Estimation of the ground heat flux at the surface during the BLLAST campaign

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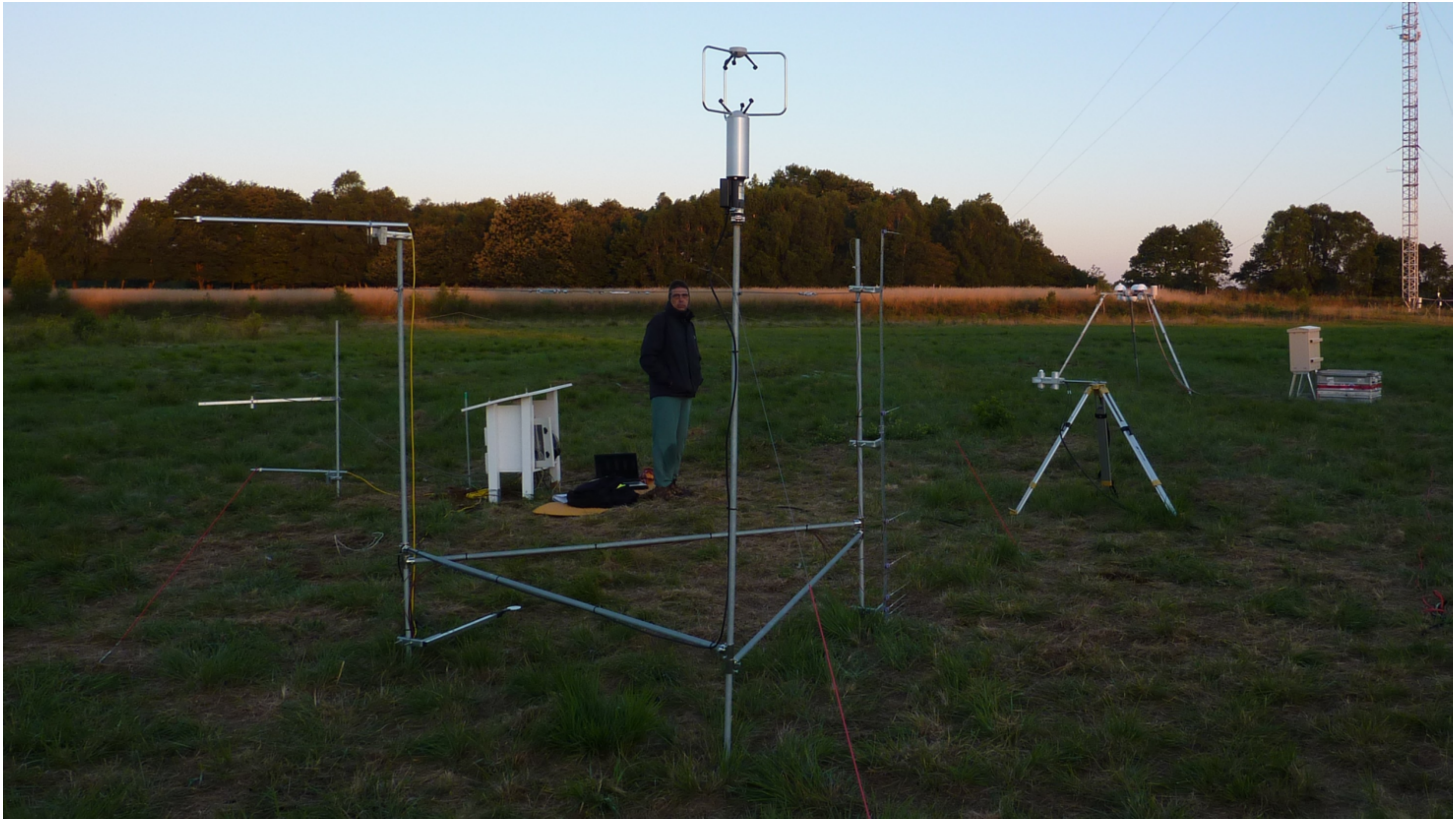
Motivation

Objective: Estimation of the ground heat flux at the surface G_0 at the small-scale heterogeneity (ssh) site (30 June – 03 July 2011) to study the role of the (often neglected) advection term in the surface energy budget (SEB): Cuxart et al. (2014).

- Instrumentation at the ssh site (University of Bergen, University of Balearic Islands):
  - Three heat flux plates (Hukseflux: 20, 10 and 5 cm deep).
  - Soil Temperature (TCAV: 1.5–5 cm deep).
  - Water content reflectometer (CS616: 15-cm soil layer).
  - Surface Temperature (infra-red radiometer, IR120: 0.42 m^2).
- Different methods:
  - Calorimetric method (standard): failed due to instrumentation problems.
  - Harmonic analysis (Heusinkveld et al., 2004; Wang and Bou-Zeid, 2012).
- Results
- Discussion

Instrumentation at the ssh site



Soil and surface cover

Calorimetric method

Assuming a homogeneous soil:

$$G_0 = G_r + \int_0^{z_r} \rho c \frac{\partial T}{\partial t} dz \simeq G_r + \rho c \frac{\triangle T}{\triangle t} z_r$$

Storage term requires the soil temperature profile and the *volumetric heat capacity* (ρc):

$$\rho c = \rho c_d + \theta_v \rho_w c_w$$

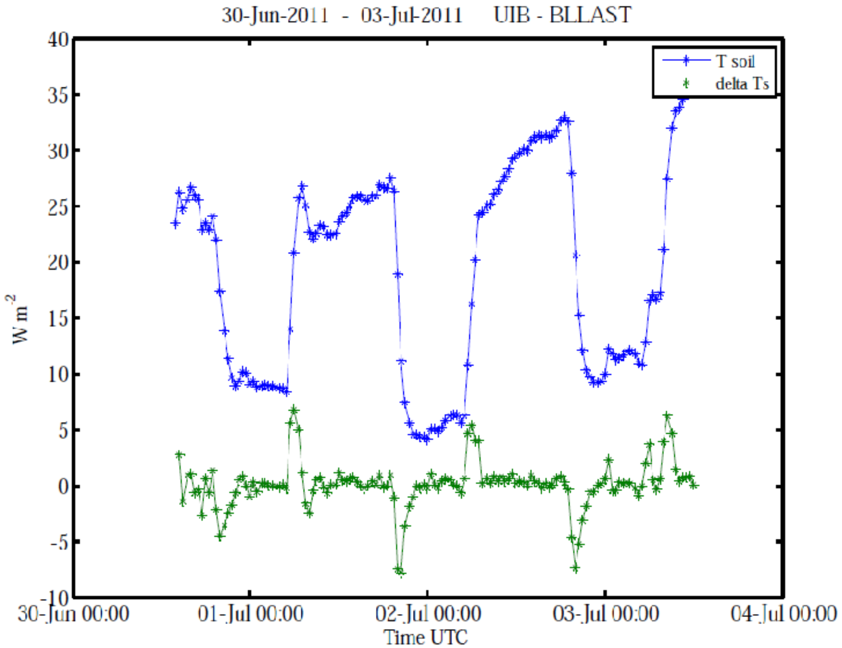
where ρ and ρ_w represent the density of bulk soil and water, respectively, and θ_v is the soil water content on a volume basis.

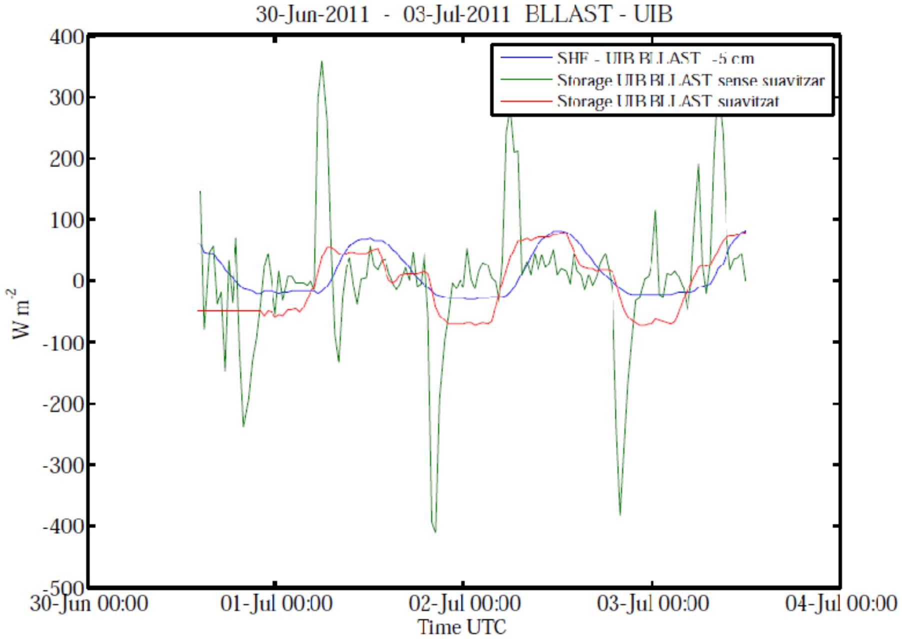
$\rho = 1300$ kg m^{-3} (silty loam soils).

$c_d = 850$ J kg^{-1} K^{-1} (dry mineral soil).

$\rho_w = 1000$ kg m^{-3} and $c_w = 4180$ J kg^{-1} K^{-1} (values for water).

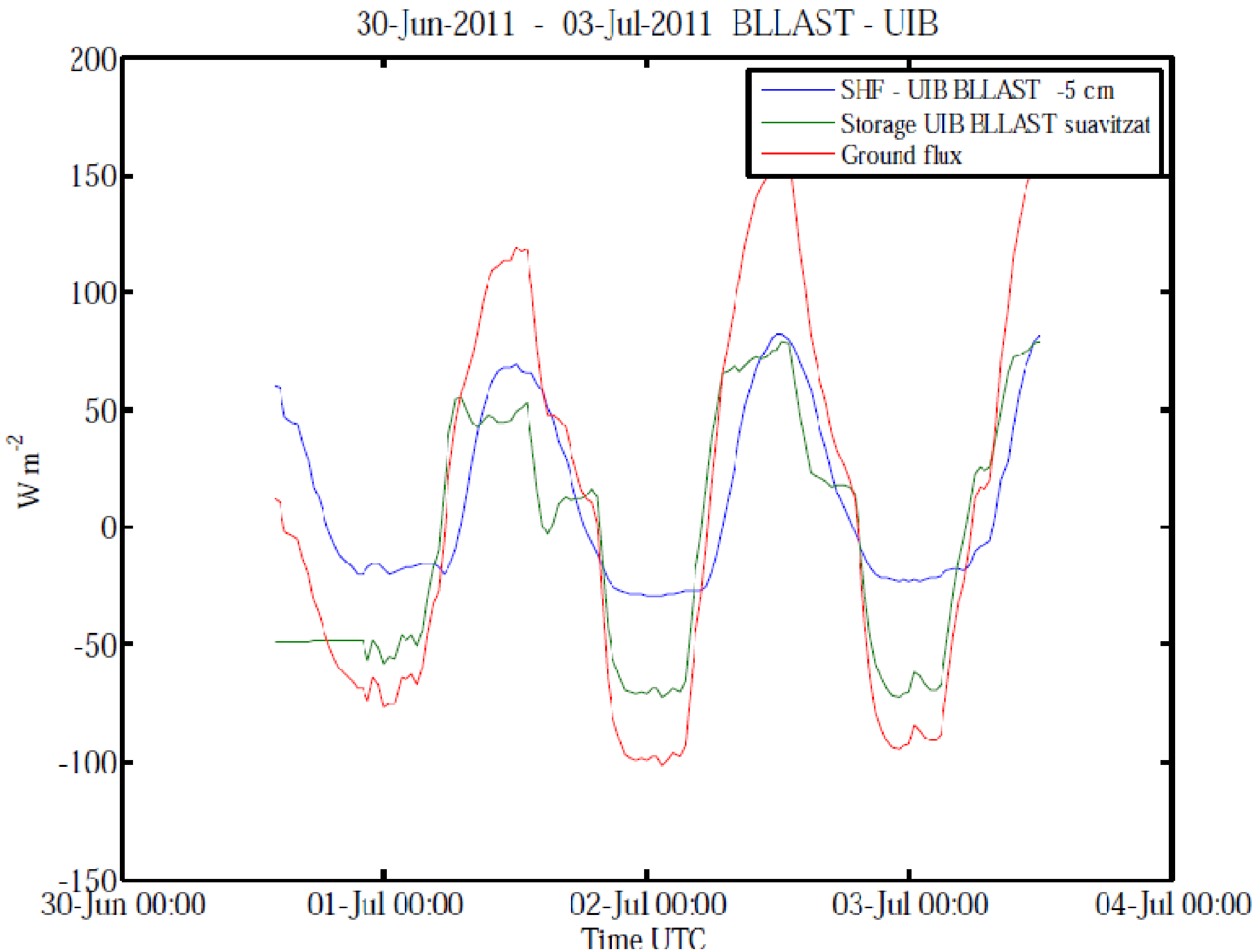
Calorimetric method (Results I)





a) Time evolution of the bulk temperature T of the upper soil layer measured by TCAV (blue) and the corresponding temperature difference $\triangle T$ in the interval time $\triangle t = 1800$ s (green). b) The measured soil heat flux at 5 cm deep (blue), the storage term calculated with the raw time series of $\triangle T$ (green) and after applying a moving average of a window size of 30 min to $\triangle T$ (red). Figures from Conangla, personal communication.

Calorimetric method (Results II)



Time evolution of the soil heat flux measured at 5 cm deep (blue), the storage term calculated from $\triangle\ T$ *with a moving average (green) and the resulting ground heat flux at the surface (red). Figure from Conangla, personal communication.*

Harmonic Analysis (I)

We depart from the equation of heat conduction for uniform, isotropic and horizontally homogeneous soils with time-invariant properties (Hillel, 1998):

$$\frac{\partial T}{\partial t} - D_T \frac{\partial^2 T}{\partial z^2} = 0 \; ; \quad D_T = \frac{\kappa}{\rho c}$$

with *thermal diffusivity* D_T and *thermal conductivity* κ.

Consider a uniform medium with a flat surface at $z = 0$; surface temperature is a periodic function of time (Fourier expansion):

$$T_0(t) = \overline{T} + A_1 \sin(\omega t + \phi_1) + A_2 \sin(2\omega t + \phi_2) + \cdots = \overline{T} + \sum_{n=1}^{M} A_n \sin(n\omega t + \phi_n)$$

where n and M are the current and highest harmonic wave number, respectively (Heusinkveld et al., 2004).

Unbounded for $z > 0$, $z \to \infty$: $T_\infty(t) = \overline{T}$.

Harmonic Analysis (II)

The solution to the given initial and boundary conditions is (Carslaw and Jaeger, 1959):

$$T_z(t) = \overline{T} + \sum_{n=1}^{M} A_n e^{-z\sqrt{n\omega/2D_T}} \sin\left(n\omega t + \phi_n - z\sqrt{n\omega/2D_T}\right)) \;, \quad d = \left(\frac{2D_T}{\omega}\right)^{1/2}$$

d: *damping depth*.

Once the field of T is found, an analytical expression for the heat flux can be found:

$$G_z(t) = \sum_{n=1}^{M} \kappa \left(\frac{n\omega}{D_T}\right)^{1/2} A_n e^{-z\sqrt{n\omega/2D_T}} \sin\left(n\omega t + \phi_n - z\sqrt{n\omega/2D_T} + \pi/4\right)$$

Note: amplitude of T_z or G_z diminishes like $e^{-z\sqrt{n\omega/2D_T}} \Rightarrow$ it falls off more rapidly for higher harmonics as the signal propagates into the solid.

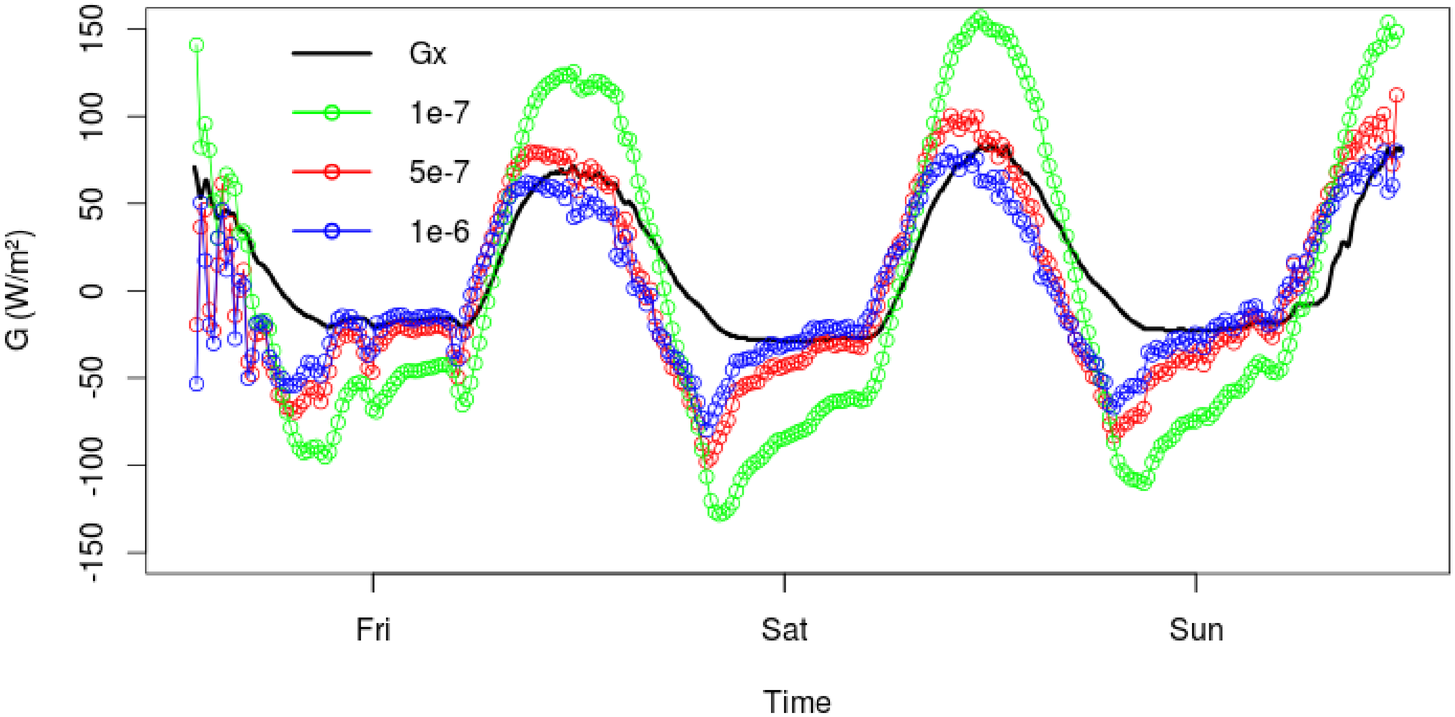
Harmonic Analysis (Results I)

First attempt: obtain G_0 by fitting $G_z[\kappa, D_T]$ to experimental data $G_r(t)$.

$$G_z(t) = \sum_{n=1}^{M} \kappa \left(\frac{n\omega}{D_T}\right)^{1/2} A_n e^{-z\sqrt{n\omega/2D_T}} \sin\left(n\omega t + \phi_n - z\sqrt{n\omega/2D_T} + \pi/4\right)$$

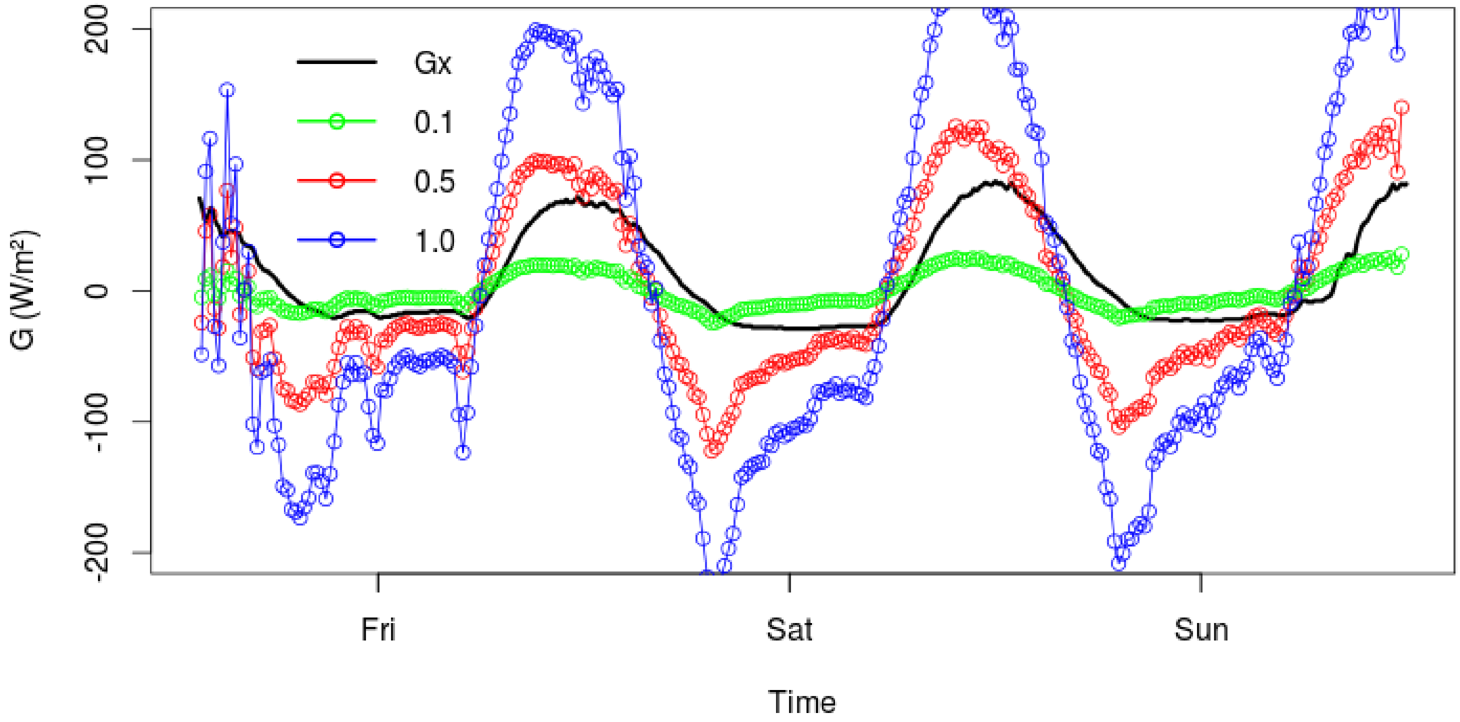
Note: A_n and ϕ_n are obtained from a Fourier-decomposition of $T_0(t)$.

Harmonic Analysis (Results I)



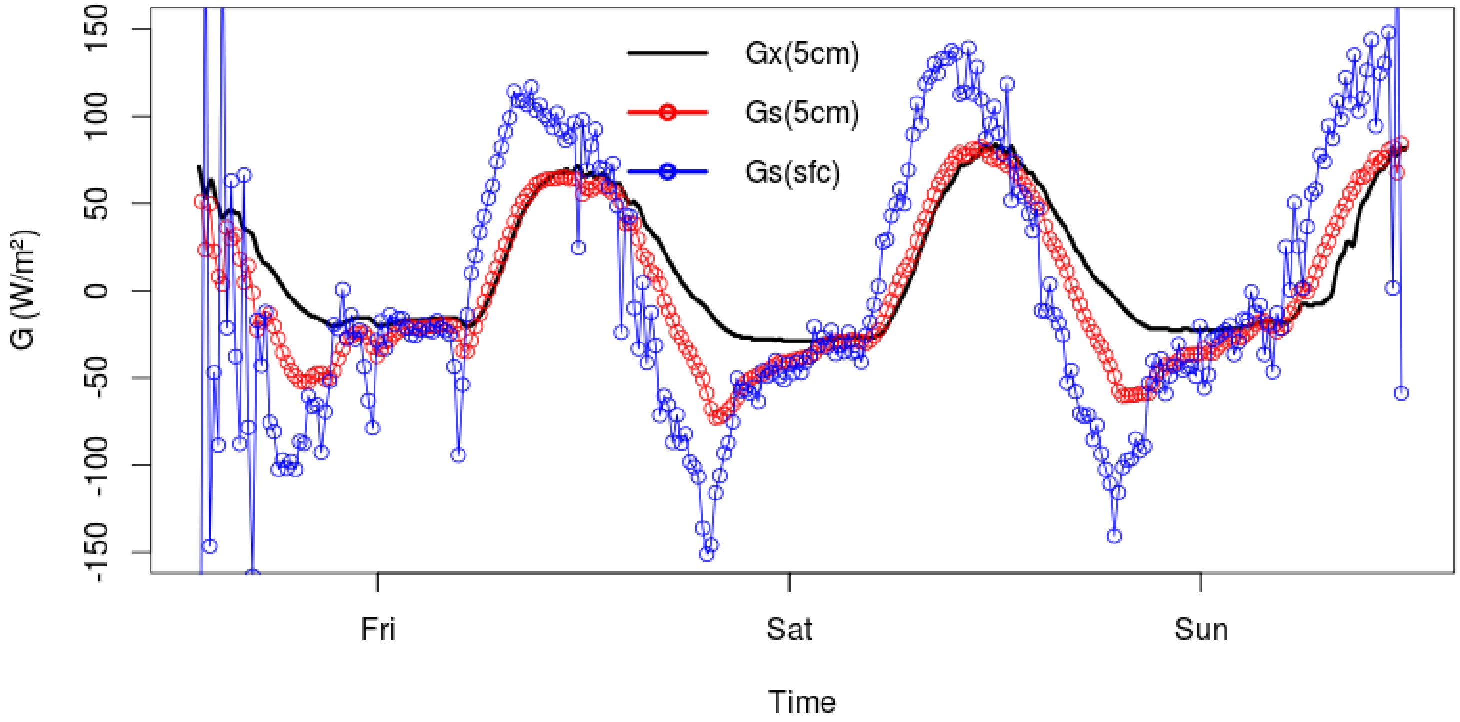
Estimated soil heat flux at 5 cm deep with a fixed thermal conductivity $\kappa = 0.4$ W m^{-1} K^{-1} and for different values of thermal diffusivity D_T: 1×10^{-7} (green), 5×10^{-7} (red) and 1×10^{-6} m^2 s^{-1} (blue). In black, the experimental heat flux measured at 5 cm deep.

Harmonic Analysis (Results II)



Estimated soil heat flux at 5 cm deep with a fixed thermal diffusivity D_T: 5×10^{-7} m^2 s^{-1} and different values of thermal conductivity κ: 0.1 (green), 0.5 (red) and 1.0 W m^{-1} K^{-1} (blue).

Harmonic Analysis (Results III)



Estimated soil heat flux at 5 cm deep (red) and at the surface (blue) with a fixed thermal diffusivity D_T*:* 5×10^{-7} *m*^{2} *s*$^{-1}$ *and thermal conductivity* $\kappa = 0.4$ *W m*$^{-1}$ *K*$^{-1}$*.*

Harmonic Analysis (Results IV)

Large differences between observed and estimated data at 5 cm during late afternoon and evening transition:

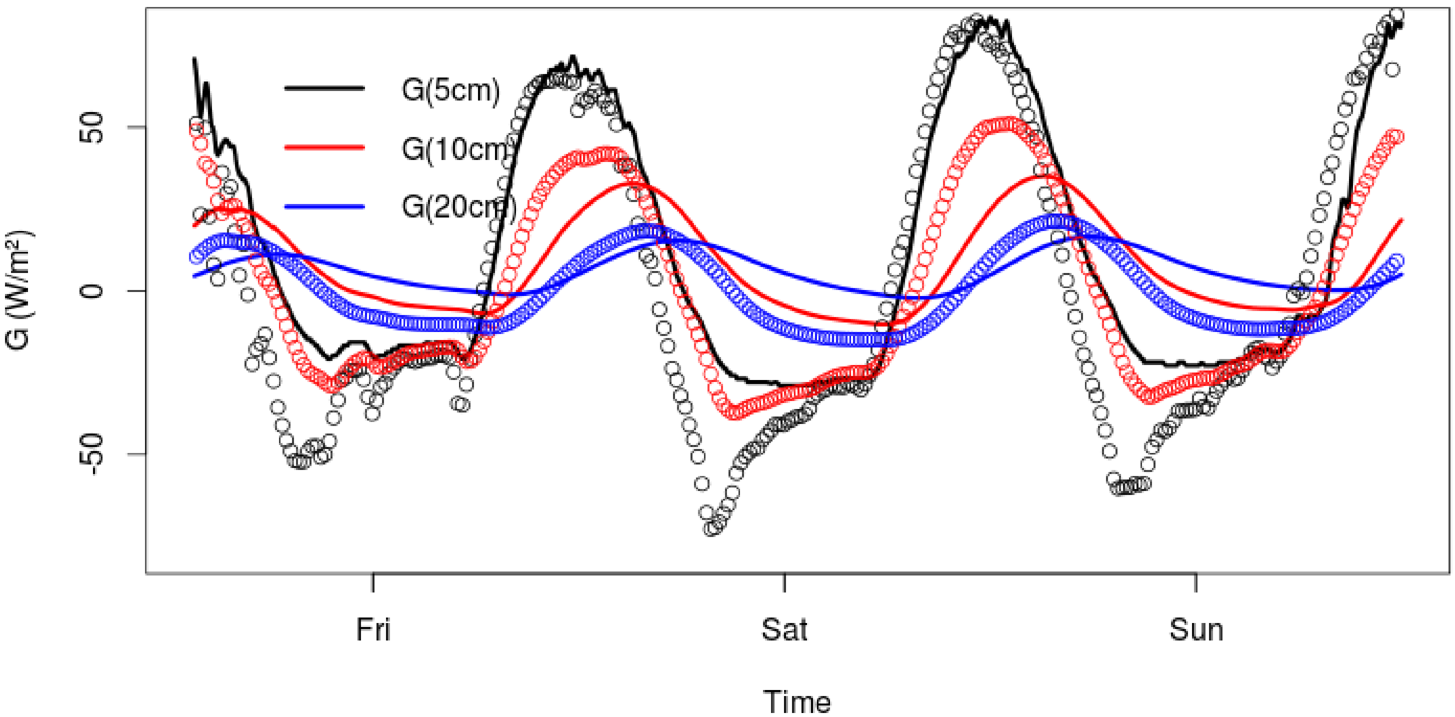
(i) The horizontal distance between the infra-red (IR) thermal sensor and the heat flux plate: both sensors do not describe the same phenomena at all scales.

(ii) Thermal properties between z_0 and z_r are not homogeneous (thin vegetation cover over the soil surface with unknown thermal characteristics).

(iii) Instrumental errors:

- IR120 very sensitive to rapid changes in body temperature, leading to transient measurement errors (radiation shield is recommended).
- Large differences in thermal conductivity between soil and sensor plate leads soil heat flux errors (Mogensen, 1970).

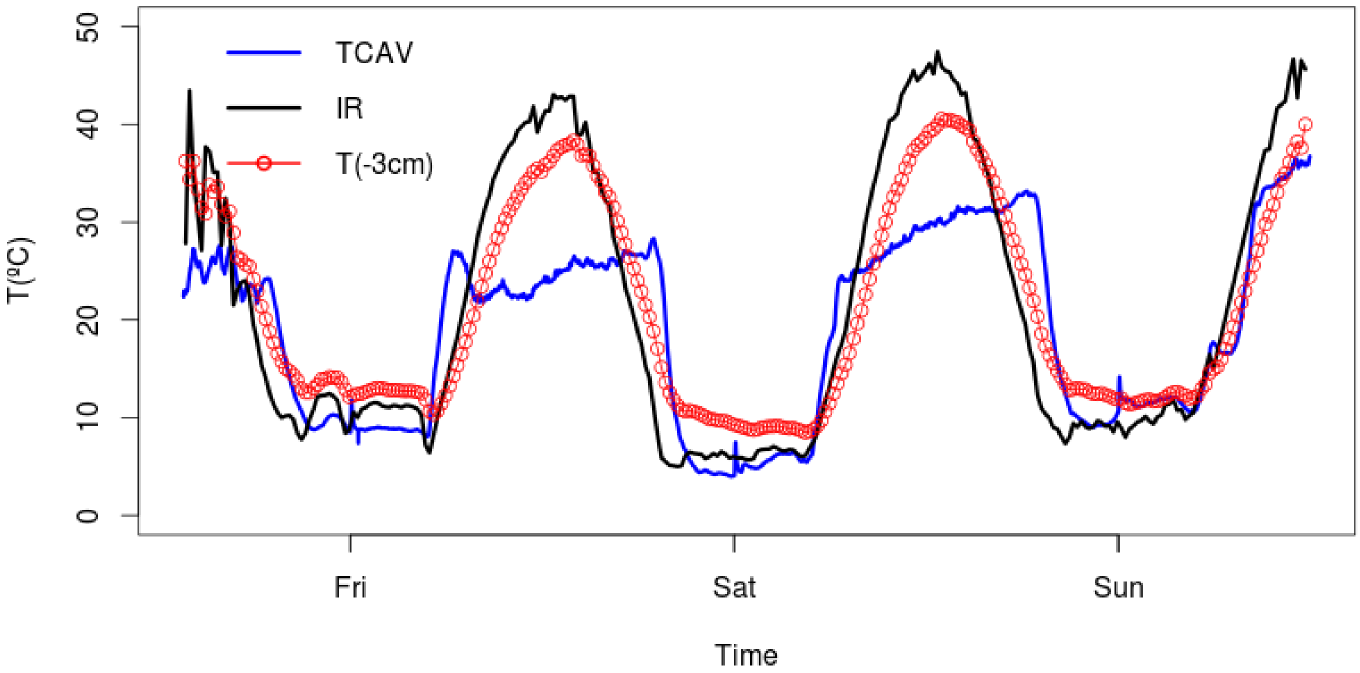
Harmonic Analysis (Results V)



Time evolution of the soil heat flux at 5 (black), 10 (red) and 20 (blue) cm deep estimated (dots) through the harmonic analysis with a fixed thermal diffusivity $D_T = 5 \times 10^{-7}$ m^2 s^{-1} and a thermal conductivity $\kappa = 0.4$ W m^{-1} K^{-1}. Filled lines represent the corresponding measurements.

Discussion (I)

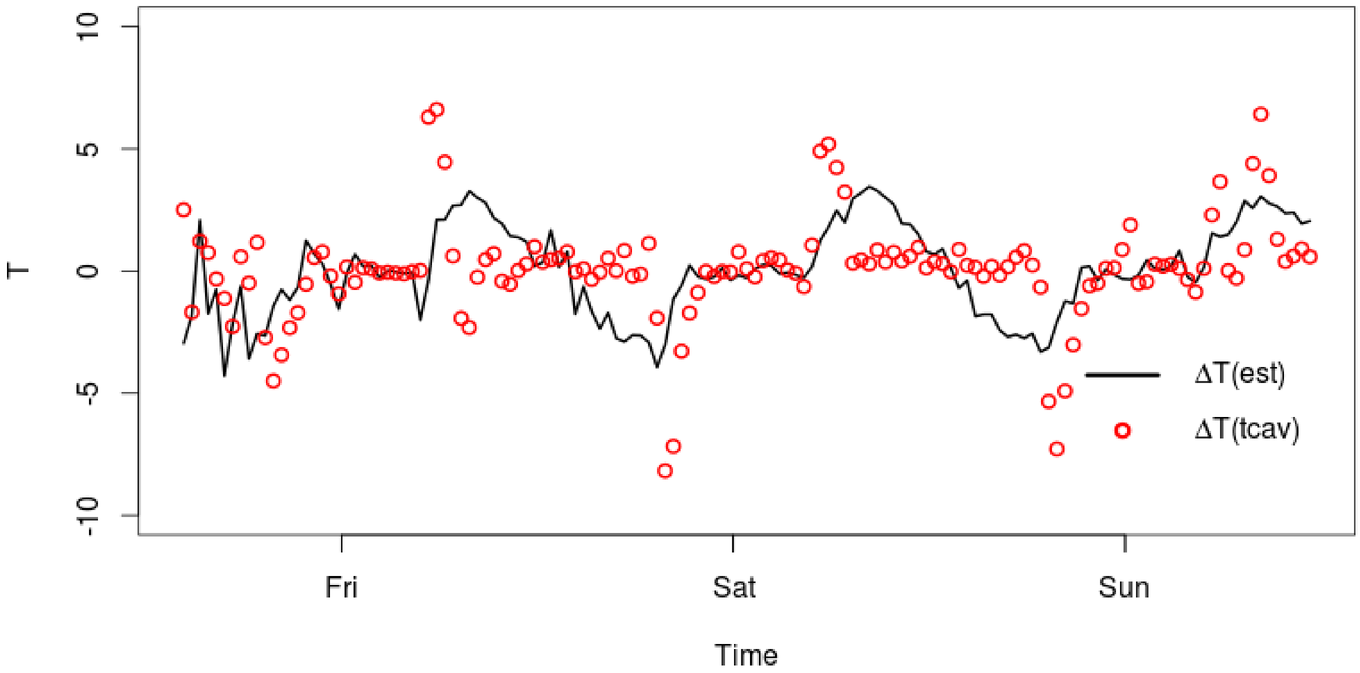
Comparing observed and estimated $T_z(t)$ at $z = 3$ cm deep



Time evolution of surface temperature measured by the IR thermometer (black), temperature of the upper soil layer measured by TCAV (blue) and temperature of the soil at 3 cm deep estimated through harmonic analysis (blue) with a fixed thermal diffusivity $D_T = 5 \times 10^{-7}$ *m*^{2} *s*$^{-1}$.

Discussion (II)

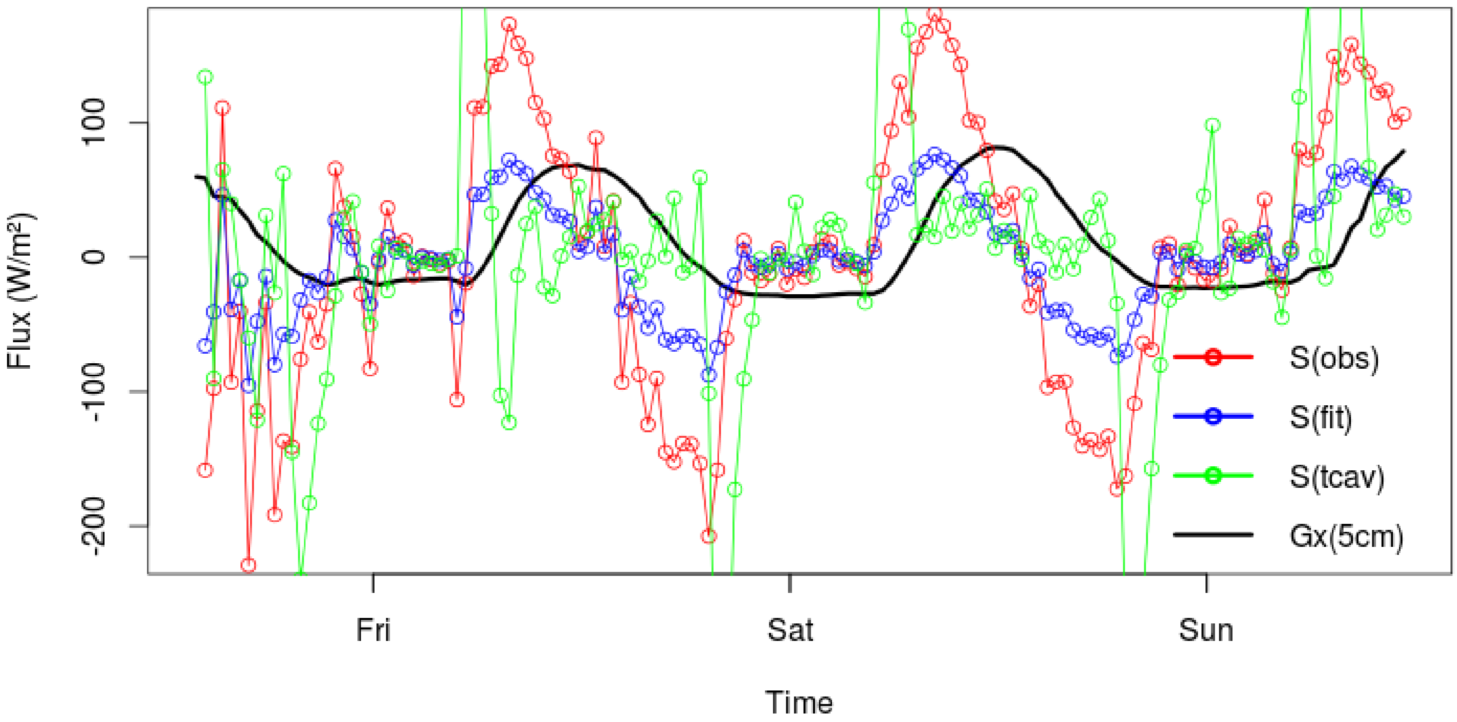
Estimated $T_z(t)$ leads to a more realistic storage term: $S \simeq \rho c \bigtriangleup T / \bigtriangleup t \; z_r$



Time evolution of the difference of temperature $\bigtriangleup T = T_f - T_i$ *of the soil layer measured by TCAV (red) or estimated by the harmonic method (black) with a fixed thermal diffusivity* $D_T = 5 \times 10^{-7}$ *m*^{2} *s*$^{-1}$.

Discussion (III)

Storage term S from an estimated $T_z(t)$ and...
Red: $< \rho c >= 1.9 \times 10^6$ J K^{-1} m^{-3}.
Blue: $< \rho c >= \kappa / D_T \simeq 0.8 \times 10^6$ J K^{-1} m^{-3}



Discussion (IV)

Storage term S from an estimated $T_z(t)$ and...
Red: $<\rho c>= 1.9 \times 10^6$ J K^{-1} m^{-3}.
Blue: $<\rho c>= \kappa / D_T \simeq 0.8 \times 10^6$ J K^{-1} m^{-3}

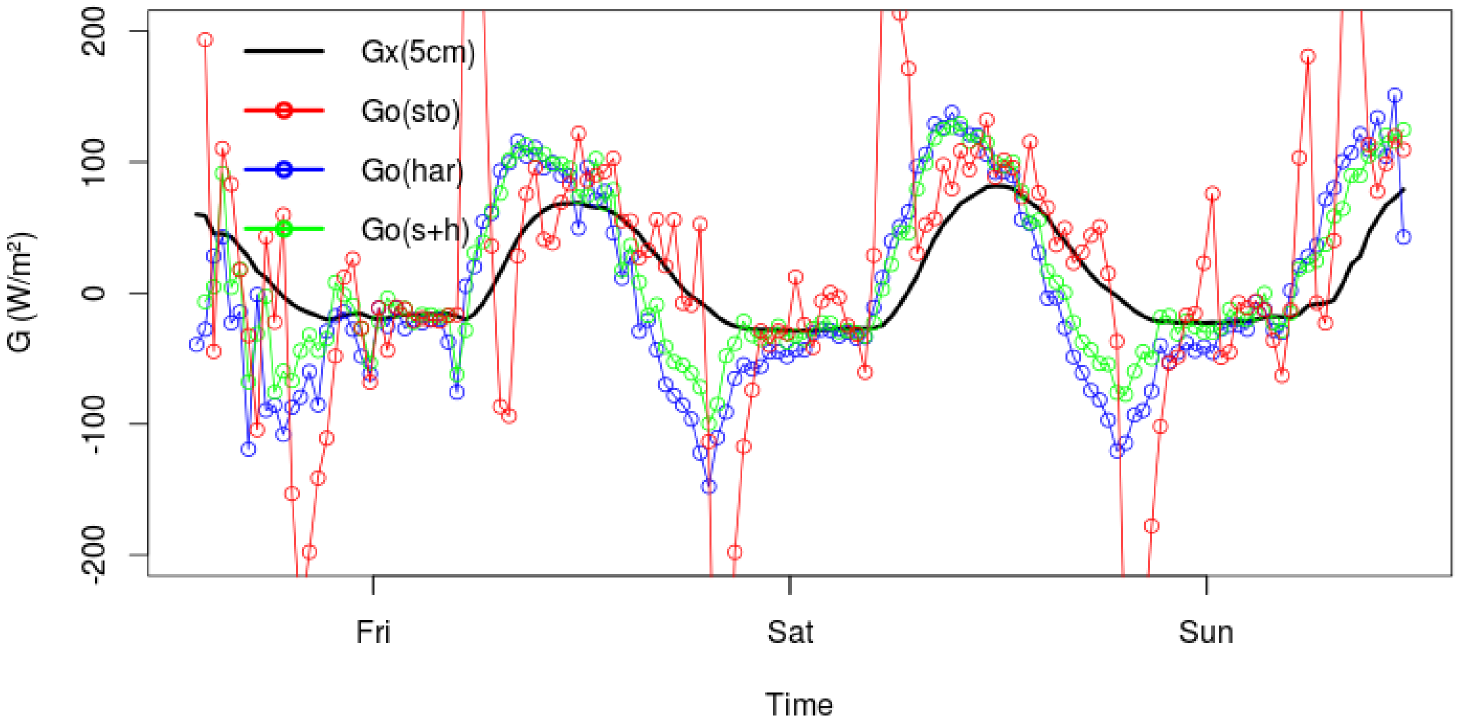
From Oke (1987):
Sandy or clay soils: $\rho c = 1.3$ (dry)–3.0 (saturated)$\times 10^6$ J K^{-1} m^{-3}.
Peat soils: $\rho c = 0.58$ (dry)–4.02 (saturated)$\times 10^6$ J K^{-1} m^{-3}.

note: Observed mean volumetric water content was 19% and peat soils contain decayed vegetation matter.

This issue opens an interesting question about the convenience of using the surface temperature and the harmonic analysis to estimate the ground heat flux at the surface in those cases where there is a canopy or vegetation cover on the soil surface. Indeed, the calorimetric method (i.e., measuring the soil heat flux and adding the storage in the upper soil layer) will provide the ground heat flux at the soil surface, but it will not account for the role that can play the vegetation cover.

Discussion (V)

Red: Estimation of the surface heat flux using the calorimetric method + S(TCAV)
Green: harmonic analysis + $S\left(\left(T_z\right)\right)$ Blue: harmonic analysis (direct fit of D_T and κ).



Conclusions

- G_0 is estimated for a 3-day period (30 June–03 July 2011) at the micro-scale heterogeneity site using different methodologies based on the harmonic analysis.
- Measurements required: Surface temperature and soil heat flux at 5 cm deep.
- The harmonic analysis allows to estimate the bulk thermal properties of the layer between z_r and the surface without any further instrumentation (i.e. ρc).
- The estimated G_0 provide large transient values during the evening transition (instrumental error?).
- The harmonic analysis can be of interest for complex sites with surface covers of unknown thermal properties (surface temperature is required).