Hydrol. Earth Syst. Sci. Discuss., 12, C6555–C6567, 2016
www.hydrol-earth-syst-sci-discuss.net/12/C6555/2016/

Hydrology and Earth System Sciences
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Discussions

Interactive comment on "Mapping evapotranspiration with high resolution aircraft imagery over vineyards using one and two source modeling schemes" *by* T. Xia et al.

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Received and published: 2 February 2016

Response to Carlos Jimenez (Referee #1)

The paper presents an example of terrestrial evaporation (ET) estimation over 2 vineyard fields by 2 thermal-based methodologies. One is a relatively new and very simple one-source algorithm with a very complex name (DATTUTDUT, I'll shorten it as DAUT hereinafter) that only requires land surface radiometric temperature; the second one is a more established methodology (TSEBS) that requires also multi-spectra imagery at different bands and its algorithm is more complex to apply. The paper is a good contribution to the field of deriving ET at the few meters resolution for agriculture and water

management applications, illustrate our current capability to use thermal imagery to estimate ET over these type of fields, and discuss some of the remaining challenges. The paper is well written with the adequate level of detail, and the work carried out is easy to follow.

Reply: Thank you for your positive comments!

Some general comments about the paper are: (1) It is expected that the more complex algorithm (TSEBS) will out perform the simpler DAUT, so I was wondering about the motivation of this comparison for a large part of the article. The idea that they could be used together in an operational scheme with TSEBS only run when DAUT fails came later in the paper. It should perhaps be presented already in the introduction (and not at the end in the conclusions) to help understanding the motivation of the paper.

Reply: We agree with this comment and include the following text in the introduction on page 6, lines 8-13: "However, more detailed comparisons between simple one-source contextual-based schemes versus more complex two-source models using high resolution imagery over different surfaces are still needed to fully understand the strengths and weaknesses of both modeling schemes. Such intercomparisons can facilitate development of hybrid schemes that leverage the strengths of different methodologies (e.g., Cammalleri et al., 2012), while incorporating simplications for routine application with airborne imagery."

(2) Although the spacecraft multispectral imagery is at sub-meter resolution, most of the data is spatially downgraded to a few meters resolution. This is required to allow TSEBS to operate, but my understanding of DAUT makes me think that it can operate at the sub-meter resolution. It would have been very interesting to have DAUT at sub-meter resolution, aggregate to meter-resolution, and compare with the TSEBS meter-resolution ET estimates. We could think that the one-source models are more adequate to deal with less "complex" pixels (in terms of soil canopy composition), so running DAUT at sub-meter resolution is likely to result in a larger number of "simpler"

pixels (i.e., full canopy or full soil coverage) and a better performance. In the context of precision agriculture applications commented in the introduction that would have been interesting to see.

Reply: We agree with the reviewer that DATTUTDUT can be operated at the sub-meter resolution since in principle its parameterizations are not affected by the spatial resolution. In the original submission, DATTUTDUT was only run with high resolution thermal data in the sensitivity analysis section. In the current version, DATTUTDUT was also applied to the native resolution thermal-IR data and the results are described in the text, as well as in the related tables (Tables 2 and 3) and figures (Fig. 6 and 7). In the text we now include the following (see page 17 line 6-11 "At both instantaneous and daytime time scales, application of DATTUTDUT with the native (finer) pixel resolution thermal imagery yielded comparable (at Site 1) or significantly greater (at Site 2) discrepancies with the tower measurements than using the 5 m pixel resolution data (see Tables 2 and 3). Changes in the agreement with the tower measurements are mainly attributable to the new hot and cold temperature pixels selected by the DATTUTDUT procedure with the finer resolution TR data." Using the finer thermal pixel resolution also had some effect on the spatial patterns/distributions of ET on some of days (see Fig. 9). This observation is included in the text (page 19, line 13-16) "Use of the finer resolution data had generally a minor to moderate effect on the EF and ET distributions except for DOY 163 where the high resolution output indicates a bimodal distribution in EF and ET compared to the unimodal distributions using the 5 m resolution output from DATTUTDAT and TSEB."

(3) Thinking about real applications of these methods, the estimation of daily ET based on the ratio of instantaneous to daytime available energy at the tower seems a bit counterintuitive in the sense that in real life the tower will probably not be there. The ET methodology can still use the EF constant assumption, but it would require an estimation of the available energy not only at the instantaneous step but also integrated over the day. This could be perhaps discussed in the text.

Reply: Discussion referring to the method used to extrapolate instantaneous to daily ET is now included on page 10, line 19-22: "In this study, the observed available energy from the two flux towers during the daytime period for all five days was used to extrapolate instantaneous model estimates to daytime ET totals. However, in practice tower measurements of A would not be available, so results using solar radiation to extrapolate to daytime ET will also be evaluated." We computed daytime ET using solar radiation with the EF expressed as follows: EF = LE_ins/Rsolar_ins = LE_daytime/Rsolar_daytime (R1) and the comparison between two methods were included in the revised manuscript (see Table 4). In Table 4, the MAE values for daytime ET using A versus Sd methods were similar for TSEB, but were larger for DATTUTDUT particularly at site 1 the north vineyard. A discussion of the results in Table 4 is on page 17 line 12-19: "In practice, we will not have observations of available energy, A, from a flux tower for extrapolating the instantaneous ET from a single airborne observation to daytime ET, but instead are more likely to have weather station observations of incoming solar radiation, Sd. Results using Sd for extrapolating model estimates instead of flux tower measurements of A are listed in Table 4. In general, the differences between modeled and measured daytime ET (using RE method) increase, although not significantly for TSEB. On the other hand, discrepancies with the ET measurements for DATTUTDUT at the north vineyard (site 1) increase dramatically due to the large overestimation of instantaneous LE on DOY 162 and 219 (see Fig. 6b)."

(4) The section about water consumption is just a comparison of TSEBS and DAUT field integrated ET with field integrated tower ET assuming that the tower ET fetch is representative of the whole field. It is of interest as it shows the variability that can exist at the field scale and the need of ET methodologies that could capture that variability. I imagine that for other type of crops growing in irrigated fields (i.e., water availability is not an issue) the variation would be smaller and micrometeorological methods still van be of utility. For this concrete example, based on the paper findings the variability seems related to a large extent to changes in LAI across the field. What about water availability, may it play a role here? The vineyards are drip irrigated, does this imply that

water availability is constant through the field and ET response does not reflect water stress? I imagine that in practical applications there can be challenges in separating ET variability caused by water availability or biomass variability, and how this can be used to infer water stress and condition irrigation management.

Reply: Yes, we quite agree with the referee that both water availability and biomass will influence the spatial distribution of ET in field. Since the vineyards are drip irrigated, and the irrigation is replenishing available water in the vine root zone, the vine-rows with higher LAI are likely to have greater amount of root zone water. This suggests that either irrigated water was not evenly distributed across the vineyard and/or soil water holding capacity varied due to soil textural differences. The non-uniform distribution of irrigated water is illustrated in Fig. R1 below where some areas were over-irrigated or the water holding capacity of the soil was exceeded with the excess water causing re-growth of the senescent cover crop planted in the inter-row. This variation in root zone water availability is likely reflected in the spatial distribution in vine LAI. This point is more clearly articulated in the revised manuscript on page 23 line 10-16. : "The climate in this region is quite arid during the growing season with the drip irrigation being the only water source for the vines. As a result, the water availability (or soil water content) condition in the vine root zone plays a crucial role in the vegetation biomass. Therefore it is reasonable to assume there would be a strong correlation between ET and vine LAI as representative of the water availability in the root zone. The spatial variation in vine LAI is likely due to variation in the amount of irrigated water and/or variability in soil water holding capacity."

Figure R1. Example of inter-row cover crop re-growth due to excess irrigated water and/or soil water holding capacity.

Some more specific comments: P11911.L10. I thought DAUT only required thermal images, no shortwave imagery as the downwelling radiation is based on astronomical calculations and the albedo scaled based on the thermal information.

Reply: Yes, the reviewer is correct that only a thermal image is required in the DATTUTDUT model.

P11913.L10. Given the importance of Rn for the ET estimation, it may be good to detail a bit how TSEBS operated here (as it is detailed for DAUT later in the text). My understanding is that it requires the downward SW and LW components (but these inputs are not listed in P11920.L8 as key inputs to TSEBS).

Reply: More details about the calculation of Rn in TSEB is now included (see Eq. (4) and (5) in the revised manuscript). Sd can be from the measurement or calculated using astronomical information, and Ld can be calculated from meteorological data such as Brutsaert's (1975) longwave equation: Ld = 1.24(ea/Ta)ˆ(1/7)σTaˆ4 (R2) where ea is actual water vapor pressure (kPa), Ta is air temperature (K), σ is the Stefan-Boltzmann constant (5.67×10-8 W m-2 K-4). Text is now included to describe how Sd and Ld are computed on page 7 line 8-12: "Sd is either computed using sun-earth astronomical relationships under clear-sky conditions as done by DATTUTDUT (see below) or measured from a nearby weather station, and Ld is either measured or often computed using formulas based on weather station observations of air temperature and vapor pressure (i.e., Brutsaert, 1975)."

P11917.L18. A map of LAI for one of the DOYs discussed my help illustrate the difference between both vineyards, and being useful also for the water consumption discussion later in the paper where ET variability within the field is linked to LAI variability.

Reply: An example of a LAI map for DOY 163 is now provided (see Fig. 4) and illustrates the variation in vine biomass/LAI for the north and south vineyards.

P11920.L1. See previous comment about imposing the scale where TSEBS can operate (few-meters) to DAUT.

Reply: We now run DATTUTDUT using the native (finer) pixel resolution of the thermal imagery as well as aggregated to 5 m used by the TSEB model.

P11920.L17. Ground-based reflectance was not collected for all the flights, but could the existing ground-based data have been used for a local (and possibly more accurate) calibration of the DN values? Was the existing ground-based data limited in terms of sampling the reflectance space? The airborne sub-meter and 30 meter LandSat resolutions are quite different.

Reply: We agree with the referee that using the ground-based data to fit the DN∼reflectance relationship is a better way to obtain the reflectance maps. Unfortunately, the ground-based samples were very limited. The location of the sample sites are shown in Fig. R2 as the yellow stars. There are only a handful of sites where reflectance data were collected with most samples concentrated near the flux tower sites. Therefore it was felt that there was not a wide enough range in sampled reflectance values to provide a reliable conversion equation between DN and surface reflectance.

Figure R2. The location of the ground sampling sites for reflectance data.

P11921.L5. If we consider the 3 bands separately, the agreement to the ground based reflectance does not look that good, especially for the NIR. Any reason for the aircraft NIR being in worse agreement with the ground based NIR (if my impression of the NIR being worst than the others from looking at Figure 2 is correct)?

Reply: The reviewer is correct. The RMSD for NIR, green and red bands are 7.15%, 2.11% and 2.28%, respectively, and the error for NIR is relatively large. It is not known the source for the larger error with the NIR channel, although most likely it may be a drift in the sensor calibration so that the conversion of DN to reflectance was not constant for all flights.

P11922.L10. It may be of interest to give some details about the flux footprint model.

Reply: More details about the two-dimensional flux footprint model are included on page 15 line 14-15 although it is fairly standard, commonly used technique: "This footprint model contains a lateral dispersion formulation to obtain a two-dimensional

weighted source-area of flux from the upwind direction." The citations for this footprint model applied to imagery by Li et al. (2008) and the actual derivation of the model formulations given in Hsieh et al.(2000) provide all the necessary details.

P11923.L1. Wondering if bias and RMSD were similar for the estimates of Ts and Tc.

Reply: In Figure 5 of the revised manuscript the bias and RMSD for Ts and Tc are listed separately in the two plots. The Bias for Ts and Tc are both 0.5 °C, and the RMSD values for Ts and Tc are 2.5 and 2.4 °C, respectively indicating similar difference statistics for both soil and canopy temperature estimates.

P11923.L15. Some percentage figures may be nice to help judging the RMSD (e.g., the fraction of the expected instantaneous fluxes corresponding to the reported RMSD).

Reply: A percentage value is now listed in the text of the revised paper on page 16 line 13-16: "Table 2 clearly shows that the RE closure adjustment method yields better overall agreement between measured and modeled fluxes with the average error computed as the ratio of RMSD and avereage observed flux value of ∼27% for H and LE for the two sites, while the BR method has an error of ∼37%."

P11924.L10. I would argue that the very simplistic determination of the Rn-G in DAUT is also key here, independent of the one-two source differences in how the fluxes are treated and the implications of the contextual scaling approach by DAUT. It would be curious to see how TSEBS and DAUT would score if their radiative inputs were exchanged (i.e., TSEBS using the downward SW and LW from DAUT, and DAUT using TSEBS available energy, if this makes any sense).

Reply: DATTUTDUT was run using Rn and G from TSEB, and the results are shown in Table 5 along with a discussion in the text on page 18 line 21-28: "Using measured Sd from the towers instead of computing from the sun-earth astronomical relationships routinely applied by DATTUTDUT, there is only a minor reduction in the differences with the tower fluxes. An overall improvement in DATTUTDUT estimation of LE is achieved by adopting TSEB estimates of Rn and G (see Table 5). This is particularly true for the north vineyard (site 1). However, even with this better agreement in estimated LE, the discrepancies with observed LE from DATTUTDUT is still larger than with the output of TSEB. This indicates that the errors in available energy using the DATTUTDUT formulations are not the only significant source of error in estimating the LE flux." On average (the average value of Site 1 and 2) MAE and RMSD for LERE are reduced from $\sim$65 and 84 W m-2 to $\sim$52 and 68 W m-2, which are still larger than $\sim$37 and 44 W m-2 from TSEB. Therefore, using Rn and G from TSEB does have some value, however there still other sources of error for DATTUTDUT. Future applications will try to improve the Rn-G algorithm in DATTUTDAT. Both the algorithm for energy and radiative exchange are mentioned as the potential strengths of the TSEB modeling scheme compared with DATTUTDUT on page 17 line 21-24: "It is hypothesized that this likely results from a better physical representation of the energy and radiative exchange within TSEB, since it explicitly considers differences in soil and vegetation radiation and turbulent energy exchange and affects on the radiative temperature source"

P11926.L25. For someone that works in evaluating satellite TR, this 3K bias is a relevant figure. Any ideas about the reasons suspected to be behind this bias? Out of curiosity, how are the ground-based TR measurements collected? TIR cameras?

Reply: As for possible reasons for the TR bias, the flying height for IOP 3 is 480 m above ground (see Table 1) which is higher than the other IOPs. It may be that the higher altitude caused greater atmosphere attenuation of the thermal signal at the sensor altitude. However, the aircraft-based TR was higher than the ground-based TR measured by the Apogee IRTs and CNR1 emitted longwave sensor converted to a TR value.

P11927.L10. This is a nice exercise showing the relatively large sensitivity to the TR errors form thermal methods that depends on the absolute value of TR. I would argue that a more realistic determination of the TR uncertainties from available instruments is needed so this uncertainty can be properly propagated into the ET estimations errors.

Reply: We believe the 3K bias in TR is a fairly large uncertainty and that in the other cases (days with aircraft imagery) the error in TR is smaller based on comaprsions with ground-based TR sensors. However, there is also the added complication of the pixel resolution which can give you a wide range in TR values based on whether the sensor is viewing sunlit or shaded plant canopy or bare soil/cover crop inter-row.

P11928. L4. As discussed in this paragraph, perhaps a slightly more "complicated" but effective way of selecting the end members of the TR distribution could greatly improve DAUT estimates.

Reply: We agree with the reviewer. Modeled flux from DATTUTDUT model is largely dependent on the selection of the end members from the thermal imagery. There have been a number of published procedures to more reliably determine the temperature end members based on land cover considerations and vegetation cover information (such as using NDVI), although Timmermans et al. (2015) did not find more complex end member selection techniques consistently gave better results. However, as noted by Timmermans et al (2015) certain land cover conditions can cause significant errors in the automated end-member selection technique. Possibly adopting a technique similar to the one described by French et al. (2015) would improve reliability of DATTUTDUT flux estimates. This is a project for a future study.

P11931.L14. This section looks to me more just the "Conclusions" (the previous section was already labeled "Results and Discussions").

Reply: The title of this section is modified as "Conclusions" in the revised manuscript.

P11934. I imagine that the UAV technology is targeting the sub-meter resolution. Given the limitation of TSEBS to work beyond the plot/micrometeorological scale, any thoughts about possible candidates to complement DAUT for high precision agriculture (i.e., another thermal based ET methodology able to work at the sub-meter scale, operationally more demanding but able to deal with the cases where DAUT fails to provide decent ET estimates)?

Reply: This is a good question. We are indeed exploring this issue by adapting the TSEB to operate at the sub-meter resolution by developing a module that uses the coarser resolution output of TSEB at∼5 m to define the key inputs to run TSEB in a parallel resistance network mode for plant canopy only pixels and bare soil/substrate only pixels. This will be the basis of a future paper on this topic.

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/12/C6555/2016/hessd-12-C6555-2016-supplement.pdf

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 11905, 2015.

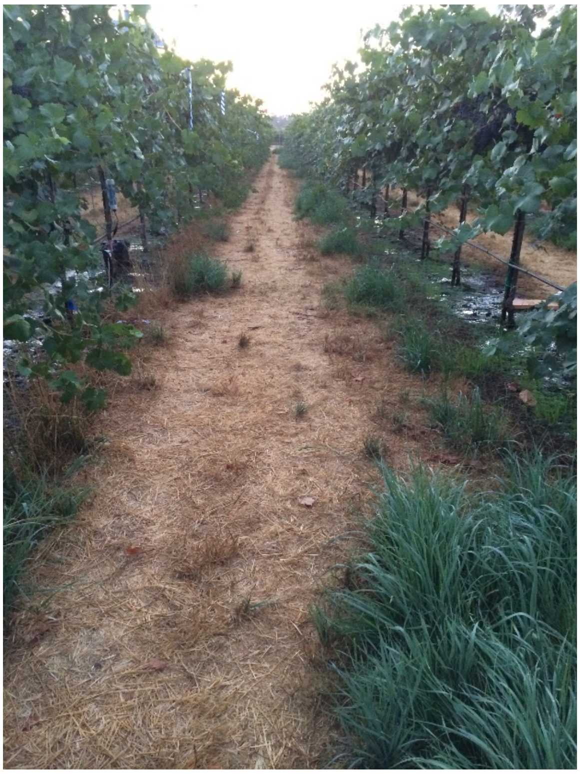

Fig. 1. FigureR1_InterRowExample

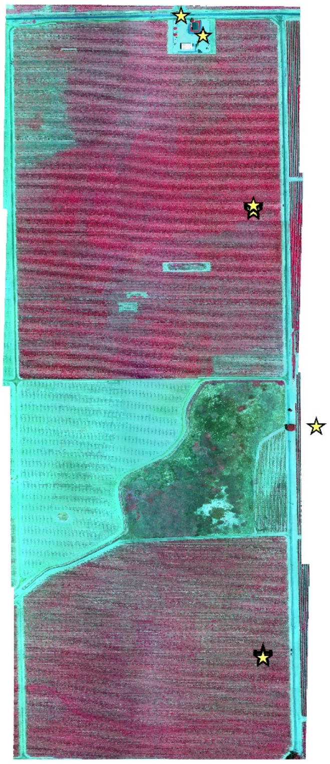

Fig. 2. FigureR2_CropScanLocation