Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2018-310-AC3, 2018

Hydrology and Earth System Sciences Discussions
Open Access

Interactive comment on "Understanding model biases in the diurnal cycle of evapotranspiration: a case study in Luxembourg" *by* Maik Renner et al.

Maik Renner et al.

mrenner@bgc-jena.mpg.de

Received and published: 24 September 2018

The second reviewer raised three major aspects (model input, shortwave vs. net radiation, novelty). We already replied to these aspects in a separate author reply (https://doi.org/10.5194/hess-2018-310-AC1) in order to follow up within the open interactive discussion. Unfortunately, the reviewer did not reply to that during the interactive discussion. Our key arguments are presented in the mentioned author reply. In this author reply we will respond to all comments step by step and report how we intend to improve our manuscript to take the comments of the reviewer into account.

We repeat each reviewer comment in bold font, followed by our reply. Changes in the text of the main manuscript are highlighted in blue color.

Printer-friendly version

Discussion paper

Reviewer 2: "The author's objectives of the study were to use measurements of hourly incoming shortwave radiation as an independent forcing of the land-atmosphere exchange and assess the response and phase lags of surface heat fluxes. The authors argue that models of ET should be able to capture the magnitude of hysteretic loops under differ- ent conditions."

Reply: We agree with this summary of the manuscript.

Reviewer 2: "The writing is good, and the article is well structured. The major concern I have is that incoming solar radiation (Rsd) is used rather than the available energy (Rn-G). It is expected that phase lags would occur between Rsd and LE since much energy is stored in the ground surface during the day and then released at night, so it is unclear what the novel aspects of the paper really are. All the results are fairly straightforward, but again, they are to be expected based on the study design of using Rsd instead of Rn-G.
Additionally, descriptions of what was assumed or used as input to the models, (specifically the PT and FAO-56 PM equations) is not adequate, only Rn is in the PT equation listed, not Rn-G as stated in the original equation, so there could be an error in the analysis. It is unclear if measured G was used in the FAO-56 PM equation, or if it was estimated, and same goes for Rn. Based on the lack of clarity as to what Rn and G model was used in the FAO-56 approach, those results cannot be assessed as is. While there is some good discussion on process, the novelty of the study is lacking."

Reply: We believe that there are some misunderstandings, which we tried to resolve in our first reply to Reviewer 2, please see (https://doi.org/10.5194/hess-2018-310-AC1). Further author remarks can be found below.

Reviewer 2: "Perhaps a more useful and/or complementary analysis would be to

focus on the hourly distribution of the energy balance closure ratio, and assess the controlling factors of the distribution, if any, as it relates to soil moisture and other conditions."

Reply: While the analysis of the energy balance closure was not a focus of our work, we actually considered potential impacts by the way the energy balance was closed (instantaneous closures using a daily mean Bowen Ratio). To assess the potential impact of the closure method we also computed the phase lag statistics for the non-corrected latent heat flux (see Figure 7, Tables 3 and 4). Results show that the phase lag estimates are very similar showing that the correction does not influence magnitude of the observed phase lags.

To improve the communication of this result we adapted P15L11 in the manuscript as follows:
The uncorrected observations showed a slightly lower wet-dry difference , highlighting that the method to close the energy balance closure gap does not significantly influence the estimated phase lag.

Reviewer 2: "Pg 2 Line 29-30: LE is strongly correlated with Rsd, not the other way."

Reply: The text will be adapted.

Reviewer 2: "Pg 2 Line 21-22: Would be good to give a quick summary of these metrics, and why some are more useful than others if they are to be used or referenced later. This would be good so that when the alternative metric is proposed below the reader has some context."

Reply: We agree with the reviewer that the introduction needs a better motivation on the existing metrics. Therefore we provide a summary of the different metrics in use and explain why we are using the metric of a phase lag.

There is a strong need to investigate and to derive metrics based on comprehensive observation that characterize the whole land surface-atmosphere system (Wulfmeyer et al. 2018). Several authors proposed different multivariate metrics to better evaluate land-atmosphere (L-A) interactions in observations and models. Generally, these metrics explore internal relationships between state variables to better characterize key processes and to guide a more systematic exploration and understanding of model deficiencies. A number of ***metrics*** *focus on the diurnal evolution of the* ***heat and moisture budgets in the planetary boundary layer*** *(e.g., Betts 1992, Santanello et al. 2009, Santanello et al., 2017). Also* ***statistical metrics*** *exploring the strength of linear relationships between surface heat fluxes and states to surface radiation components have been employed to evaluate the performance of reanalysis with observations (Zhou and Wang 2016, Zhou et al., 2017, 2018). Furthermore, there are* ***pattern-based metrics*** *which focus on non-linear interactions at the diurnal time scale. Wilson et al., (2003) proposed the method of a diurnal centroid to measure the timing of the surface heat fluxes and their timing difference, which was more recently used by Nelson et al., 2018 to quantify the timing of evapotranspiration under different dryness condition for the FLUXNET dataset. In contrast Matheny et al., 2014 and Zhang et al., 2014 explored the diurnal relationship of the latent heat flux to vapor pressure deficit showing a pronounced hysteresis loop. Zheng et al., 2014 also included air temperature and net radiation as references variables and showed that the hysteresis loops of* λE *to* D_a *or* T_a *are large, while there are only small hysteresis effects when Rn was used. Hysteresis loops have also been found when heat fluxes plotted against net radiation (Camuffo and Bernadi 1982; Mallick et al., 2015), with many studies showing hysteretic loops of the soil heat flux against net radiation (Fuchs and Hadas, 1972; Santanello and Friedl, 2003; Sun et al., 2013). The presence of an hysteresis loop indicates that there is a time dependent non-linear control on the variable of interest, typically induced by heat storage processes. Camuffo and Bernardi (1982) showed that the magnitude and direction of such hysteretic loops can be estimated by a multi-linear regression of the variable of interest against the forcing variables and its first order time-derivative. This simple model allows to estimate storage effects on diurnal (Sun et al. 2013) to seasonal time scales (Duan and Bastiaansen 2017).*

Reviewer 2: "Pg 3 Line 2: I don't think that the other controls (other than Rn and Rsd) on LE remains unclear. . . it is pretty simple from an energy balance perspective (which is what is being discussed so far in terms of Rn and Rs) . . . LE = Rn – H – G . . . Lots to dig into with H obviously. . . and G, and perhaps that is where some of the controls need more study?"

Reply: We believe that writing the energy balance with $R_n = \lambda E + H + G$ is sufficient when direct measurements are used. However, when modeling the problem it is clear that all terms may depend on each other. For a mechanistic understanding a full treatmeat of the surface energy balance with explicit treatment of all radiation components is required. Reviewer 1 pointed to a recent study by van Heerwaarden et al. (2010) which discusses the complex interactions of at the surface, the surface layer and the planetary boundary layer, all feeding back on LE. The importance of controls on LE must be considered unclear, since there exist different schemes with different input variables to model LE. Many of the input variable are themselves strongly affected by the land-atmosphere exchange and its feedbacks.

Reviewer 2: "Page 3 Line 16: Why is Rn not used? Better yet, why isn't Rn-G (available energy) used? I don't see that why Rn (and Rn-G) is not used if the authors are indeed trying to better understand controls on LE. . . longwave radiation is a big component of Rn, and G lags no doubt control some of this hysteresis. I feel that the authors are missing too much energy if they just focus on Rsd.
Page 3 Line 23: The PT equation requires Rn, not Rsd, so how can you say you focus on using Rsd, but use the PT equation and not use Rn? Same with the PM equation. Please explain how and if Rs is used in these equations here and you can go into greater detail in the methods if needed. "

Reply: Our analysis focusses on the diurnal relation of evapotranspiration and relevant

Printer-friendly version

Discussion paper

surface energy balance fluxes and states to incoming solar radiation. Since Rsd is independent of the surface, it is an ideal reference to calculate phase lags. We acknowledge that all models which we compare in this study actually use net radiation (Rn) as an input variable, which would also justify to directly use Rn as a reference for the phase lag analysis which is suggested by the reviewer. The differences in the obtained phase lag using Rsd or Rn are not substantial. However, there are sound reasons to rather use Rsd than Rn as reference variable:

- R_n is not independent of the surface conditions

$\rightarrow$ fully coupled models would need to compute R_n by solving the surface energy balance including the turbulent heat fluxes

- It is more consistent to use R_{sd} for the phase lag analysis of other observed surface fluxes and states which are used as input to the models
- for example the phase lag analysis of the vertical temperature gradient (Ts-Ta) would not be useful when Rn is used as reference since the temperature gradient reflects a large part of the net longwave exchange which is part of R_n

To better communicate our reasoning we will provide a paragraph in the introduction on the surface energy balance and explain why we are using R_{sd}.

Reviewer 2: "Page 4 Line 7: but RH and VPD is coming from gridded weather data, no? So this is a forcing and outside the evaporation model, correct?"

Reply: The reviewer mentioned the MOD16 algorithm which was compared with other approaches with surface observations in Yang et al. (2015). That approach uses VPD as an input variable (forcing) which depends on air temperature. While there is some uncertainty when RH and VPD is obtained from coarse reanalysis products instead of in-situ observations, the main physical argument is that VPD (temperature) of the air cannot resolve the spatial variability of surface water limitation as compared to surface temperature.

Reviewer 2: "Page 6 Line 28-34: This is concerning since the heat storage in the soil slab above the G plate was estimated rather than measured. Sounds like the estimate didn't con- sider changes in soil moisture, which is a big factor in the potential to store heat within soils. Any errors in the estimate, or bad heat storage measurements could cause "perceived hysteresis" when comparing to other energy balance components. When was the harmonic calibrated, to dry or wet conditions, or both? Did the harmonic behave differently (have different parameters) when assessed during wet vs dry conditions as anticipated?"

Reply: The total ground heat flux can be obtained by measuring the soil heat flux at a given depth and an correction based on an estimate of heat storage changes above the heat flux plate (Massman 1992). The preferred method for the heat storage changes above the heat flux plate are soil temperature measurements. However, the upper soil temperature sensor failed after two weeks and the following period was characterized by a longer dry period. To circumvent this problem we used an alternative method based on a harmonic transformation of the heat flux plate measurements. The critique of the reviewer is that we did not take the soil moisture dependency of this method into account. This method requires an estimate of the damping depth D which was obtained by the exponential decay of the temperature amplitude of soil temperature measurements.

D is proportional to the square root of the thermal diffusivity and is only weakly dependent on soil moisture for clayey soils above 0.1 m3 m-3 water content (Jury and Horton, 2004) we had at our site. For the present work, D was determined by the exponential decay with depth of the soil temperature amplitude measured for the diurnal cycle in

Printer-friendly version

Discussion paper

2, 5, 15, and 30 cm depth at 15 different days between 12th June and 4th July. The mean of 12.27 ± 0.91 cm of these determinations was used for harmonic analysis. As mentioned in the manuscript, the upper soil sensors began to fail after 30th June and no determinations of D were possible after 4th July. Ten (five) determinations were performed for soil moisture contents >15% (<15%) where D was obtained to 12.55 ± 0.65 cm (11.71 ± 1.15 cm). The differences between the calculated ground heat fluxes using $D = 12.27cm$ and $D = 12.55$ and $D = 11.71cm$, respectively, were always $< 10Wm^{-2}$ so that the used value of $D = 12.27cm$ is a good compromise. For the data until 30th June we find a linear relationship with a slope of 1.05 and $R^2 = 0.94$ for the ground heat flux calculated with harmonic analysis of the HFP fluxes and the heat flux plate method with correction for heat storage. Please also find a figure attached to this reply which shows the diurnal cycles of the total soil heat flux estimates obtained by the upper soil temperature measurements (magenta) and the soil heat flux from the harmonic correction of the soil heat flux plate (blue). The plot only shows sunny days used in the analysis and also reports the top soil moisture of that day. The plots shows higher soil heat fluxes under the wetter conditions for both methods. We thus consider that the total soil heat flux obtained by the harmonic correction of the soil heat flux plate characterizes the diurnal dynamics of the soil heat conduction rather well.

We will add a summary of this explanation to the description in section 2.2.

Reviewer 2: "Page 8 Line 31: What time step was Qgap (the energy balance closure) assessed? Every 30min?"

Reply: Yes, the gap has been determined for each time step.

Reviewer 2: "Page 10 Line 25: The PT equations uses Rn-G, not simply Rn as writ- ten. What did you use? Rn or Rn-G (see equation 14 of the PT paper - ftp://ftp.library.noaa.gov/docs.lib/htdocs/rescue/mwr/100/mwr-100-02-0081.pdf).

The phase lag results can't be interpreted until this is cleared up."

Reply: We corrected equation 7 to use (Rn-G). This was also used in the analysis, so the interpretation will not change.

Reviewer 2: "Page 11 Line 14-16: Is Rsd used and then Rn and G is estimated following the procedures of FAO-56, or is the measured Rn-G used? This needs to be spelled out to understand the results."

Reply: Our strategy is to use all model forcing directly from the observations. The procedures of FAO are only recommended when input data is missing. We added one sentence to make this clear: *All other input variables to equation (8) where directly obtained from the observations.*

Reviewer 2: "Figure 6. Be consistent calling incoming shortwave Rsd vs Global radiation. . . you say both."

Reply: We updated the figures labels of Figures 6, 8, 9 and 11 accordingly.

Reviewer 2: "Figure 7 isn't very useful since it is Rsd on the x, and not Rn-G. I guess I don't see the point since phase lag is to be expected (and greater for wet conditions as shown), and it is unclear how G was considered in the FAO approach."

Reply: This comment regards the question of using Rsd or Rn as reference to quantify the phase lag. We already replied to this in a separate author reply. With respect to Figure 7, which shows the phase lag of the different latent heat flux estimates against Rsd we find a general wet-dry difference in the observations and most models but not for the Penman-Monteith based approaches. We also computed the phase lag of the key model input parameters in Fig 12. The reviewer suggested to used Rn-G as a reference. Doing this will not change Figure 7 much and thus also not the conclusions. See also Table 1 of our previous reply https://doi.org/10.5194/hess-2018-310-AC1.

Reviewer 2: "Page 17 line 4-5: The authors state that “Generally, there was only a small hysteresis in the available energy (Rn – G) (Table 4)” which is exactly what one would expect if Rn-G was used. So by not including longwave and G there is phase lag, which is to be expected, so I don’t see the point of the paper really. . . . Also, there would be more phase lag in wet soil conditions, than in dry conditions since heat storage is greater when there is more water in the soil. By not considering G, you get phase lags. . . is there something novel to see here?"

Reply: We replied to this point in a separate reply. The soil heat flux shows a small phase lag to Rsd which increases in magnitude when wet. However, the phase differences of the turbulent heat fluxes are even larger in magnitude than the ones of G, see Table 4 and Fig.12. These phase lags are also present when Rn-G is used as reference (instead of Rsd). This is consistent with the argument that the soil heat flux is too small to compensate the diurnal imbalance caused by solar radiation. Hence the land-atmosphere heat exchange strongly contributes to balance the large diurnal forcing of solar radiation.

We will put more emphasis on this important point in the revised discussion of the manuscript.

Reviewer 2: "Page 20 and Figure 11: The results of the hysteresis in humidity variables are what you would expect. The VPD is lowest in the morning, and highest in the mid to late afternoon, and largely a function of es, since it is a fairly humid environment, so what is novel here?"

Reply: We believe that the diurnal course of VPD is known to most researchers. The key point is that VPD is used as the driving gradient in the Penman-Monteith approaches. This gradient shows a strong hysteresis loop, while the surface to air temperature difference, which is the driving gradient of the energy balance residual approaches shows only a small hysteresis. Visualizing this difference in the two driving gradients (cf. Fig. 9 and Fig 11) should highlight the key differences in these approaches.

Reviewer 2: "Page 25 Line 22: Yes this was quantified, but it was expected, and it changes in time and space, based on the land surface conditions, and met. forcings."

Reply: We will update the conclusions of the manuscript to improve the clarity of our writing, see also our reply to reviewer 1 https://doi.org/10.5194/hess-2018-310-AC2.

Reviewer 2: "Page 25 Line 23: Explain exactly how these results have practical application for re- mote sensing based models? This was never fully described, that is why this phase lag issue is so important for remote sensing studies of LE to consider or include."

Reply: There are three points which are relevant for remote sensing based approaches:

- We did the comparison for three different remote sensing approaches, highlighting why energy balance approaches are better suited given better agreement in terms of the phase lag. Hence we guide model selection for remote sensing based evapotranspiration retrievals. This is the main contribution of this manuscript.
- The phase lag analysis allows to estimate the magnitude of heat storage changes. This is relevant because heat storage changes in the surface must

also be modeled by remote sensing based approaches.

- The phase lag information can be used to improve sub-daily and daily heat flux estimates from instantaneous observations usually provided from polar-orbiting satellites. Thereby one can use Eq. 1 of the manuscript with knowledge of the phase shift and incoming solar radiation to model the diurnal cycle of the heat flux. This would extend the usual assumption of a constant evaporative fraction over a day (Crago and Brutsaert, 1996; Alfieri et al., 2017).

We will update the discussion of the manuscript to make our contribution for remote sensing based approaches clear.

Reviewer 2: "Page 25 Line 30-33: There is too little information on the specifics in the paper of FAO-PM approach applied to assess if this is a correct conclusion."

Reply: As already comment above, we will add information on input variables in the text (in addition to Table 2 summarizing the input data).

References

Alfieri, J. G., Anderson, M. C., Kustas, W. P., and Cammalleri, C.: Effect of the revisit interval and temporal upscaling methods on the accuracy of remotely sensed evapotranspiration estimates, Hydrol. Earth Syst. Sci., 21, 83–98, doi:10.5194/hess-21-83-2017, 2017.

Crago, R. and Brutsaert, W.: Daytime evaporation and the self-preservation of the evaporative fraction and the Bowen ratio, Journal of Hydrology, 178, 241–255, doi:10.1016/0022-1694(95)02803-X, 1996.

Jury, W. A. and Horton, R.: Soil Physics, John Wiley & Sons, Inc, 6th edn., 2004.

van Heerwaarden, C. C., Vilà-Guerau de Arellano, J., Gounou, A., Guichard, F., and Couvreux, F.: Understanding the Daily Cycle of Evapotranspiration: A Method to Quantify the

Influence of Forcings and Feedbacks, Journal of Hydrometeorology, 11, 1405–1422, doi: 10.1175/2010JHM1272.1, 2010.
Yang, Y., Long, D., Guan, H., Liang, W., Simmons, C., and Batelaan, O.: Comparison of three dual-source remote sensing evapotranspiration models during the MUSOEXE-12 campaign: Revisit of model physics, Water Resources Research, 51, 3145–3165, doi: 10.1002/2014WR015619, 2015.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-310, 2018.

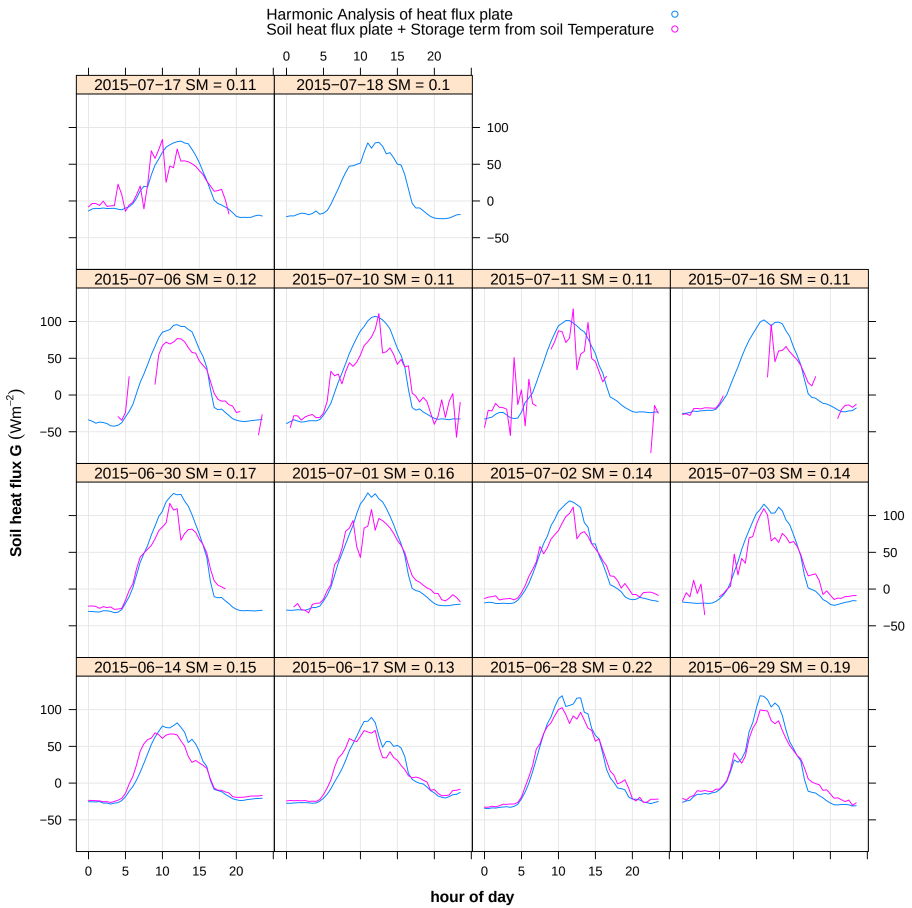

Fig. 1. Comparison of two different estimates of the total soil heat flux for sunny days. Note, that the upper soil temperature sensor was unreliable after 2015-06-30.