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Interactive comment on "Predicting evapotranspiration from drone-based thermography – a method comparison in a tropical oil palm plantation" *by* Florian Ellsäßer et al.

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General comments The manuscript by Ellsasser et al. makes an interesting and useful contribution to the burgeoning literature on using UAVs to measure ecosystem properties and processes, in this case measurements of surface temperature for use in models of the surface energy balance to predict spatial variations in the latent heat flux and for comparison to eddy covariance-derived estimates of the same.

Dear Reviewer,

Thank you for taking the time to revise our manuscript. We welcome your comments and believe that they helped to improve our manuscript considerably. Please find our point-by point replies below.

Sincerely,
Florian Ellsäßer

The appendix describing the various energy balance/ET models should be better integrated with the main body of the manuscript, and as noted below some of the model equations need more clarification. In general, a reader should not have to read other previous papers to understand the approaches tested here (e.g., see my comments below regarding lines 174-175).

As suggested by the reviewer we will integrate the key information from the appendix into the main body of the manuscript starting from line 158:

2.3 Energy balance models

LSTs are recorded as 'snapshots' representing an instantaneous state of surface temperatures. Soil-Vegetation-Atmosphere Transfer models use these instantaneous observations of LST to solve the energy balance equation and estimate instantaneous fluxes. In our study the one-source energy balance model DATTUTDUT (Timmermans et al., 2015) and two two-source energy balance models, TSEB-PT (Norman et al., 1995) and DTD (Norman et al., 2000), were applied. For the TSEB-PT and DTD model directional radiometric temperatures are used and no calculation of aerodynamic temperature by using an excess resistance term is needed (Hoffmann et al., 2016). The proximity of the thermal camera to the surface is much closer compared to other *typical carriers (such as satellites or planes) and hence atmospheric effects are supposed to be largely reduced. To use a uniform input for all the applied models, we used directional radiometric temperature recordings from the drone as input without applying further corrections. All models in this study use instantaneous land surface temperatures (LST) to solve the energy balance equation:*

$$Rn = G + H + LE \tag{1}$$

Where Rn is the net radiation, G is the ground heat flux and the turbulent fluxes H and LE represent sensible and latent heat flux, respectively. Rn is estimated by calculating the budget of incoming (↓) and outgoing (↑) long- (l) and short-wave (s) radiation:

$$Rn = R_s^{\downarrow} + R_s^{\uparrow} + R_l^{\uparrow} + R_l^{\downarrow} = (1-\alpha) * R_s^{\downarrow} + \varepsilon_{surf} * \varepsilon_{atm} * \sigma * T_{air}^4 - \varepsilon_{surf} * \sigma * T(\theta)_{surf}^4 \tag{2}$$

*Where the short-wave component is calculated by multiplying incoming shortwave radiation Rs↓ [W m^{-2}] with its absorption ratio deducted from the combined soil and vegetation albedo α. The long-wave radiation budget is calculated from surface (soil and vegetation) emissivity ε_{surf} and atmospheric emissivity ε_{atm}, the Stefan-Boltzmann constant σ (5.6704*10^{-8} W m^{-2}*K^{-4}), air temperature T_{air} and radiometric land surface temperature $T(\theta)_{surf}$ (both in K).*

2.3.3 DATTUTDUT

Key input for the DATTUTDUT model is a LST map from where the hottest and the 0.5% quantile of coldest pixels are extracted, assuming that hot pixels are a result of very little to no evapotranspiration and cold pixels origin in a high evapotranspiration rate

(Timmermans et al., 2015). Fully modeled Rn is calculated based on down-welling short-wave radiation estimates calculated using sun-earth geometry to solve eq. 2. Surface albedo P0 is calculated as in Timmermans et al. (2015) based on the assumption that dense vegetation appears colder than rocks or soil in the thermal imagery (Brutsaert, 1982; Garratt, 1992):

$$P_0 = 0.05 + ((T_0 - T_{min})/(T_{max} - T_{min})) * 0.2 \tag{3}$$

Down-welling shortwave radiation $R_s\downarrow$ is calculated from the dimensionless atmospheric transmissivity τ and the exo-atmospheric shortwave radiation SWexo = 1360 W m^{-2} (Timmermans et al., 2015). Transmissivity τ is calculated as described in Burridge and Gadd (1977) using the solar elevation angle α that was determined from the geographic position of our site and the coordinated universal time (UTC) of the measurements:

$$\tau = 0.6 + 0.2 * sin(\alpha) \tag{4}$$

$$R_s \downarrow = \tau * SW_{exo} \tag{5}$$

Timmermans et al. (2015) suggest using a constant value of 0.7 for τ and 0.8 atmospheric emissivity (ε_{atm}), but as our flight times range from 09:00 to 16:30 h local time we decided to include the solar elevation angle as in eq. 4. Further, we used a constant surface emissivity (ε_{surf}) of 0.98 and not 1.0 as in the original formulation of the DATTUTDUT model. Since the DATTUTDUT model is a one-source energy balance model we used a uniform surface emissivity of 0.98 as recommended for vegetation dominated areas (Jones and Vaughan, 2010). Air temperature T_{air} was calculated as the 0.5% quantile of the coldest pixels in the image.

As the original DATTUTDUT formulation doesn't account for cloud cover, eq. 5 is replaced by measured short-wave irradiance as in Brenner et al. (2018) for model runs with Rn_sw. For model runs with Rn_mes eq. 2 was replaced by Rn measurements recorded at the EC-tower.

The sum of the turbulent fluxes is calculated by subtracting G from Rn. The result is fractioned into its components H and LE, using the evaporative fraction (EF) (Timmermans et al., 2015):

$$EF = LE/(LE + H) = LE/(Rn - G) = (T_{max} - T(\theta)_{surf})/(T_{max} - T_{min}) \quad (6)$$

Provided with an easy-to-use graphical user interface, a version of the DATTUTDUT model was implemented recently as a QGIS 3 plugin (QWaterModel) (Ellsäßer et al., 2020).

TSEB-PT

TSEB-PT calculates surface-energy budgets from the recorded LSTs splitting observations into a canopy and a soil fraction (Norman et al., 1995; Song et al., 2016; Xia et al., 2016). The model consists of two parts: First an initialization part where all parameters that do not depend on soil and canopy temperature partition and knowledge of atmospheric stability are computed. Afterwards an iterative part where the Monin-Obukhov length is stabilized and the fluxes are finally derived. To begin this process vegetation cover $f_c(\theta)$ is computed as in Campbell and Norman, (1998):

$$f_c(\theta) = 1 - exp((-0.5\Omega(\theta) * LAI)/(cos(\theta))) \quad (7)$$

where LAI is leaf area index, θ is the sun zenith angle and Ω is a nadir view clumping

factor to represent the cross-row structure in which the oil palm is planted (Kustas and Norman, 1999). Guzinski et al., (2014) suggest a maximum limit of 0.95 for $f_c(\theta)$, so that a small fraction of the soil is still visible and extreme magnitudes for soil temperature are avoided. Roughness parameters are calculated from vegetation height. Tair was measured at the EC-tower, T(θ)surf was recorded with the drone both similar to descriptions in Hoffmann et al. (2016). Calculation of aerodynamic temperature by using an excess resistance term is not needed, since TSEB-PT uses directional radiometric temperature as input (Hoffmann et al., 2016). For the two-source energy balance models we used a canopy emissivity of 0.98 and soil emissivity of 0.95. The emissivity values are based on averages for the 8-14 μm taken from Jones and Vaughan, (2010). The TSEB-PT model requires additional in situ meteorological measurements of long- and short-wave radiation, wind speed, barometric pressure and relative humidity, which in our case were recorded at the EC tower. Further, measured data on LAI as well as surface and canopy albedo are required. The three resistances in the soil-canopy-atmosphere heat flux network, the aerodynamic resistance to heat transport (R_A), the resistance to heat transport from the soil surface (R_S) and the total boundary layer resistance of the leaf canopy (R_X) are calculated as in Norman et al. (2000, 1995). Net radiation and the three resistances remain constant during the model runs. After finishing the computation of all constant parameters, the iterative part of the model starts assuming Monin-Obukhov length tends to infinity. In the first iteration Rn is partitioned into a soil and canopy fraction by calculating net radiation divergence ΔRn (Hoffmann et al., 2016; Norman et al., 2000):

$$\Delta Rn = Rn * (1 - exp((-K * LAI * \Omega_0)/\sqrt{((2cos(\theta_s)))}) \quad (8)$$

where K is an extinction coefficient that varies according to LAI (Hoffmann et al., 2016). We are aware of the fact, that the determination of K using LAI is disputed as other studies found no significant correlation of K and LAI (Zhang et al., 2014). With ΔRn *known, sensible heat flux is then estimated using the Priestley-Taylor approximation:*

$$H_c = \Delta Rn * (1 - \alpha_{PT} * f_G * (D/(D+\gamma)) \quad (9)$$

αPT is the Priestley-Taylor coefficient and both γ the psychrometric constant and the slope of the saturation pressure curve D were calculated as in Allen et al. (1998). Canopy temperature T_C was computed by summing up the results of the linear approximation in equation (A7) for $T_{C,lin}$ and ΔT_C from equation (A11) both from Norman et al. (1995). Knowing canopy temperature T_C and fraction of view covered by vegetation fθ as in Hoffmann et al. (2016), soil temperature T_S can be calculated:

$$T_s = (T(\theta)R^4 - f_\theta * T_C^4)/(1 - f_\theta)^{(1/4)} \quad (10)$$

With soil and canopy temperatures and the resistances of the soil-canopy-atmosphere heat flux network known, fluxes can be calculated with equations (9), (10), (11) and (13) from Hoffmann et al. (2016). Total latent and sensible heat fluxes are calculated as the sums of canopy and soil fluxes. In the following iterations, a recalculation of Monin-Obukhov length takes place until a stable value is reached and the resulting fluxes are derived. For the model runs with Rn_mod and Rn_mes the model net radiation is forced accordingly.

DTD

The Dual-Temperature-Difference (DTD) model works very similar to TSEB-PT and differs mainly in the way how sensible heat flux is calculated (Hoffmann et al., 2016). In the DTD model, the absolute temperatures of land surface and air (as used in the TSEB-PT) are supplemented with a second set of early morning reference measurements of LST and air temperature, thus creating a dual-temperature difference

(Norman et al., 2000). The first observation is recorded in the early morning hours and the second observation is recorded later on the same day at any given time. We used two IRTs attached to the EC tower (see EC methodology for details and Sect. 2.7 for the limitations) for the necessary early morning reference readings of absolute temperature and used the averaged LSTs to create a uniform map as input for the DTD model (similar as e.g. in Hoffmann et al., 2016). This relates measurements at any time during the day to measurements recorded in the morning, when fluxes are assumed to be minimal, and thereby accounts for measurement biases of LST (Anderson et al., 1997; Hoffmann et al., 2016). H flux is then calculated using the time-differential temperature and a series resistance network as it is recommended for densely vegetated regions to consider interaction of soil and canopy fluxes (Guzinski et al., 2014; Li et al., 2005). A detailed description of the model can be found in Guzinski et al. (2014) and Norman et al. (2000).

Calculation of evapotranspirated amount of water:

The actual amount of evapotranspirated water (ET_w) in mm h^{-1} was calculated as in Timmermans et al. (2015):

$$ET_w = ((LE * t)/1000000)/(2.501 - 0.002361 * (T_{air} - 273.15)) \quad (11)$$

Where LE is the latent heat flux in W m^{-2}, t is the respective timespan in seconds and T_{air} is the air temperature in Kelvin.

I agree with the other reviewer that more discussion of the various uncertainties in EC-derived ET need to be discussed. While it is the reference method here it is also subject to many uncertainties.

As addressed in the reply for reviewer one, we will add the following information regarding uncertainties of the reference EC method:

Methods section:

EC data processing and quality checks were performed following the methodology described in Meijide et al., (2017). Following Mauder and Foken, (2006), flux estimates during low turbulence and thus stable atmospheric conditions were removed from the analysis; however, low turbulence mainly occurred during night hours and was not observed during the daytime drone flights. Generally, the EC method is associated with uncertainties of 5 - 20% (Foken, 2008), mainly due to problems with energy balance closure (Wang et al. 2012). Further limitations are the high costs and quite specific requirements regarding size and terrain of the study site.

Statistics section:

Both methods, the reference EC technique and the drone-based estimates, are associated with a certain degree of uncertainty. To account for the uncertainty in both, a model II Deming regression (Deming, 1964) was applied for the analysis.

The writing is generally fine but there are a few very awkward sentences that I suggest re-writing (see below).

We thank the reviewer for taking the time to point out the need for rewording these sentences. We revised them accordingly.

Specific comments

Lines 90-91: “the hottest and a group of coldest pixels in the image” – This is not and independent clause as it is missing a verb

We will adjust the sentence accordingly:

In the one-source energy balance model DATTUTDUT (Deriving Atmosphere Turbulent Transport Useful To Dummies Using Temperature) (Timmermans et al., 2015) fluxes are estimated by relating single pixel temperatures to local temperature extremes.

Lines 105-107: This sentence is confusing and needs to be re-written.

We will adjust the sentence accordingly:

Model II method comparisons require a sample size of at least n=60 data pairs (Legendre and Legendre, 2003), which constrained previous studies with smaller sample sizes to using error terms and correlation coefficients instead of a full method comparison.

Line 110: replace “presented” with “current”

We will adjust the sentence accordingly:

The current study was conducted in the lowlands of Jambi province (Sumatra, Indone-

sia) where over the last decades, large areas of rainforest have been converted to rubber and oil palm plantations (Clough et al., 2016; Margono et al., 2012).

Line 147: Quote the manufacturer's measurement uncertainty here, as you also discuss it later when mentioning thermal cameras. The true uncertainty is surely closer to 1-2 K for cameras like this.

As suggested by the reviewer, we will add more differentiated information on relative and absolute thermal accuracy to this section:

The sensor covers spectral bands ranging from 7.5 to 13.5 μm with a relative thermal accuracy of 0.04 K and an absolute thermal accuracy of $\pm$2K (FLIR Systems, USA).

Line 164: Provide the assumed surface emissivities used in each model and component

As suggested, we will add a sentence on assumed surface emissivities to the Methods:

Since the DATTUTDUT model is a one-source energy balance model we used a uniform surface emissivity of 0.98 as recommended for vegetation dominated areas (Jones and Vaughan, 2010). For the two-source energy balance models we used a canopy emissivity of 0.98 and soil emissivity of 0.95. The emissivity values are based on averages for the 8-14 μm taken from Jones and Vaughan, (2010).

Lines 174-175: Need to better explain this approach. P-T is usually used to predict LH fluxes not SH fluxes.

For the application of the TSEB-PT model we follow the workflow provided in Hoffmann et al., (2016). There, it is described in detail how the Priestley-Taylor (PT) approximation is used to calculate the canopy sensible heat flux from net radiation divergence estimates. This is now pointed out more clearly in the Methods of our manuscript:

With ΔRn known, sensible heat flux is then estimated using the Priestley-Taylor approximation.

Lines 196-207: Do these models assume a closed energy balance? If so how does that affect your estimates?

As mentioned in the Methods section, all models assume energy balance closure; in accordance with the reference EC method, we applied the Bowen Ratio method for energy balance closure:

Line 228-230:

As the applied drone-based models all assume full energy balance closure, we used the Bowen ratio closure method (Pan et al., 2017; Twine et al., 2000) to compute full closure for the EC measurements. The Bowen ratio method was found to produce the most congruent results in conjunction with drone-based latent heat flux estimates (Brenner et al., 2017) and was therefore applied in this study.

Line 219: Was this an aspirated measurement of Tair?

We appreciate this insightful question by the reviewer. We originally used the Tair measurements at 22m on the EC tower but, inspired by the reviewer's comment, have re-run all models with the temperature measurements at 16.3 m (i.e. ~2m above the canopy). However, the absolute average temperature difference between the two measurement heights is below 0.24 °C.

We have adjusted the following sentence in the methods section:

Air temperature and relative humidity were measured with thermohygrometers (type 1.1025.55.000, Thies Clima, Göttingen, Germany) at 16.3 m height. We re-ran the models with the temperature measurements at 16.3 m. We further received an email with recommendations on how to improve the model performance (e.g. vegetation parameters) of the two-source energy balance models and started implementing these in the models. The revised manuscript will also include the fully revised model results. The pre-results are saved in the supplementary material.

Line 222: These are IRTs not thermal cameras, so you do not know exactly which canopy elements you are measuring! Were they capturing only leaves all of the time? Also, what surface emissivity was assumed for these measurements of surface temperature? Did you correct for the influences of reflected longwave radiation, relative humidity, distance to object, etc? And what are measurement uncertainties of the IRTs?

We thank the reviewer for this valuable comment. To avoid confusion, we now consistently apply the term IRT throughout the manuscript. We will further add more detail on the issues raised by the reviewer to the Methods:

The two IRTs used in our study (IR100 Radiometer, Campbell Scientific Inc., Logan, USA) have a field-of-view (FOV) of 8-10°. Considering the distance from their fixed location on the tower to the average height of the oil palm canopy, they cover a circular area of 2.2 m^2, over which they average the received thermal signal. The recorded canopy area comprises different functional parts of the canopy (e.g. leaflets, petioles). On average, we assumed a surface emissivity of 0.98 for the canopy area (Jones and Vaughan, 2010). We did not correct the values recorded with the IRTs for any other influences; the distance from the canopy surface to the sensors was only about 10-12m.

Line 229: Describe the Bowen ratio closure method in more detail.

As suggested by the reviewer, we will add more detail about the Bowen ratio closure method to the Methods:

The energy balance closure (EBC) of the reference EC measurements was 0.77 (r^2 = 0.87), which is in line with EBC reported for other tall vegetation canopies (Stoy et al., 2013). Since the used energy balance models assume full EBC, we applied the so-called Bowen ratio closure method to the EC data (Pan et al., 2017). The method assumes that wind measurements miss some of the total covariance and dispersive fluxes. Therefore, underestimations of LE and H are carried over proportionally because of similarity among fluxes (Twine et al., 2000). The Bowen ratio closure method proportionally assigns the underestimated turbulent energy to LE and H fluxes to reach full EBC.

Line 247: “systematic”

We will adjust the sentence accordingly:

Statistics such as r^2 have their limitations in method comparison since they are designed to indicate how well the resulting model of the regression describes the outcome and are not necessarily a good measure for systematic bias between methods.

Line 273: I think you mean "alive"

We will adjust the sentence accordingly:

The plantation is very well managed, so that all oil palm canopies are alive, no oil palms have died and only dry leaves are removed.

Lines 278-286: As noted above these measurements were not made with thermal camera but with IRTs. Please update.

As mentioned above we will now consistently apply the term IRTs throughout the manuscript.

Line 280: Is the 122 number based on 2 maps/flight?

Yes. We re-worded the sentence to point this out more clearly:

To check whether the two IRTs measure similar temperatures compared to drone

recorded LSTs, we extracted a total of 122 'IRT-sized' (i.e. ~2.2 m^2) LST footprints from the drone-recorded maps and plotted the measured and adjusted temperatures of both recording systems against each other (Fig. A1).

Line 293-294: Is this peak SW measured during the flight or average SW?

We applied 10 min averages of all SW data that were recorded during a respective flight. We will add this information to the methods section:

The measured solar-irradiance was recorded as 10 min averages of short-wave irradiance.

Line 295: By "canopy air temperature" do you mean the Tair measured at 22m?

We thank the reviewer for this valuable question. As already mentioned in a previous reply, we originally used Tair as measured at 22m on the EC tower, but now have re-run all models using Tair measured at 16.3m (i.e. ~ 2m above the canopy).

We have adjusted the following sentence in the methods section:

Air temperature and relative humidity were measured with thermohygrometers (type 1.1025.55.000, Thies Clima, Göttingen, Germany) at 16.3 m height.

Line 302-303: This is an awkward sentence – rewrite.

As suggested, we re-wrote the sentence:

Congruence of LE estimates with reference EC measurements differed among the three applied models and was further affected by the configuration of the Rn assessment (Fig. A3).

Line 303: The first time you cite Fig. A3 you need to discuss why modeled Rnet is so poor.

As suggested by the reviewer we will add a sentence discussing the poor performance when applying modelled Rnet:

The assumptions for Rn_mod were not always met as cloud cover was present during several flights (Table A1); consequently, the corresponding net radiation estimates were too high, leading to a substantial overestimation of latent heat fluxes.

Line 304: Replace “congruence” with “agreement” or “fidelity”

We will adjust the sentence accordingly:

Generally, error metrics were reduced and agreement was increased the more measurement-controlled the Rn determination process was.

Line 307-308: Perhaps this poor agreement in morning and late afternoon is not surprising since the dATTUDUT method is based on modeled Rnet..?

We thank the reviewer for this insightful comment. We will add a section to the manuscript that addresses both this comment and the following comment (please refer to the following answer).

Line 308-309: It’s worth breaking out the description of the performance of the TSEBPT estimates into a separate sentence. Are these estimates uniformly higher than the EC estimates or only during part of the day?

We thank the reviewer for this insightful comment. We will add a section to the manuscript that addresses both this comment and the previous comment:

DATTUTDUT LE estimates closely agreed with EC measurements around noon, but were higher in the morning and afternoon hours, which is caused by overestimations of Rn from the Rn_mod method. LE estimates from TSEB-PT were consistently higher than EC measurements, with particularly large divergences around noon (Fig. 2a).

Lines 335-336: Seems like this sentence is missing a word or two.

We adjusted the sentence accordingly:

The TSEB-PT model in Rn_mes configuration also showed no significant continuous errors but was subject to proportional bias (Fig. 4c). The TSEB-PT overestimated LE particularly around noon, when fluxes are very high (Fig. 2c and 3c).

Line 352: I’m unclear what you mean about the X-level for the bias in EC reference fluxes.

The bias of two applied methods can be expressed in an X- and a Y-level, bias on X-axis (horizontal) and bias on Y-axis (vertical) respectively. We were particularly interested in the bias of the new drone-based methods based on the EC technique (here: X-level).

Lines 405-406: Are you referring to the slope in this sentence?

We agree with the reviewer that the wording was previously unprecise and adjusted the sentence accordingly:

An opposite situation was found for the DTD model where the confidence intervals for the slope indicated no proportional errors, but the intercept revealed a continuous error for the analytical method.

Lines 455-457: Well before this discussion of errors you should define what you mean by proportional versus continuous errors.

Following the suggestion by the reviewer, we will add the following information to the Methods section:

If the confidence intervals for the intercept of the Deming regression include zero, there is no constant or continuous error between the two methods. If the confidence intervals for the intercept do not include zero, both methods differ by a constant amount, i.e. the new method has a continuous error compared to the reference method. In contrast, the confidence intervals of the slope of the Deming regression indicate whether there

is a proportional error between the methods, which increases proportionally with the magnitude of the predicted value.

Line 500: Replace “results in” with “predict”

We will adjust the sentence accordingly:

In the histograms of LE fluxes from all pixels within the single studied footprints (Fig. 6), the DATTUTDUT and DTD models predict a bell-shaped normal distribution but very different value ranges.

Line 503: eliminate comma after “both”

We will adjust the sentence accordingly:

Mean and median are very similar indicating close to zero skewness for both the DATTUTDUT and DTD model.

Line 520: Which edge? Computer or edge of study area?

We adjusted the sentence for further clarification:

Autonomous acquisition of LSTs over EC stations and the surrounding areas can be supplemented by on-board and ground sensors. Energy-balance models can then potentially be calculated using edge computing schemes on-board the drone to enable *a dense temporal resolution of LST, flux and ET maps in almost real-time.*

Line 542: Replace "cameras" with "IRTs"

As mentioned above, we will now consistently apply the term IRTs throughout the manuscript.

Line 565: How are the surface epsilon (emissivity) terms estimated? Do they vary spatially across the image?

We thank the reviewer for this insightful comment, and have expanded the according method section to clarify the issues raised by the reviewer. As already mentioned above, we will add this information to the methods part of the manuscript.

Since the DATTUTDUT model is a one-source energy balance model we used a uniform surface emissivity of 0.98 as recommended for vegetation dominated areas (Jones and Vaughan, 2010). For the two-source energy balance models we used a canopy emissivity of 0.98 and soil emissivity of 0.95. The emissivity values are based on averages for the 8-14 μm taken from Jones and Vaughan, (2010).

Lines 579-580: Show the equations for calculating radiometric LSTs.

Since we used a radiometric thermal camera we did not have to calculate the radiometric LSTs from a greyscale picture (as e.g. in Cohen et al., 2005); there thus is no equation. The energy-balance models in our study use the directional radiometric temperature that was recorded with the thermal camera on the drone. A further

substitution of temperatures or correction procedures (e.g. excess resistance) is not necessary (Hoffmann et al., 2016). We will add a sentence to the Methods to point this out more clearly:

For the TSEB-PT and DTD model directional radiometric temperatures are used and no calculation of aerodynamic temperature by using an excess resistance term is needed (Hoffmann et al., 2016). The proximity of the thermal camera to the surface is much closer compared to other typical carriers (such as satellites or planes) and hence atmospheric effects are supposed to be largely reduced. To use a uniform input for all the applied models, we used directional radiometric temperature recordings from the drone as input without applying further corrections.

Line 588: I assume this (Po) is a shortwave albedo?

Correct, Po is the short-wave surface albedo. It was taken from Timmermans et al., (2015). We added a sentence to the Methods to clarify this:

Surface albedo P0 is calculated as in Timmermans et al. (2015) based on the assumption that dense vegetation appears colder than rocks or soil in the thermal imagery (Brutsaert, 1982; Garratt, 1992).

Line 600: This model assumes cloud-free conditions (with a constant transmissivity)?

Yes, in its original formulation the DATTUTDUT model assumes cloud free conditions (Timmermans et al., 2015). For simplicity Timmermans et al. (2015) suggest using a constant value of 0.7 for the transmissivity or to follow a simple parameterization scheme for instantaneous shortwave atmospheric transmissivity following the description in Burridge and Gadd, (1977). We chose the second option and calculated short-wave transmissivity using the solar elevation angle. We added a sentence to the Methods to point this out more clearly:

Transmissivity τ is calculated as described in Burridge and Gadd, (1977) using the solar elevation angle α that was determined from the geographic position of our site and the coordinated universal time (UTC) of the measurements.

Line 605: Is that supposed to be an epsilon symbol as in equation 2?

Yes, this is supposed to be a ϵatm. We have adapted the manuscript accordingly:

Timmermans et al. (2015) suggest using a constant value of 0.7 for τ and 0.8 atmospheric emissivity (ϵatm), but as our flight times range from 09:00 to 16:30 h local time we decided to include the solar elevation angle as in eq. 5.

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