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# Quantifying the uncertainty in estimates of surface- atmosphere fluxes through joint evaluation of the SEBS and SCOPE models

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## Abstract

Accurate estimation of global evapotranspiration is considered of great importance due to its key role in the terrestrial and atmospheric water budget. Global estimation of evapotranspiration on the basis of observational data can only be achieved by using remote sensing. Several algorithms have been developed that are capable of estimating the daily evapotranspiration from remote sensing data. Evaluation of remote sensing algorithms in general is problematic because of differences in spatial and temporal resolutions between remote sensing observations and field measurements. This problem can be solved by using Soil Vegetation Atmosphere Transfer (SVAT) models, because on the one hand these models provide evapotranspiration estimations also under cloudy conditions and on the other hand can scale between different spatial resolutions.

In this paper, the Soil Canopy Observation, Photochemistry and Energy fluxes (SCOPE) model is used for the evaluation of the Surface Energy Balance System (SEBS) model. SCOPE was employed to simulate remote sensing observations and to act as a validation tool. The advantages of the SCOPE model in this validation are (a) the temporal continuity of the data, and (b) the possibility of comparing different components of the energy balance. The SCOPE model was run using data from a whole growth season of a maize crop.

It is shown that the original SEBS algorithm produces significant uncertainties in the turbulent flux estimations due to the misparameterizations of the ground heat flux and sensible heat flux. In the original SEBS formulation the fractional vegetation cover is used to calculate the ground heat flux. As this variable saturates very fast for increasing LAI, the ground heat flux is underestimated. It is shown that a parameterization based on LAI greatly reduces the estimation error over the season from  $RMSE = 25 \text{ W m}^{-2}$  to  $RMSE = 18 \text{ W m}^{-2}$ . The uncertainties in the sensible heat flux arise due to a misparameterization of the roughness height for heat. In the original SEBS formulation the roughness height for heat is only valid for short vegetation. An additional parameterization

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for tall vegetation was implemented in the SEBS algorithm to correct for this. This improved the correlation between the latent heat flux predicted by the SEBS and the SCOPE algorithm from  $-0.05$  to  $0.69$ , and led to a decrease in error from  $123 \text{ W m}^{-2}$  to  $94 \text{ W m}^{-2}$  for the latent heat, with SEBS latent heat being consistently lower than the SCOPE reference. In addition the stability of the evaporative fraction was investigated.

## 1 Introduction

Accurate estimation of evapotranspiration, ET, is considered of great importance due to its key role in hydrology and meteorology. It is involved in many feedback mechanisms, for example between the water and the energy balance, and those between the land surface and the atmosphere. Accurate estimation of ET is of importance for applications such as irrigation management, weather forecasting and climate model simulations. Despite the importance of accurate estimates of ET, no validated global evapotranspiration product exists that meets all spatial and temporal requirements for a comprehensive water cycle analysis. In response to the demand for such a product, the Water Cycle Multi-mission Observation Strategy (WACMOS), launched by the European Space Agency (ESA), aims at developing a daily evapotranspiration product on a global scale with a 1km resolution

It is challenging to find an algorithm suitable for the global scale with such high spatial and temporal resolution. The algorithm should include the most important exchange processes while retaining a minimum of input parameters. Remote sensing based evapotranspiration algorithms, such as TSEB and SEBAL, cannot be used for estimating global evapotranspiration because they either require local calibration (SEBAL) (Bastiaanssen et al., 1998) or too many input parameters (TSEB) (Kustas and Norman, 2000; Timmermans et al., 2007). The Surface Energy Balance System SEBS (Su, 2002) circumvents the calibration problem by using a more physically based parameterization of the turbulent heat fluxes for different states of the land surface and the atmosphere (Su et al., 2001), through implementation of the similarity theory (Brutsaert,

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1999; Obukhov, 1971; Monin and Obukhov, 1954), while keeping the number of required input variables to a feasible minimum. Of the different available models, SEBS provides the best compromise between the detail levels of the model description on the one hand, and the input requirements for the purpose of the WACMOS project on the other hand.

Because ET cannot be detected directly from space, most remote sensing algorithms (including SEBS) estimate ET from latent heat flux (Kalma et al., 2008; Glenn et al., 2007). This latent heat flux is calculated as the residual of the energy balance. The accuracy of the product thus depends on the accuracy of the other components of the energy balance: net radiation, ground heat flux and sensible heat flux. These components are calculated for the overpass time of the satellite. To scale the estimates up to a daily (24-hour) value, an assumption about the diurnal cycle of the fluxes is needed (Rauwerda et al., 2002; Shan et al., 2008).

Validation of ET products is problematic, because spatially distributed data for validation are not available. The SEBS algorithm has been validated locally for many low vegetation types (Shan et al., 2008; Timmermans et al., 2005; Jia et al., 2003; McCabe and Wood, 2006; Su et al., 2005). Extra uncertainty enters the validation process due to differences in spatial and temporal resolution between the remote sensing observations and the ground measurements (Kite and Droogers, 2000).

Footprints of ground measurements range between  $100\text{ m}^2$  and  $250\text{ m}^2$  for Bowen ratio stations (Pauwels and Samson, 2006; Pauwels et al., 2008) to around  $0.1\text{--}0.3\text{ km}^2$  for scintillometer stations (Hartogensis, 2006). These scales are much lower than the desired spatial resolution of the WACMOS project of  $1\text{ km}^2$ . The required temporal resolution (daily) is difficult to obtain using a single satellite sensor. Combining observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Along-Track Scanning Radiometer (AATSR), and the MEdium Resolution Imaging Spectrometer (MERIS) can enhance this temporal resolution, although cloud contamination still is present. Validation of the various heat fluxes using long time series of remote sensing imagery is therefore very difficult.

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The objective of the research described in this paper is to create a methodology for evaluating the suitability of the SEBS model (or any other remote sensing-based evapotranspiration algorithms for that matter) in providing the spatial and temporal resolutions required by the WACMOS project. The application of a Soil Vegetation Atmosphere Transfer (SVAT) model (Olioso et al., 1999) would be ideal for such an evaluation. In order to create long time series, the input for this SVAT model should be based mostly on meteorological parameters and other field data.

The recently developed Soil Canopy Observation of Photochemistry and Energy fluxes model, SCOPE, (van der Tol et al., 2009) presents us with the possibility of estimating turbulent heat fluxes and radiative transfer using only a limited amount of data. This SVAT model combines accurate estimates of optical and thermal radiation, (Verhoef et al., 2007), with a detailed representation of the biophysical processes through an extensive aerodynamic resistance model (Verhoef et al., 1999) and energy balance modeling at the leaf level. This SCOPE model was used to calculate the turbulent heat fluxes and the hyperspectral outgoing radiances. These radiances are converted into sensor bands using a sensor simulator (Timmermans, 2009). These band observations were then fed through the SEBS preprocessor for the calculation of land surface temperature (LST), albedo and emissivity (Sobrino et al., 2004). Finally turbulent heat fluxes estimated by the SEBS algorithm was compared to those estimated by the SCOPE model.

In Sect. 2.1 the SEBS and SCOPE model are explained in more detail, as well as the method for coupling the two models together. In Sect. 2.2 the field site and data collection is described, and in Sect. 2.3 the investigations into the LAI retrieval algorithm and the parameterizations of the different fluxes (ground heat flux, sensible heat flux and daily evapotranspiration) are discussed. The discussion and conclusions follow in the final two sections.

## 2 Methodology

In this investigation the SCOPE model is coupled to the SEBS model. SCOPE estimates both the turbulent fluxes and hyperspectral radiative transfer. Through a sensor simulator and the SEBS preprocessor the input variables for the SEBS algorithm are calculated using these “observations”. This way the SCOPE model acts as a forcing and validation tool for the SEBS algorithm. This methodology is illustrated in Fig. 1.

The advantage of simulating band radiances enables estimation of evapotranspiration for dates when there is no remote sensing observation (for example when there are clouds) and is therefore suitable for creating long time series. This capability, in combination with a sensor simulator, enables the model also to reproduce past, current and future satellite sensor observations (Timmermans et al., 2009; Verhoef, 2008), and to combine several sensors in a synergistic manner. This synergistic use however falls outside the scope of the presented investigation.

The investigation into the uncertainties in SEBS flux estimates focuses mainly on the effect of high vegetation types on the daily evapotranspiration, because SEBS has so far been validated only for low vegetation types (Shan et al., 2008; Timmermans et al., 2005; Jia et al., 2003; McCabe and Wood, 2006; Su et al., 2005). For high vegetation types some of the parameterizations in SEBS might fail due to the complex nature of the turbulent heat exchange. Focus of this paper will be on the height dependence of the LAI retrieval, the ground heat flux parameterization, the aerodynamic resistance estimation and its dependence on the roughness height for heat, and the diurnal stability of the evaporative fraction.

### 2.1 SEBS

The Surface Energy Balance System, SEBS, makes use of the energy balance (Eq. 1) to estimate the latent heat flux at the time of overpass. In order to scale from the instantaneous to the daily time scale, it is assumed that the evaporative fraction (Eq. 2)

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remains constant over the day.

$$R_n = G_0 + H + \lambda E, \quad (1)$$

$$\Lambda = \frac{\lambda E}{R_n - G} = \frac{\Lambda_r \cdot \lambda E_{\text{wet}}}{R_n - G}, \quad (2)$$

$$\Lambda_r = 1 - \frac{H - H_{\text{wet}}}{H_{\text{dry}} - H_{\text{wet}}} \quad (3)$$

5 Here,  $R_n$  is the net radiation [ $\text{W m}^{-2}$ ];  $G_0$  the soil heat flux [ $\text{W m}^{-2}$ ];  $H$ ,  $H_{\text{dry}}$ , and  $H_{\text{wet}}$  are the actual, dry limit and wet limit sensible heat flux [ $\text{W m}^{-2}$ ], respectively;  $\lambda E$  and  $\lambda E_{\text{wet}}$  are the actual latent heat fluxes [ $\text{W m}^{-2}$ ] at overpass and the hypothetical wet limit; and  $\Lambda$  and  $\Lambda_r$  are the evaporative fraction  $(\lambda E)/(R_n - G)$  [-] and relative evaporation [-].

10 SEBS was developed by (Su, 2002) for the estimation of atmospheric turbulent fluxes using satellite earth observation data. SEBS is a remote sensing algorithm for estimating (daily) evapotranspiration. It consists of a set of algorithms for the determination of the land surface physical parameters and variables, such as albedo, emissivity, land surface temperature, and vegetation coverage, from spectral reflectance and radiance data (Su, 1996; Su et al., 1999). It includes an extended model for the determination  
15 of the roughness height for heat transfer (Su et al., 2001) and a formulation for the estimation of the evaporative fraction on the basis of the energy balance at limiting cases.

In the original formulation, SEBS calculates evapotranspiration based on the net radiation, the ground heat flux and the evaporative fraction. The net radiation is calculated using incoming shortwave radiation, albedo, air and land surface temperature and emissivity. The ground heat flux is estimated based on the weighted average of ground heat flux over vegetated (Monteith, 1973) and bare soil (Kustas and Daughtry, 1989). The evaporative fraction is estimated through the relative evaporation using the sensible heat fluxes (Eqs. 2 and 3). This sensible heat flux is calculated iteratively

through use of the Obukhov length and the friction velocity. The equations required to calculate the evapotranspiration, ground heat flux and the sensible heat flux are shown in Eqs. (4)–(7).

$$\lambda E = \Lambda(R_n - G_0) \quad (4)$$

$$G_0 = R_n(\Gamma_c + (1 - f_c)(\Gamma_s - \Gamma_c)) \quad (5)$$

$$H = \rho_a C_p \frac{(\theta_o - \theta_a)}{r_a} \quad (6)$$

$$r_a = \frac{[\ln(h_c/z_{0h}) - C_w]}{k u_*} \quad (7)$$

Here  $f_c$  is the fractional vegetation cover [-];  $\Gamma_c$  and  $\Gamma_s$  are the values [-] of the ratio of the net radiation to ground heat flux ratio for the full canopy limit and the bare soil limit;  $\rho_a$  is the density of air [ $\text{kg m}^{-3}$ ];  $C_p$  is the specific heat coefficient of air [ $\text{J Kg}^{-1} \text{K}^{-1}$ ];  $r_a$  is the aerodynamic resistance [ $\text{s m}^{-1}$ ];  $u^*$  is the friction velocity [ $\text{s m}^{-1}$ ];  $k$  is the von Karman constant [-];  $\theta_o$  and  $\theta_a$  are the potential temperatures of the land surface and air [K];  $h_c$  is the height of the vegetation [m];  $C_w$  is the correction term for atmospheric (in) stability correction term [-], and  $z_{0h}$  is the roughness height for heat [m]. The correction for the atmospheric stability depends on the state of the atmosphere and the measurement height. In SEBS  $C_w$  is calculated using the Monin-Obukhov Similarity theory (MOS) if the measurements were performed within the atmospheric surface layer, and Bulk Atmospheric Similarity theory (BAS) if the measurements were performed above this surface layer. The roughness height for heat is calculated based on the roughness height for momentum,  $z_{0m}$ , through the relationship given by  $kB^{-1} = \ln(z_{0m}/z_{0h})$ . This  $kB^{-1}$  (Massman, 1999; Su et al., 2001) is calculated based on the weighted average between limiting values of soil and full canopy (Eq. 8).

$$kB^{-1} = kB_c^{-1} f_c^2 + kB_m^{-1} f_s f_c + f_c^2 kB_s^{-1} \quad (8)$$

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Here,  $f_s$  is the fractional soil coverage [-]. The bare soil contribution is calculated as  $kB_s^{-1} = 2.46(Re_*)^{1/4} - \ln(7.4)$ , with  $Re_*$  the roughness Reynolds number. The full canopy contribution is given by  $kB_c^{-1} = kC_d / \left[ 4C_t\beta \left( 1 - e^{-n/2} \right) \right]$ , with  $C_d$  the drag coefficient of the leaves,  $C_t$  the heat transfer coefficient of the leaves,  $\beta$  the ratio between the friction velocity and the wind speed at canopy height, and  $n$  the cumulative leaf drag area. Finally, the soil-canopy interaction contribution is calculated using  $kB_m^{-1} = k\beta z_{0m} / (C_t^* h_c)$ , with  $C_t^*$  the heat transfer coefficient of the soil.

The errors in the final estimation of evapotranspiration can be contributed to either propagation of input errors, or errors induced by poor parameterizations of the surface processes in the model. Uncertainties in the input data usually originate from the atmospheric correction of the remote sensing imagery, or from the difference in surface parameter retrieval algorithms. Using the SCOPE model to simulate these variables, this uncertainty is removed in the analysis.

## 2.2 SCOPE model

The Soil Canopy Observation of Photochemistry and Energy fluxes, SCOPE, model is used to circumvent these problems as it is able to simultaneously simulate top-of-canopy satellite imagery and estimate the evapotranspiration. This enables the separation of uncertainties in the input parameters and the errors induced by parameterization errors.

The SCOPE model is a soil-vegetation-atmosphere-transfer (SVAT) model that couples radiative transfer of optical and thermal radiation with leaf biochemistry processes (van der Tol et al., 2009). This coupling is performed, similar to the CUPID model (Norman, 1979), at the leaf level using an energy balance approach model. It calculates the aerodynamic resistances (Verhoef et al., 1999), the within-canopy canopy heat flux vertical distribution, the hyperspectral outgoing radiances (Verhoef et al., 2007) over the whole spectrum, the photosynthesis of C3 (Farquhar et al., 1980) or C4 vegetation, and stomatal resistance (Cowan, 1977).

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The radiative transfer of outgoing and internal optical and thermal radiation in SCOPE is based on FluorSAIL with added analytical parts from the unified 4SAIL model (Verhoef et al., 2007). This model calculates the directional outgoing radiance of the land surface at specific wavelengths, taking into account the spectra of incoming solar and diffuse radiation, canopy structure and the component temperatures of the soil and canopy. The SCOPE model uses a discrete version of the directional radiance equation because the leaf energy balance is solved for different layers ( $x$ ). In addition, the radiation depends on the sun-canopy-observer geometry and on leaf orientation, because the biophysical processes are different for sunlit and shaded components. The FluorSAIL model originally was intended to compute only canopy reflectance and fluorescence, but the addition of thermal radiation and considering the energy balance on the individual leaf level allowed the construction of an SVAT model like SCOPE.

Recently, a sensor simulator has been added to the SCOPE model (Timmermans et al., 2009) for estimating thermal bands of different satellites. This sensor simulator has been modified in this research to cover the optical part of the spectrum and extra sensors (MODIS, AATSR)., (Timmermans, 2009). This sensor simulator integrates the measured radiances with the sensor band sensitivity to calculate the “measured” band radiances. Using the optical and thermal radiation from the radiative transfer model, SCOPE is now able to reproduce past, current and future satellite sensor data (Verhoef and Bach, 2007; Verhoef, 2008; Timmermans et al., 2009). At the moment SCOPE does not simulate the path of the radiation through the atmosphere, and consequently simulates the observed radiances like the sensor is situated at the top of the canopy.

### 3 Experimental setup

The meteorological data used for the forcing of the SCOPE model was obtained at The University of Reading Crops Research Unit experimental site (Sonning, United Kingdom). The data set used comprises micrometeorological variables, such as air temperature,  $T_a$ , wind speed,  $U_a$ , and actual vapor pressure,  $e_a$ . In addition the energy

balance fluxes were measured for a complete growth cycle of maize during the summer of 2002 (see van der Tol et al., 2009b, for a detailed overview of the site, and sensors used). A unique feature of this particular dataset is that after the maximum canopy height and LAI ( $3.7 \text{ m}^2 \text{ m}^{-2}$ ) was achieved the canopy was thinned out. The LAI values obtained after this thinning were approximately 2.0, 1.0, 0.5 and  $0.25 \text{ m}^2 \text{ m}^{-2}$ ). Leaves were systematically removed from the canopy, without modifying the height of the crop. This abrupt change is clearly seen in the different surface parameters (LAI and canopy height) measured, as shown in Fig. 2. The stepwise change in leaf area density provides a perfect dataset for testing the variability of the LAI retrieval methods and the effect on the surface energy balance.

## 4 Results

### 4.1 Leaf area index

Although not part of the original SEBS formulation, LAI in many SEBS-based investigations is calculated from NDVI using the parameterization presented in Eq. (10) (Su, 1996). However this parameterization is only valid for sparse vegetation types; for denser vegetation types it produces values of LAI that are unrealistically high. Author, like (Song et al., 2008), couple LAI to NDVI using a logarithmic expression (Eq. 10). These two retrieval algorithms are shown in Eqs. (9 and 10).

$$\text{LAI} = \text{NDVI} \sqrt{\frac{1 + \text{NDVI}}{1 - \text{NDVI}}} \quad (9)$$

$$\text{LAI} = A \ln \left( 1 - \frac{\text{NDVI}}{B} \right) \quad (10)$$

Here, the values of A and B depend on the vegetation type, which for maize is given as  $A = (-2.11)^{-1}$  and  $B = 0.9$ . However, this method cannot be implemented into SEBS

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as NDVI values higher than 0.9 are found, and therefore this parameterization should be modified. As proof of the validity of the methodological concept the NDVI values calculated from the SCOPE simulations are compared to the LAI values measured in the field. The results of this comparison are shown in Fig. 3. Here, the original parameterization by Su, the new parameterization by Song et al. (2008) and the parameterization based on Song et al. (2008) but with optimized A and B values, are shown.

It is clear that the parameterization of (Song et al., 2008) with the optimized values, produces more accurate values of LAI than the other two methods. Both relationships between LAI and NDVI given in (Su, 1996) and the original by (Song et al., 2008) produce too high results. With the original values of Song et al. (2008) the maximum value of NDVI is assumed to be 0.9, while here we find NDVI values as high as 0.92. This causes the relationship to produce non-realistic values. The optimized relationship was set for higher maximum NDVI values, and although it produces slightly lower LAI values, the values of LAI do not become infinite for  $NDVI > 0.92$ . Using these optimized coefficients the difference between measured and estimated LAI resulted in a  $RMSE = 0.3 \text{ m}^2 \text{ m}^{-2}$ .

## 4.2 Ground heat flux

The original ground heat flux in SEBS uses the fractional vegetation cover to perform a weighted average between bare soil coverage and the full canopy ground heat flux (Kustas and Daughtry, 1989). As the fractional vegetation cover saturates much faster than the height of the vegetation or the LAI, this causes an underestimation of the ground heat flux for medium to high leaf area indices. (Kustas et al., 1993) proposed to use the LAI instead of the fractional vegetation cover, see Eq. (11). They argued that this parameterization is more physical than the approach used in (Kustas and Daughtry, 1989) as it represents the extinction of the incoming solar radiation more realistically. Values for  $C_{r0}$  and the extinction coefficient  $a$  depend on the vegetation type, and in general can be assumed to be 0.34 and 0.46, respectively (Brutsaert, 2005).

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$$\frac{G_0}{R_n} = C_{r0} \exp(-a \text{LAI}) \quad (11)$$

The values of  $C_{r0}$  and  $a$  in the current paper are retrieved by using the incoming optical radiation from SCOPE, the land surface temperature obtained through the simulated AATSR sensor and the ground heat flux obtained through measurements. In the SCOPE model the ground heat flux is calculated using a slab model for the ground. Although the soil temperatures found from the model are consistent with the observations, the ground heat fluxes are too high compared to the measured values. Therefore for this investigation the in-situ measurements are used, instead of the simulated values.

The first step is to sort the observations based on the LAI of the vegetation. In order to achieve a high accuracy, a long time series of both net radiation and ground heat flux is needed, during which LAI does not change. The different classes are filtered, based on the number of values found in the histogram; occurrences below 50 observations are filtered out. The field in Sonning is therefore well suited for this investigation as the maize was thinned in steps, from very high LAI ( $3.7 \text{ m}^2 \text{ m}^{-2}$ ) to very low leaf area index ( $0.25 \text{ m}^2 \text{ m}^{-2}$ ). Note that only daytime values between 10:00 and 16:00 h are used. After filtering the coefficients in Eq. (11) are retrieved. The results are shown in Fig. 4.

The ratio between the ground heat flux and net radiation behaves exactly as predicted; the observations fall well within the theoretically predicted values set by the bare soil and full canopy limits. In addition it is observed that the ratio of net radiation and ground heat flux correlates very well with LAI. However, lower values of both the extinction coefficient ( $a = 0.26$ ) and the amplitude ( $C_{r0} = 0.18$ ) are found than the values advised by (Kustas et al., 1993; Brutsaert, 2005).

These low values for the amplitude and the extinction coefficient originate from the high variation in the  $R_n - G_0$  ratio for classes with a low LAI. This high variation is caused by non-uniform shading affects of the soil due to the low fractional vegetation cover. When dealing with sparse vegetation the amount of radiation reaching the soil is highly dependent on the geometry of the sun and the leaf orientations.

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The high values of the ratio between ground heat flux and net radiation originate for particular sun-leaf geometries. For these cases the sun-beam directly strike the soil, without being attenuated by the vegetation. Low values for the ratio between ground heat flux and net radiation originate from low solar zenith angles. For these cases the canopy appears to be dense and closed. These deviations need to be investigated in more detail; therefore the original values of  $C_{r0}$  and  $a$  given by (Kustas et al., 1993) have been used, instead of the values found in this paragraph. Using the parameterization of (Kustas et al., 1993) the difference between observed and measured ground heat flux was  $18 \text{ W m}^{-2}$  which is a decrease when compared original SEBS parameterization with a  $\text{RMSE} = 25 \text{ W m}^{-2}$ .

### 4.3 Roughness heights

The sensible heat flux in SEBS is calculated from the aerodynamic resistance and the difference in potential temperature between the land surface and the atmosphere at measurement height (Eqs. 6 and 7). This resistance has been shown in the previous section to depend on the roughness height for heat, the friction velocity and the logarithmic windspeed profile of the wind speed. (Jacobs et al., 1989; Liu et al., 2007) found that the value of aerodynamic resistance for maize ranged from 20 to  $50 \text{ s m}^{-1}$ . However, when using the original SEBS parameterizations we found it to vary between 80 and  $200 \text{ s m}^{-1}$ , resulting in a unrealistically low sensible heat flux, compared to the measured maize  $H$ -values.

The error in the aerodynamic resistance appears to be caused by the parameterization of the roughness height for heat. In the original SEBS parameterization this roughness height is estimated based on the  $kB^{-1}$ . In SEBS this variable is usually higher than 8.0; the roughness height for momentum is always higher than the roughness height for heat (i.e.  $kB^{-1} > 0$ ), except for bare soils for which negative values of  $kB^{-1}$  have been found (see Verhoef et al., 1997b). Small negative values have also been found for tall, dense canopies (Liu et al., 2007; Jia, 2004). Values for closed canopies are usually around 2, but  $kB^{-1}$  increases for sparse canopies (up to 15 for

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very sparse canopies), Values of  $kB^{-1} > 8$  are therefore deemed too large, especially for the maize crop with  $LAI = 3.7 \text{ m}^2 \text{ m}^{-2}$ . However,  $kB^{-1}$  values can be calculated from the direct measurements (Liu et al., 2007) or in our case SCOPE simulations, as shown in Eq. (12).

$$kB^{-1} = \rho_a C_p \frac{(T_s - T_a)}{H} k u_* - \ln \left( \frac{z - d_0}{z_{0m}} \right) + \Psi_h \left( \frac{z - d_0}{L} \right) \quad (12)$$

Here  $T_s$  and  $T_a$  are the temperatures for the land surface and the atmosphere [K],  $z$  is the measurement height [m],  $d_0$  is the displacement height [m], and  $\Psi_h$  is the MOS atmospheric stability function for heat [-]. The results are shown in Fig. 5. Note the decrease in  $kB^{-1}$  as the canopy height and density increase throughout the season. The relatively sudden rise in  $kB^{-1}$  around day 220 is caused by the thinning of the canopy. The minimum value calculated for  $kB^{-1} = -0.5$ . This low value is attributed to the height of the canopy. In high, dense vegetation the incoming radiation only affects the leaf temperature in the upper part of the canopy; in the lower region the radiation is absorbed too much to play a significant role in the temperatures of the leaves (Liu et al., 2007; Jia, 2004). However these leaves or twigs still play a role as part of the sink for momentum. This process is well represented in the SCOPE model, as the radiative transfer in this model is more accurately represented than in the SEBS model. Hence, instead of the original parameterization for  $kB^{-1}$  in SEBS, which produces values that are too high, the method of (McNaughton and van den Hurk, 1995; Bosveld et al., 1999) for  $kB^{-1}$  is used, for high values of LAI and  $h_c$ , see Eq. (13).

$$kB^{-1} = 52 \frac{\sqrt{u_* l}}{LAI} - 0.69 \quad (13)$$

Here  $l$  is the characteristic height for the canopy; in the maize canopy this corresponds to a leaf width of 0.03 m. The temporal variability for  $kB^{-1}$  for this method is also shown in Fig. 5, along with the temporal variability of  $kB^{-1}$  calculated with the original method employed in SEBS, and with the values based on the SCOPE estimations (Eq. 12).

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It is obvious that the new parameterization of  $kB^{-1}$  correlates much better with observed values than the original SEBS parameterization. Even the thinning of the LALis clearly characterized using this method, illustrated by the good correspondence of  $kB^{-1}$  at the end of the measurement period. However the method only applies for closed canopies, and is less accurate for low vegetation. Therefore it is opted to use this method only when the LAI is above the threshold value of 1.5 and only when  $h_c > 1$  m.

#### 4.4 Instantaneous heat fluxes

Finally, after implementation of the new parameterizations for high canopy types, the surface heat fluxes can be calculated. The results of these calculations are shown in Fig. 6. In this figure the net radiation, ground heat flux, sensible heat flux and the latent heat fluxes are shown. All SEBS estimated fluxes, except the latent heat, have a high correlation with the SCOPE estimated values for the fitted values.

- The net radiation of SEBS and SCOPE have a high correlation and is fitted with a slope of 0.81 and a  $RMSE = 54 \text{ Wm}^{-2}$ . The (optical) reflected and thermal radiation as measured for the maize canopy, are very similar to those predicted by SCOPE (not shown); this implies that the land surface temperature (LST), albedo and emissivity are retrieved correctly from the SCOPE simulations. This is observed most clearly for day 186 when the differences between measured and modeled net radiation are the highest. The difference in the net radiation arises because SEBS uses air temperature to calculate the longwave incoming radiation (Brutsaert, 2009). However, the variation in the downwelling diffuse radiation for medium cloud coverage cannot be taken into account using solely the air temperature. Instead the separation of incoming radiation into diffuse and direct radiation should be based on measurements.
- The ground heat flux calculated by SEBS is much lower than the SCOPE estimated ground heat flux. This is explained in the previous paragraph, and arises

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because SCOPE estimates the ground heat flux using the Force-Restore method, which in this case overestimated the ground heat flux. The differences between the measurements and the SEBS derived ground heat flux decreased from  $RMSE = 21 \text{ Wm}^{-2}$  to  $RMSE = 18 \text{ Wm}^{-2}$  using the new parameterization. The new SEBS formulation for  $G_0$  (Brutsaert, 2005; Kustas et al., 1993) clearly follows the measurements of the ground heat flux.

- The SEBS sensible heat flux has improved a lot using the new parameterization for the roughness height of heat. The differences (expressed as RMSE) between SEBS and SCOPE decreased when using the new parameterization, from  $100 \text{ Wm}^{-2}$  to  $56 \text{ Wm}^{-2}$ ; the correlation increased from  $-0.07$  to  $0.68$ . Only for high LAI values is SEBS underestimating the sensible heat. This indicates that additional processes play a role in the sensible heat flux for high LAI values, other than those already estimated using the new parameterization.
- The latent heat flux calculated by SEBS is considerably higher than the latent heat flux predicted by SCOPE. The new parameterizations improved the estimation of  $\lambda E$ , as illustrated by the reduction in RMSE from  $123 \text{ Wm}^{-2}$  to  $94 \text{ Wm}^{-2}$ . This difference originates mainly due to the overestimation of the evaporative fraction for very high LAI. In Fig. 6 this can be clearly observed because the slope for the sensible heat flux deviates as much from the 1:1 line as the slope of the latent heat flux (but in opposite directions). This will be investigated further in the next section.

## 4.5 Evaporative fraction

The evaporative fraction, EF, in SEBS is to be calculated based on  $\Lambda = \Lambda_r \lambda E_{\text{wet}} / (R_n - G)$ , but in SCOPE is calculated as  $\lambda E / (H + \lambda E)$ . In SEBS, EF therefore depends on the actual sensible heat flux, and the sensible heat flux at the hypothetical dry and wet limit. The sensible heat flux at these limits is calculated respectively as the maximum available energy, for the dry scenario, while for the wet scenario  $H$

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is calculated from  $R_n - G_0 - \lambda E$ , with  $\lambda E$  derived from the Penman Monteith equation. The evaporative fraction is calculated by SEBS at the time of overpass and considered constant during the rest of the day. However several researchers have reported a diurnal dependence of the evaporative fraction (Li et al., 2008; Farah et al., 2004; Lu and Zhuang, 2010).

Combining SCOPE and SEBS allows us to investigate not only the diurnal pattern of EF, but also the uncertainties of EF at overpass time and the daily average of EF. The results of the comparison are shown in Fig. 7. Here, the diurnal pattern of the evaporative fraction is shown for the complete growing season, for all individual days (the left panel), and for a 10-day average.

As expected, the evaporative fraction at night is much lower than the evaporative fraction during the day, as the nighttime latent heat is close to zero. During day time the evaporative fraction varies for most days, except from those with low LAI values. This is shown most clearly when studying the diurnal variation of the 10-day average EF values. The 10-day average EF remains stable for the days 170–180, 240–250 and 250–260. These days correspond to low LAI values of 0.25, 0.5 and 0.25, respectively. For days 230–240, (LAI = 1.0) the evaporative fraction starts to vary diurnally. For all other days (i.e. those with LAI > 1.0) EF has a pronounced diurnal pattern. For LAI > 2.0 EF has the same pattern: with EF lower in the morning than later in the day. Therefore the average evaporative fraction is higher than the instantaneous evaporative fraction. This is confirmed in Fig. 7.

Figure 8 shows both the instantaneous evaporative fractions at overpass time calculated by SEBS and SCOPE and the daily average values of the evaporative fraction calculated by SCOPE. The daily evaporative fraction is in all cases higher than the instantaneous EF by SCOPE, except for the low LAI classes (at the very start and end of the experimental period). The comparison between instantaneous/daily average evaporative fractions by SEBS and SCOPE is hampered due to the large variation in the SEBS evaporative fraction. This variation occurs when net radiation is very low. In these cases the evaporative fraction predicted by SEBS becomes very low. The

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parameterization. Because currently SCOPE is overestimating the ground heat flux, the ground heat flux from measurements was used to calibrate an alternative, more physical, parameterization (Kustas and Daughtry, 1989); it characterizes the extinction of radiation through a dense canopy. Values for the different coefficients were obtained through investigation of the ratio of soil heat flux and net radiation for different LAI classes. Variations in the coefficients originated because the measured values for low LAI values showed high variation. Therefore, instead of using the optimized coefficients, it was decided to use the original Kustas parameter values.

The last parameterization modified was that describing the relative magnitude of the roughness height for momentum and heat, as expressed by the parameter  $kB^{-1} = \ln(z_{0m}/z_{0h})$ . In high dense canopies most of the radiation is absorbed by the leaves at the top of the canopy. Therefore the position of the virtual source of the sensible heat, as expressed by  $z_{0h}$ , is relatively higher in the canopy than for low vegetation. This physical process was not characterized correctly in the original parameterization taken from Su. Hence, to take this effect into account, a simple parameterization by Bosveld based on LAI and the friction velocity was used. This change in parameterization resulted in an improvement of the correlation between SEBS and SCOPE modelled sensible heat flux from  $-0.07$  to  $0.68$ .

After implementing all the new parameterizations, the various energy balance fluxes and the evaporative fraction were calculated. Even though the roughness height for heat was improved greatly using a new parameterization, SEBS still underestimated the sensible heat flux for high LAI values. This means that some processes are still not characterized well enough and further investigation is required. Using the instantaneous, wet and dry limit sensible heat fluxes, the evaporative fraction, EF, was calculated in SEBS. This EF was compared to the instantaneous and daily averaged EF simulated by SCOPE. SCOPE calculated a diurnal pattern in the evaporative fraction causing the daily average to be higher than the SCOPE-obtained instantaneous EF at overpass time. EF from SEBS however was of the same order as the SCOPE daily averaged evaporative fraction. This originates from the low values of the SEBS estimated

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instantaneous sensible heat. Although the new parameterization for  $kB^{-1}$  over tall vegetation can still be improved further, estimations by SEBS can already be used for daily evapotranspiration estimations because the obtained valued for the evaporative fraction appears to represent correctly the daily average.

In conclusion, the methodology presented in this paper enabled a thorough investigation in the different parameterizations of SEBS. The advantage of the method presented in this paper, i.e. combining SEBS with SCOPE, is mainly that for days where there are no acquisitions we can still continue the investigation. Although no actual remote sensing imagery was used, the methodology, through the use of the sensor simulator, proved the viability of using the AATSR sensor for calculating the different land surface fluxes. The SCOPE model at the moment overestimates the ground heat flux; this should be addressed in the next version of the SCOPE model. A version of SCOPE that incorporates a detailed multi-layer below-ground parameterization of heat, water and gas fluxes will be developed in the context of the UK (NERC) funded FUSE project (NE/I007288/1).

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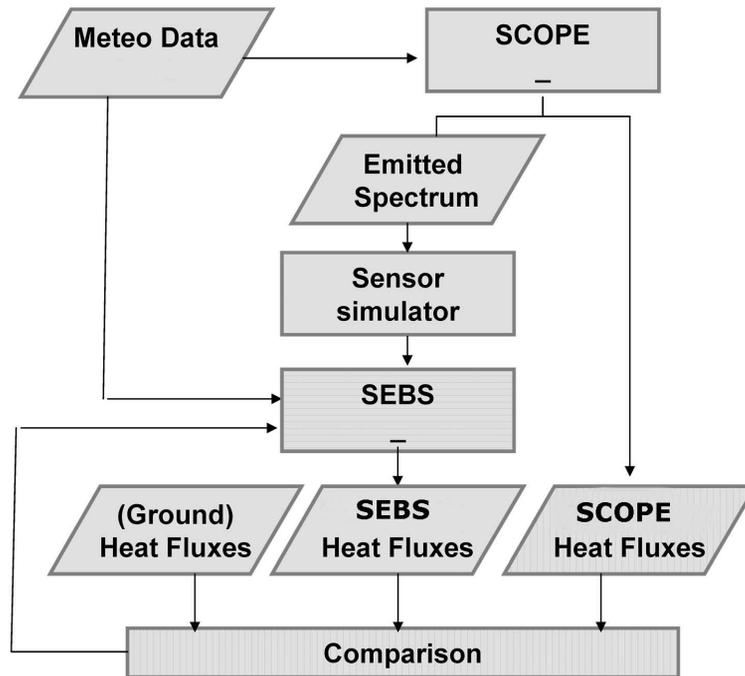
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**Fig. 1.** Methodology flowchart for comparing SEBS with SCOPE.

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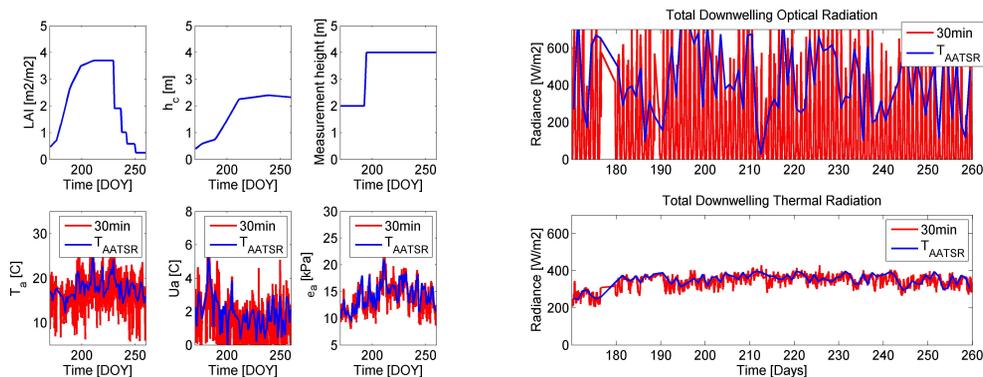
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**Fig. 2.** SCOPE input parameters and variables measured at the experimental site during 2002. In the top left panel the surface parameters are shown. In the bottom left panel the atmospheric driving variables. In the right panel the incoming optical and thermal radiance data are shown. The red lines depict half hourly in situ measured data, and the blue lines depict the values at AATSR overpass time ( $T_{\text{aatsr}}$ ).

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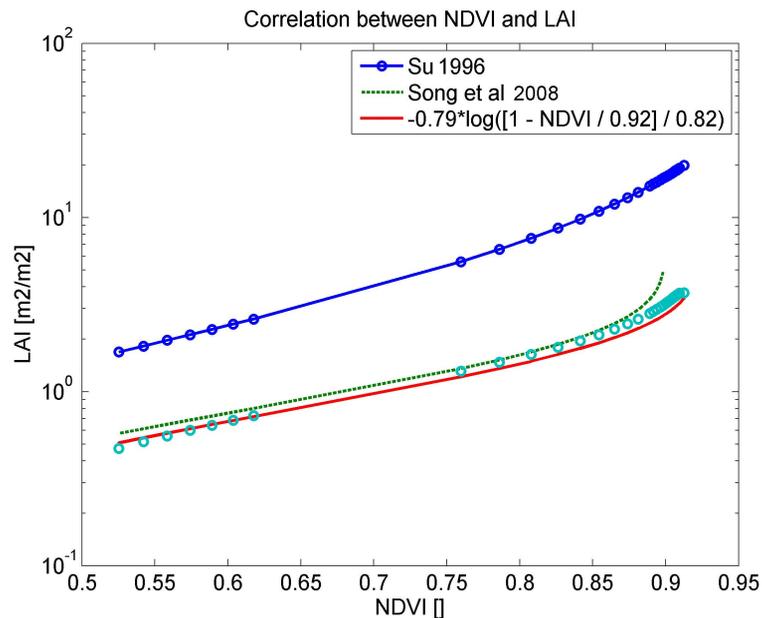
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**Fig. 3.** NDVI – LAI relationships. The LAI values obtained by measurements (open circles) and the Su (line with closed circles) and Song parameterizations are shown. The Song parameterization is shown with its original values (the green dotted) for A and B and also for the optimized values (solid red line).

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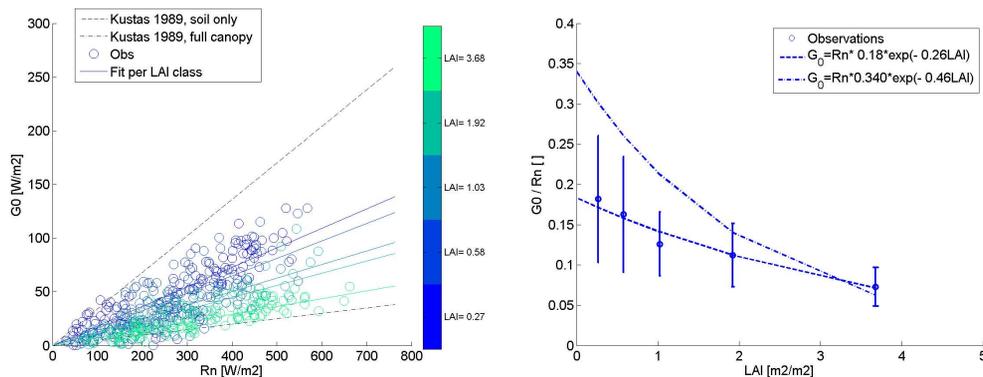
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**Fig. 4.** Comparison between the soil heat flux and the net radiation. In the left panel a scatter plot between the net radiation and the ground heat flux is shown for different LAI classes. In this panel also the theoretical limits by Kustas et al. (1983) are shown. The slopes of the fitted data are shown in the right panel. The errorbars denote the standard deviation of the retrieved  $R_n - G_0$  ratio. In this panel the parameterization of Kustas et al. (1983) with original values and optimized values is also shown.

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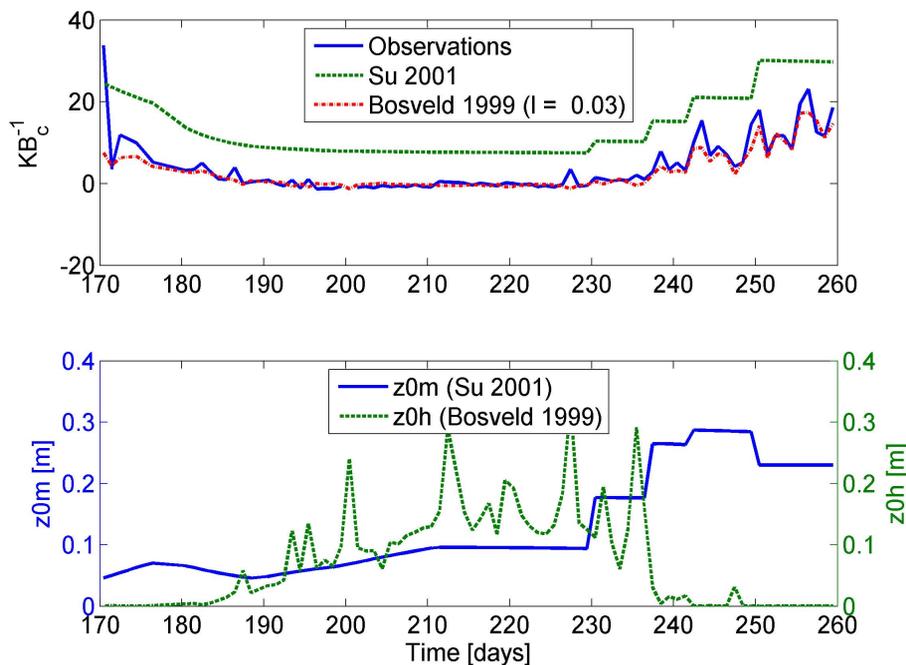
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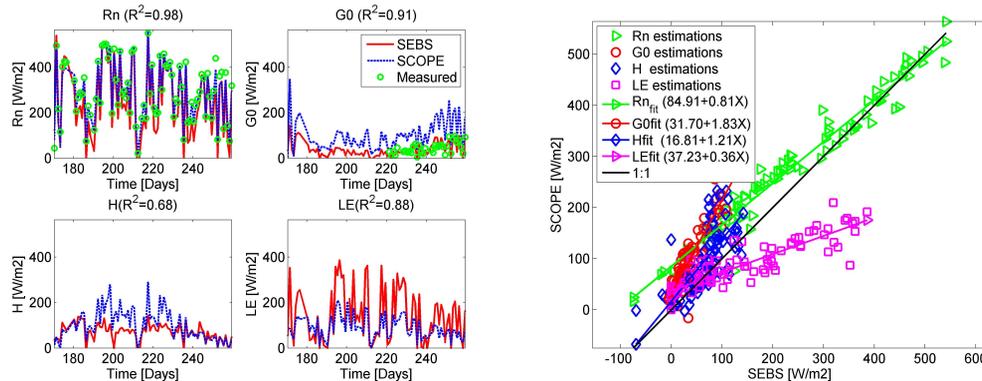
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**Fig. 5.** Top panel: Seasonal variation in the daily  $kB^{-1}$  values for the maize canopy, calculated from observations, the parameterizations from Su (2001) and Bosveld et al. (1999). In the bottom panel the roughness length for heat and momentum is shown for Su (2001) and for the new  $kB^{-1}$  parameterization. The new values of the roughness length for heat, are calculated using the  $kB^{-1}$  parameterization of Bosveld (1999), and the roughness length for momentum by Su (2001).

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**Fig. 6.** Comparison of instantaneous surface heat fluxes predicted by SEBS and SCOPE. In the left panel the diurnal measurements and estimations are shown. There were no measurements of sensible heat and latent heat over the thinned maize field. In the right panel a scatterplot between SEBS and SCOPE estimated heat fluxes is shown. The instantaneous surface heat fluxes from SEBS show a high correlation with the SCOPE estimated surface heat fluxes. SEBS underestimates the sensible heat flux for a fully developed maize canopy (between day 200 and 220).

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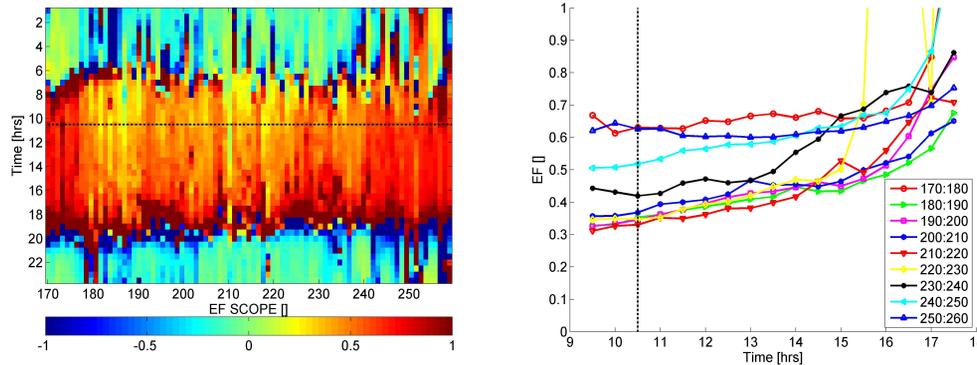
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**Fig. 7.** Diurnal variation of the evaporative fraction during the maize growing season. In the left panel the diurnal evaporative fraction as calculated by the SCOPE model for each separate day is shown. In the right panel the 10-day average of the diurnal evaporative fraction as calculated with SCOPE is shown. The dotted line represents the overpass time of AATSR.

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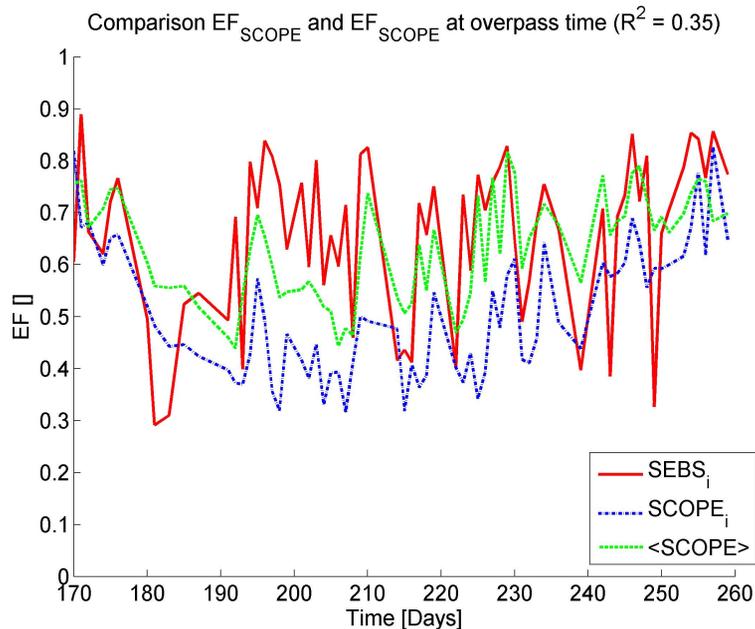
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**Quantifying the uncertainty in estimates**

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**Fig. 8.** Variation in evaporative fraction during the maize growing season. Evaporative fractions at overpass time calculated by SEBS and SCOPE are shown, as well as the daily average values of the evaporative fraction by SCOPE.

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