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Hydrology and Earth System Sciences
Discussions

# *Interactive comment on* "Estimating evapotranspiration with thermal UAV data and two source energy balance models" *by* H. Hoffmann et al.

**H. Hoffmann et al.**

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Thanks for valuable comments and for highlighting the importance of focusing on all components of the surface energy balance.

GENERAL COMMENTS ABOUT SOIL HEAT FLUX

In this study we use two standard models that have been tested and proven valuable in other studies, in order to investigate whether land surface temperatures collected with a UAV are of sufficient quality to give reliable results for surface energy balance components – with special focus on latent heat flux (LE). In our perspective, the study



gives confidence that the DTD model in particular estimate reliable fluxes. Further the models and the spatially high resolution surface temperature-input, reveal patterns in evaporation which could not have been quantified through more established techniques, such as Eddy covariance systems or with use of satellite data.

We are aware that there are shortcomings in the methodology due to spatial variations also in parameters which per se cannot be measured from UAV instrumentation, but view the study as progress towards reliable flux measurements from UAV data.

We do agree with the reviewer that some uncertainty can be associated with the estimation of the soil heat flux (G) and appreciate the comments about the time issue where intermittent cloud cover will have an effect on the measured G values, which is not presently accounted for in the MS. Weather conditions with fast changes in the radiation levels as a consequence of intermittently cloudy condition occur on four occasions during the experiment and therefor are of relevance in present study. We're facing some challenges concerning the design of the experiment on this matter because it does not allow much further interpretation of temporal variability beyond the half hourly time steps that the flux data provides. However, this time-scale issue will be mentioned and discussed in revised MS.

Further, G was measured from two heat flux plates located approximately 3 cm below the soil surface directly under the net radiometer in the plowing layer of the homogeneous sandy loam soil of the barley field. We have no direct measurements that support a spatial interpretation of the variation in the soil heat flux, nor in the net radiation, beyond what the EC tower provides, and for that reason cannot evaluate the uncertainty associated with this.

In the model calculations of LE presented in the MS, G is not used directly from the measurements but parameterised in the two models (see attached G equations). Both models take into account the changing plant cover over the season and for that reason can also account for a changing proportion of radiation conducted to the top soil layers.

G is hence not estimated from a fixed proportion of Rn, which we do agree could have introduced unnecessary errors. Attached Fig.1 shows the proportion of Rn on the barley field that is attributed to heating of the top soil layers, G. The proportion varies over the season as a function of the increasing plant cover, and thus we do agree that a fixed proportion would have led to errors.

In the new version of the MS we've included measured and modelled G (attached Fig. 2) which reveals that the modelled G values are lower than measured, but also that the role of G in the energy budget, and thus in the two models, has limited impact for the estimation of latent heat flux.

ANSWER TO MINOR COMMENTS

Please replace 'evapotranspiration' by 'evaporation' throughout. See, f.e., doi 10.1002/hyp.5563 for why.

Ans: The authors of this MS agree to change 'evapotranspiration' to the more simple and correct 'evaporation'. This study operates with two evaporation sources: Transpiration and evaporation from soil respectively. The term 'evaporation' will be used when evaporated water is regarded as stemming from a single source.

P7470 l27: What is 'explicates'?

Ans: 'explicate' is replaced with 'outline'.

P7473 l 1: Is it not rather tens or hundreds of meters?

Ans: Thermal bands of satellites that are most often described in the academic literature such as Landsat and MODIS have spatial resolutions equal to or lower than 1000 meters. However numerous satellites collect data within the thermal spectra with spatial resolutions above 1000 meters e.g. GOES-R, GOSAT, Seasat, GMS-5, MOS-1, Electro-L. Therefore we write tens to thousands meters.

P7473: So what would you say is the main difference between your UAV/evaporation



work and that of others? Would be good to say that in one sentence or so before line 25.

Ans: The way this work is different from earlier work, described in the introduction, is summed up in line P7473L25 to P7474L6. The authors find that the most exciting and useful frame of this work is the application of UAV platforms into new fields. We will emphasize this by rewriting the sentence before L25 into:

'However, research in possibilities and limitations of UAV platforms is still at an early stage and the present paper introduces the usage of UAV platforms into the fields of heat fluxes and hydrology.'

P7474: Why not put 'Site description' under materials and methods instead of as a single paragraph?

Ans: In the revised MS we merge 'Site'with 'Method' under the heading 'Materials and methods'. This heading also covers paragraphs from the former 'Data description and processing'.

P7475 l15: Reference does not fit reference in reference list. This is just one my eye fell on so please check throughout or use some system that does not allow for such differences.

Ans: The g in Keijman has been deleted and references and reference list has been double-checked to ensure that such mistakes will not occur in revised MS.

P7475: I find the explanation of TSEB a bit long. If you can refer more to literature, that would not be a loss in my opinion.

Ans: The TSEB explanation has been re-structured and re-written, trying to give a better overview with only essential equations. Please see revised MS which will soon be uploaded.

P7478: I find "Data description and processing" a strange heading and it contains a

mix of methods and results. Please redistribute accordingly for it does not help the reader to be going back and forth between the two.

Ans: The former “Data description and processing” paragraph is now covered in the ‘Materials and methods’ paragraph (see answer under P7474). Further the following section has been moved to ‘Results and discussion’:

‘The view zenith angle (Sect. 3.1) of ortho-mosaics was set to 0° for all pixels, hence the largest possible amount of soil was assumed visible. The maximum view zenith angle of the thermal camera is 15° and setting a theoretical view zenith angle to 0° could lead to a small overestimation of latent heat flux. Using a maximum value composition when generating thermal ortho-mosaics may have accommodated any bias due to 0° view zenith angle in models. However, a mean value composition was used because the mosaics produced with this method compared well with mosaics produced manually in which the edges of the images were eliminated due to vignetting effects. Using a mean value composition is thus assumed to enable the usage of entire images without eliminating or correcting vignetting edges and hence allowing a larger coverage and image overlap. The difference between using a mean and a maximum value composition was approx. 0.3° Kelvin and 5 W m-2 evapotranspiration on average for the study site.’

P7480 l 25-29: This paragraph is rather unclear. Please rewrite.

Ans: Section: ‘However, a mean value composition was used because the mosaics produced with this method compared well with mosaics produced manually in which the edges of the images were eliminated due to vignetting effects. Using a mean value composition is thus assumed to enable the usage of entire images without eliminating or correcting vignetting edges and hence allowing a larger coverage and image overlap. The difference between using a mean and a maximum value composition was approx. 0.3° Kelvin and 5 W m-2 evapotranspiration on average for the study site.’

Has been rewritten into:



‘However, a mean value composition was used because the mosaics produced with this method compared well with mosaics produced manually in which the edges of each image were removed. Edges were removed in order to eliminate the vignetting effect which generally affects particularly thermal images and therefor also the images collected in this study. Using a mean value composition is thus assumed to enable the usage of entire images without eliminating or correcting for vignetting effects. Using entire images allow a larger image overlap which is crucial when images are mosaicked in Photoscan. The difference between using a mean and a maximum value composition was approx. 0.3° Kelvin and 5 W m-2 latent heat flux for mosaic from 10 April 2014.’

P7481 l2: ‘value’ and ‘has’ seems more correct.

Ans: Yes, ‘values’ and ‘have’ have been replaced by ‘value’ and ‘has’.

P7481 l18: ‘is’ should be ‘was’

Ans: Yes, done.

P7482 l17: Please include a good reference for EddyPro.

Ans: This paper will serve as reference: Fratini, G. and Mauder, M.: Towards a consistent eddy-covariance processing: an intercomparison of EddyPro and TK3, Atmospheric Meas. Tech., 7(7), 2273–2281, doi:10.5194/amt-7-2273-2014, 2014.

P7482 l28: Unclear sentence, mainly due to the fact that there is no clear agent behind ‘applying’ (dangling modifier).

Ans: The sentence is now:

‘When applying the surface energy balance expression any residual was assigned to latent heat flux, as recommended by Foken et al. (2011).’

P7483 l25: ‘likely to contain’ Ans: The sentence in L25 is now:

‘These areas, likely to contain less healthy plants will have higher LST and produce

lower rates of evapotranspiration.'

P7486: In general, the paper is well written but this page needs some re-writing. There are again these dangling modifiers without agents ibn lines 3 and 12. Lines 20-25 is a good example of a run-on sentence.

Ans: P7486 has been re-written in general. Re-writing of lines 3, 12 and 20-25 is shown below:

'Comparing statistical parameters in this study to the study made by Guzinski et al. (2014) on the same field site with the same models but driven by satellite data, similar results are seen when only Landsat images are used. Guzinski et al. (2014) obtained RMSE values of 46 W m-2 for Rn, 56 W m-2 for H and 66 W m-2 for LE, obtained using TSEB-PT and Landsat data (Table 2, column NDH in Guzinski et al. (2014)) which are comparable to RMSE values of 44 W m-2 for Rn, 59 W m-2 for H and 67 W m-2 for LE, obtained using DTD in this study'

Have been re-written into:

'Guzinski et al. (2014) applied their TSEB-PT study to the same field site as the present study but they used thermal satellite images from Landsat as boundary conditions as oppose to thermal UAV images. A comparison between these two studies shows similar accurate result. Guzinski et al. (2014) achieve RMSEs of 46 W m-2 for Rn, 56 W m-2 for H and 66 W m-2 for LE (Table 2, column NDH in Guzinski et al. (2014)). This study achieves RMSEs of 44 W m-2 for Rn, 59 W m-2 for H and 67 W m-2 for LE, using the DTD model.'

And:

'Also, when comparing results in this study with those computed with the original DTD model (Norman et al., 2000) and several other studies seeking to estimate surface energy balance components from remotely sensed data (Colaizzi et al., 2012; Guzinski et al., 2013; Norman et al., 2000), the results in the present study are in the same order



of agreement.'

Has been re-written into:

'Further, a comparison between this study and other studies seeking to estimate surface fluxes from remotely sensed data (such as Colaizzi et al. (2012); Guzinski et al. (2013); Norman et al. (2000)) show that measured and modelled fluxes are in same order of agreement.'

And:

'The majority of data is retrieved under cloudy or overcast conditions. Data collected during sunny conditions are enclosed by black circles in Fig. 3A-C. Fluxes from sunny, cloudy and overcast days cannot immediately be categorized as being different from one another when looking at Fig. 3A-C. Table 5 shows statistical parameters calculated using only data from days with cloudy or overcast weather conditions. RMSE and MAE are better for both Rn H and LE for both models, except for the MAE and MAE as percentage of measured fluxes for H computed with TSEB-PT which increased to 50 W m-2 from 49 W m-2 and to 78 % from 52 % respectively. r values for Rn are almost alike for data only including cloudy and overcast conditions and data also including sunny condition with values of 0.99 and 0.98 respectively. r is worse for H but better for LE for both models when looking at data that only includes cloudy and overcast conditions, see Table 4 and 5. Statistical parameters presented in Table 5 and the overall good results in the present study compared to above mentioned studies using satellite data (hence data collected in sunny conditions), validate the application of TSEB-PT and DTD models in cloudy and overcast weather conditions.'

Have been re-written into:

'Contrary to studies using satellite images, the majority of data in this study is retrieved under cloudy or overcast conditions. Data collected during sunny conditions are enclosed by black circles in Fig. 3A-C and Table 5 shows statistical parameters calculated

using only data from days with cloudy or overcast weather conditions. Based on Fig. 3A-C and on a comparison between statistical parameters in Table 4 og 5, no significant difference can be seen between data collected during cloudy, overcast and sunny weather conditions. It is thus concluded that the TSEB modelling scheme can be applied to data obtained in all three weather types.'

P7487 l6: Would 'concatenated' not be better than 'generated'?

Ans: Yes, 'concatenated' is used in revised MS.

P7487 l15: Instead of 'Comparing' you could say A comparison. . .reveals that. . .

Ans: The sentence has been rewritten into: 'A comparison between present results and results from other studies estimating surface energy fluxes from heat flux models and remotely sensed LST, reveal that. . .'

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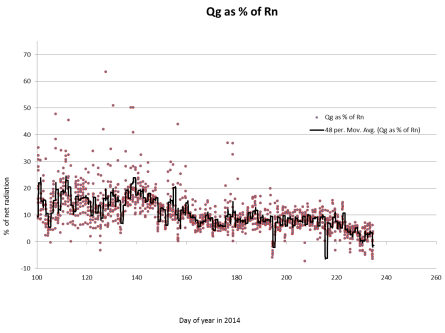


Figure 1 - Measured soil heat flux (Qg/G) as percentage of Net radiation (Rn) during daytime 10 to 16h over the course of the growing season.

**Fig. 1.**

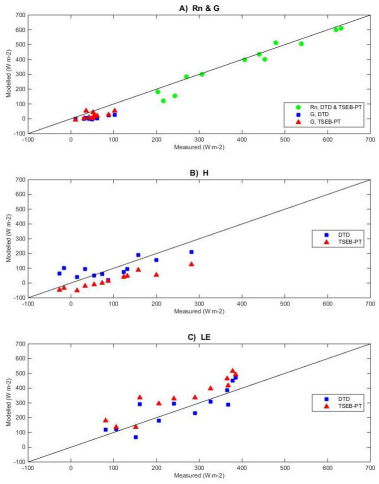


Figure 2 - Modelled vs. measured surface energy fluxes. G values are included in the upper and former Rn graph.

**Fig. 2.**



**Model calculations of G**

**TSEB PT:**
Soil heat flux is computed following Liebethal and Foken (2007):

$G = 0.3R_{n,s} - 35$

where $R_{n,S}$ is net radiation that reaches the soil surface computed as $R_{n,S} = R_n - \Delta R_n$.

$\Delta R_n$-definition:

$$\Delta R_n = R_n\left[1 - \exp\left(\frac{-\kappa F \Omega_0}{\sqrt{2\cos(\theta_s)}}\right)\right]$$

where $R_n$ is net radiation, $\Omega_0$ is the nadir view clumping factor that depends on the ratio of vegetation height to plant crown width which is set to 1.0, $\theta_s$ is the sun zenith angle calculated by model from time of the day, $\kappa$ is an extinction coefficient varying smoothly from 0.45 for LAI more than 2 to 0.8 for LAI less than 2 and F is the total Leaf Area Index (LAI).

**DTD:**
Computations of soil heat flux ($G$) differ between the two models because the difference in radiometric temperature between sunrise and midday observations in DTD can be used as an approximation of the diurnal variation in soil surface temperature. Soil heat flux computations are derived from the soil heat flux model of Santanello and Friedl (2003):

$$G = R_{n,S} A \cos\left(2\pi \frac{t + 10800}{B}\right)$$

where $t$ is time in seconds between the observation time and solar noon, $A = 0.0074\Delta T_R + 0.088$, $B = 1729\Delta T_R + 65013$ and $\Delta T_R$ is an approximation of the diurnal variation in the soil surface temperature from UAV data.

$R_{n,S} = R_n * \exp(-\kappa F \Omega_0)$
where $\kappa$ varies smoothly between 0.45 for LAI more than 2 to 0.8 for LAI less than 2, F is LAI and $\Omega_0$ is the nadir view clumping factor.

**Fig. 3.**