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Interactive comment

Interactive comment on "Imprints of evaporation and vegetation type in diurnal temperature variations" *by* Annu Panwar et al.

Annu Panwar et al.

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Response to the reviewer # 1 HESSD

Dear Reviewer,

Thank you. We appreciate the time and effort that you have dedicated to providing your valuable feedback on our manuscript. We found your comments extremely helpful and we have been able to incorporate changes to reflect most of the suggestions. These changes are highlighted in "*italic*" with the line numbers in this response letter, and in red color within the manuscript. The line numbers might change with future edition of the manuscript.

Your comments are in blue bold color, which we answer in the black color. Some of the compre-

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Discussion paper

hensive questions are split within the comment in blue font. Figure Rn denotes figures which are in the supplement of this response; here n is the figure number.

Interactive comment

on "Imprints of evaporation and vegetation type in diurnal temperature variations" by Annu Panwar et al.

Anonymous Referee # 1

Received and published: 1 April 2020

The study by Panwar proposed a metric "warming rate" to quantify the diurnal variation in surface and air temperature, and investigated the sensitivity of the warming rate to evaporative fraction and aerodynamic conductance in different land cover conditions. The authors concluded that the surface warming rate is sensitivity to the evaporative fraction over the short vegetation, but no imprint of evaporation is found in the diurnal surface/air temperature. This is an interesting study, and it is on a topic of relevance and general interest to the readers of this journal. However, some parts of the manuscript are hard to follow, and need some improvements and better discussions.

We are glad that you find this study interesting and relevant to HESS journal. To further improve our manuscript we have gone through each of your comments.

My major concerns are:

1. **What is the purpose of calculating the temperature warming rate to evaporative fraction?**

   Previous studies suggest that aerodynamic resistance (or conductance) plays a major role in land use-induced temperature change (Zhao et al. 2014; Chen and

Dirmeyer 2016; Winckler et al. 2019). The surface warming rate can be mainly associated with aerodynamic conductance. The consistency between the distribution of the warming rate in Figure 3 and the distribution of aerodynamic conductance in Figure 5 may support this idea - higher conductance corresponds to a lower warming rate. How is the distribution of the evaporative fraction? And why not calculate the sensitivity of "the sensitivity" to aerodynamic resistance, but only use aerodynamic conductance as a secondary factor?

We assume the reviewer wants to ask "what is the purpose of calculating the response of temperature warming rate to evaporative fraction?"

In this study we show if diurnal temperature responds to evaporative conditions in different vegetation types. For this, we use warming rate because it removes the dominant contribution of the solar radiation and allows us to investigate the effects of evaporative conditions and vegetation types in diurnal temperature variation. Expression of warming rate is also directly related to evaporative fraction and aerodynamic conductance of vegetation, which is obtainable from surface energy balance. Evaporation cools that means any heating of diurnal temperature due to unit absorption of solar radiation will dampen due to evaporative cooling. To quantify this effect we look at the relationship of warming rates to evaporative fraction.

Previous studies suggest that aerodynamic resistance (or conductance) plays a major role in land use-induced temperature change (Zhao et al. 2014; Chen and Dirmeyer 2016; Winckler et al. 2019).

We completely agree that the aerodynamic conductance plays a major role in land use-induced temperature change. Our findings also show that the warming rates of forests are lower predominantly due to their high aerodynamic conductance (L415-416).

We are aware of the listed studies that capture the impact of vegetation properties in temperature, in fact we have already cited them (Juang et al., 2007; Lee et al., 2011;

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Discussion paper

Luyssaert et al., 2014; Zhao et al., 2014) in the introduction section, see L67-70.

These studies are relevant to our work but not the same. The cited studies show the change in surface energy balance components due to land cover change, which leads the changes in temperature. On the other hand our study looks at the diurnal scale and explore the local impact of variation in evaporative conditions and aerodynamic conductance on diurnal course of surface and air temperature in different vegetation types.

The surface warming rate can be mainly associated with aerodynamic conductance. The consistency between the distribution of the warming rate in Figure 3 and the distribution of aerodynamic conductance in Figure 5 may support this idea - higher conductance corresponds to a lower warming rate.

We partially agree with this notion. However, surface temperature warming rate are mainly associated to the aerodynamic conductance only in forests but not in the short vegetation. Eqn. 5 in the manuscript shows, the variation in warming rate is not just dependent on aerodynamic conductance of vegetation but also on the evaporative conditions. As result, surface temperature warming rate of the short vegetation are higher on dry days and lower on the wet days (evaporative days), Figure 6a. This sensitivity is also captured in the observations, Figure 4.

How is the distribution of the evaporative fraction?

The range in evaporative fraction for each site is already present in the manuscript; see Figure A1.b in the Appendix. Additionally, the density distribution of the evaporative fraction is provided in the supplement of this response, Figure R1.

And why not calculate the sensitivity of "the sensitivity" to aerodynamic resistance, but

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Discussion paper

only use aerodynamic conductance as a secondary factor?

This is exactly what we show. Our model demonstrates that (Eq. 6) the warming rates are not only sensitive to aerodynamic conductance but also to the sensitivity of aerodynamic conductance to evaporative fraction. Figure 5 shows that the aerodynamic conductance increases on dry days, which we call as enhanced aerodynamic conductance . The sensitivity of warming rates to both the factors is quantified and compared in Figure 7b. Our study found that the aerodynamic conductance is the primary factor but the enhanced aerodynamic conductance is also somewhat important especially in the forests, L438

2. **One of the main conclusions of this study is that the warming rates do not carry imprints of evaporation in the forest. What is the physical mechanism of this absent imprints? Why does the high aerodynamic conductance of the forest result in no imprint of evaporation in diurnal temperature variations? Does this necessarily mean ET of the forest has little impact on temperature? The authors need to provide more explanations of the physical processes and more discussions on the implications of the warming rate sensitivity.**

We have split the response into several parts. Additional explanations of the physical mechanism and implication of warming rate is also added in the discussion section.

What is the physical mechanism of this absent imprints?

The physical mechanism explaining the insensitivity of diurnal temperatures to evaporative conditions in the forests is still unclear. It is not the main objective of the study but certainly one of the next questions to answer.

So far, our model explains the absent imprints of evaporation in forest by their high aerodynamic conductance. Also, the aerodynamic conductance of forest enhances on dry days, which means enhanced buoyancy in forest on dry days. Based on our results and model we speculate that the enhanced buoyancy on dry days might explain the reduced warming rates and their weak response to evaporative fraction in the forests. This is now expressed in the discussion section, L537-542.

"*Our model shows, diurnal temperature variation in forests has weak to no imprints of evaporative conditions due to their high aerodynamic conductance. Additionally, observations show enhancement of aerodynamic conductance of forest on dry days, which also contributes in reduced warming of surface temperature. Based on our findings, we speculate that the enhanced aerodynamic conductance increases the buoyancy that may explain the physical mechanism causing the lower warming rates and their weaker response to evaporative conditions in the forest.*"

Why does the high aerodynamic conductance of the forest result in no imprint of evaporation in diurnal temperature variations?

This is explained in Eq. 5 of the model, which demonstrates the dependency of surface temperature warming rate to evaporative fraction and aerodynamic conductance.

$$\frac{dT_s}{dR_s} \approx \frac{(1-f_e)}{c_p\ \rho g_a} + \frac{dT_a}{dR_s} \qquad Eq.\,(5)$$

In the above equation the denominator term ($c_p\ \rho g_a$ is higher for the forest because of their high aerodynamic conductance than the numerator term $(1-f_e)$. That means Eq. 5 is not very sensitive to variations in evaporative fraction. This sensitivity is also demonstrated in Figure 6a of the manuscript.

Does this necessarily mean ET of the forest has little impact on temperature?

ET or evaporative fraction of the forest has little impact on the diurnal variation of the temperature. It does not necessarily mean that the mean temperatures of the forests are insensitive to evaporation.

To indicate this in the text, we have now added the following line in the discussion, L532-535

"*It is also reflected in similar diurnal variations of surface and air temperature that are mostly insensitive to changes in evaporative fraction. Thus, evaporative fraction has little to no impact on the diurnal variation of temperatures in the forest. But, it does not necessarily indicate that the mean temperatures of forest are insensitive to evaporation.*"

3. **Throughout the manuscript, "evaporation (or ET)" and "evaporative fraction" are used as interchangeable terms. However, the evaporative fraction also carries information about the sensible heat flux. I am wondering what the sensitivity of the warming rate to ET based on the observational analysis.**

Thank you for pointing it out. In order to avoid such confusion we have replaced "evaporation" with "evaporative fraction" . It also helps in simplifying the model description.

This change is implemented throughout the text. This also applies to the title, which now reads as:

" *Imprints of evaporative condition and vegetation type in diurnal temperature variations*"

However, the evaporative fraction also carries information about the sensible heat flux.

We agree that evaporative fraction carries information about the sensible heat flux. Besides latent heat flux, sensible heat flux also cools the surface temperature, which is depicted in Eq. 3. Therefore, it is important to account all the turbulent heat fluxes to determine surface temperature.

Moreover, in the text we refer evaporative conditions as dry or less evaporative, when turbulent heat flux is dominated by sensible heat flux, and wet or evaporative, when turbulent heat flux is dominated by latent heat flux. This notion is now updated in the text (L104-106).

"*We observed that the warming rate of surface temperature decreases from dry (less-evaporative, sensible heat flux dominates) to wet (evaporative, latent heat flux dominates) conditions but the warming rate of air temperature remained unaffected by evaporative conditions.*"

I am wondering what the sensitivity of the warming rate to ET based on the observational analysis.

As depicted in Eq. 3, warming rate of surface temperature is not only dependent on LE or ET but also on sensible heat flux (H).

$$\frac{dT_s}{dR_s} = \frac{1}{k_r} - \frac{1}{k_r}\,\frac{d\,(H + LE)}{dR_s} \qquad Eq.\,(3)$$

We opt evaporative fraction because it contains information on both the turbulent heat fluxes, LE and H. Only taking LE is not numerically correct as per our model. Although, one can still see how warming rate responds to LE in the observations, Figure R2 in the supplement of this response.

4. **A similar issue to my 3rd point - the authors should note that aerodynamic conductance and evaporative fraction are not independent (Rigden and Li 2017). However, in their analysis, aerodynamic conductance and evaporative fraction were treated as two independent factors that govern the diurnal variations of surface temperature. For instance, "model reveals a strong sensitivity of the warming rates to evaporative fraction and aerodynamic conductance" ; "the diurnal variations in temperatures are mainly governed by their aerodynamic properties resulting in no imprint of evaporation in diurnal temperature variations." If considering the dependency of aerodynamic conductance and evaporative fraction, will their conclusions be the same?**

We agree that aerodynamic conductance and evaporative fraction are not independent. To account for this, we also show the observed sensitivity of aerodynamic conductance to evaporative fraction and its consequences on warming rate. Your concern that this sensitivity should also reflect in warming rate is valid and already accounted in our study.

Eq. (5) calculates the warming rate using evaporative fraction (f_e and aerodynamic conductance (g_a .

$$\frac{dT_s}{dR_s} \approx \frac{(1-f_e)}{c_p\ \rho g_a} + \frac{dT_a}{dR_s} \qquad Eq.(5)$$

We use daily observations of evaporative fraction and aerodynamic conductance to calculate daily surface temperature warming rates (Figure 6b). That means, g_a is not the mean of the site and varies with f_e . So, yes we do not consider a constant aerodynamic conductance and it is sensitive to f_e . To review this concern in the manuscript we have added following sentences in the model and result section.

L180-184

"*Eq. (5) shows that morning to noon warming of surface temperature is a function of evaporative fraction, aerodynamic conductance and also of the warming rate of air temperature. Generally, vegetation has a characteristic aerodynamic conductance that depends on the surface roughness but it is important to consider that their daily aerodynamic conductance can vary with the daily evaporative conditions.*"

L405-406

"*Also, daily* g_a *is not independent of the daily evaporative conditions, so their dependency is certainly captured here.*"

"the diurnal variations in temperatures are mainly governed by their aerodynamic properties resulting in no imprint of evaporation in diurnal temperature variations." If considering the dependency of aerodynamic conductance and evaporative fraction, will their conclusions be the same?

Yes we have already considered the dependency of aerodynamic conductance to evaporative fraction. Our conclusion is based on Eq. (6), where $g_a^{'}$ captures the sensitivity of g_a to f_e . Generally, g_a is observed to increase on dry days, which we also call as enhanced aerodynamic conductance.

$$\frac{dT_s}{dR_s}^{'} = -\frac{1}{c_p\ .\ \rho.g_a} - \frac{1-f_e}{c_p\ .\ \rho.g_a} . \frac{g_a^{'}}{g_a} + \frac{dT_a}{dR_s}^{'} \qquad Eq.(6)$$

Figure 7b demonstrates that the sensitivities of warming rate to evaporative fraction will be slightly different if you consider $g_a^{'} \neq 0$ than the case when $g_a^{'} = 0$. In forest enhanced aerodynamic conductance are important than in the short vegetation. But overall it is the high aerodynamic conductance of forest that reduces the responses of warming rate to evaporative fraction.

Specific comments:

1. **L28-29: Why use diurnal temperature variations to predict evaporation? And this conclusion seems opposite to the conclusion in L567-568.**

   The conclusions in the abstract (L28-29) and in the conclusion (L567-568) sections are exactly the same. See the sentence in L581-582

   "*This implies that the diurnal variation of surface temperature of short vegetation should be useful for estimating evaporation.*"

   Why use diurnal temperature variations to predict evaporation?

   We use diurnal temperature because it is one of the well-observed variables in meteorology. In a diurnal scale solar radiation directly warms the temperature but one may speculate that the enhanced evaporation will slow down this warming.

   We found that warming rate of surface temperature decreases linearly with evaporative fraction. This relationship can be useful in estimating evaporation, which is one of the important but rarely measured variable in meteorology.

   And this conclusion seems opposite to the conclusion in L567-568.

   No, they are not opposite.

   L567-568, "... *diurnal temperature variations can be understood and predicted by relatively few factors, solar radiation, aerodynamic conductance and evaporative fraction.*" summarizes the last figure (figure 8), where we show that the diurnal temperature range

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Discussion paper

can be estimated from solar radiation, aerodynamic conductance and evaporative fraction using the model. It is a general statement irrespective of the vegetation type. However, the importance of these three factors varies with vegetation. For example information of evaporative fraction is not necessarily important for forests but very important for short vegetation, which is explained in lines L74-475 and L479-481.

2. **L95: Define surface temperature. Skin temperature? I noted it is explained in the later section, but it would be better to explain it here.**

   To resolve it, we have added "or skin" in bracket, in L96.

   "*Figure 1a shows a greater surface (or skin) temperature warming rate compared to air temperature warming rate for a cropland site.*"

3. **Section 2 should be a subsection of section 3 or at least after section 3. It should be a consistent order with the structure of the result section.**

   The model section is presented before the data and method section, because we think it is convenient for the reader to first understand what data one needs in order to conduct this analysis based on our model. To illustrate this in the text we have added the following sentence in the introduction, L125-127

   "*Based on the model formulation we identify the data needed for the study. Description of data and methodology is given in data and method section.*"

   We have also added an additional sentence supporting why we introduce model in section 2, L138-140

   "*To understand how diurnal temperature variation responds to evaporative condition and* *vegetation types, we first present quantitative expressions of diurnal temperature warming rate based on surface energy balance.*"

4. **L166: How to get the reference temperature Tref?**

   The T_{ref} in Eq.2 is the global mean of surface temperature which is $\sim$ 288 K, L166. This information is also added in the text, L175-177.

   "*To get k_r we consider T_{ref} $\sim$ 288 K which is the mean global surface temperature such that the term k_r $(1 - f_e)$ varies by $\sim$ 4.87 Wm^{-2} K^{-1} to $\sim$ 0.54 Wm^{-2} K^{-1} from dry (f_e =0) to wet (f_e =1) conditions*
   "

   Nevertheless, choice of T_{ref} does not affect the model outputs. The model is relatively insensitive to any particular values of T_{ref} because the effect of term k_r $(1 - f_e)$ is ignored in the model due to its smaller magnitude.

5. **L187-188: Which two equations?**

   Corrected, see line L197-198

   "*On multiplying Eq. (5) with daily maximum solar…*"

6. **L208-211: Why are these two filters used? Can the authors provide more explanations for the first filter?**

Author realizes that the sentence at L208-209 complicates the understanding of the filters used for data analysis, so it has been removed.

The first filter is used to select summer days (L202-205) and the second filter selects the clear sky days among the summer days (L209-211).

Can the authors provide more explanations for the first filter?

As explained in L209-211 the days with solar radiation greater than the median of its annual distribution are treated as summer days. Figure R3 in the supplement of this response demonstrates our methodology:

7. **L220: The FLUXNET site also provides information about the vegetation type. Is the reported land cover type consistent with the 1km IGBP land cover product?**

Yes, we used the land cover information provided by FLUXNET website which can be found here:

https://daac.ornl.gov/FLUXNET/guides/Fluxnet_site_DB.html# datasetoverview

A reference to this dataset is now added, L24-225.

"*The information on the vegetation type is obtained from the FLUXNET land cover classification (Falge et al., 2017) that is based on the International Geosphere-Biosphere Programme (IGBP) Data and Information System*"

8. **L277-278: The difference should be attributed to the low aerodynamic conductance? For the short vegetation, the conductance is low, which means the heat**

transfer from the surface to the lower atmosphere is less efficient.

We completely agree that the major differences in the surface temperature warming rates should be attributed to aerodynamic conductance. Lines L277-278 discuss the possible reasons for the spread in surface temperature warming rate within the short vegetation type.

There was a typing error; it was not "*air temperature warming rate*" but "*surface temperature warming rate of cropland sites*" . See the corrected sentence below L279-281

"*Within the short vegetation type, grassland and shrubland sites show much greater surface temperature warming rates than the surface temperature warming rate of the cropland sites*"

9. **L292-293: Where is the consistency in Figure A2?**

Figure A2 shows the warming rate responses to evaporative fraction for each site. The word ???consistency??? was used for ???similar??? negative responses in all the sites of short vegetation type.

To avoid such confusion we have rephrased the sentence by replacing ???consistency??? term with the term ???similar???

See the modified version, L300-303

"*Short vegetation shows a mean decrease of $\sim$ 23 x 10^{-3} K/W m^{-2} in surface temperature warming rate from dry to wet condition. However, air temperature warming rate decreases only by $\sim$ 5 x 10^{-3} K/W m^{-2}. Similar responses were reported in our previous study for a cropland site (Figure A2, site no. 8).*"

10. **L293-295: It is very confusing here. First, this sentence does not explain anything from the previous sentence. Second, Figure 4 only shows the sensitivity of the warming rate. Is the actual range of the evaporative fraction 0_1 from dry to wet days? In methodology (L167), the range is defined as 0.1_0.9?**

L293-295: It is very confusing here. First, this sentence does not explain anything from the previous sentence. Second, Figure 4 only shows the sensitivity of the warming rate.

Description of appendix figures is now removed in the main manuscript in order to avoid any confusion with Figure 4.

Is the actual range of the evaporative fraction 0_1 from dry to wet days? In methodology (L167), the range is defined as 0.1_0.9?

Mathematically a unit change in evaporative fraction is 0 to 1 but physically this range is unreasonable for vegetated surface. Therefore, to obtain the response of warming rate to unit change in evaporative fraction we use the slope of linear regressions of observed warming rate and evaporative fraction.

Assumption that evaporative fraction is ∼ 0.1 on dry days and ∼ 0.9 on wet days in the model section is discard by sticking to the standard mathematical definition of unit chance in evaporative fraction. Such that L167 reads:

"*Considering T_{ref} ∼ 288 K, the term $k_r \ (1 - f_e)$ varies by ∼ 4.87 Wm^{-2} K^{-1} to ∼ 0.54 Wm^{-2} K^{-1} from dry (f_e =0) to wet (f_e =1) conditions.*"

Also, the following sentence is now added in the result section explaining that $\frac{dT'}{dR_s}$ is obtained by slope of the regression between warming rate and evaporative fraction, see L291-295

“*Mathematically,* $\frac{dT'}{dR_s}$ *is the change in warming rate from dry (* f_e *=0) to wet (* f_e *=1) condition which is obtained from the slope of the linear regression of daily warming rates and daily evaporative fraction.*”

11. **Figure 4: The label of the color bar is not correct.**

    Thank you. Corrected, see Figure R4 in the supplement of this response letter:

12. **L369: Figure 6a?**

    Corrected

13. **L373: same issue as above.**

    Corrected