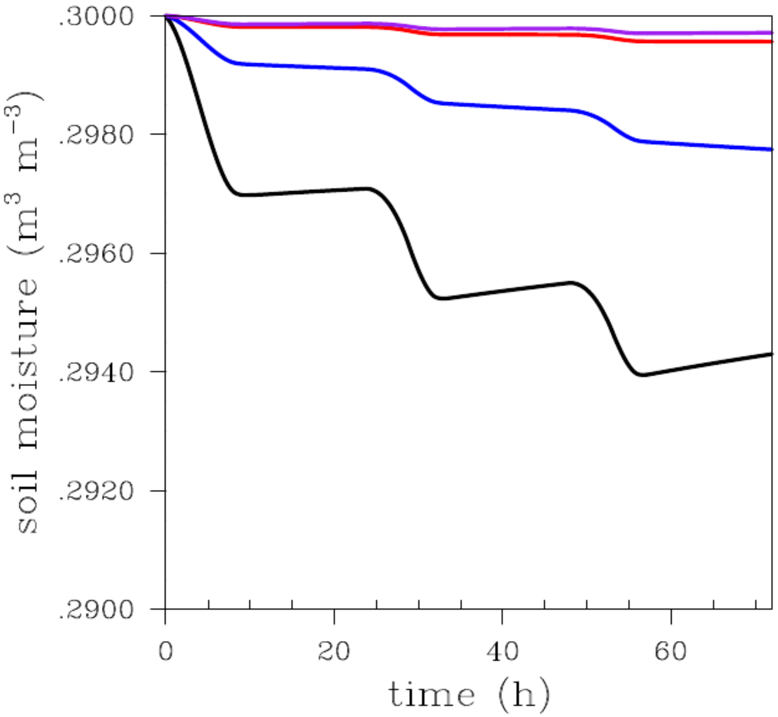


Example 1: Convective boundary layer (multi-day run!)



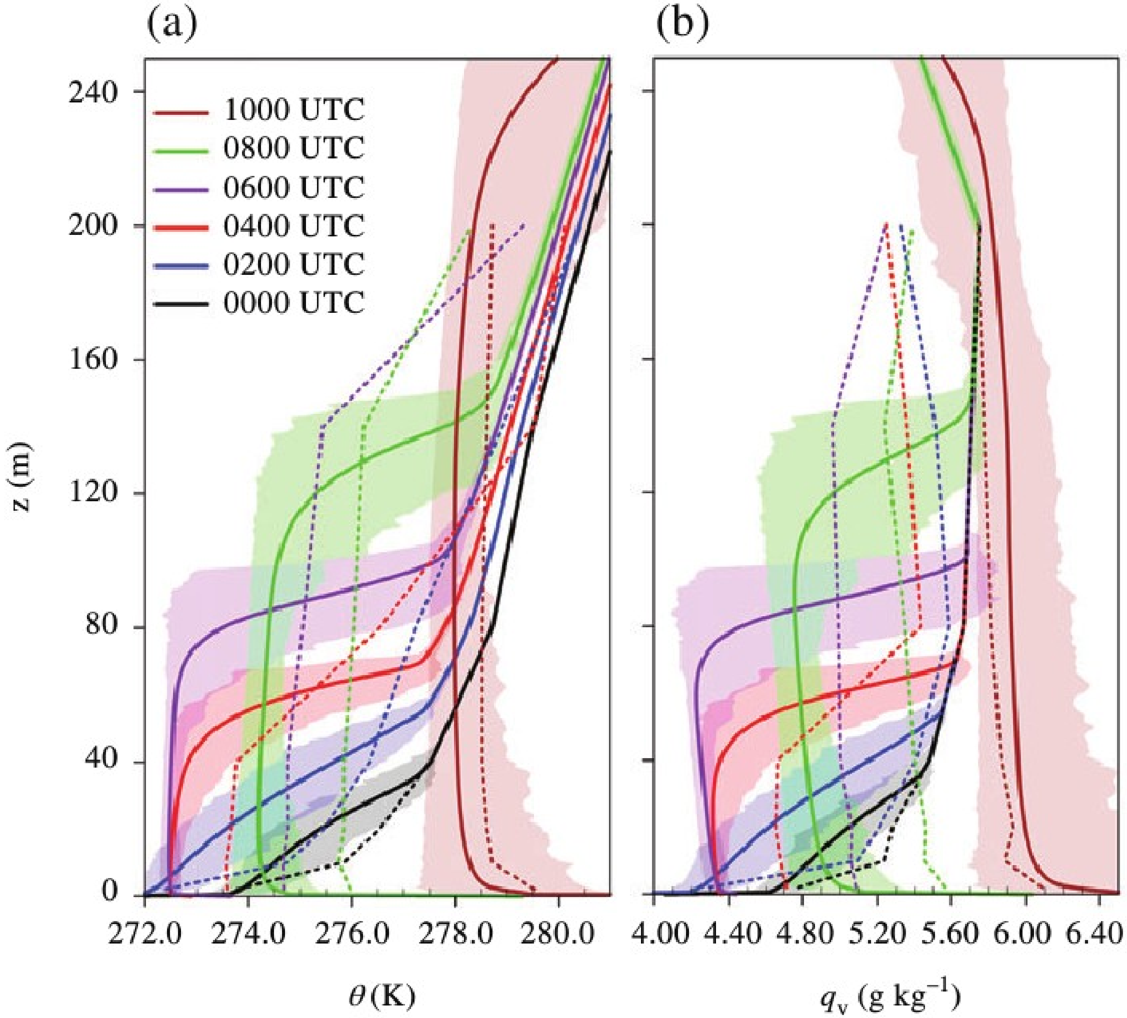
Example 1: Convective boundary layer (multi-day run!)



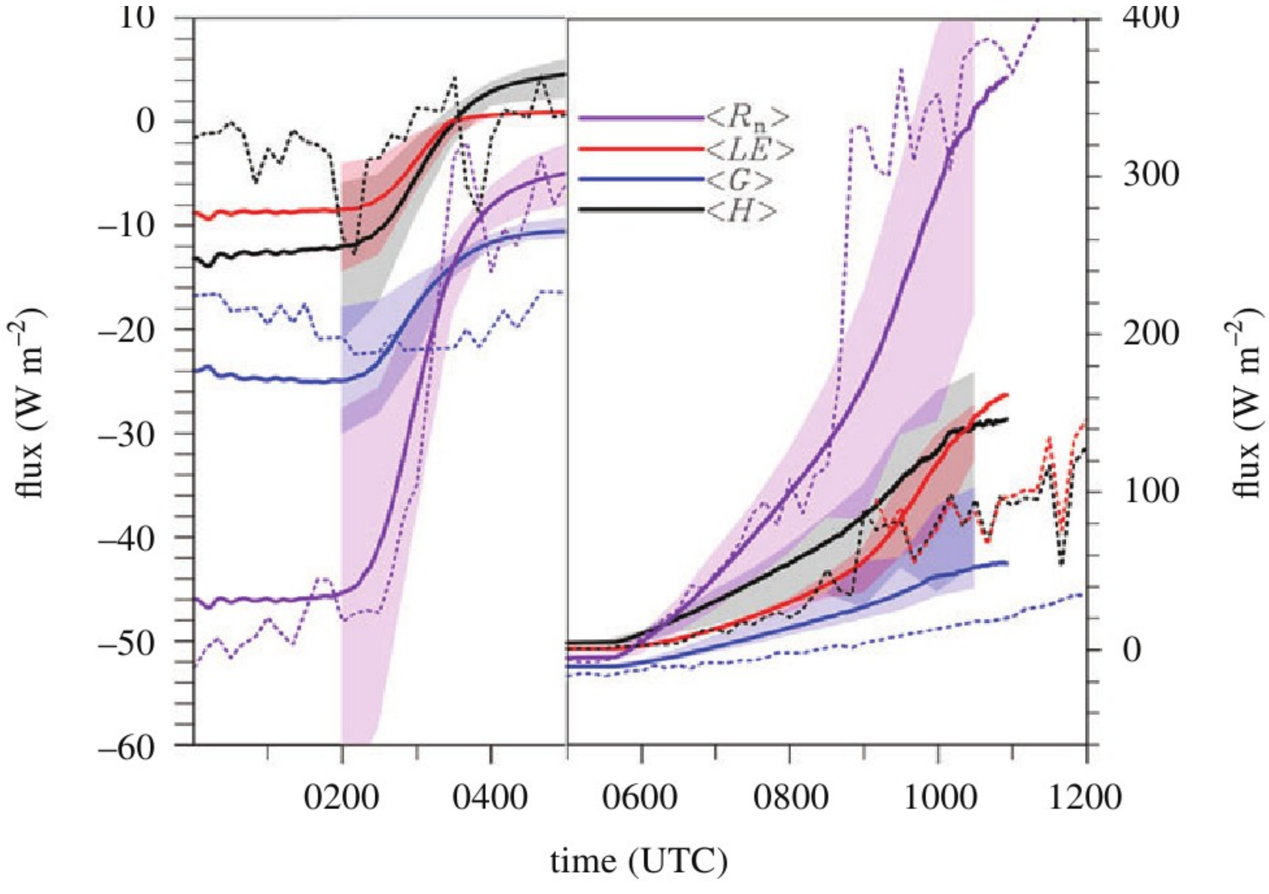


Example 2: Nocturnal boundary layer (with fog)

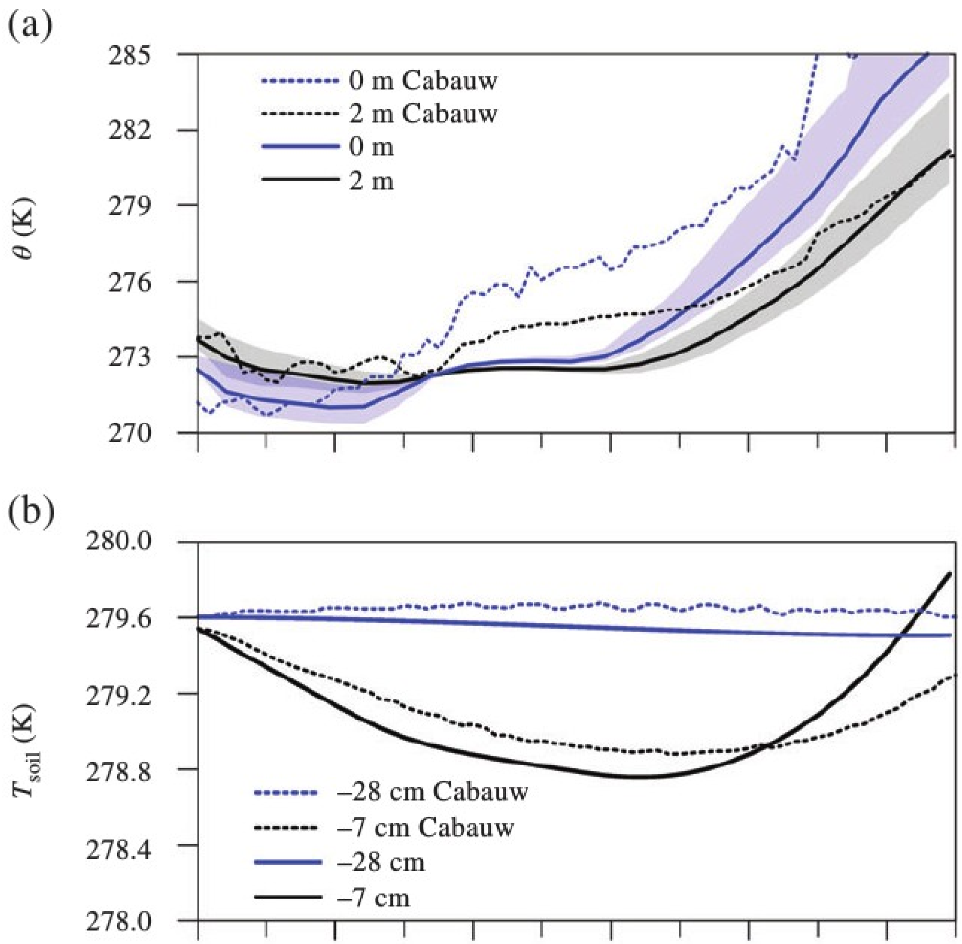
- Setup:
  - Cabauw (short grass)
  - 00 – 12 UTC
  - Grid: 1 m
  - 4 layers in soil
  - Initial conditions: Cabauw obs.



Example 2: Nocturnal boundary layer (with fog)

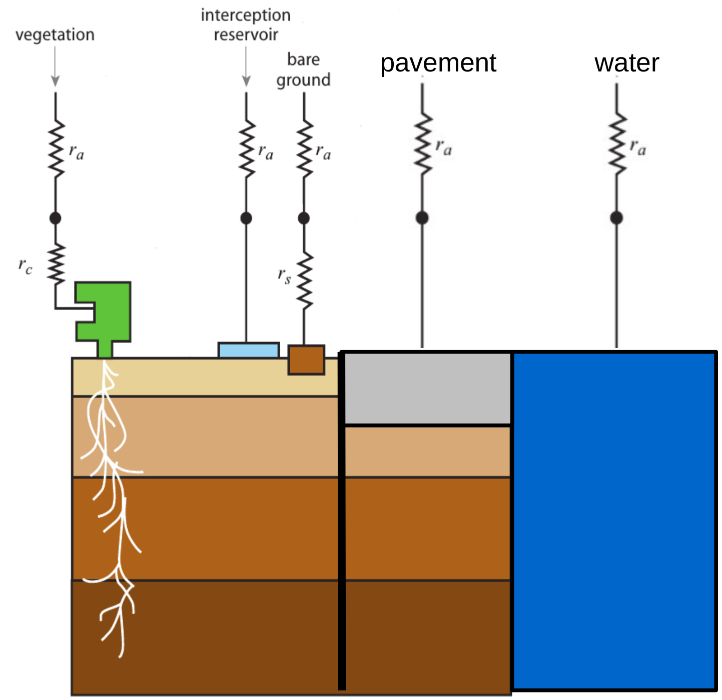


Example 2: Nocturnal boundary layer (with fog)



Summary

- Energy balance solver for different surface types
- Multiple (8) layers with varying depth
- Vertical transport of heat and water
- Currently no ice phase
- Requires a radiation model
- Validation of the LSM:
- Gehrke et al. (2021, https://doi.org/10.5194/gmd-14-5307-2021)



Outlook

- PALM also has an urban surface model for building surfaces (BSM/USM)
- Complex terrain requires special radiation code (shading, reflections)