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1. INTRODUCTION

In micrometeorology, historically relative little attention has been paid to measurement of the ground heat flux at the surface. The reason is that it was considered a small term comprising typically about one tenth of the net radiation for vegetated surfaces (De Bruin and Holtslag 1982). Recently, however, interest for ground heat flux has increased, because of two reasons. First, micrometeorological research has shifted towards drier areas where the ground heat flux is a more important component of the surface energy budget (Passerat de Silans et al. 1997; Heusinkveld et al. 2004). Second, the ground heat flux is acknowledged as an important component of the surface energy balance in stable nocturnal conditions (Van de Wiel et al. 2002).

In most application, the ground heat flux at the surface is not measured directly, but derived from measurements of the soil heat flux and soil temperatures at certain depths below the surface. Usually, this is done by the method of Van Wijk and De Vries (1963), where it is assumed that time series of ground heat flux and soil temperature can be analyzed using harmonic analysis. Inserting the harmonics in the diffusion equation gives then a set of ordinary differential equations that can be solved yielding the vertical distribution of amplitudes and phase shifts of the harmonics with depth. Extrapolation to the surface of these amplitudes and phase shifts gives the harmonic Fourier series of the surface ground heat flux, which can be used to retain the ground heat flux at the surface.

The method described above has two main disadvantages. First, the method assumes that the parameter values are constant over the period over which the harmonic analysis is applied. It is therefore usually applied on a daily basis (see for instance Massman 1992), implying that for each individual day in the record the temperature and soil heat flux data are decomposed, using the daily cycle as the base harmonic. However, as Massman (1992) points out, the penalty is that transients in the soil temperature, caused by long-term soil temperature variations, are ignored or worse, mapped on the resolved frequencies. Second, the method uses in many applications, measurements of the soil heat flux and soil temperature at such depths (Beljaars and Bosveld 1997) below the surface that high-frequency variations in the ground heat flux are damped.

The aim of this abstract is to show results of a novel method for determining the surface ground heat flux for the Cabauw site in the Netherlands (Beljaars and Bosveld 1997)

The new method derives the ground heat flux by applying the adjoint technique i.e. a technique where observations are statistically optimally assimilated into a model that describes in detail the transport of heat from the grass vegetation into the soil and within the soil column. A framework is established in which surface ground heat flux estimates are obtained that are both dynamically consistent and are optimal with respect to the different measurements taken at the soil site of the Cabauw site.

2. MODEL AND METHODS

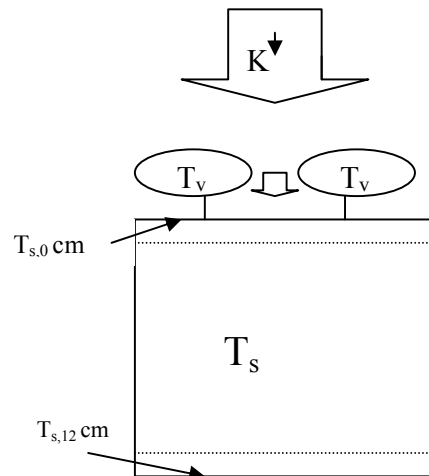


Figure 1, schematic description of the soil-vegetation-system.

To calculate the surface heat flux at the surface we use a setup as described in Fig. 1. In the model we calculate the exchange of heat between the vegetation and the soil and transport of heat through the soil column, whereby the temperature of the vegetation and the soil temperature at 12 cm depth are prescribed as boundary conditions of the system. The transport of heat from the vegetation to the soil is calculated from:

$$G_0 = \Lambda(T_v - T_0) + \alpha K^\downarrow, \quad (1)$$

where G_0 is the ground heat flux into the surface, T_v is the temperature of the vegetation, T_0 is the temperature of the upper soil level, α is transmissivity of the vegetation to short wave radiation, and K^\downarrow is the incoming short wave radiation. The transport of

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heat through the soil column is computed by solving the diffusion (Fourier) equation:

$$c_p \frac{\partial T_s}{\partial t} = \lambda \frac{\partial^2 T_s}{\partial z^2}, \quad (2)$$

Where c_p is the volumetric heat capacity, T_s is the soil temperature, t is time, λ is the soil heat conductivity, and z is the depth below the surface. Here, we solve eq. (2) using an explicit finite-difference scheme with a time step of 2 s and a layer thickness of 0.0024 m, resulting in 50 layers.

To solve the system described by eqs. (1) and (2) the parameters Λ , λ , α , and c_p need to be specified. In this paper, these are determined by applying a variational data assimilation technique that quantifies these parameters by combing the model described in eqs. (1) and (2) with measurements taken at the soil site in Cabauw. We use here the so-called adjoint approach where a cost function is minimized that penalizes deviations from a priori chosen values for the parameters, misfits between modeled output and data, ensuring that the solution satisfied the physics of the model. The cost function reads (Margulis and Entekhabi 2001,2004):

$$J = (\mathbf{p} - \mathbf{p}_{ap})^T C_p^{-1} (\mathbf{p} - \mathbf{p}_{ap})^T + (\mathbf{Z} - \mathbf{M}(\mathbf{y}))^T C_v^{-1} (\mathbf{Z} - \mathbf{M}(\mathbf{y})) + 2 \int_{t_0}^{t_f} \boldsymbol{\mu}^T \left[\frac{d\mathbf{y}}{dt} - \mathbf{F}(\mathbf{y}, \mathbf{p}) \right] dt,$$

where \mathbf{p} is the vector containing the parameters, \mathbf{p}_{ap} is the vector contain a priori estimates of the parameter values, C_p is the error-covariance matrix of the a priori values, \mathbf{Z} is the vector containing the measurements, \mathbf{M} is the vector that gives the modeled equivalents of the measurements as function of the prognostic variables contained in vector \mathbf{y} , C_v is the error-covariance matrix of the measurements, $\boldsymbol{\mu}$ contains the Lagrange multipliers (adjoint variables), and \mathbf{F} is the time-propagation vector of the model. To minimize J we express its first variation in terms of the state variables and the control parameters. This yields the adjoint model of (1) and (2), and gradients of the cost function with respect to the different control parameters. The latter can be used in a steepest descent algorithm to find the optimal values, but are usually a function of the Lagrange multipliers. The Lagrange multipliers are obtained by integrating the adjoint model backward.

Our approach can be summarized as follows (see Margulis and Entekhabi 2001, 2004 for details):

1. the heat transport model is run forward using the temperature of the vegetation and the temperature at 12 cm as boundary conditions;
2. the adjoint of the heat transport model run backward, driven by the discrepancies between modeled and measured soil

temperatures at 0 cm, 2 cm, 4 cm, and 8 cm and ground heat fluxes at 5 cm and 10 cm;

3. the control variables, the skin conductivity describing the transport of heat between the vegetation and the upper soil, the soil conductivity of the soil and the volumetric heat capacity of the soil are updated;
4. decision is made whether steps 1 to 3 are repeated or the values of the control variables have converged sufficiently.

3. OBSERVATIONS

The Cabauw site is located in the Western part of the Netherlands (51.97 N, 4.93 E) at about 2 m below average sea level. The area surrounding the tower is flat and land use consists mainly of pastures and meadows interrupted by water channels, thin lines of trees and some scattered villages.

The temperature of the short grass vegetation in Cabauw is determined at the soil site as the infrared radiation temperature. It is measured using a Heimann KT-15-85 radiation thermometer, which is mounted 2 m above the surface looking downward with a M6 lens with a field of view of 40°.

At the same site six WS31S soil heat flux plates, fabricated by TNO-Delft are installed, at depth of 5 cm and 10 cm at the three corners of an equilateral triangle. The body of these plates have a diameter of 110 mm and is 5 mm thick, while the conductivity of the plates is 0.25 W M⁻¹ K⁻¹. The heat flux at a certain depth results then as the linear average of the measurements taken at all corners of the triangle. Unfortunately, because of the difference in conductivity between the plates and the soil, the heat flux through the plates cannot be directly related to the heat flux through the soil. To do so, we have applied the approach proposed by Philip (1961), where we have used the heat conductivity that follows from the optimization as the soil heat conductivity in the correction equation.

Soil temperatures are measured at depths of 0 cm, 2 cm, 4 cm, 8 cm, and 12 cm, along a profile in the centre of the equilateral triangle. The thermometers are KNMI home-made and consist of 35 cm long Nickle needle with an electrical temperature-dependent resistance around 500 Ohm.

4. SETUP AND RESULTS

We have run the (adjoint) model for five consecutive days in 2005. The control variables are optimized for each day separately, implying that the control variables are allowed to vary on a day-to-day basis, but are constant on sub-daily time scales. Each day, at 0:00 UTC the model is initialized using the measured temperature profile.

As a priori value for λ a value of 1.0 W m⁻¹ K⁻¹ is adopted, for c_p a value of 1.8E6 W m⁻³ K⁻¹ is adopted, for Λ a value of 4 W m⁻² K⁻¹ is adopted, and for α a value of 0.03 is adopted. We assume that

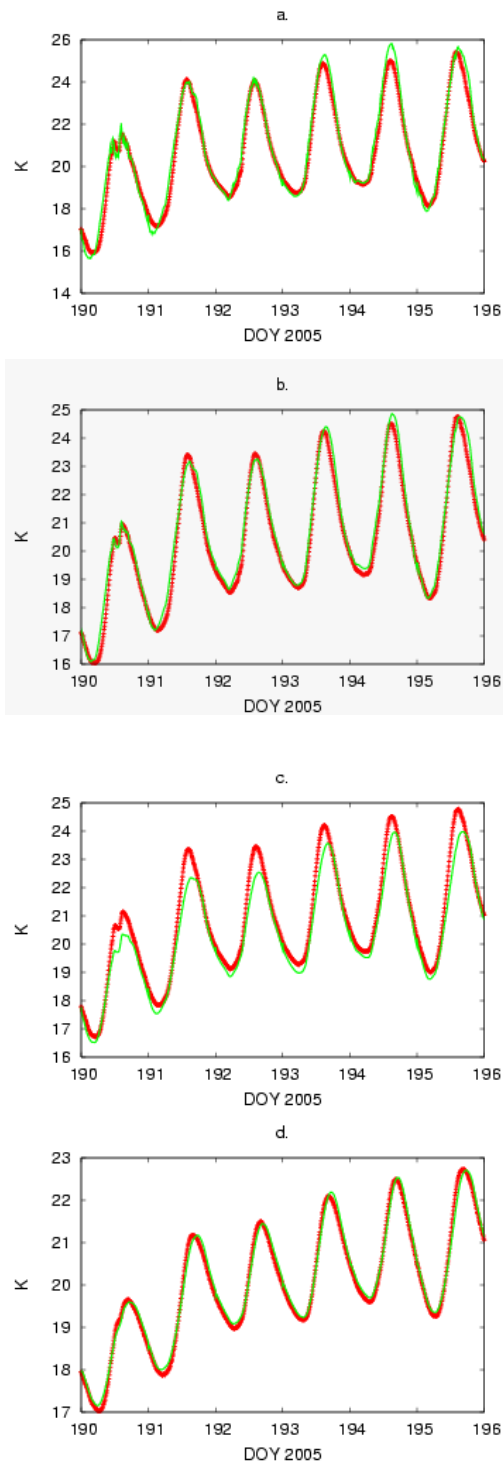


Figure 2: Time series of measured (red/thick) and modeled (green/ thin) temperature at 0 cm (a.), 2 cm (b.) 4 cm (c.) and 8 cm (d.)

these values are uncorrelated (non-diagonal elements of a priori error-covariance matrix are zero) and that the standard deviation of the a priori error is $0.1 \text{ W m}^{-1} \text{ K}^{-1}$ for λ , $1.8\text{E}5 \text{ W m}^{-3} \text{ K}^{-1}$ for c_p , $1 \text{ W m}^{-2} \text{ K}^{-1}$ for $\text{W m}^{-2} \text{ K}^{-1}$, and 0.015 for α . For the error-covariance matrix of the soil temperature measurements we have assumed that errors in the soil temperatures and the ground heat flux are uncorrelated. For the standard deviation of the soil temperature error a value of 1 K is adopted, while the standard deviation in the ground heat flux is both at 5 cm and at 10 cm taken as 5 W m^{-2} . Note that these error estimates contain all mismatches between model output and measurements, such as sensor errors, errors in depth estimates of the sensors, and representation errors.

For July 9, 10, 11, 12, 13 and 14 2005 Fig. 2 shows time series of the modeled and observed temperatures at 0 cm (a.), 2 cm (b.), 4 cm (c.) and 8 cm (d.).

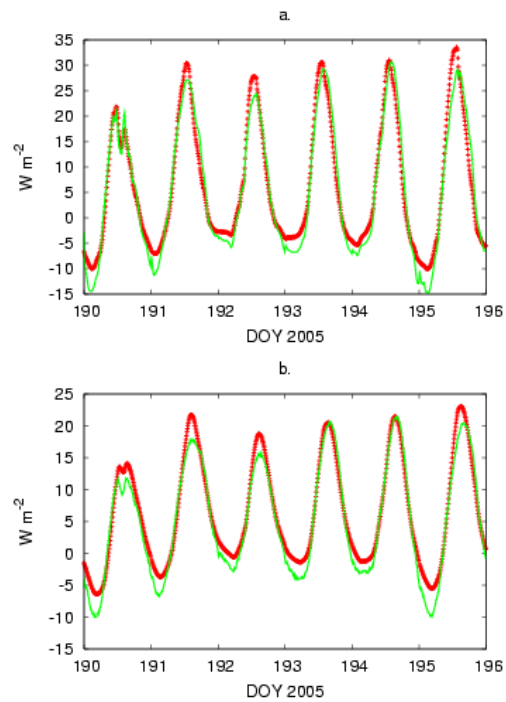


Figure 3: Time series of measured (red/thick) and modeled green or (green/thin) ground heat flux at 5 cm (a.) and 10 cm (b.)

It appears that the optimized model gives very good predictions of the temperature at 0 cm, and at 2 cm. The daily cycle of the temperature at these depths is predicted correctly, while the model is able to simulate sub-daily variations, such as apparent at DOY 2005 190.5. In contrast to the temperatures at 0 cm, and 2 cm, the model has problems estimating the temperature at 4 cm. It underestimates the minimum temperature at 4 cm, leading to an underestimation of the midday temperature as well. The temperature at a depth of 8 cm, is however again well simulated.

Fig. 3 shows time series of the simulated and measured ground heat flux at 5 cm (a.) and at 10 cm (b.). Here, positive numbers indicate downward fluxes. It appears that the model tends to underestimate the ground heat flux both at 5 cm and 0 cm during nighttime conditions when the flux of heat is upward, whereas it underestimates the ground heat flux in daytime conditions when the flux of heat is downward.

Fig. 4 shows time series of the ground heat flux at the surface according to the approach proposed in this study and the old approach where it is estimated from extrapolating Fourier amplitudes and phase shifts toward the surface. It appears that the new method predicts estimates of the ground heat flux that are similar to the old method in conditions when the flux is directed upward. In contrast, it gives lower predictions of the ground heat flux in conditions when the flux of heat is directed downward. The main difference between the old method and the new method is however the detail. The new method predicts a much more variable ground heat flux, reflecting the noise in the atmospheric signal, most often due to the appearances and disappearances of clouds.

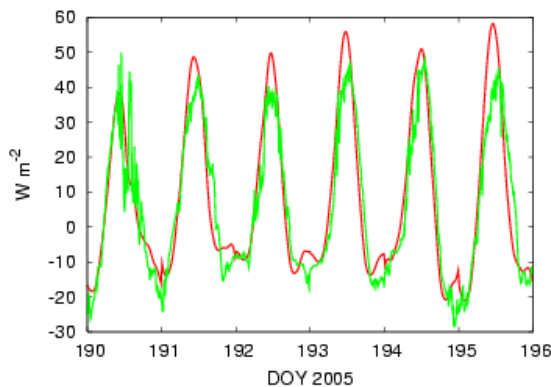


Fig. 4 Ground heat flux, as calculated using the Fourier method (red/thick) and the new method (green/thin).

5. DISCUSSION AND CONCLUSION

In this study we have presented a novel approach to estimate the ground heat flux at the surface. Using measurements of the infrared vegetation temperature and the soil temperature at 12 cm as boundary conditions, our method calculates the optimal ground heat flux taking account of all available soil measurements.

In accordance with previous method, the proposed method facilitates the control variables to vary on scales longer than one day. But in contrast to these methods, the use of realistic boundary conditions for the vegetation temperature and at 12 cm, and realistic initial conditions accommodates the impact of slow cycles on the ground heat flux. Also, the use of temperature close to the surface and the temperature of the vegetation, allows the simulation of

the impact of high-frequency variations on the ground heat flux at the surface.

The results indicate that the optimized is well capable of simulating soil temperatures at various depths below the surface. It thus gives estimates of the ground flux that are consistent with the measured vertical temperature profile in the soil. The method however appears to slightly overestimate the upward (nighttime) flux at 5 cm and 10 cm, while it underestimates the downward flux (daytime) flux at 5 and 10 cm. Though the method is capable of diagnosing these inconsistencies, it is not clear why underestimates the soil heat fluxes at 5 cm and 10 cm during daytime and overestimates the upward soil heat flux. The most probable reason for this is a daily cycle in the conductivity of the heat conductivity or the volumetric heat capacity of the soil or vertical variations of the values of these parameters. Studying the impact of sub-daily variations and vertical variations of these parameter and other parameters, and accommodating these in the current method should therefore be a focus of further research.

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