A closer look at skin layer heat transfer in the surface energy balance

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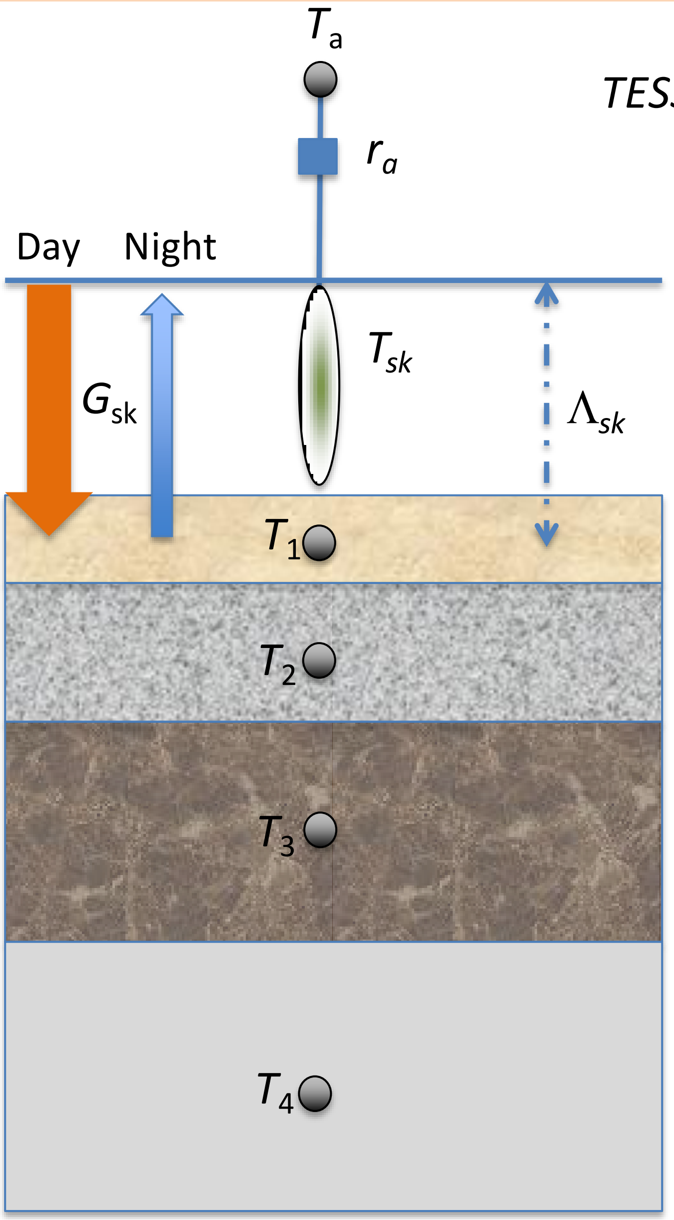
Energy balance in ECMWF TESSEL scheme



TESSEL: Tiled ECMWF Scheme for Surface Exchanges over Land

$$R_{n,*} = H + LE + G_{sk}$$

$$G_{sk} = \Lambda_{sk}(T_{sk} - T_1)$$

A **skin temperature** T_{sk} forms the interface between the soil and the atmosphere. The **skin conductivity**, Λ_{sk}, provides the **thermal connection** between the skin level and the soil or snow deck.

The skin represents the vegetation layer, the top layer of the bare soil, or the top layer of the snow pack, has <u>**no heat capacity**</u> and therefore responds 'instantaneously' to changes in e.g. radiative forcing.

Depth of soil layers: 0.07, 0.21, 0.72 and 1.89 m

TESSEL Λ_{sk} for different surface types

Table 8.2 *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 8.1–8.2 and Subsection 8.2.2). For tiles 6 and 7, $\Lambda_{a,u} = 15 W\ m^{-2}K^{-1}$ and $\Lambda_{a,s} = 10 W\ m^{-2}K^{-1}$ 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.

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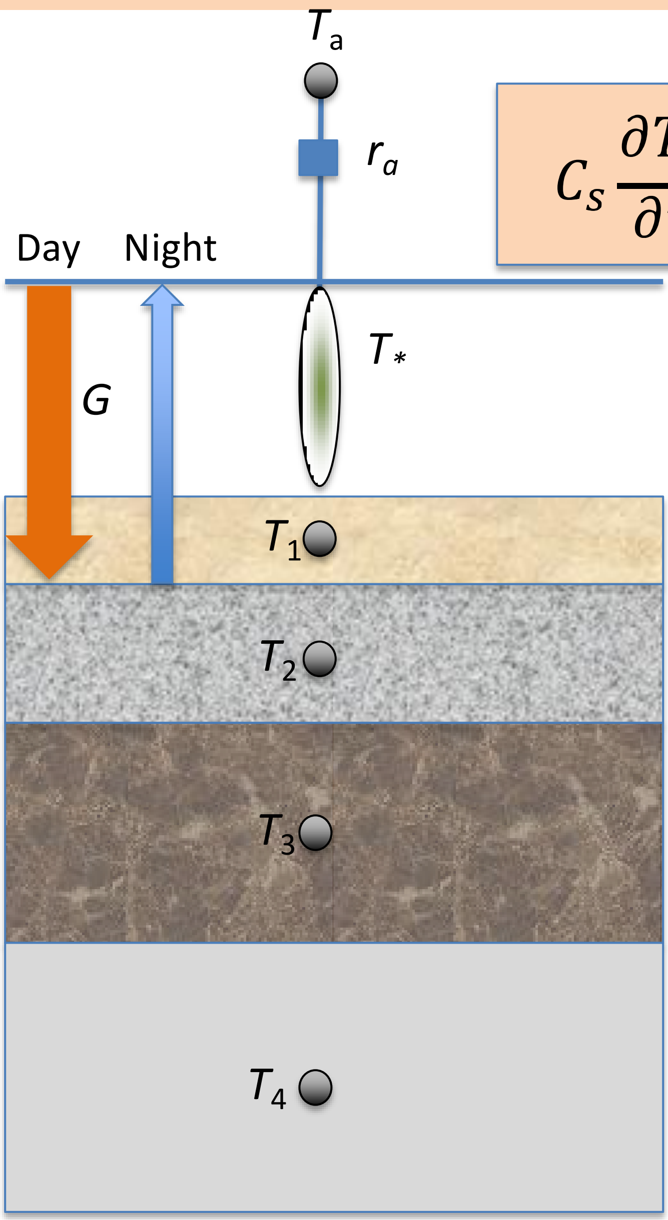
Energy balance in JULES scheme



JULES: Joint Environment Land Simulator

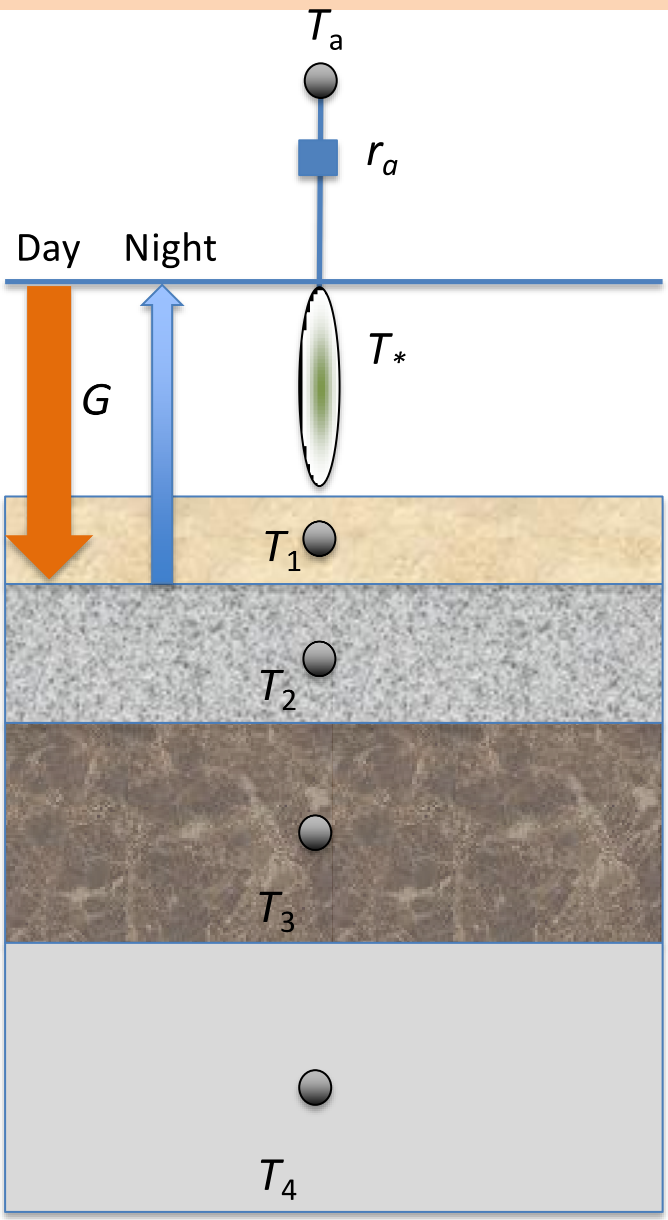
$$C_s \frac{\partial T_*}{\partial t} = (1-\alpha)R_{s\downarrow} + \varepsilon_s R_{l\downarrow} - \varepsilon\sigma T_*^4 - H - LE - G$$

- **Thermal inertia** is associated with the surface mass which is coupled to the underlying soil.
- A **surface temperature**, T_* , forms the interface between the soil and the atmosphere.

The surface represents the vegetation layer, the top layer of the bare soil, or the top layer of the snow pack, and <u>has a **heat capacity**</u>

Depth of soil layers: 0.10, 0.25, 0.65 and 2.0 m

‘Skin layer heat flux’ in JULES scheme



Depth of soil layers: 0.10, 0.25, 0.65 and 2.0 m

$$G = G_v^r + G_v^a + G_s$$

The vegetation fraction is coupled to the soil using

1. **radiative exchange** and
2. atmospheric **turbulence**,

whereas the soil is coupled through

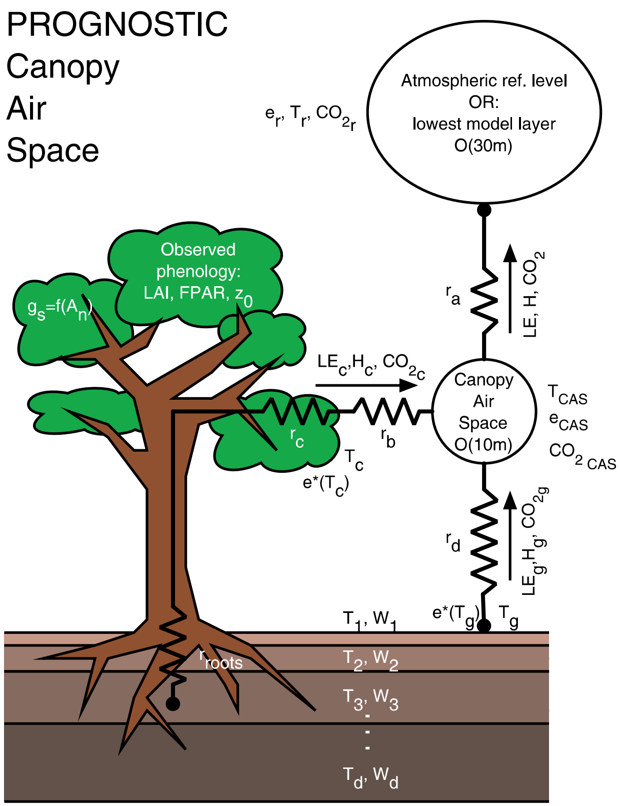
3. **conduction**. These three terms are given by:

$$G_v^r = \varepsilon_s \varepsilon_{soil} \sigma T_*^4 - \varepsilon_s \varepsilon_{soil} \sigma T_1^4$$

$$G_v^a = \nu \frac{\rho c_p}{r_a^c} (T_* - T_1)$$

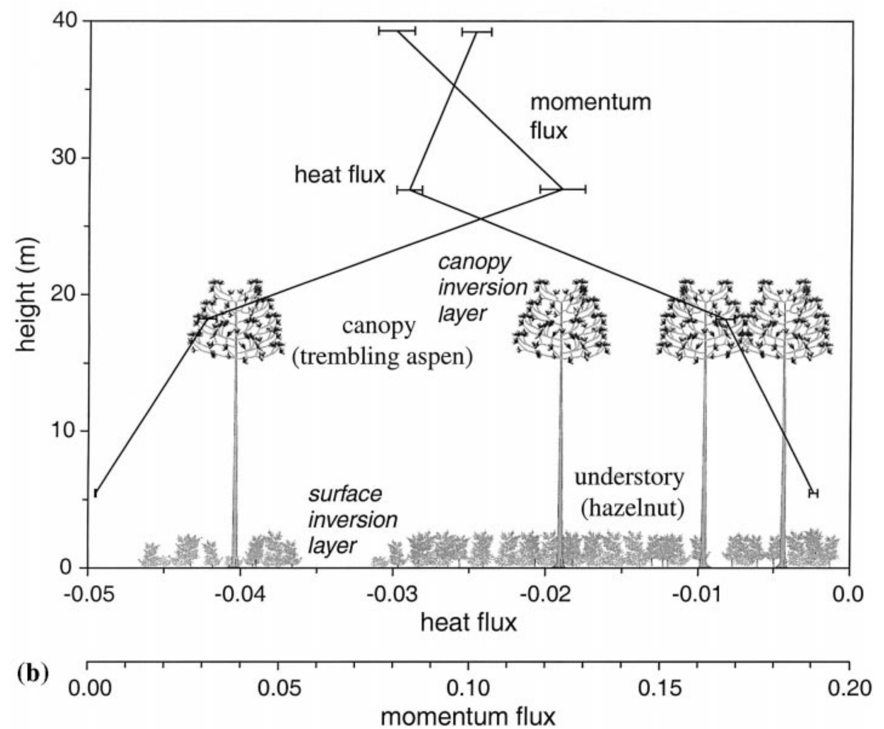
$$G_s = (1 - \nu) \lambda_{soil} (T_* - T_1) / \Delta z$$

Canopy storage & within-canopy transfer



Vidale & Stockli (2004)

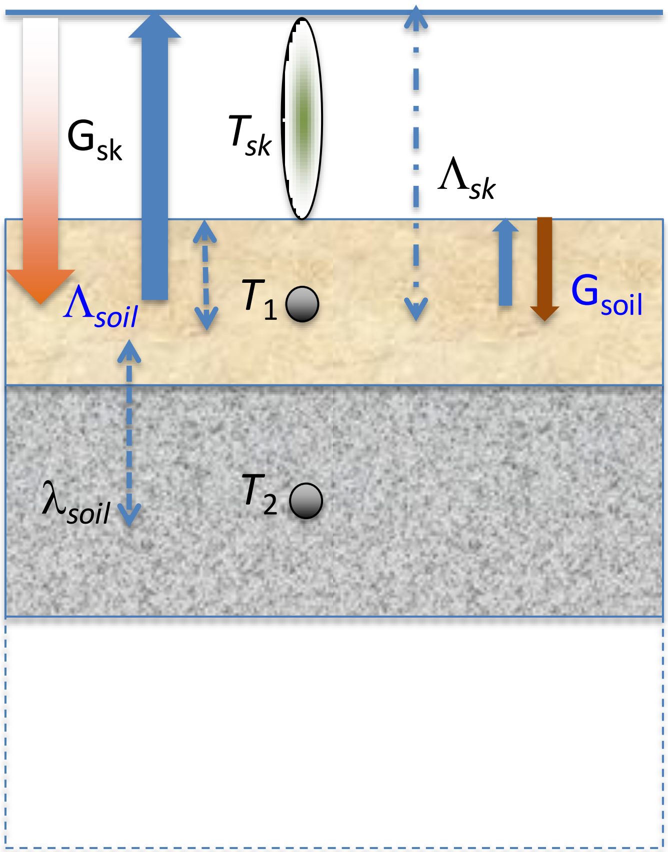
- **Canopy storage** is occasionally considered in land surface models, but not in TESSEL (no capacity for skin layer). In Jules the <u>vegetation has a capacity</u>
- **Within-canopy transfer is not explicitly considered in TESSEL**, but approximated in JULES



Nocturnal mixing in a Boreas aspen forest subcanopy

Research questions

- Study measured G_{sk}
- How does G_{sk} vary diurnally/seasonally?
- Compare measured and modelled G_{sk}
- What processes/parameters affect G_{sk}?
- Realistic values of Λ_{sk} for different surface types?
- Is the approach developed by TESSEL/JULES adequate?
- Should Λ_{sk} really be assumed constant throughout the day for most surfaces?
- What about canopy storage and within-canopy transfer?



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Multi-year, half-hourly datasets used to study G_{sk} and Λ_{sk}

Location	Falkenberg	Lindenberg	Tharandt	Cabauw
Surface type	Grass	Needleleaf forest	Needleleaf forest	Grass
Latitude	52° 10' N	52°18' N	50°58' N	51°97' N
Longitude	14° 07' E	13°95' E	13°34'E	4°93' E
Country	Germany	Germany	Germany	Netherlands
Elevation [m a.s.l.]:	73	42	380	-1
Topography	fairly flat	fairly flat	gently sloped	flat
Vegetation height (m)	< 0.20	18	26	0.1
LAI (m^2 m^{-2})	< 2	4	7.2	< 2
Dominant species	grass	Pine	Norway spruce	grass
Understorey	N/A	N/A	Wavy hair grass	N/A
Climate	Marine /continental (P= 563)	Mar. /cont. (P= 563)	Mediterranean/ montane (P=820)	Maritime (P=793)
Reference height (m)	2.4	30.0	42	1.5/5
Length of dataset	2003-2009	2003-2009	1998-2003	2003-2009

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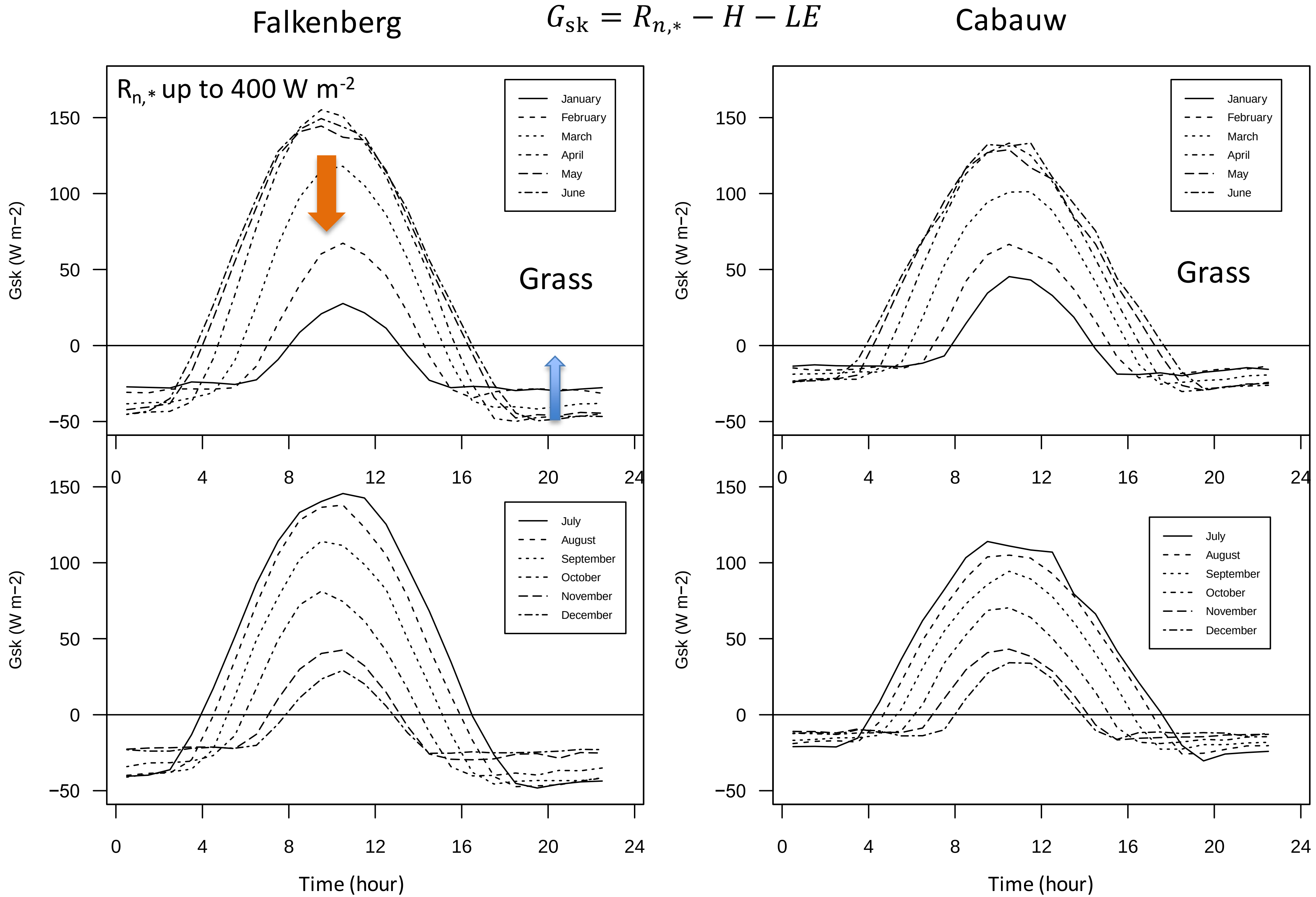
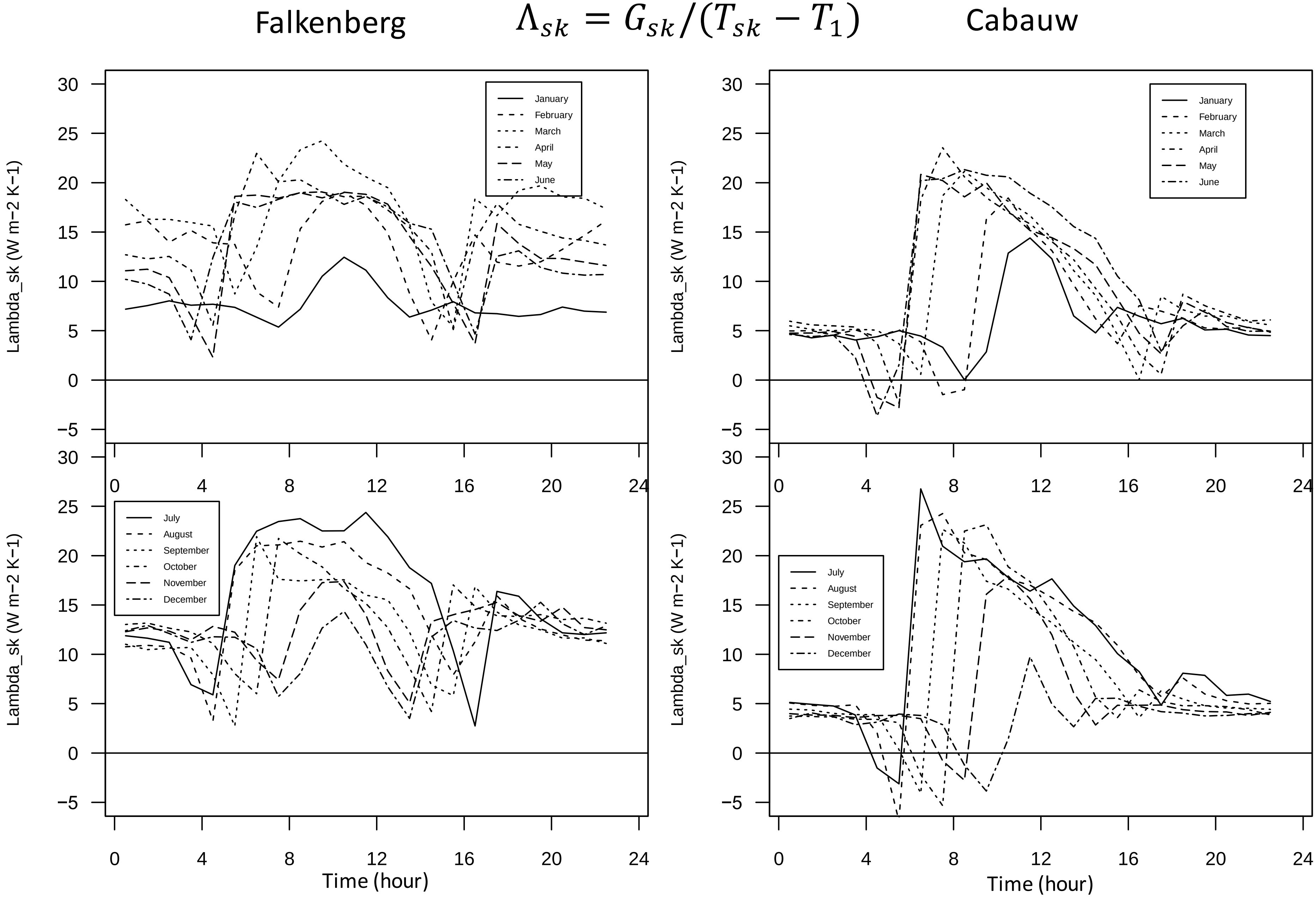
Falkenberg versus Cabauw grass: top-down G_{sk}

$$G_{sk} = R_{n,*} - H - LE$$

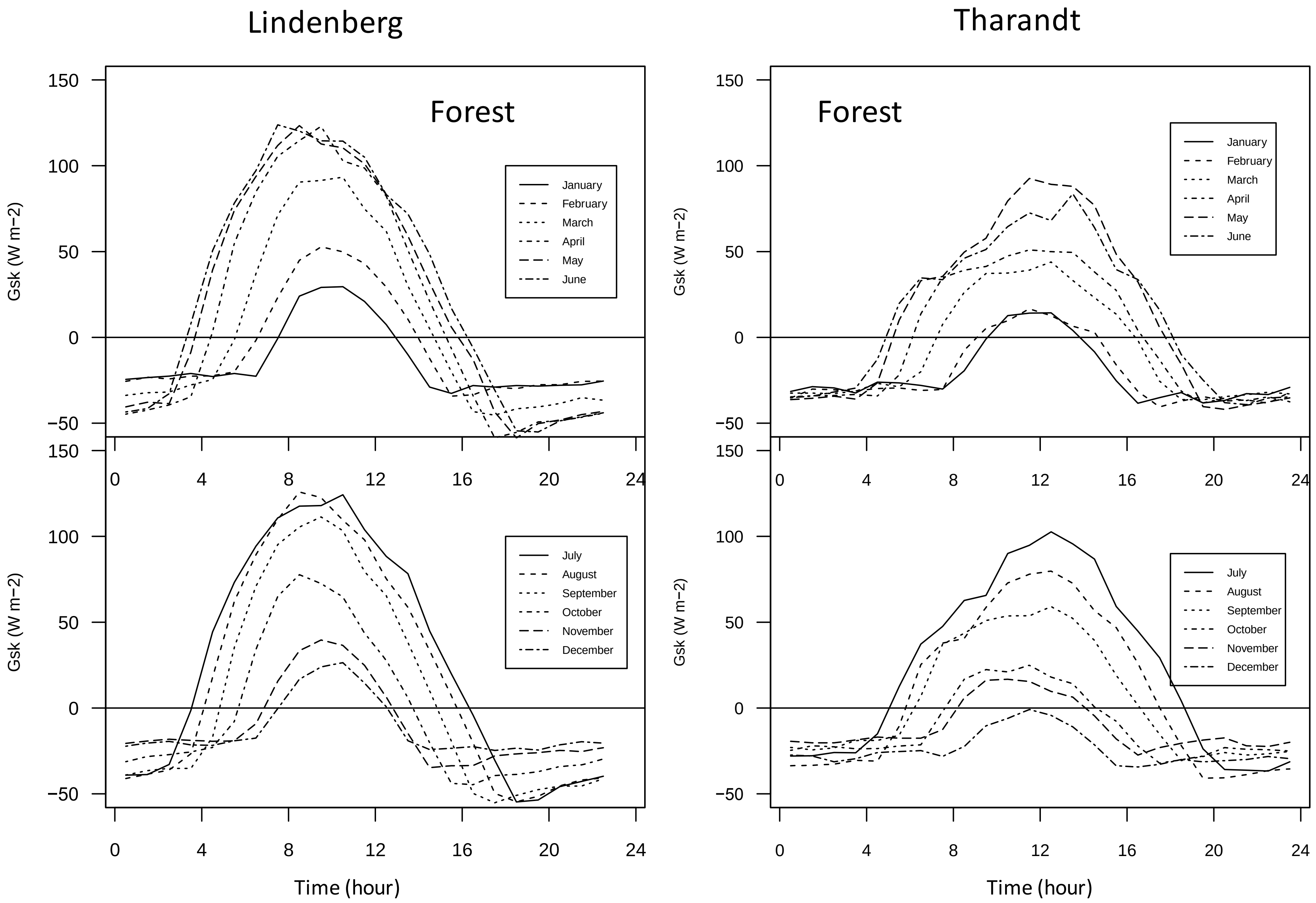


Falkenberg versus Cabauw grass: Λ_{sk}

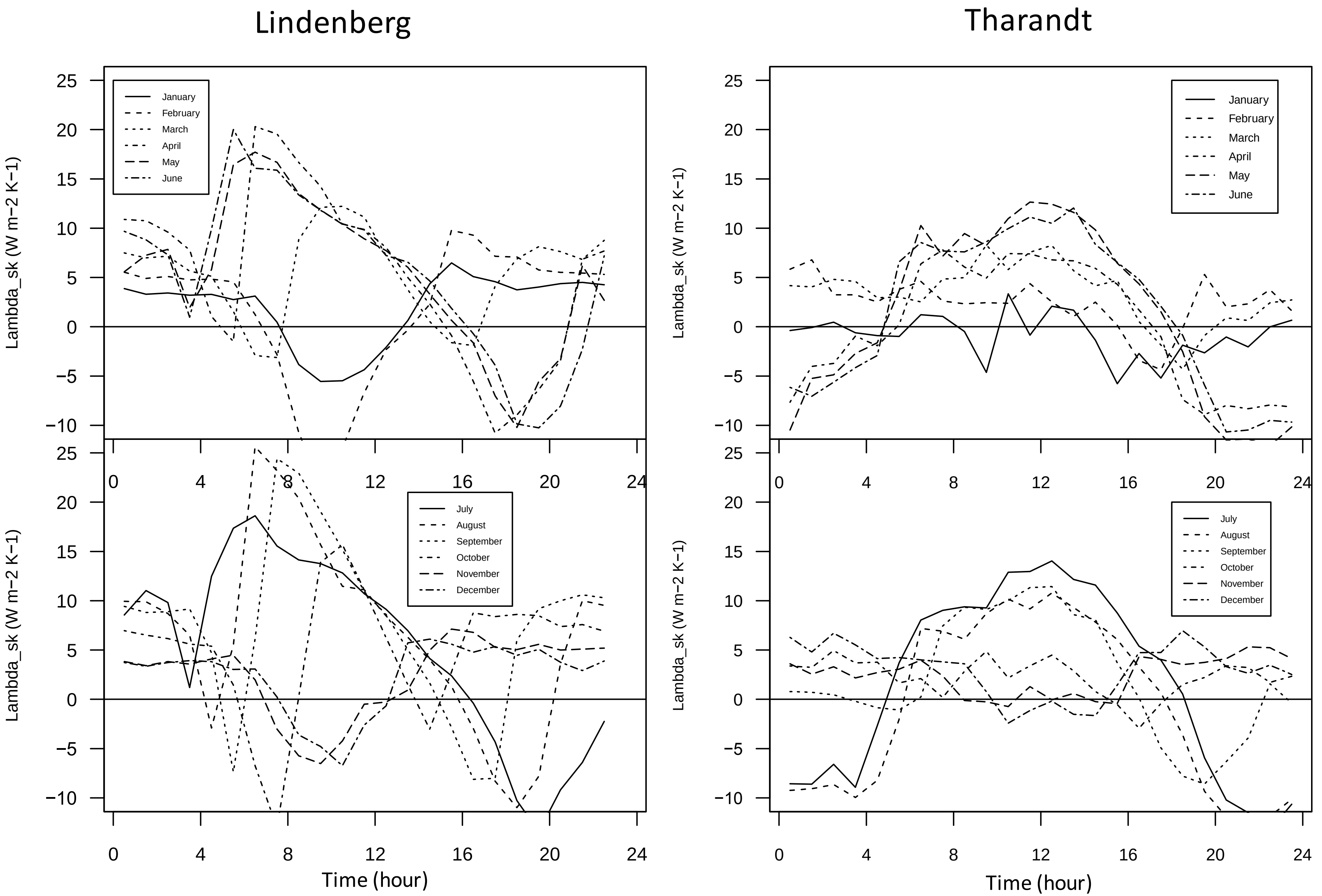
$$\Lambda_{sk} = G_{sk}/(T_{sk} - T_1)$$



Lindenberg versus Tharandt forest: G_{sk}



Lindenberg versus Tharandt forest: Λ_{sk}



Components of in-situ, bottom-up G_{sk}

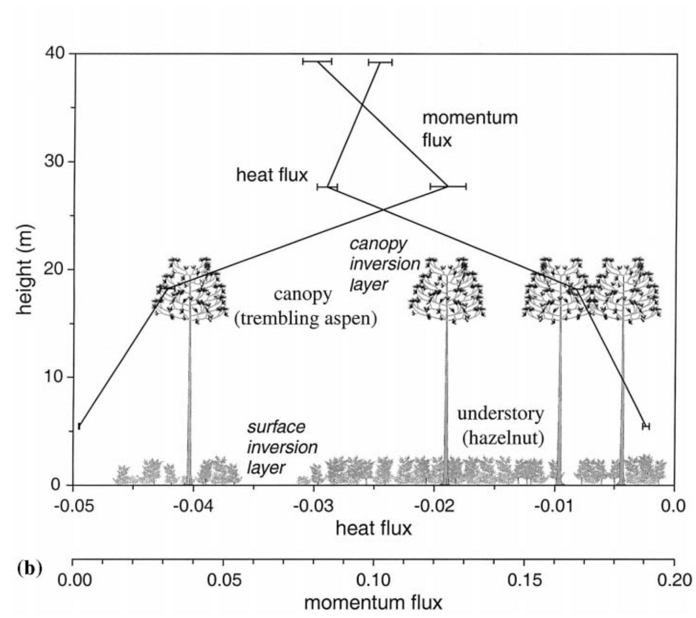
$$G_{sk} = G_{soil} + G_{veg}$$ (bottom-up)

$$G_{veg} = J_H + J_E + J_B + J_P$$

$$J_H = \int_0^{z_r} \rho_a \, c_p \frac{\delta T_a}{\delta t} dz$$

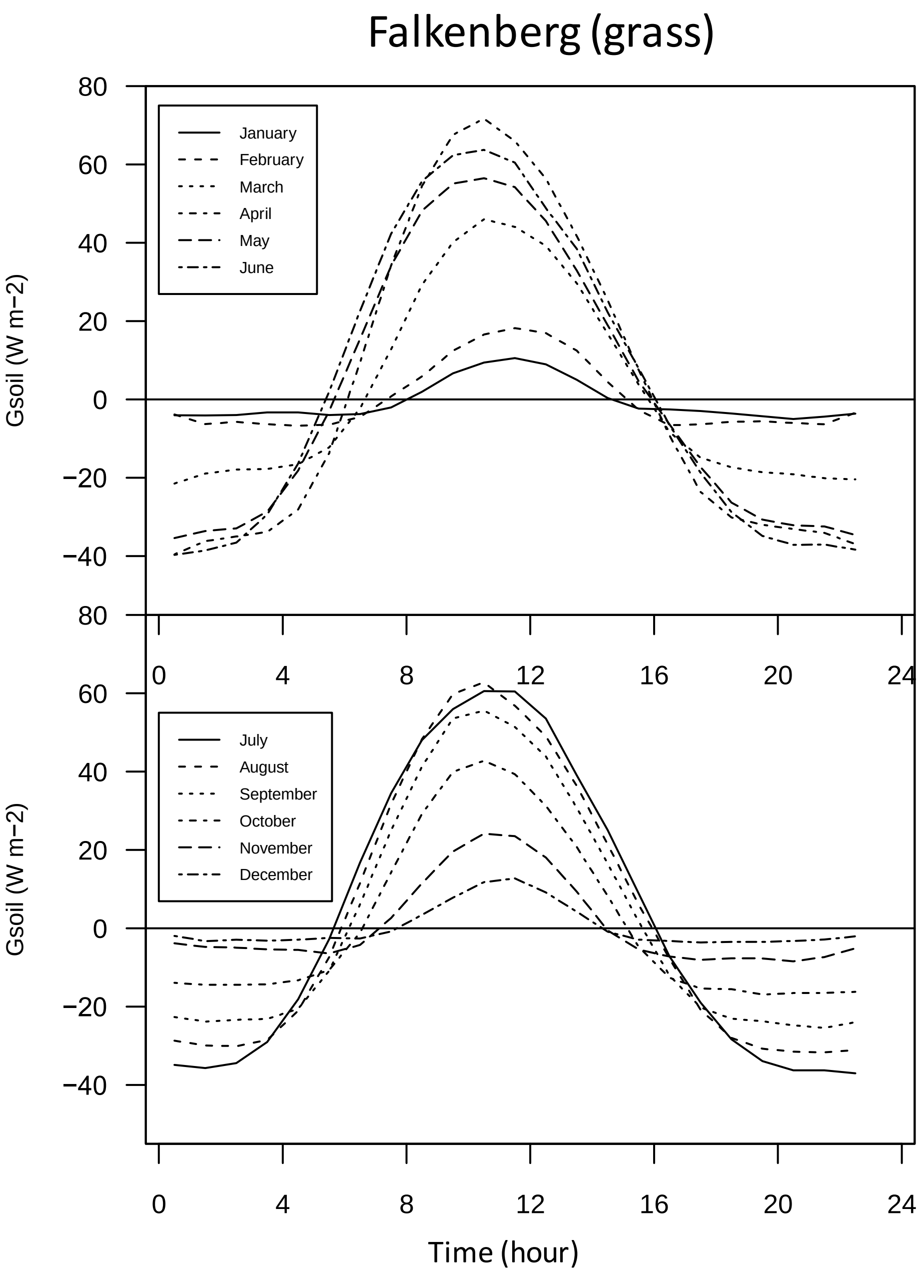
$$J_E = \int_0^{z_r} L \frac{\delta \rho_v}{\delta t} dz$$

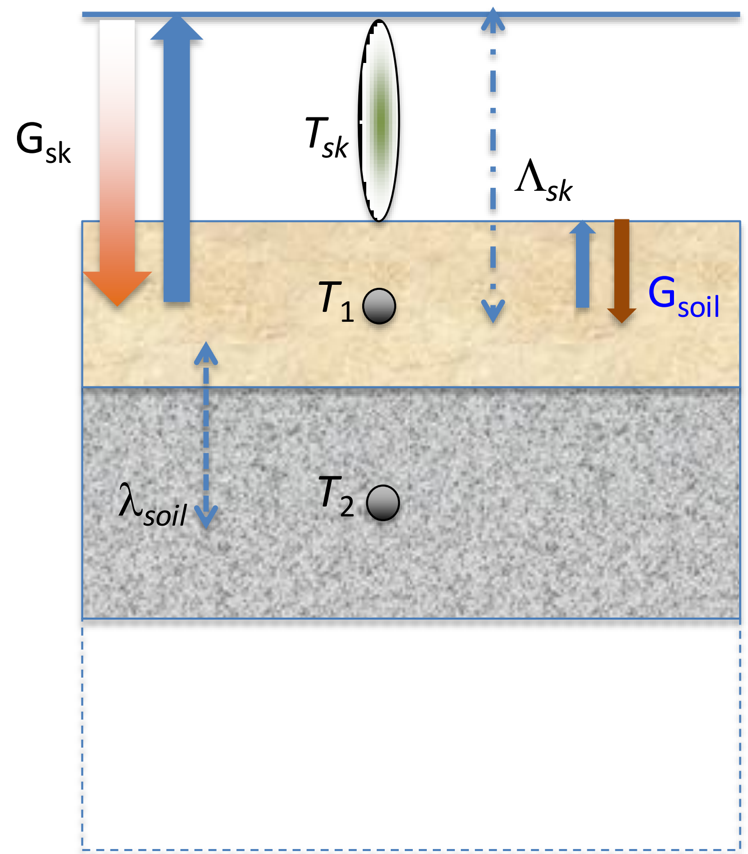
$$J_B = m_{veg} c_{veg} \frac{\Delta \overline{T_B}}{\Delta t}$$



J_H and J_E are the sensible and latent heat storage fluxes in the air column below the flux measurement height, z_r, above the canopy. J_B is the heat storage flux in the above-ground biomass and J_P is the rate of energy storage by photosynthesis

Monthly averaged diurnal course G_{soil} (grass)



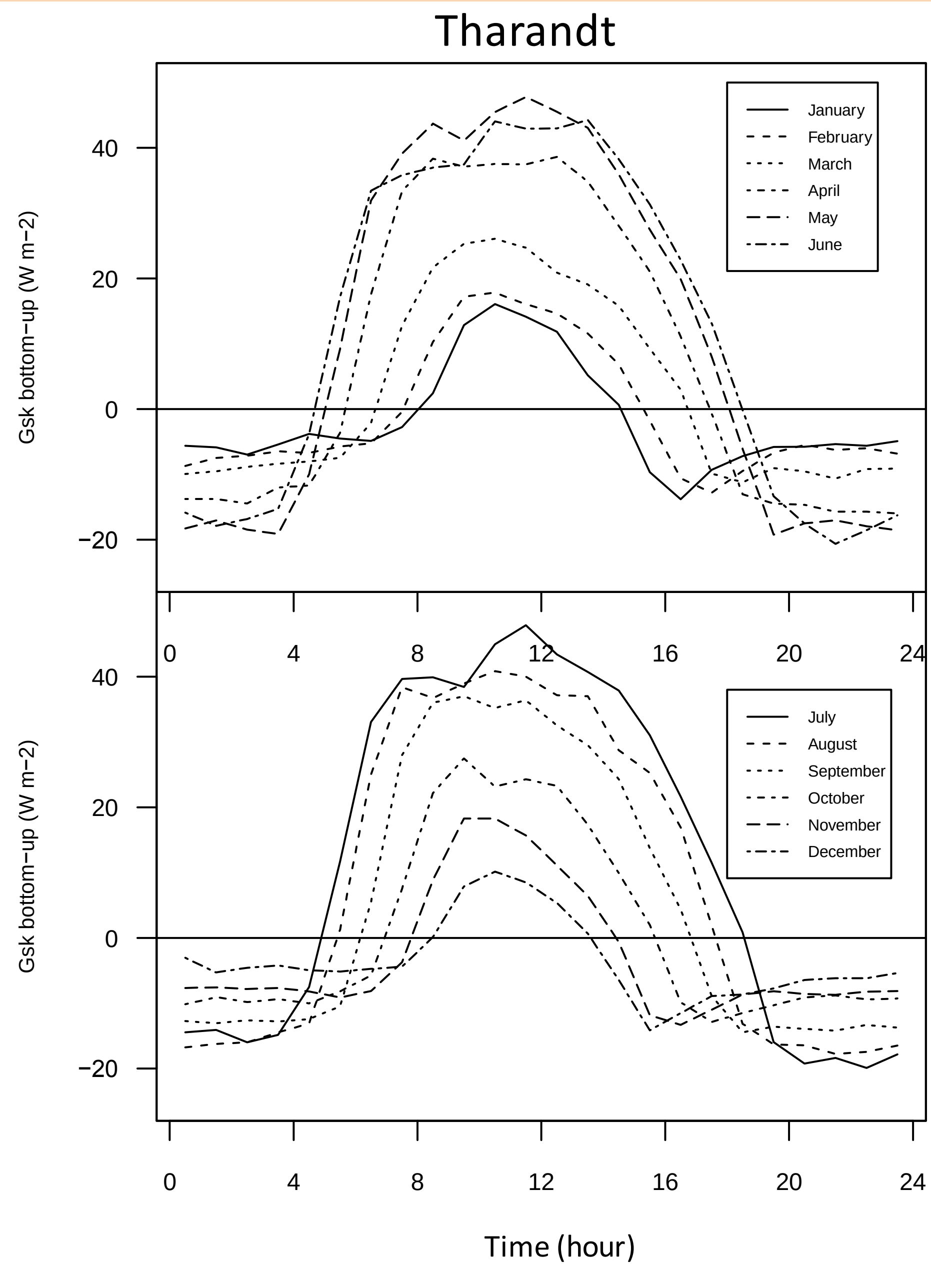


Role of canopy storage

$$R_n - G_{soil} - G_{veg} = H + LE$$

$$G_{veg} = J_H + J_E + J_B + J_P$$

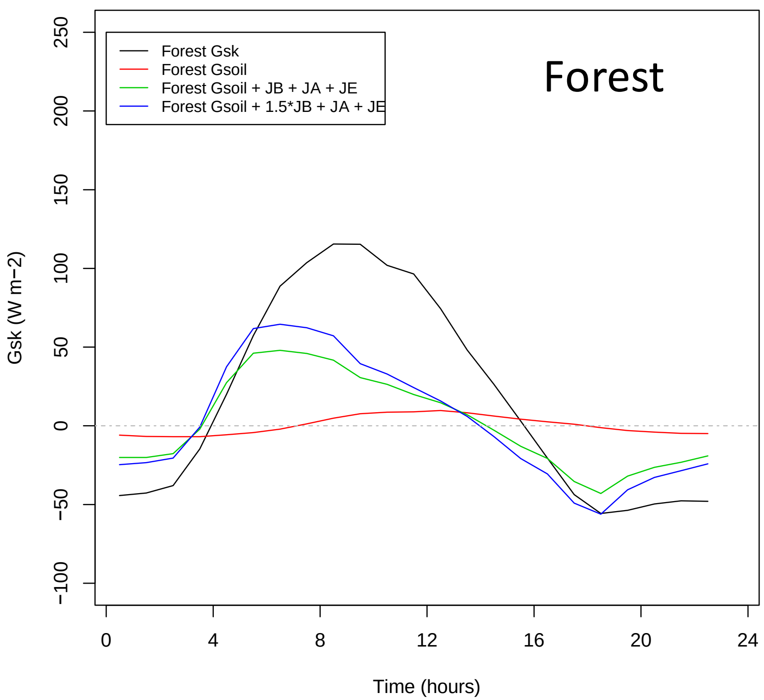
- J_A and J_E are the **sensible and latent** heat storage fluxes in the air column below the flux measurement height
- J_B is the heat storage flux in the **above-ground biomass**
- J_P is the rate of energy storage by **photosynthesis**.

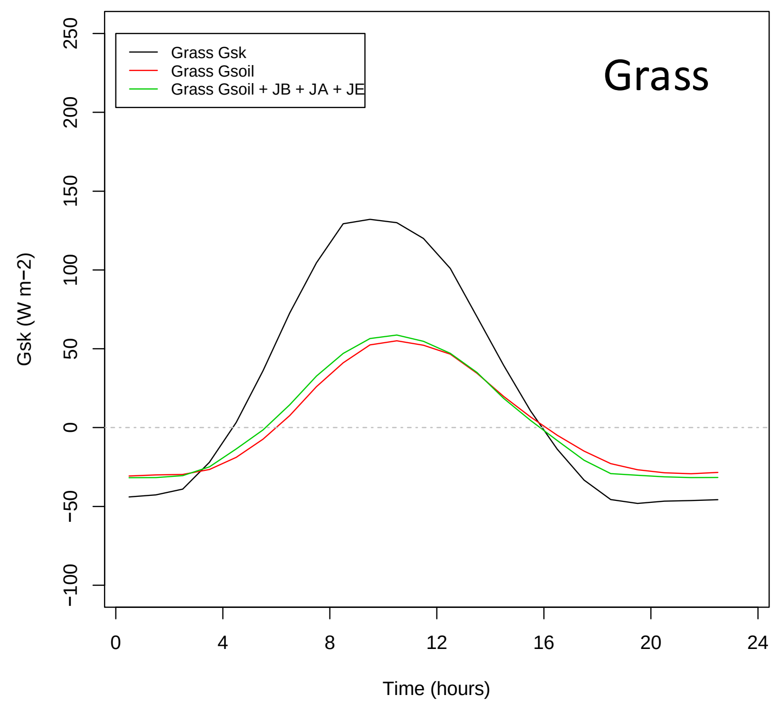


Bottom up versus top-down values of G_{sk}

- (Top-down): $G_{sk} = R_{n,*} - H - LE$
- (Bottom-up) = $G_{sk} = G_{soil} + J_H + J_E + J_B$
- J_B requires estimates of canopy biomass (large uncertainties)
- Years 2003-2008
- AMJJAS

Lindenberg/Falkenberg





Modelled components of G_{sk}: JULES

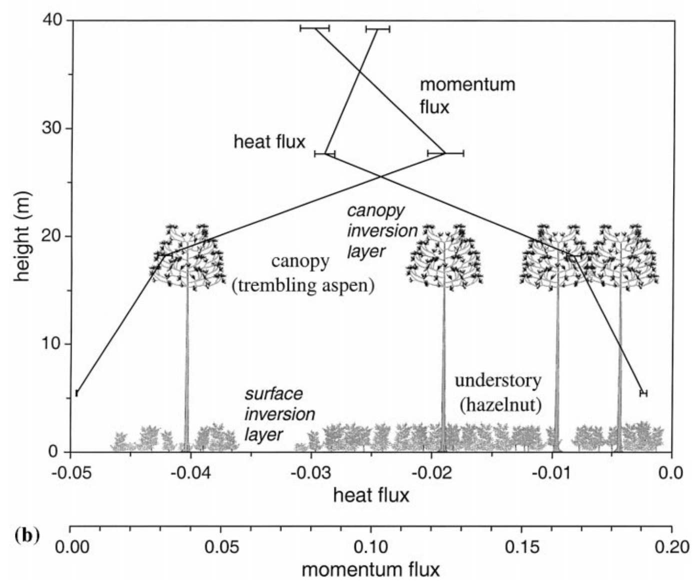
$$G_v^r = \varepsilon_s \varepsilon_{soil} \sigma T_*^4 - \varepsilon_s \varepsilon_{soil} \sigma T_1^4$$

$$G_v^a = \nu \frac{\rho c_p}{r_a^c}(T_* - T_1)$$

$$G_s = (1-\nu)\lambda_{soil}(T_* - T_1)/\Delta z$$

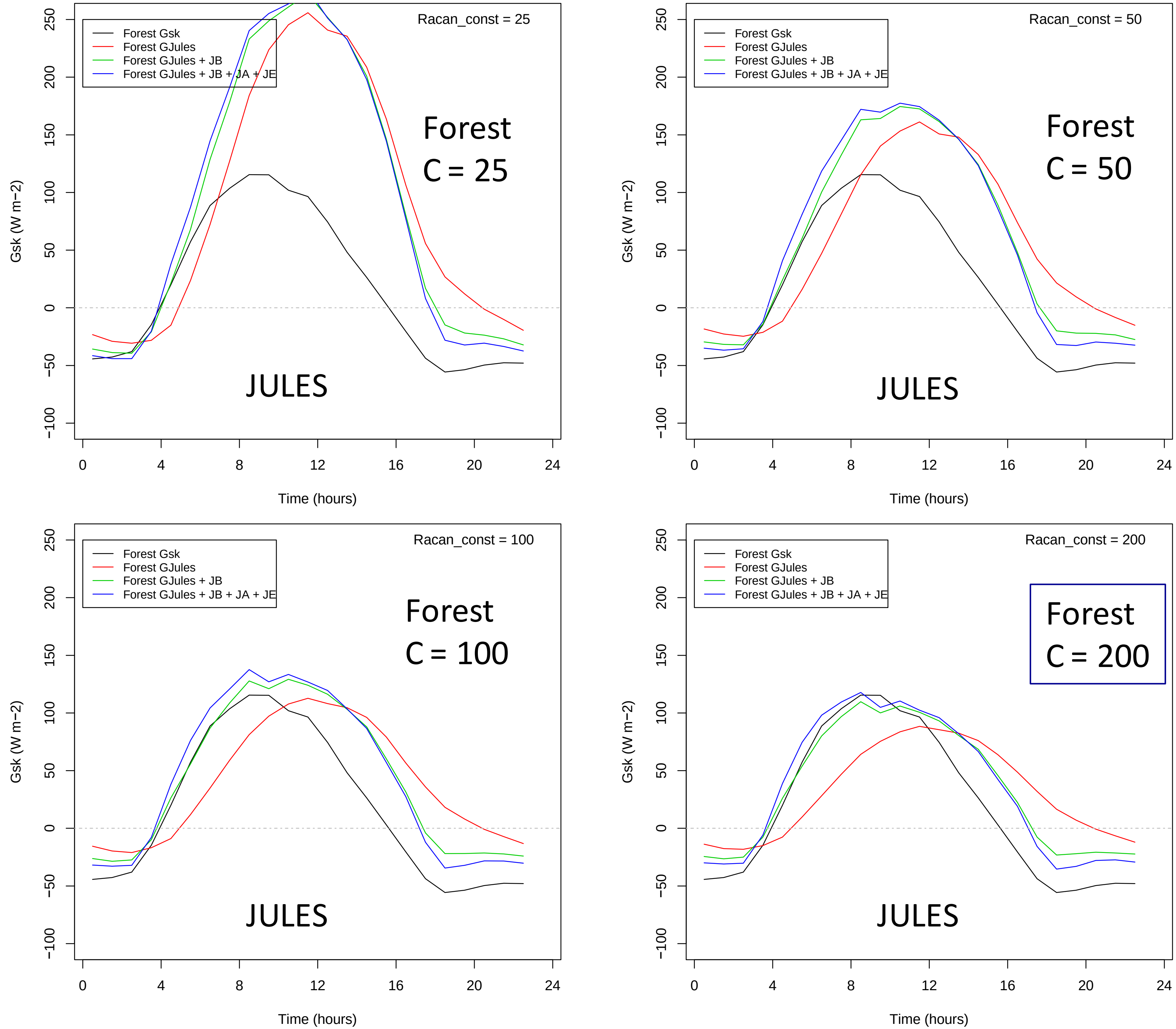
$$r_a^c = C/u_*$$

$C = 43$

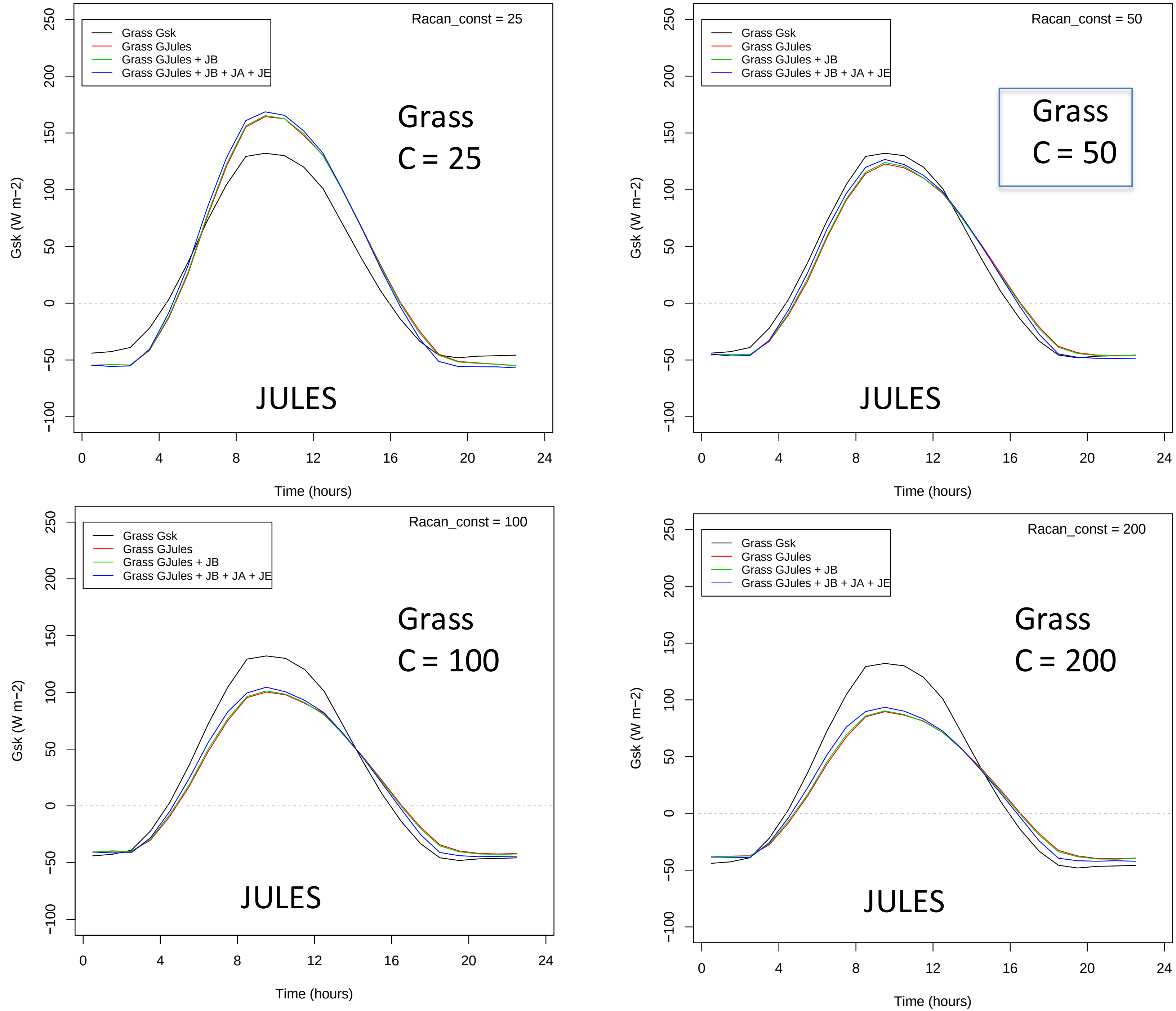


$$J_B = m_{veg} c_{veg} \frac{\Delta \overline{T_B}}{\Delta t}$$

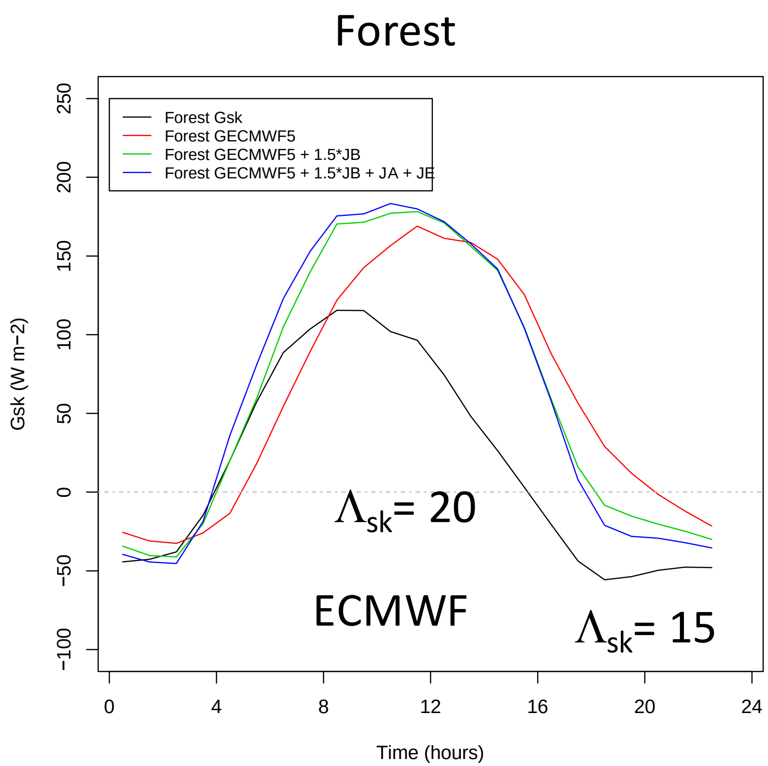
$$C_s \frac{\partial T_*}{\partial t} = (1-\alpha)R_{s\downarrow} + \varepsilon_s R_{l\downarrow} - \varepsilon \sigma T_*^4 - H - LE - G$$

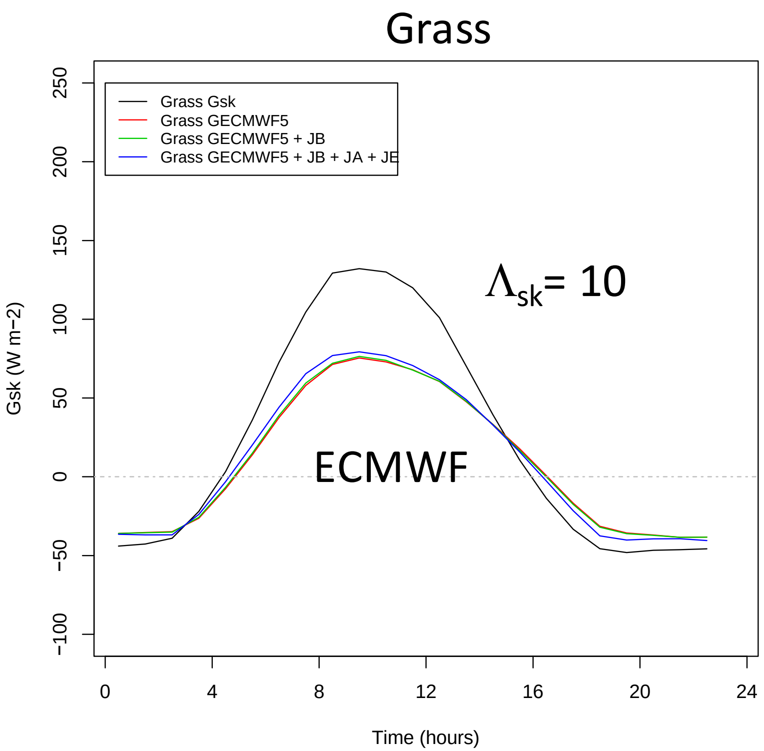


Racan_const = 25
Forest Gsk
Forest GJules
Forest GJules + JB
Forest GJules + JB + JA + JE
Forest
C = 25
JULES
Gsk (W m−2)
Time (hours)
Racan_const = 50
Forest Gsk
Forest GJules
Forest GJules + JB
Forest GJules + JB + JA + JE
Forest
C = 50
JULES
Gsk (W m−2)
Time (hours)
Racan_const = 100
Forest Gsk
Forest GJules
Forest GJules + JB
Forest GJules + JB + JA + JE
Forest
C = 100
JULES
Gsk (W m−2)
Time (hours)
Racan_const = 200
Forest Gsk
Forest GJules
Forest GJules + JB
Forest GJules + JB + JA + JE
Forest
C = 200
JULES
Gsk (W m−2)
Time (hours)


Racan_const = 25
Grass Gsk
Grass GJules
Grass GJules + JB
Grass GJules + JB + JA + JE
Grass
C = 25
JULES
Gsk (W m−2)
Time (hours)
Racan_const = 50
Grass Gsk
Grass GJules
Grass GJules + JB
Grass GJules + JB + JA + JE
Grass
C = 50
JULES
Gsk (W m−2)
Time (hours)
Racan_const = 100
Grass Gsk
Grass GJules
Grass GJules + JB
Grass GJules + JB + JA + JE
Grass
C = 100
JULES
Gsk (W m−2)
Time (hours)
Racan_const = 200
Grass Gsk
Grass GJules
Grass GJules + JB
Grass GJules + JB + JA + JE
Grass
C = 200
JULES
Gsk (W m−2)
Time (hours)

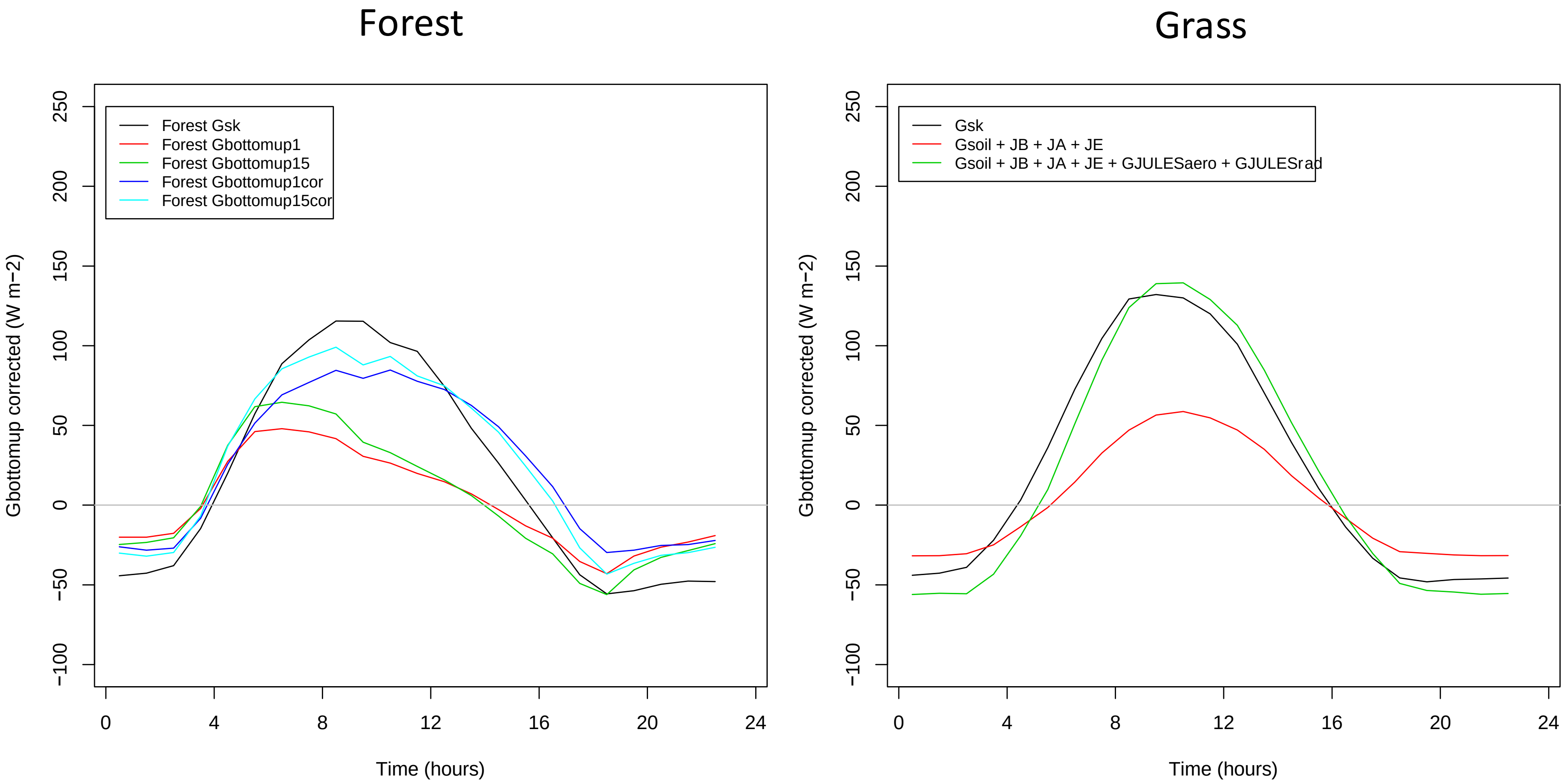
G_{sk}_ECMWF





- ECMWF equation (red) overestimates for forest & underestimates for grass
- Λ_{sk} is incorrect
- Taking heat storage into account improves timing, but not amplitude
- Standard G_JULES (with C=50) for grass performs better than G_ECMWF

Bottom-up plus radiation and aerodynamic term of G_{sk}_JULES



Conclusions so far

- $\boldsymbol{G_{sk}}$ varies **diurnally and seasonally**

- G_{sk} takes up a large part of R_n (around 25%), even for a grass surface
- Λ_{sk} varies **diurnally and seasonally** and is a function of **ustar/stability**

- **Counter-gradient in-canopy transfer** causes negative Λ_{sk} values

- Models do quite well, but a simple Λ_{sk} is not enough

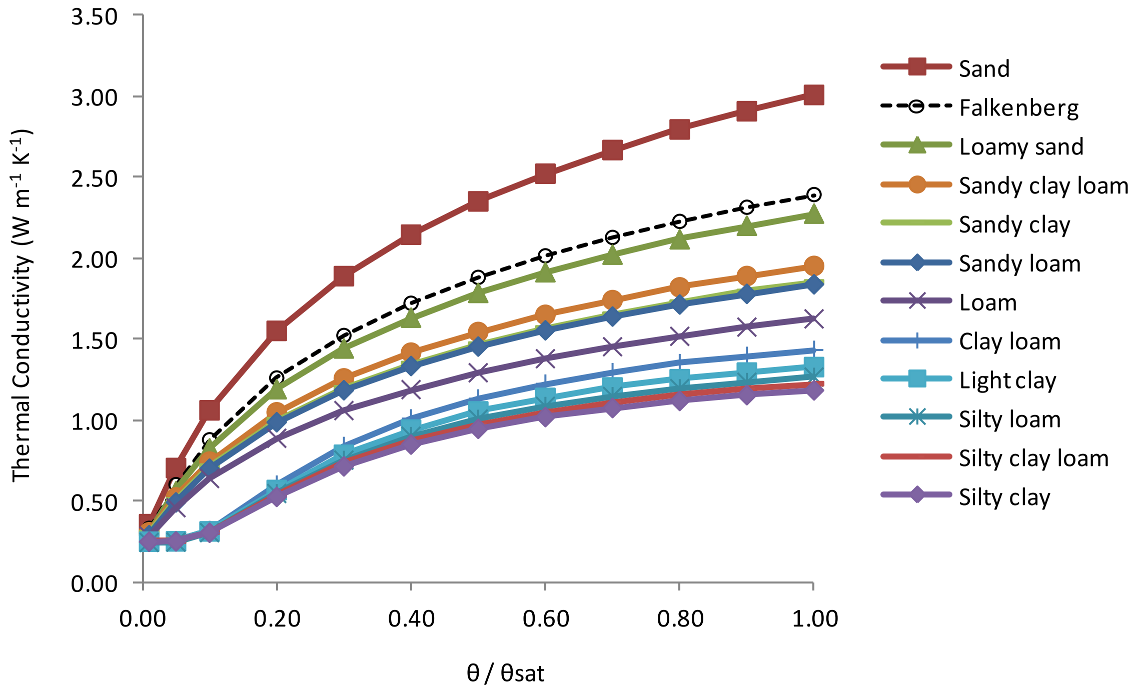
- **JULES** does better, but in-canopy aerodynamic transfer could be improved via e.g. a two-layer model.

Theory behind λ_{soil}

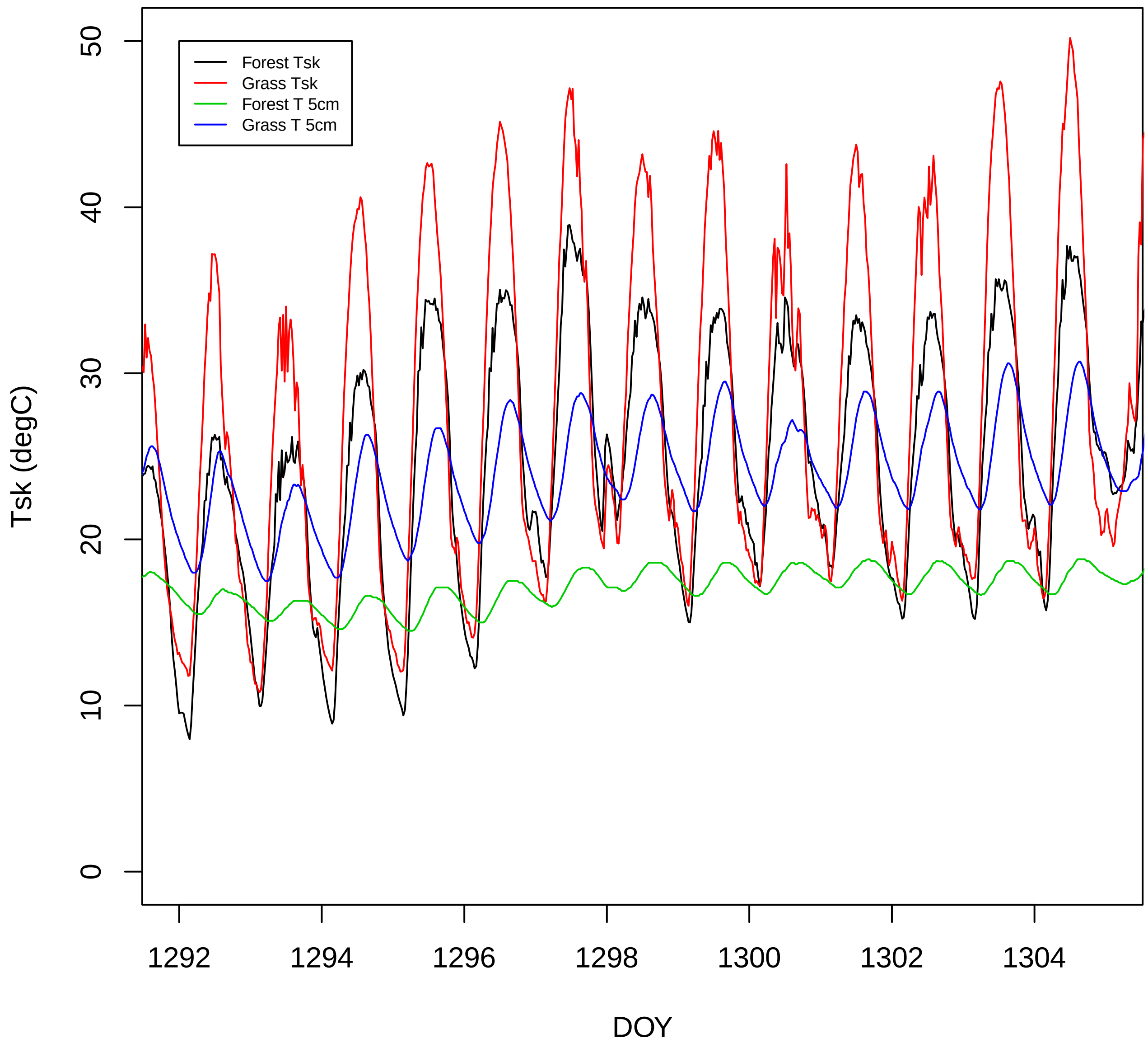
The soil thermal conductivity, λ_{soil}, depends on the soil-water content following Peters-Lidard et al. (1998) (see also Farouki, 1986; Johansen, 1975)

$$\lambda_{soil} = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry}$$

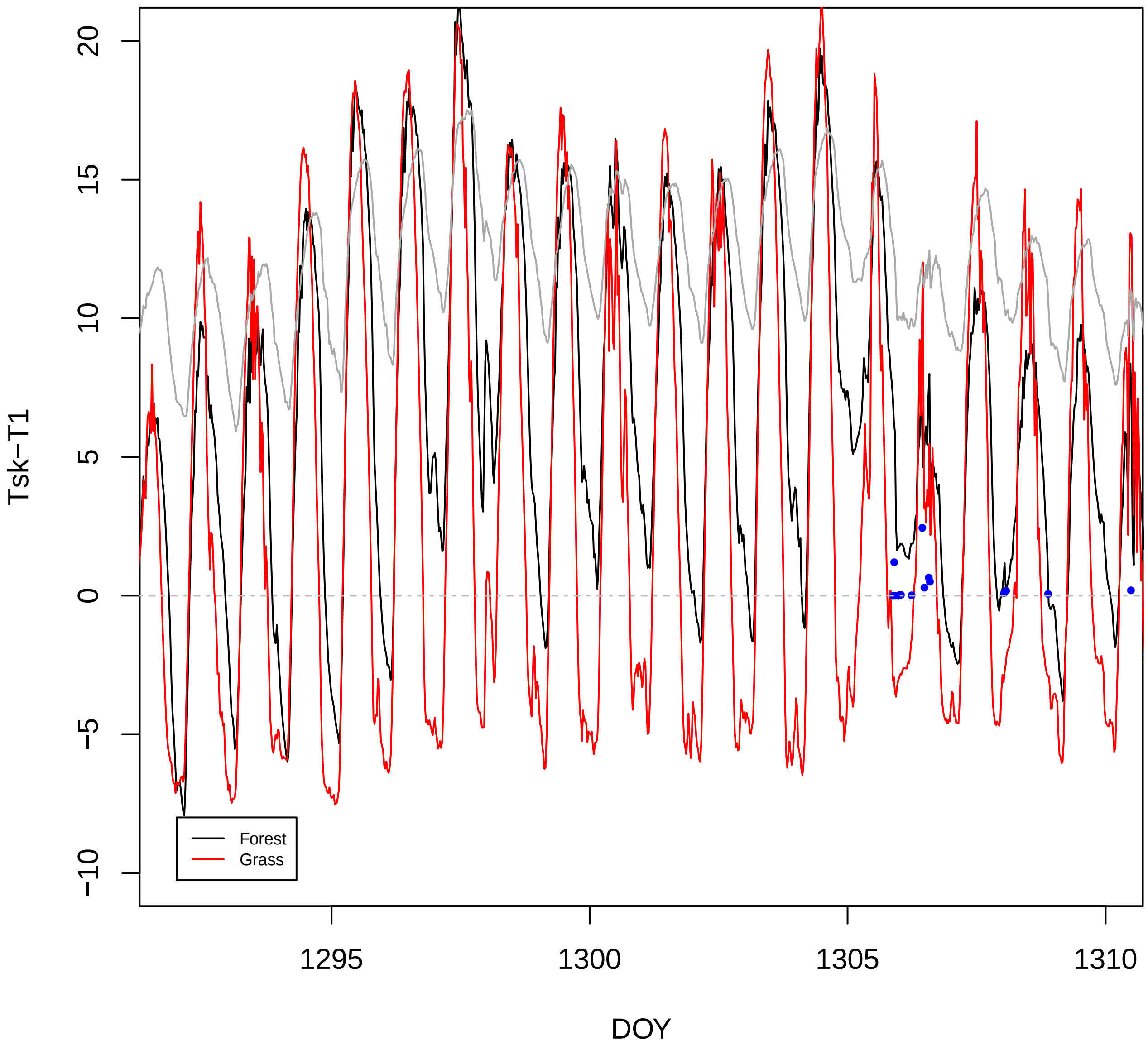
Standard soils: Cosby et al. (1986).



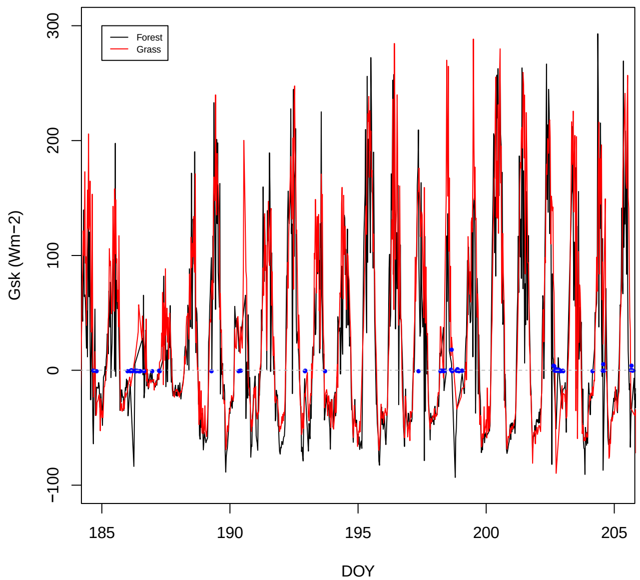
Recent work on Lindenberg/Falkenberg

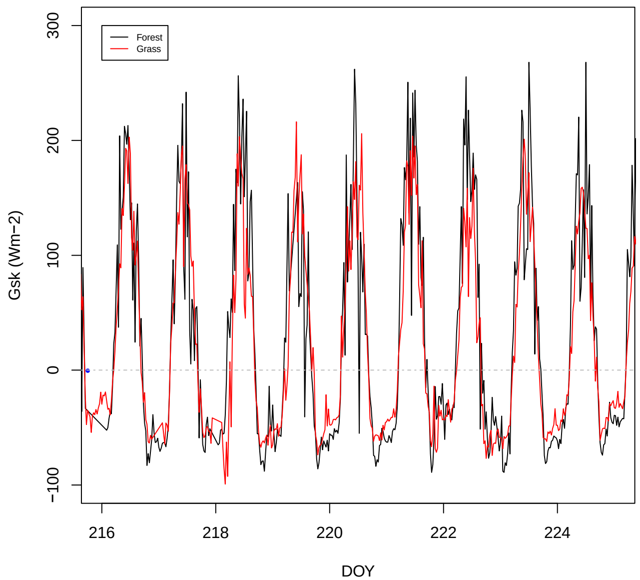


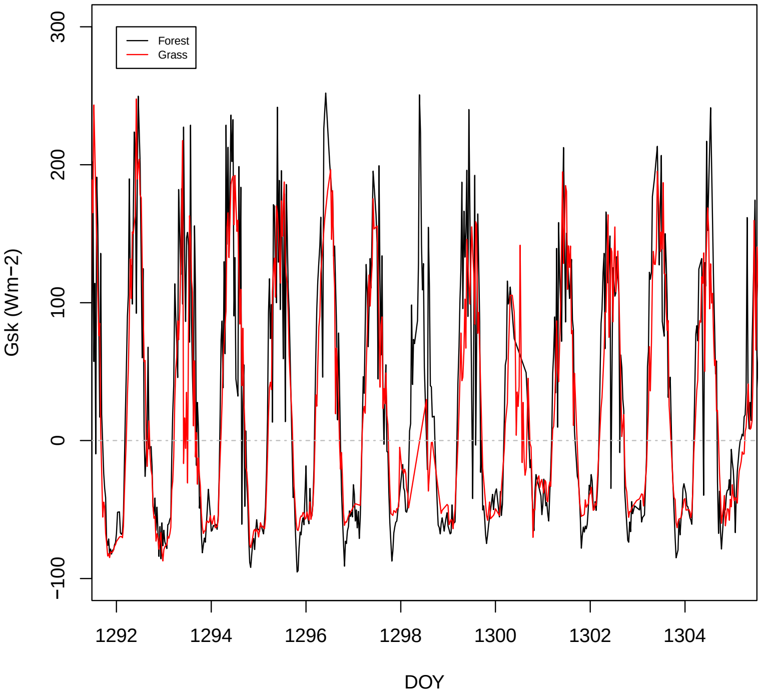
Recent work on Lindenberg/Falkenberg



Recent work on Lindenberg/Falkenberg







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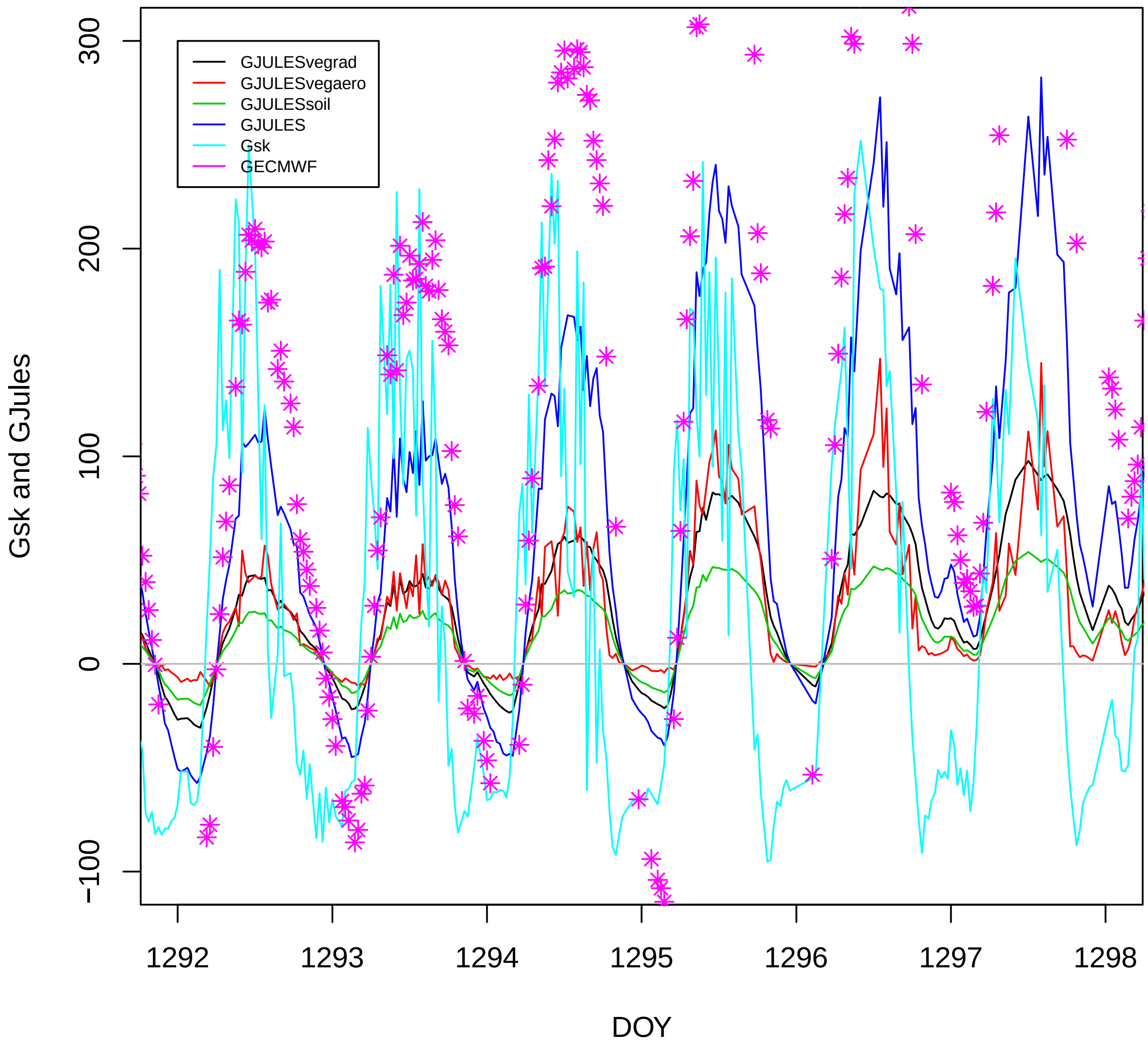
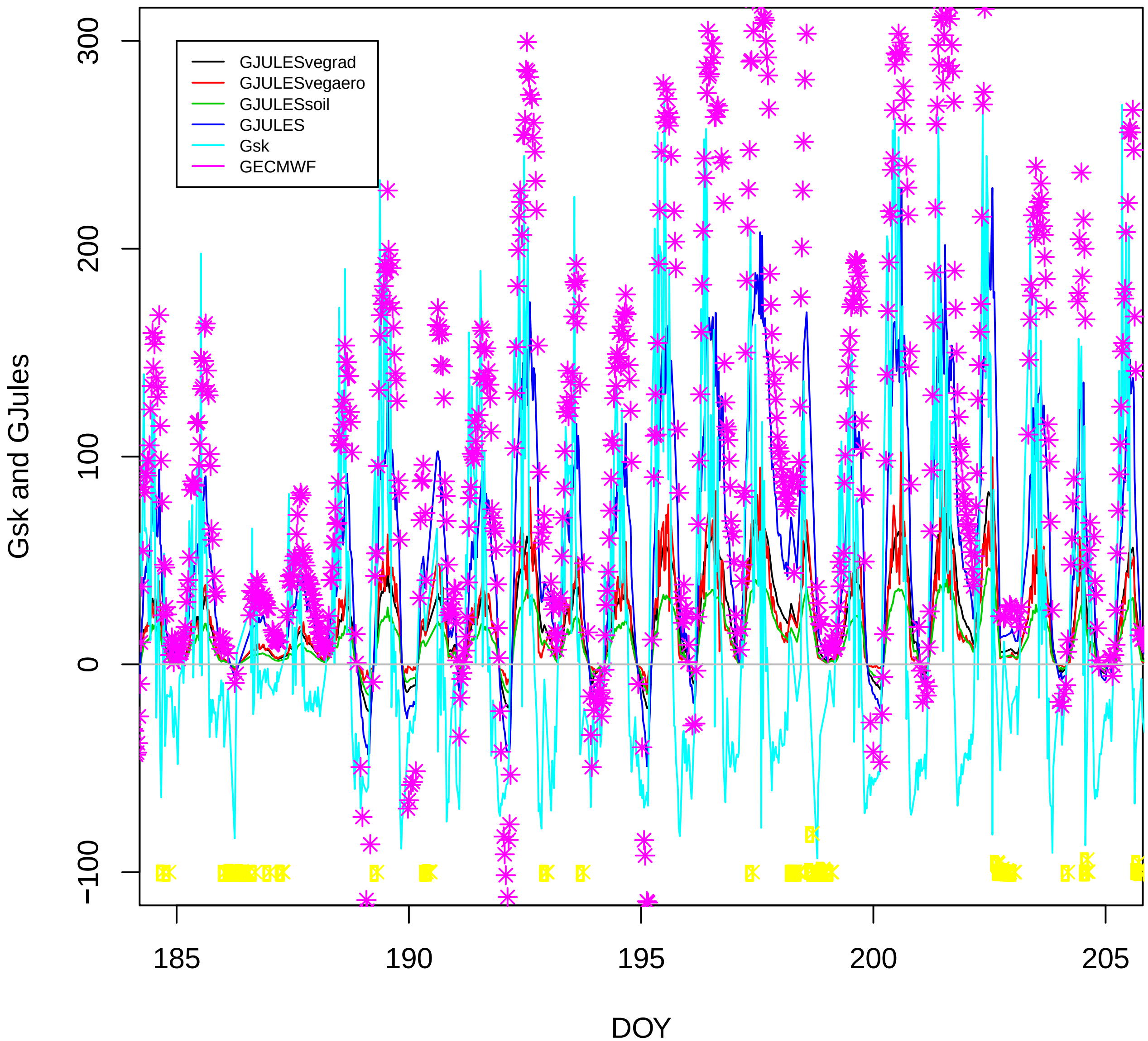


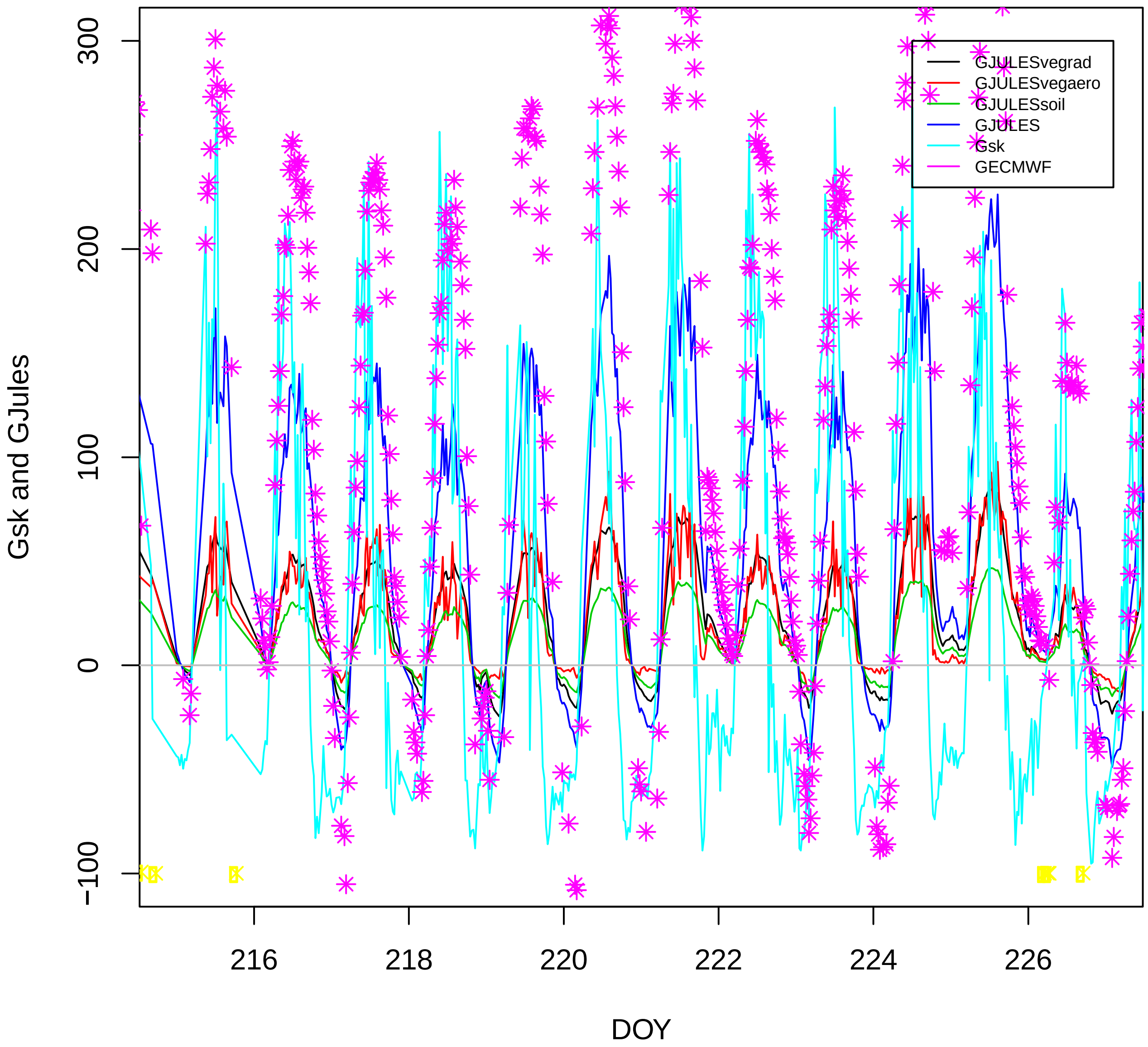
Forest

Recent work on Lindenberg/Falkenberg



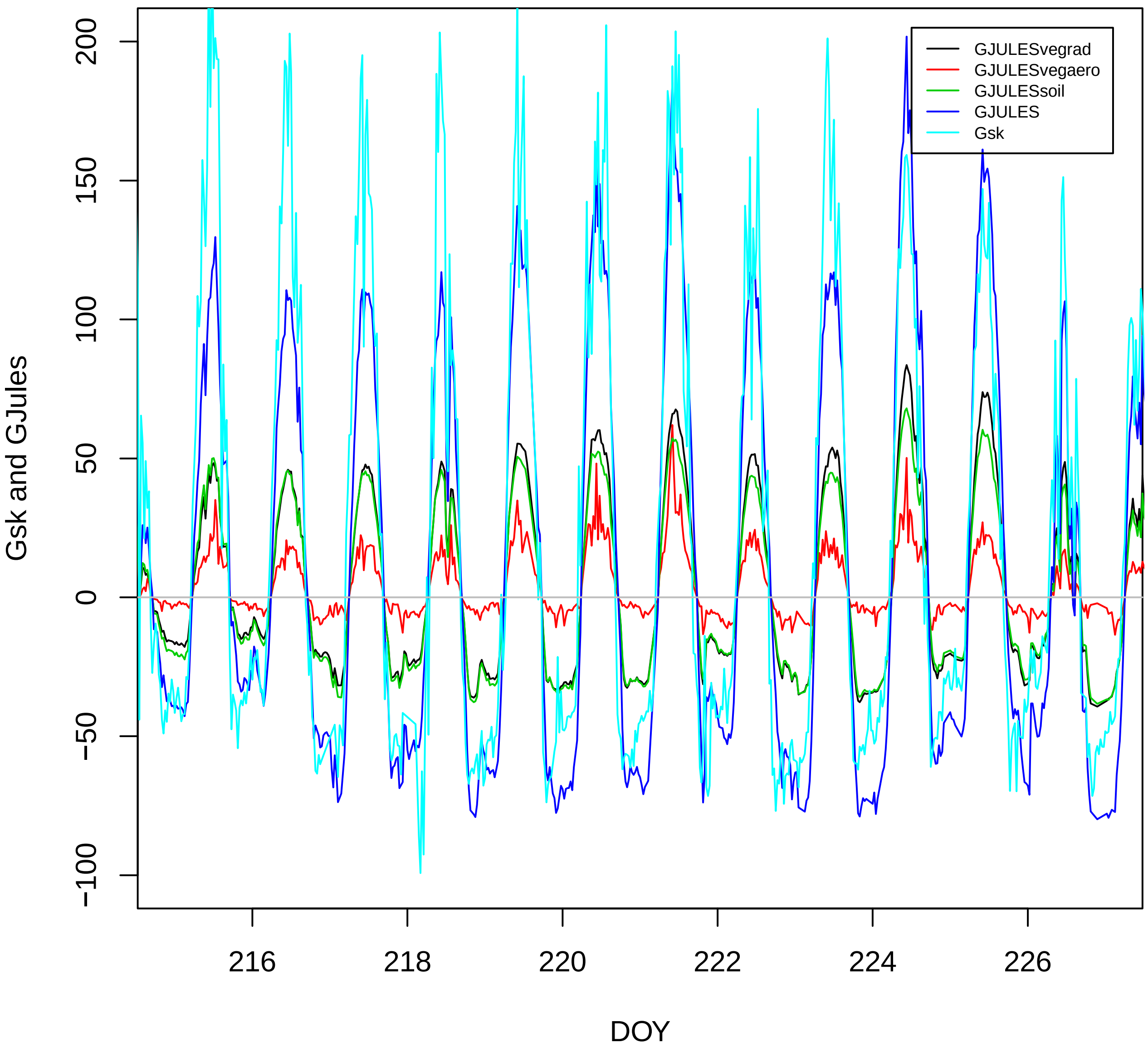
Forest

Recent work on Lindenberg/Falkenberg



Forest

Recent work on Lindenberg/Falkenberg



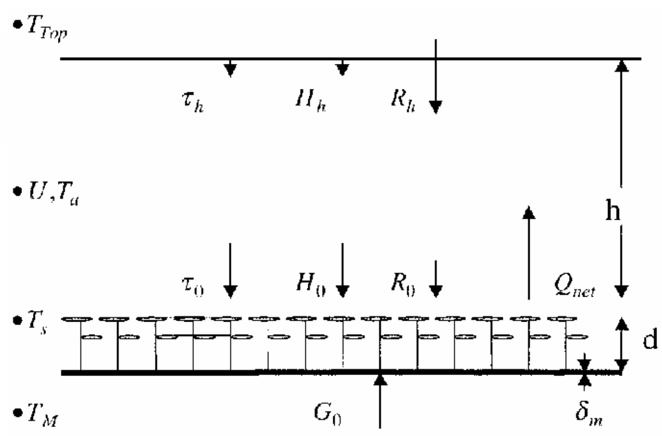
Grass

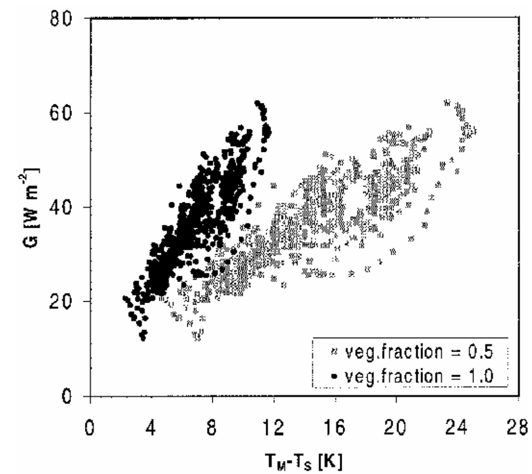
Bulk conductance of the mulch/stagnant air layer within the vegetation

Some authors (Van der Wiel et al.; Steeneveld et al.) use the term ***bulk conductance of the mulch/stagnant air layer within the vegetation***

$$G = (\lambda_m/\delta_m)(T_M - T_S).$$

$$\Lambda_{sk} = {}^{\lambda_m}/_{\delta_m}$$





λ_m the conductance in W m^{-1} K^{-1} (although conductivity would be a better term), and δ_m is the thickness of the mulch/stagnant air layer (in m).

Values for the bulk conductance between 2 and 7 W m^{-1} K^{-1} are reported (Duynkerke, 1991; Van de Wiel et al., 2003); however**, in none of the papers is δ_m explicitly taken into account.**

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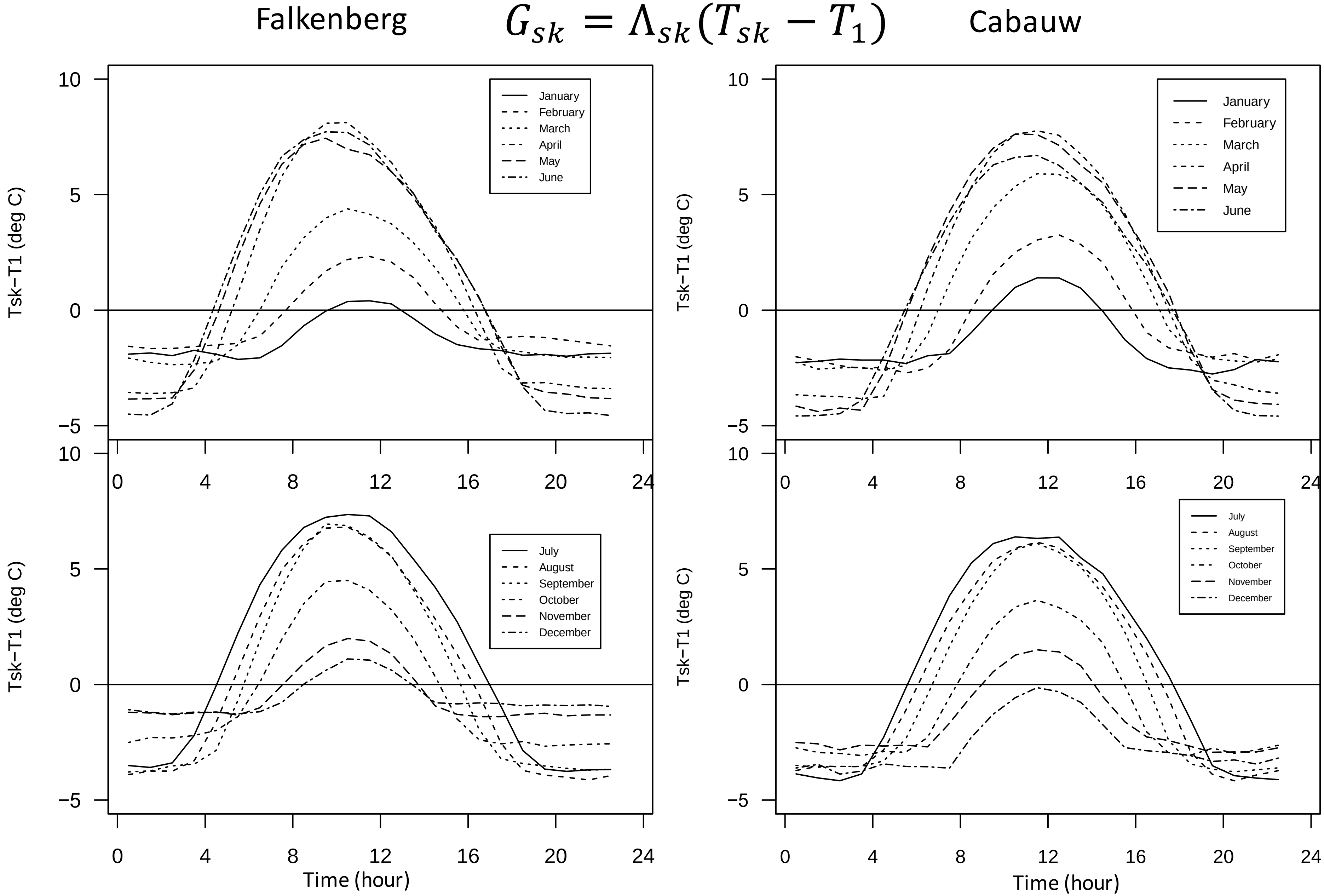
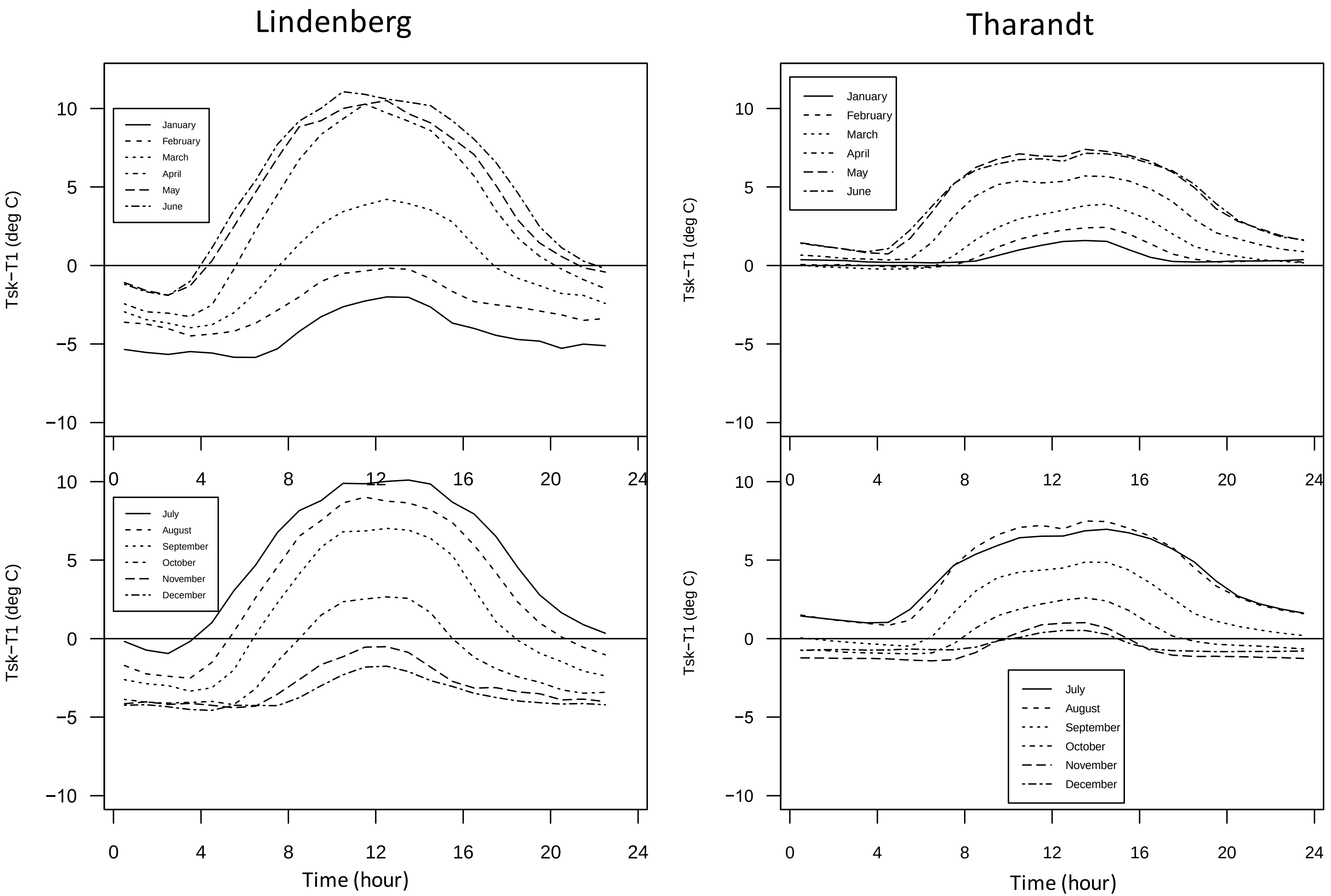
Falkenberg versus Cabauw grass: T_{sk}-T_1

$$G_{sk} = \Lambda_{sk}(T_{sk} - T_1)$$



Lindenberg versus Tharandt forest: T_{sk}-T_1



History of Λ_{sk} approach

Viterbo & Beljaars (J Climate 8; 1995): a uniform value of **7 W m^{-2} K^{-1}** (based on Cabauw grassland)

Van den Hurk & Beljaars (J Applied Meteorology 35; 1996):

- "**Empirical effective conductivity** for heat transfer through the skin layer
- For completely bare soil, Λ can be related to a physical **soil thermal conductivity**
- When a dense vegetation cover is present, the heat flow into the soil and vegetation layer will also be affected by **turbulent exchange** within the vegetation
- …. value of Λ_{sk} includes **heat conductivity of the canopy elements**, the **air** within the canopy layer and the conductivity of the **topsoil layer**
- Considerably **different values** may be expected for **different types of surfaces**
- Use **7 W m^{-2} K^{-1}** for vegetated part of grid box and **17 W m^{-2} K^{-1}** for bare soil part"

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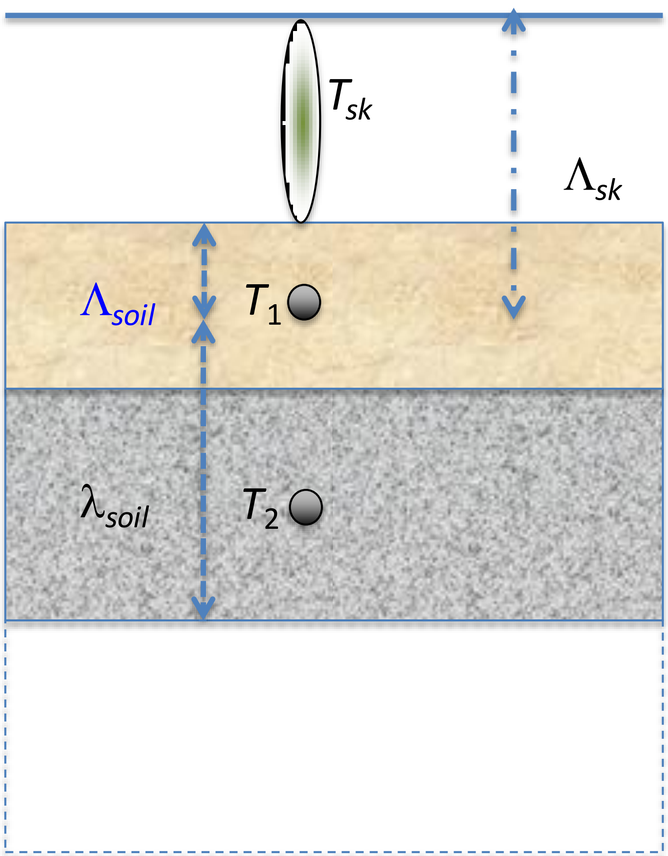
What affects ‘skin layer transfer’?

- Season
- Time of day
- Type of vegetation
- Soil moisture content
- (Soil type)
- (Turbulence strength)
- (Wind speed)

Energy balance in ECMWF TESSEL scheme, 2



$$G_{sk} = \Lambda_{sk}(T_{sk} - T_1)$$

$$\Lambda_{soil} = \lambda_{soil}/z_{soil,1}$$

$$\Lambda_{sk} = \lambda_{sk}/(z_{soil,1} + z_{veg})$$

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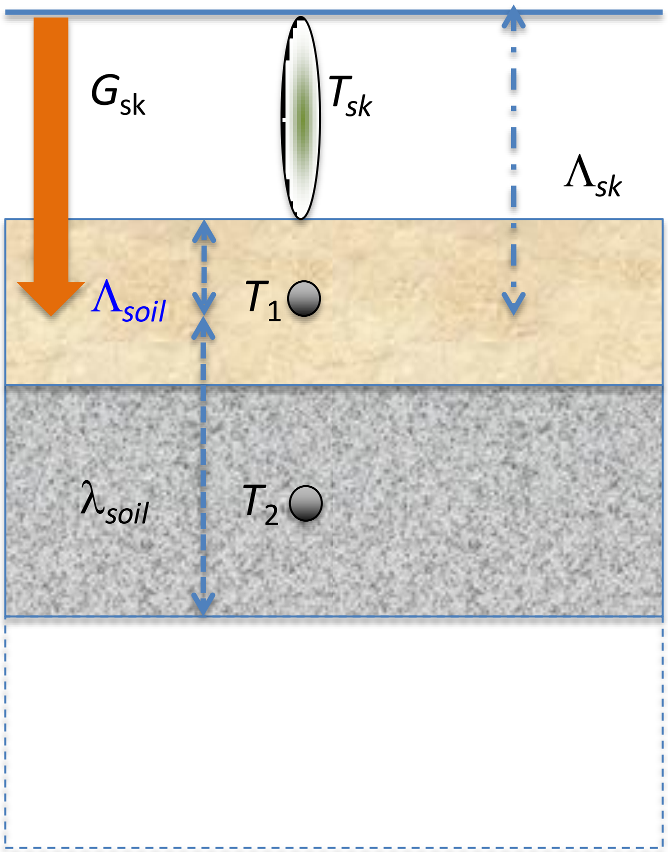
Skin layer heat flux TESSEL/JULES schemes



TESSEL

$$G_{sk} = \Lambda_{sk}(T_{sk} - T_1)$$

JULES

$$G = G_v^r + G_v^a + G_s$$

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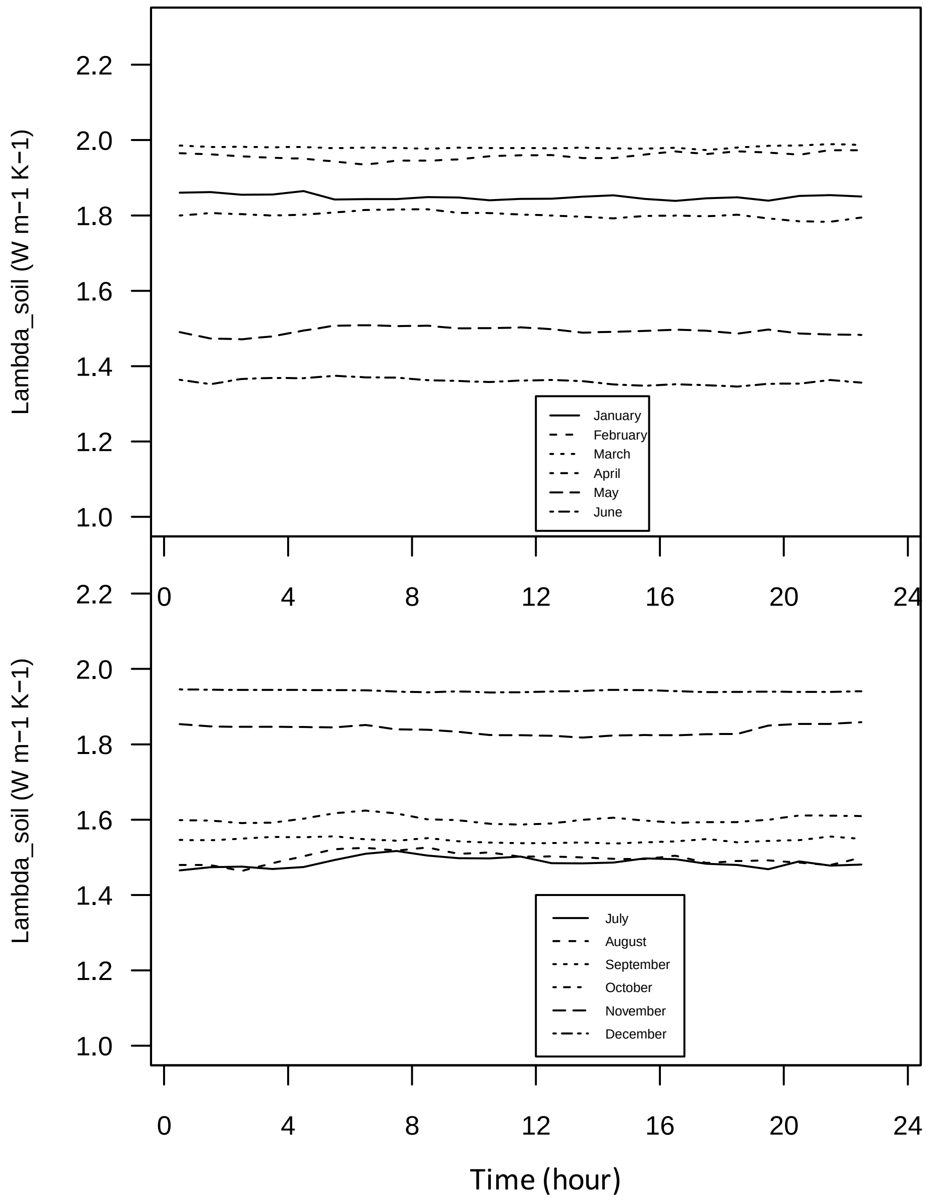
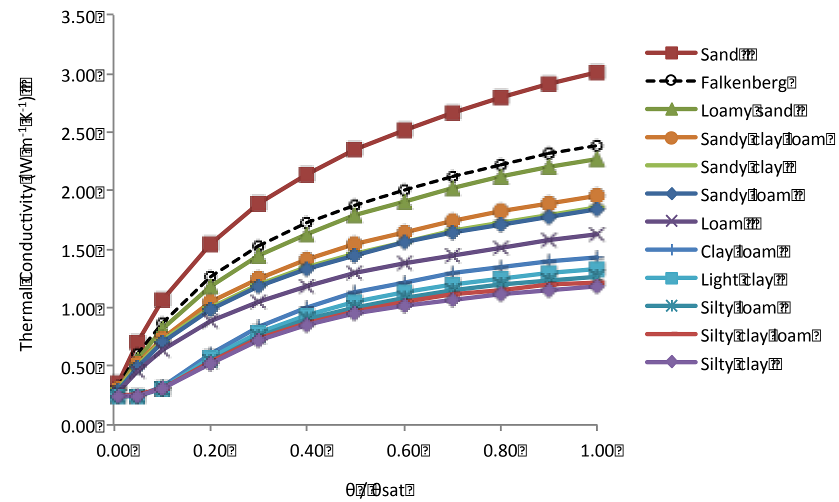
Soil thermal conductivity, λ_{soil}, for Falkenberg grass





$$\Lambda_{soil} = \lambda_{soil}/z_{soil,1}$$

Falkenberg grass:

Λ_{soil} ~ 28-40 W m^{-2} K^{-1}