Hydrol. Earth Syst. Sci. Discuss., 12, C3881–C3890, 2015
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12, C3881–C3890, 2015

Interactive Comment

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

H. Hoffmann et al.

helene.hoffmann@ign.ku.dk

Received and published: 28 September 2015

We thank referee#1 for the thorough review and very valuable feedback.

Answer to General comments:

Our main ambition with the present paper has been to show how UAV data can substitute or supplement satellite data in estimation of evapotranspiration. To do that we've flown a UAV during the growing season of 2014 with a thermal camera over a barley field where we also operate an eddy covariance tower, which could act as ground reference for fluxes and radiative parameters obtained by the UAV. As such, we do not have

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detailed verification of the latent heat fluxes (e.g. heterogeneity soil properties) beyond what the changing footprint of the EC tower can provide. We can for that reason not provide ground based verification of differences within the ETa maps. We can only provide plausible explanations for these differences. Plausible explanations involve soil properties applicable to the entire field and irrigation management. The spatial discussion in the revised MS will be expanded by including these aspects as exemplified under 'Specific comments'.

With regard to EC-footprint coverage, these overlapped entirely with UAV data except for a few cases where approx. 3% were lacking. In these cases, the lacking bit was simply obtained from the ETa maps and added in order to reach 100%. This will be stated in the revised MS.

The method section will be re-written to make the model description clearer and specific comments from P5L22-25 to P7L25-27 (regarding the method section) will all be considered.

The authors of the present MS think it is a good idea to publish the MS as a Technical note. However we will let the editor make the final decision regarding this matter.

Answers to Specific comments: The corrections and comments under Specific comments are applied directly to the revised MS if issues are not touched upon in the following.

P3L2-5 & P3L5-6: Check syntax.

Ans: Section (1) has been re-written into section (2): (1) The significant contribution provided by the original TSEB model, is the partition of remotely sensed LST observations into two layers; a soil temperature and a canopy temperature, which enables a partition of heat flux estimations into soil and canopy respectively. The temperature partition allows the model to avoid the need for estimating the so called excess resistance term, which is difficult to derive reliably. As most of the remote sensing

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systems only provide a single radiometric observation, Norman et al. (1995) proposed applying an iterative process to derive the canopy and soil temperature. It is based on an initial guess of canopy transpiration, which was based on the Priestley and Taylor potential evapotranspiration (Priestley and Taylor, 1972). (2) Norman et al. (1995) partitions remotely sensed LST observations into two layers; a soil temperature and a canopy temperature, using a Priestley-Taylor approximation (Priestley and Taylor, 1972). The temperature partition enables a partition of heat flux estimations into soil and canopy heat fluxes. Further, it eliminates the necessity of estimating the 'excess' resistance term, which is empirically determined and difficult to reliably derive. The 'excess' resistance term is used in single-layer models in order to correct for a substitution of directional radiometric temperature in place of the aerodynamic temperature when calculating sensible heat fluxes (Eq. (5), (8) and (9) in Norman et al. (1995)) The Priestley-Taylor approximation partition the divergence of net radiation in the canopy into sensible and latent heat fluxes and an initial guess of canopy transpiration is used to split LST into soil and canopy temperatures.

P3L11: The term "TSEB-PT" is not used throughout the MS

Ans: The TSEB-PT expression is used when this specific algorithm is used. The TSEB expression is used when referring to both the TSED-PT and the DTD model; the two source energy balance modelling scheme. This difference will be clarified in a revised version of the MS.

P3L18-45: Too extensive.

Ans: Line 18-45 is re-written and shortened to: Trying to overcome this issue, Norman et al. (2000) developed the Dual-Temperature-Difference model (DTD), incorporating two temperature observations into the TSEB modelling scheme; one conducted an hour after sunrise and another conducted later the same day when flux estimations are desired. One hour after sunrise, the surface heat fluxes are minimal and observations acquired at this time represent a 'starting point' for the temperatures collected later the

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same day. For agricultural and some hydrological purposes, there is a shortcoming in spatial and temporal resolution of satellite observations (Guzinski et al., 2014). This is especially true in areas prone to overcast weather conditions, such as in northern Europe where present study is conducted, as satellite thermal infrared and visible observations cannot penetrate clouds (Guzinski et al., 2013). Unmanned aerial vehicles (UAVs) (or Remotely Piloted Aircraft System, RPAS, in its most recent terminology) enable a critical improvement for both spatial and temporal resolution of remotely sensed data. UAVs can operate at any specific time of day and year provided that strong wind and rainfall are absent. Therefore, the UAV platform enables data acquisition one hour after sunrise, granting inputs in better accordance with the DTD requirements and due to the relative low flying height, also during overcast conditions (Hunt Jr et al., 2005). When UAV data are combined with the presented models, spatially detailed heat flux maps can be generated and provide insight to different evapotranspiration rates and plant stress at decimeter scale.

P5L6: What is the size of the test area?

Ans: 400x600 m. The size of test area is included in section 2 of revised MS.

P5L6: Please provide information on soil properties.

Ans: The soil profile consists of an upper 0.25 m organic topsoil and course sand from topsoil and downwards. Soil porosity of the upper 1st m range between 0.35 and 0.40 and the available soil water [pF 2.0–4.2, suction pF = log10(suction in centimeters of water)] is 19% (vwater/vsoil) in the upper 0.20 m of the plow layer and only 6% (vwater/vsoil) in the remaining part of the root zone, necessitating frequent irrigation to maintain crop growth during growing seasons. This will be stated in the revised MS.

P5L8: 990 mm precipitation is quite a lot. Why is irrigation needed? Please describe the irrigation management in more detail.

Ans: Because of the soil properties stated above, irrigation is performed consistently

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throughout the growing season. In 2014 (investigated year) irrigation was performed five times: May 23d, May 29th, June 5th, June 15th and June 25th. Approx. 25 mm of water was applied on each occasion. The type of irrigation system is a traveling irrigation gun that rotates. The gun is automatically pulled across the field in tramlines that run in north-south direction, using the same pattern over the season. The irrigation tubing is wound around a steel drum as the gun moves and it has to be moved manually to a new tramline when the distance of one tramline has been traveled. Description of irrigation management will be included in the revised MS.

P5L9: These statements should be more quantitatively described (e.g. in days per year).

Ans: Average wind speed on agricultural site in 2014 was 3.8 m/s and westernly wind occurred 30% of the time. This is included in the revised MS.

Comments P5L22-P7L25-27

Ans: Regarding the model description, section 3 will be re-written in order to give a more thorough review of models and to make relationships between collected data and algorithms more clear.

P9L22: What is the resulting position accuracy after correction?

Ans: Since no ground control points are used, (stated in P10L1-2) an overall position accuracy cannot be calculated. However an error of 0.5 m was attained in experiment with a single ground control point as check point in post-processing of thermal images.

P10L3-4: Figure 2 is not really needed because the ETa maps already show the resolution of the data.

Ans: We agree and figure 2 is not included in new MS.

P10L14-20: For potential users, it would be interesting to know, how much difference the different composition techniques would produce in terms of estimated ETa.

Ans: The difference between using a mean and a maximum value composition technique is approx. 0.3 Kelvin degrees and 5 Wm-2 latent heat flux on average for the study site. This will be included in the revised MS.

P10L29: Please show the respective EC-footprint weights in the ETa maps (e.g. using isolines). Since the ETa maps are covering very different areas, it should be analysed to which degree missing ETa information within the EC-footprints may have influenced the results.

Ans: Even though the shape and placement of the EC-footprints differs for each ETa map, the EC-footprints are within the extent of ETa maps and the cultivated area except in a few cases, see answer under 'General comments'. The ETa maps are the actual results and spatial pattern should stand out clear. Therefore we will map out the 90% footprint with a single line on ETa maps in order to keep spatial evapotranspiration patterns to stand out clear.

P11L9-13: Given the limitations in the model description, it is unclear how most of these data sets find their way into the modelling.

Ans: Because the TSEB-PT and the DTD model are thoroughly described in other papers e.g. Norman et al. (1995) and Guzinski et al. (2014), a detailed description of algorithms seems unnecessary in this paper. However the description of models (section 3) will be re-written and the relationship between parameters and algorithms will be enhanced.

P11L11-12: The values for these parameters used for each ETa estimation should be presented.

Ans: Values not obtained from Guzinski et al. 2014 and values that differ between each model run/ETa map will be listed in revised MS, see table in fig. 1.

P12L22: Shouldn't the patterns be exactly the same, since no further spatial information is added?

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Ans: Yes the patterns are the same, this will be stated more clearly.

P12L22-24: How will this affect the results?

Ans: This will not affect the results or the comparison between ETa maps and measurements from the eddy towers since the EC-footprints are within the final maps and the cultivated area expect a few exceptions, see answer under 'General comments'.

P13L1-4: The effect of tramlines should be presented in more detail. I have difficulty to spot the tramlines in the ETa maps, so please add information in the maps. You could determine differences of ETa rates.

Ans: The mentioning of differences between tramlines and areas with barley should provide a sense of how detailed the maps are. This might be unnecessary and the comparison between tramlines and barley areas will be excluded and instead this section will focus on spatial patterns as a consequence of irrigation systems and soil properties.

P13L7-8: Please provide possible reasons.

Ans: Possible reasons include soil properties (see answer under P5L6) and irrigation management which will be discussed in revised version of the MS.

P13L9: "bodes"?

Ans: We acknowledge the incorrect choice of word and 'bodes well for' will be replaced with 'demonstrates'.

P13L15-17: This is statement is rather trivial.

Ans: Following line will be deleted from revised MS: Accurate computation of net radiation (Rn) is essential in order to satisfactory model sensible and latent heat fluxes.

P13L19-26: As you point out, the R_n estimates include the R_s,in from the EC-station. There you should compare the R_l values, which are purely determined from UAV measurements.

Ans: Yes, comparing R_l values does give valuable insight to the quality of UAV data and a graph showing modelled vs measured R_l will be included and discussed in revised MS.

P13L27-28: This statement is difficult to comprehend. Please reformulate.

Ans: The sentence have been reformulated to: The majority of the surface on 10 April 2014 comprises of soil, which albedo and emissivity varies with water content. If the soil was comparably wetter compared to the time of albedo and emissivity estimations for model input, the LST would be underestimated.

P14L3-8: Here you are comparing Rn not ETa. Rn is determined at the meteorological station with much higher resolution. Thus, you could compare the same measurement periods. The variations in irradiance should be recorded by both systems, so that the average should be similar.

Ans: Yes, the nature of different measurements was confused here. Following sentence will be moved to flux section: LST collected with UAVs are instantaneous but also a mosaic of instantaneous LST collected in a time span of 20 min. Comparing this kind of measurement to a 30 min flux average from the eddy covariance system can lead to substantial disagreement.

P14L10-11: reformulate "steadier trend prediction".

Ans: 'Steadier trend prediction' is replaced by 'a better linear relation'.

P14L1516: This data should be presented.

Ans: We acknowledge that even though G is of little significance, data should be presented. We will include modelled vs measured G data in fig. 3 and discuss results in revised MS.

P16L22: Which kind of calibration, if any, was applied in this study?

Ans: The thermal camera is used with factory calibrations.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 7469, 2015.

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Date	LAI	Canopy height (m)	Green veg. fraction	$Albedo_{soil+veg.}$
10 April 2014	0.48	0.02	1	0.142
22 April 2014	0.88	0.08	1	0.181
15 May 2014	1.49	0.12	1	0.182
22 May 2014	3.90	0.30	1	0.226
18 June 2014	4.03	0.95	0.7	0.181
02 July 2014	3.43	1.10	0.3	0.202
22 July 2014	3.02	1.20	0.02	0.189

Fig. 1.

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