

Letter to the Editor – Submission of revised manuscript

Dear Dominic Mazvimavi,

Thank you for providing the opportunity to revise our manuscript. We are grateful to the reviewers for their constructive comments that have improved our manuscript, although the main findings remain same. We wish to submit the revised version of the manuscript for further consideration in the journal.

We would like to clarify the summary of the major changes adopted in the revised version, which are:

- There is slight change in the title of the manuscript. The new title is
“Imprints of **evaporative conditions** and vegetation type in diurnal temperature variations”
Following the suggestion of the first reviewer, we use now **evaporative conditions**, which is a more general term than **evaporation**, which could have been confused by the readers as the amount of water evaporated.
- An additional (new) affiliation of one of our coauthor (Maik Renner) is included.
- Following the concern of second reviewer, in Section 2 (2. Modeling temperature-warming rate), we have now considered the diurnal variation of aerodynamic conductance in our model; see Eq. (4) to Eq. (9) in the manuscript. The new variables are described within the text and also in Table A1 in the Appendix.
- In the new version, the aerodynamic conductance is calculated from sensible heat flux, a method that is consistent with our surface energy model. In the previous version, we used the frictional velocity for calculating the aerodynamic conductance in a way that is only suitable for neutral conditions and therefore not appropriate for the unstable conditions during daytime. This change is reflected in Figure 5, Table 2 and Figure A3 in the Appendix.
- With the new method to estimate aerodynamic conductance from the sensible heat flux, we did not find a relationship of aerodynamic conductance to evaporative fraction (see Figure RR1, in this response letter). Therefore, we have now removed the associated figures and text from the manuscript.
- To highlight our model performance, we have merged figure 6a and 7b from the old version of the manuscript into Figure 6 in the revised version.
- Figure 7 (previously Figure 8) is now reorganized in accordance to our updated model. Our conclusions remain nevertheless mostly the same. For a better interpretation of our findings we have calculated and discussed the contribution of each term contributing to the diurnal temperature range in percentages.
- The discussion on the implication of our findings and model is now extended. We have discussed how our study is valuable in understanding the diurnal temperature range; effects of land cover change, and the role of forests in cooling temperatures.
- The conclusion of our study remains similar to our previous version, now containing added and updated information following the suggestions of the reviewers.
- We improved the language, as recommended by Reviewer #2, and streamlined the text to reduce some redundancies.

To address all reviewers' comments, detailed responses are previously delivered. For completeness, these are added below, with the comments of reviewers in blue followed by our response in black. The manuscript text referred in the responses is shown in italics. In addition to these responses, we highlight all changes made in the manuscript in the text below, considering the major concerns and comments of the reviewers. The changes in the manuscript are highlighted in blue.

These additional documents cover the following page ranges:

- Page 3 to 4: Response to the First Reviewer
- Page 5 to 6: Response to the Second Reviewer
- Page 7 to : Marked up version of the revised manuscript.

We hope that we have addressed all of the comments from the reviewers in a satisfactory way.

We look forward to the outcome of your assessment.

Yours sincerely,

Annu Panwar

On behalf of the co-authors

Response to the First Reviewer

Dear Reviewer,

Thank you for finding our study interesting and relevant to the readers of the journal. We believe that we answered to your every comment in our previous response letter. Here we highlight all the changes stimulated by your review. Some of these changes are also discussed in response to the second reviewer.

- “Throughout the manuscript, “evaporation (or ET)” and “evaporative fraction” are used as interchangeable terms.”

For avoiding such confusion we use term “evaporative conditions” and “evaporative fraction” throughout the manuscript.

This is also reflected in the title, which was,

“Imprints of evaporation and vegetation type in diurnal temperature variations”

And now is modified to,

“Imprints of evaporative condition and vegetation type in diurnal temperature variations”

- 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.

We would like to notify that in the revised version of the manuscript, our calculation of aerodynamic conductance is based on sensible heat flux and not on frictional velocity. Calculating aerodynamic conductance from sensible heat flux makes our surface energy balance model consistent. This change has slightly improved our model performance and its interpretation.

Based on our updated analysis of aerodynamic conductance we find that the aerodynamic conductance and evaporative fraction has no strong relationship in the observations. See below, Figure RR1.

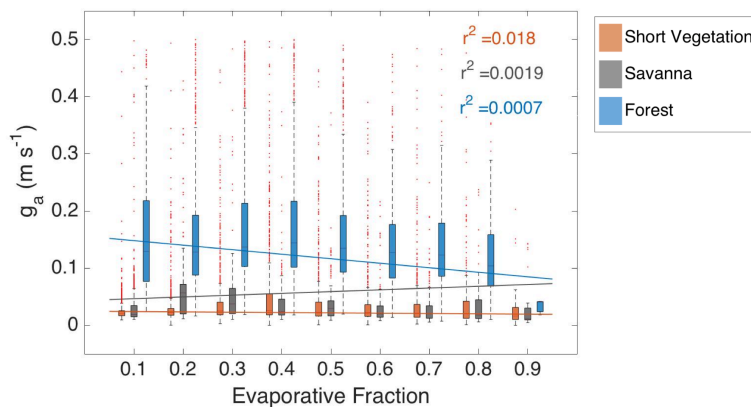


Figure RR1 Box plot of observed relationship between morning mean aerodynamic conductance and morning mean evaporative fraction in short vegetation, savanna and forest.

These results are in contradiction to Rigden and Li 2017, because similar to our previous method they calculate aerodynamic conductance from frictional velocity and not from sensible heat flux. This is a very important distinction that we also highlight in the manuscript. See lines 379-382,

“This finding is different to the study by Rigden and Li (2017) who showed that the aerodynamic resistance depends on the Bowen ratio. This difference can be attributed to their way to estimate aerodynamic resistance from the frictional velocity and wind speeds, which assumes neutral conditions, whereas we obtain aerodynamic conductance from sensible heat flux.”

- 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.

This is very intriguing observation.

For clear interpretation of our results we have now added the contribution (in %) of evaporative conditions and aerodynamic conductance in cooling temperatures, see lines 490 to 497,

“Evaporation reduces DT_sR by ~18 % (short vegetation: $(1.26-1.51)/1.51 = -16.55$ %, savanna: $(1.37 - 1.64)/1.64 = -16.46$ %, and forest: $(2.22 - 2.84)/2.84 = -21.83$ %). On comparing Figure 7 b and 7c, we found that the high aerodynamic conductance of forests reduces DT_sR by 56 % $((0.98 - 2.22)/2.22 = -56\%)$. In other words, the higher aerodynamic conductance of forests causes a substantially larger cooling than evaporation. The diurnal variation of the aerodynamic conductance then reduces the DT_sR further, being stronger in short vegetation $((0.86 - 1.32)/1.32 = -35\%)$ and savanna $((0.90 - 1.40)/1.75 = -35.25$ %) than in forests $((0.77 - 0.98)/0.98 = -21\%)$.”

Our model and observational findings shows that it is the high aerodynamic conductance of forest that cools the diurnal temperature; evaporative cooling is a secondary factor. This is an important finding, and is now discussed in detail in the discussion section. See lines 561 to 567,

“... the low DT_sR of forests mostly to their high aerodynamic conductance (~56 %), with evaporation playing only a secondary role (~22 %). This finding is consistent with studies that showed that the warming induced by deforestation to be mainly the consequence of changes in aerodynamic conductance rather than changes in evaporative conditions (Bright et al., 2017; Chen and Dirmeyer, 2016; Lee et al., 2011b; Zhao et al., 2014b). This aerodynamic effect is thus important for the cooling effect of forests (Ellison et al., 2017; Li et al., 2015; Tang et al., 2018), which our analysis and analytical model supports.”

Does this necessarily mean ET of the forest has little impact on temperature? What is the physical mechanism of this absent imprints?

Yes, our study shows that the aerodynamic conductance of the forest is the dominant cooling agent whereas evaporation is secondary. The mechanism is discussed in discussion section in lines 550 to 558,

“We can only speculate about the physical mechanism behind this finding. While it is well established that the greater aerodynamic roughness of the forest leads to a greater aerodynamic conductance for neutral conditions (T.R. Oke, 2002) we also find that the diurnal variation is much larger than the mean (the term dg_a/dR_s). This enhancement is most likely related to buoyancy, which is produced when the surface is heated by the absorption of solar radiation during the day. The finding that the relative enhancement of aerodynamic conductance between forests and non-forests is the same, and that this enhancement is insensitive to evaporative fraction, seems to be surprising and would need further investigations about their physical explanations.”

Thank you

Response to the Second Reviewer

Dear Reviewer,

Thank you for your constructive comments and encouraging words. Your suggestion to consider diurnal cycle of aerodynamic conductance has improved our model and its interpretation. The main results remain same but with your suggestion a broader perspective on the importance of aerodynamic conductance is now recognized in the revised manuscript. Here we revisit your comments that are implemented and discussed in the manuscript.

- My main difficulty is to see why, when deriving equation (4), both the evaporative fraction and the aerodynamic conductance can be considered constant with R_s . This needs some justification. Later in the paper it is mentioned (L241-242) that evaporative fraction is stable during daylight hours, which should probably mentioned before presenting Eq. (4). Why can the diurnal variation of g_a be ignored?

Thank you for pointing out this. In the revised version, diurnal aerodynamic conductance, represented as dg_a/dR_s , is now considered in the model, and in our observational analysis. Following are the changes resulted on using dg_a/dR_s ,

1. In the model section the warming rate is now given by (Eq. 7), Line 198

$$\frac{dT_s}{dR_s} \approx \frac{(1 - f_e)}{c_p \cdot \rho \cdot \bar{g}_a} + \frac{dT_a}{dR_s} - \frac{\overline{T_s - T_a}}{\bar{g}_a} \cdot \frac{dg_a}{dR_s}$$

, And its response to evaporative fraction by (Eq. 9), Line 213

$$\left(\frac{dT_s}{dR_s}\right)' = -\frac{1}{c_p \cdot \rho \cdot \bar{g}_a} + \frac{dT_a'}{dR_s} - \left[\frac{(\overline{T_s - T_a})}{\bar{g}_a} \cdot \frac{dg_a}{dR_s}\right]'$$

The last term of Eq.9 is solved using observations, shown in Figure 5 and discussed in lines 373 to 388.

We have now emphasis more on demonstrating the implication of our study in estimating and analyzing factors shaping the diurnal range of surface temperature (DT_sR), which is a known index for quantifying the diurnal variation of temperatures.

2. In section 3 (3. Data and Methods), we mention the updated method of calculating aerodynamic conductance and its diurnal variation. See lines 278 to 282

“The aerodynamic conductance (g_a) is obtained from the observed sensible heat flux from $g_a = H / (c_p \cdot \rho \cdot (T_s - T_a))$. Since aerodynamic conductance is not constant over the day, its diurnal variation is described by dg_a/dR_s , which is estimated from a linear regression of morning to noon half hourly values of g_a and R_s .”

3. In section 4 (4.1 observational analysis), we have added the information on aerodynamic conductance and its diurnal variation in Table 2; which is also demonstrated in Figure 5.
4. We have also updated the representation of model performance in Figure 6, where we show how well the model reproduces the warming rate and its response to evaporative fraction. The overall performance of model has slightly improved after considering the contribution of diurnal aerodynamic conductance.
5. Figure 7 demonstrates the contribution of each term in cooling diurnal range of surface temperature. In the revised version we also distinguish the contribution of mean aerodynamic conductance and its diurnal variation. For better interpretation, we have summarized the contributions in percentage, See Lines 488 to 497.
6. We realize that our findings and their implications require more discussion, that is why we

have added two new paragraphs in the discussion section, see Lines 545-558 and 569 to 577.

7. Conclusions of our studies remain almost the same. However, we have added the following lines to demonstrate the importance of diurnal variation of aerodynamic conductance and its role in cooling diurnal temperatures.

Line 609 to 613

*“.. in forests, surface temperature is strongly aerodynamically coupled to air temperatures by their high aerodynamic conductance, so that these lack sensitivity to evaporative fraction. Hence, diurnal temperature variations of forested sites do not seem to carry a notable effect of evaporation. What this shows is that the effect of evaporative conditions on diurnal temperature variations delicately depends on the presence or absence of forests.
And Line 658 to 661”*

8. We have updated figure A3 that shows the mean morning time aerodynamic conductance of each site.

- Plots using green and red are going to be difficult to read for colorblind people.

In this version of the manuscript we use dark red, grey and blue color for short vegetation, savanna and forests, respectively. In addition to distinguishing colors, we also use different symbols in scatter plots.

Imprints of [evaporative conditions](#) and vegetation type in diurnal temperature variations

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Abstract. Diurnal temperature variations are strongly shaped by the absorption of solar radiation, but evaporation, or the latent heat flux, also plays an important role. Generally, evaporation cools. Its relation to diurnal temperature variations, however, is unclear. This study investigates the diurnal response of surface and air temperatures to [evaporative conditions](#) for different vegetation types. We use the warming rate, [defined as the increase](#) of temperature [in response](#) to absorbed solar radiation in the morning, and evaluate how [it changes with](#) evaporative fraction, [which is an indicator of the evaporative conditions](#). Results for 51 FLUXNET sites show that the [warming rate](#) of air temperature carries very weak imprints of [evaporative fraction](#) across all vegetation types. However, [the](#) warming rate of surface temperature [is strongly sensitive to](#) evaporative [fraction with a value of](#) $\sim 23 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$, [indicating stronger evaporative cooling for moister](#) conditions. Contrarily, warming rates of surface and air temperatures are similar at forest sites and carry literally no imprints of [evaporative fraction](#). We explain these contrasting patterns with an [analytical](#) surface energy balance model. The [derived expressions](#) reproduce [the observed](#) warming rates [and their sensitivity](#) to evaporative [fraction in all vegetation types](#). [Multiplying the warming rate with daily maximum solar radiation gives an approximation for the](#) diurnal [surface](#) temperature [range \(DT_sR\)](#). We use our model [to](#) compare the individual contributions of solar radiation, evaporative conditions and vegetation [\(by its aerodynamic conductance\)](#) in shaping [DT_sR and show that](#) the high aerodynamic conductance of forests reduces [DT_sR substantially more \(-56%\) than evaporative cooling \(-22%\)](#). We further show that the strong diurnal variation of aerodynamic conductance (~ 2.5 times of the mean across vegetation types) reduces [DT_sR by ~35 % in short vegetation and savanna, but only by ~22% in forests](#). We conclude that diurnal temperature variations [may](#) be useful to predict evaporation for short vegetation. In forests, however, the diurnal variations in temperatures are mainly governed by their [high](#) aerodynamic [conductance](#) resulting in [negligible](#) imprints of [evaporative conditions](#).

1 Introduction

Temperature is one of the most widely monitored variables in meteorology. Besides being important for our day-to-day activities, temperature serves as a primary attribute for the understanding of Earth system processes. The diurnal variation of temperature is considered informative in climate science, as described by the diurnal temperature range (DTR), which is basically the difference between daily

maximum and minimum temperatures. Information on the diurnal temperature range has facilitated a broad spectrum of research including agriculture, health welfare, climate change and ecological studies.

Over land, the diurnal variation of temperature is mainly driven by the solar energy input (Bristow and Campbell, 1984). Liu et al., (2004) shows a high correlation of 0.88 between the annual solar radiation and DTR in China. Likewise, Makowski et al., (2009) found their annual correlation to be 0.87 for Europe. Their obvious and still intricate association is also important in determining the influence of solar dimming and brightening on diurnal temperature variations (Wang and Dickinson, 2013; Wild, 2005).

Solar radiation is the dominant, but not the only factor shaping the diurnal temperature. Available energy at the surface is partitioned into latent and sensible heat flux. A higher latent heat flux signifies higher evaporation, which reduces the temperature through evaporative cooling, an effect that can be seen in [sensitivity simulations with a](#) global climate model to land evaporation (Shukla and Mintz, 1982). Another climate model-based analysis (Mearns et al., 1995) shows that differences in evaporation explain 52% of the variance in DTR in the summer season for the USA. Similarly, climate model simulations also show the high sensitivity of DTR to evaporation especially in the summer season when evaporation is not energy limited (Lindvall and Svensson, 2015). Consequently, methods to estimate evaporation use air temperature (Blaney and Criddle, 1950; Hargreaves and Samani, 1985; Thornthwaite, 1948) and remotely sensed surface temperature (Anderson et al., 2012; Boegh et al., 2002; Jackson et al., 1999; Kustas and Norman, 1999; Price, 1982; Su et al., 2007). Most of the surface energy [balance](#)-based estimates of evaporation use DTR as an input (Baier and Robertson, 1965; Vinukollu et al., 2011; Yao et al., 2013).

Clouds and precipitation are also important factors that determine DTR (Dai et al., 1999; Stenchikov and Robock, 1995). One can exclude their contribution to some extent by considering only clear sky days to [distinctly](#) identify the role of [evaporative conditions](#) on DTR. Furthermore, the partitioning of the turbulent heat fluxes into sensible and latent heat is also influenced by vegetation type. Taller vegetation has a higher aerodynamic conductance that facilitates mass and heat exchange between land and atmosphere (Jarvis and McNaughton, 1986). The greater [aerodynamic](#) conductance in forests reduces their DTR by reducing their maximum temperatures (Bevan et al., 2014; Gallo, 1996; Jackson and Forster, 2010). Few studies captured the impact of aerodynamic properties of vegetation on temperature, for example, in terms of the decomposed temperature metric theory (Juang et al., 2007; Luyssaert et al., 2014) and the theory of intrinsic biophysical mechanism (Lee et al., 2011a; Zhao et al., 2014a). Generally, the lower temperatures of forests are associated with their mean evaporative environment, although this may be affected by periods of dry and [moist](#) conditions.

In this study, we investigate how the diurnal variation in surface and air temperature responds to changes in evaporative conditions in different vegetation types. Clearly, DTR is not independent of solar radiation, which is why we develop an alternative [indicator](#), the warming rate (Panwar et al., 2019), that eliminates the contribution of solar radiation. To illustrate this, [the](#) observed [normalized](#)

diurnal air and surface temperatures are plotted against absorbed solar radiation for a cropland and forest site in Figure 1. Surface temperature is obtained from upwelling longwave radiation from the surface and air temperature above the canopy, usually measured at 2 m height. The diurnal evolution of temperature is mainly governed by the absorbed solar radiation (R_s); this is discernible from the linear increase in the morning ($20 \text{ W m}^{-2} \leq R_s \leq R_{s,\text{max}}$), as described by the slope. This dependence is accounted for by what we refer to as the warming rate, the increase in temperature due to a unit increase in the absorbed solar radiation, expressed as the derivative dT_a/dR_s for air temperature and dT_s/dR_s for surface temperature with units of $\text{K (W m}^{-2}\text{)}^{-1}$. One can approximate the warming rate by the ratio of DTR to maximum solar radiation, $R_{s,\text{max}}$, so that the warming rate can be seen as an efficient characteristic that captures effects on DTR that are not caused by solar radiation. In this study, we use linear regressions of observed data from the morning to noon to calculate warming rates.

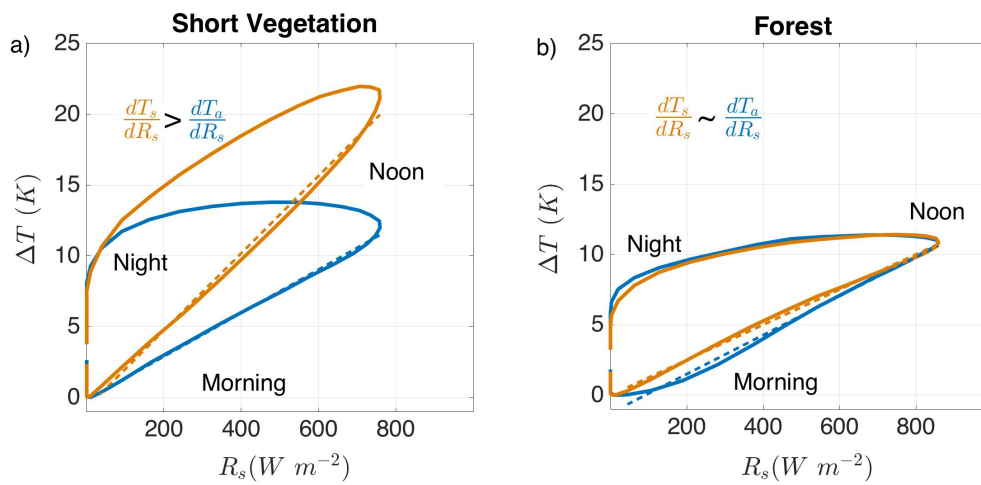


Figure 1 Mean diurnal hysteresis formed by plotting the normalized diurnal temperature ($\Delta T \equiv T - T_{\text{min}}$) against absorbed solar radiation (R_s) for summer clear sky days. Surface temperature (T_s) is depicted in orange and air temperature (T_a) in blue. (a) A short vegetation cropland site (US-ARM) in Southern Great Plains Lamont OK, United States. (b) A forest site (CA-TP4) in Ontario, Canada. The dashed lines are the linear regression of the observations falling in the morning slope of the hysteresis that corresponds to the warming rate of air (dT_a/dR_s) and surface temperature (dT_s/dR_s).

The temperature warming rate provides insights on the effects of vegetation on the diurnal variation of temperatures. Figure 1a shows a greater surface temperature warming compared to air temperature for a cropland site. Contrarily to the short vegetation site, the warming rates of the two temperatures are similar for a forest site (Figure 1b). This indicates the strong aerodynamic coupling of diurnal air and surface temperatures in forests compared to short vegetation.

Certainly, it is intriguing to find out how evaporative conditions alter this coupling. In our earlier work (Panwar et al., 2019) we looked at the temperature warming rate for a cropland site in the Southern Great Plains (which is shown in Figure 1a). We observed that the warming rate of surface temperature decreases from dry (less-evaporative, sensible heat flux dominates) to moist (evaporative, latent heat

[flux dominates](#)) conditions but the warming rate of air temperature remained unaffected. Combining the boundary layer information and heat budget expression we explained that the diurnal variation of air temperature does not contain the imprints of [evaporative conditions](#) due to the compensating role of boundary layer development. If this is a general finding, then the surface temperature warming rate can be used for estimating [evaporative conditions](#) of short vegetation. [Furthermore](#), it is also interesting to see how evaporative cooling competes with the cooling effect [of a](#) higher aerodynamic conductance [of](#) [forests](#).

In this study, we approach two major questions to advance our understanding of diurnal temperature variations: a) Do the diurnal variations of surface and air temperature respond to [evaporative conditions](#)? And b) what is the role of the aerodynamic conductance of vegetation in altering these responses? Our previous work (Panwar et al., 2019) shows the stronger imprints of [evaporative conditions](#) in diurnal surface temperature variations [in a cropland site](#). Here we examine the generality of this finding in short vegetation. Additionally, to understand the role of aerodynamic conductance in modifying these imprints we analyze data from the taller and more complex vegetation like savanna and forests.

We first present a model based on the surface energy balance to provide an expression for the [diurnal temperature variation](#) and its response to [changes in](#) [evaporative conditions](#) and aerodynamic conductance (all variables used are summarized in Table A1). [Previous studies \(Mallick et al., 2013; Ronda et al., 2001; Steduto and Hsiao, 1998\) show diurnal variations in aerodynamic conductance, which is also considered in our model.](#) To evaluate our model, we used observations from 51 FLUXNET sites that include short vegetation, savanna and forests. Surface and air temperature warming rates and their response to [evaporative conditions](#) are quantified for each site.

[The observational analysis is followed by a demonstration of](#) our model [performance that](#) reproduces observed temperature warming rates and their response to [evaporative conditions](#). [Using our model, we analyze the factors shaping the diurnal range of surface temperature \(DT_sR\). For this, the diurnal temperature range is obtained](#) by combining the warming rates with the information on solar radiation. [We](#) conclude the study by demonstrating the contribution of solar radiation, [evaporative fraction](#), aerodynamic conductance, [and its diurnal variation](#) in shaping DT_sR, using our observational analysis and model.

2 Modeling temperature-warming rate

Surface and air temperatures possess a strong diurnal variation that is driven by the absorption of solar radiation. The amplitude of this variation is also affected by other components of [the](#) surface energy balance, among which the partitioning of turbulent heat fluxes into latent and sensible heat is important. Generally, the surface energy balance is written as

$$R_s = R_{l,net} + LE + H + G . \quad \text{Eq. (1)}$$

Here, R_s is the absorbed solar radiation at the surface, $R_{l,net}$ is the net longwave radiation, LE is the latent heat flux (with L being the latent heat of vaporization and E the evaporation rate), H is the sensible heat flux and G is the ground heat flux. For simplification of the surface energy balance we linearize $R_{l,net}$ using the first order terms, such that $R_{l,net} = R_o + k_r (T_s - T_{ref})$. Here, R_o is the net radiation at a reference temperature T_{ref} . The second term, $k_r = 4 \sigma T_{ref}^3$ is the linearization constant. Incorporating this simplification of $R_{l,net}$ in Eq. (1), the surface energy balance can be rearranged to yield an expression for T_s ,

$$T_s = T_{ref} + \frac{R_s - R_o - LE - H - G}{k_r} \quad \text{Eq. (2)}$$

The warming rate of surface temperature is obtained by taking the derivative of Eq. 2 with respect to absorbed solar radiation, R_s , such that

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

Since, R_o and T_{ref} are assumed to be constants and do not vary diurnally with R_s , they disappear in Eq. (3). Additionally, it is assumed that the diurnal change in G in response to R_s is negligible ($dG/dR_s \sim 0$) compared to the other components of surface energy balance. This assumption is valid since we are considering vegetated sites for our study, although we are aware that for non-vegetated surfaces G can represent a noticeable share of absorbed solar radiation (Clothier et al., 1986; Kustas and Daughtry, 1990).

We describe the evaporative conditions by the evaporative fraction (f_e), the ratio of the latent heat flux (LE) to the total turbulent heat fluxes ($H + LE$). Given this, the term $H + LE$ in Eq. (3) can be written as $H/(1 - f_e)$, which yields

$$\frac{dT_s}{dR_s} = \frac{1}{k_r} - \frac{1}{k_r} \cdot \frac{1}{(1 - f_e)} \cdot \frac{dH}{dR_s} \quad \text{Eq. (4)}$$

Furthermore, the sensible heat flux can be expressed in terms of the aerodynamic conductance as $H = c_p \rho g_a (T_s - T_a)$, where $c_p = 1005 \text{ J kg}^{-1} \text{ K}^{-1}$ is the specific heat capacity of air, $\rho = 1.23 \text{ kg m}^{-3}$ is air density, g_a is the aerodynamic conductance, and $T_s - T_a$ is difference between surface and air temperature.

To use Eq. (4) to estimate warming rates, information is needed on dH/dR_s . Typically, H increases linearly with R_s in the morning, so that the derivative dH/dR_s is constant. Thus, the instantaneous response of H to R_s is equivalent to the mean response, such that dH/dR_s can be expressed as

$$\frac{dH}{dR_s} = c_p \cdot \rho \cdot \left[(\overline{T_s - T_a}) \cdot \frac{dg_a}{dR_s} + \overline{g_a} \cdot \frac{d(T_s - T_a)}{dR_s} \right] \quad \text{Eq. (5)}$$

Here, $(\overline{T_s - T_a})$ and $\overline{g_a}$ are the morning to noon means of $T_s - T_a$ and g_a . The diurnal variations of g_a and $T_s - T_a$ are captured by the terms dg_a/dR_s and $d(T_s - T_a)/dR_s$. When including Eq. (5) in Eq. (4), we get an approximation for the surface temperature warming rate given by,

$$\frac{dT_s}{dR_s} = \frac{(1 - f_e) - c_p \cdot \rho \cdot [(\overline{T_s - T_a}) \cdot dg_a/dR_s - \overline{g_a} \cdot (dT_a/dR_s)]}{k_r \cdot (1 - f_e) + c_p \cdot \rho \cdot \overline{g_a}} \quad \text{Eq. (6)}$$

Here, dT_a/dR_s is the warming rate of air temperature. We can further simplify this expression by considering the two terms in the denominator of Eq. (6). Considering $T_{ref} \sim 288$ K, the term $k_r (1 - f_e)$ varies between $\sim 4.87 \text{ W m}^{-2} \text{ K}^{-1}$ and $\sim 0.54 \text{ W m}^{-2} \text{ K}^{-1}$ from dry ($f_e=0$) to moist ($f_e=1$) conditions, which is much smaller in magnitude compared to the term $c_p \cdot \rho \cdot \overline{g_a}$ that is $\sim 60 \text{ W m}^{-2} \text{ K}^{-1}$ for a typical cropland site ($\overline{g_a}=0.05 \text{ m s}^{-1}$) and $250 \text{ W m}^{-2} \text{ K}^{-1}$ for a typical forest site ($\overline{g_a}=0.2 \text{ m s}^{-1}$). Because of these magnitudes, the term $k_r (1 - f_e)$ can be neglected. This leads to a further simplification of the warming rate to

$$\frac{dT_s}{dR_s} \approx \frac{(1 - f_e)}{c_p \cdot \rho \cdot \overline{g_a}} + \frac{dT_a}{dR_s} - \frac{(\overline{T_s - T_a})}{\overline{g_a}} \cdot \frac{dg_a}{dR_s} \quad \text{Eq. (7)}$$

Eq. (7) shows that the morning to noon warming rate of surface temperature is a function of evaporative fraction, the warming rate of air temperature, the mean difference of surface and air temperature, the mean aerodynamic conductance, and also the sensitivity of aerodynamic conductance to solar radiation. On multiplying Eq. (7) with daily maximum solar radiation shall provide an approximation of diurnal range of surface temperature (DT_sR)

$$DT_sR \approx \frac{(1 - f_e)}{c_p \cdot \rho \cdot \overline{g_a}} \cdot R_{s,max} + DT_aR - \frac{\overline{T_s - T_a}}{\overline{g_a}} \cdot \frac{dg_a}{dR_s} \cdot R_{s,max} \quad \text{Eq. (8)}$$

The DT_sR approximation can be validated with the observational data. Using Eq. (8), the contribution of f_e , $\overline{g_a}$, and dg_a/dR_s in shaping DT_sR can be quantified.

Next, the sensitivity of the warming rate to changes in evaporative conditions is obtained by taking the derivative of Eq. (7) with respect to evaporative fraction (f_e). To express these derivatives with respect to evaporative fraction, we use the prime ($dx/df_e = (x)'$). Therefore, $(dT_s/dR_s)'$ and $(dT_a/dR_s)'$

represent the change in surface and air temperature warming rates due to a unit change in evaporative fraction. [The sensitivity of the warming rate of surface temperature to evaporative fraction is](#)

$$\left(\frac{dT_s}{dR_s}\right)' = -\frac{1}{c_p \cdot \rho \cdot \overline{g_a}} + \left(\frac{dT_a}{dR_s}\right)' - \left[\frac{(\overline{T_s} - \overline{T_a})}{\overline{g_a}} \cdot \frac{dg_a}{dR_s}\right]' \quad \text{Eq. (9)}$$

Eq. (9) is a negative quantity provided $(dT_a/dR_s)'$ [and the third term response to evaporative fraction are](#) small (or negative). The negative sign means that the warming rate decreases with [an](#) increase in evaporative fraction. The amplitude of this decrease mainly depends on the [mean](#) aerodynamic conductance ($\overline{g_a}$) and also on its [diurnal](#) sensitivity to [solar radiation](#) (dg_a/dR_s).

[We next look into observations to obtain the values in Eq. 7 to predict the warming rate of surface temperature: \$f_e\$, \$\overline{g_a}\$, \$\overline{T_s} - \overline{T_a}\$, and \$dg_a/dR_s\$. Likewise, using Eq. \(9\) requires the observations to quantify the sensitivities of the components of its third term \(\$\overline{T_s} - \overline{T_a}\$, \$1/\overline{g_a}\$, and \$dg_a/dR_s\$ \) to evaporative fraction. We derive these quantities from observations to then show that Eq. 7 reproduces the warming rate of surface temperature and its sensitivity to evaporative fraction using Eq. \(9\). Lastly, using the values from observations and our model expression for \$DT_sR\$, shown in Eq. \(8\), we estimate the contribution of the evaporative fraction and aerodynamic properties in shaping the magnitude of the diurnal surface temperature range.](#)

3 Data and method

We use observations from 51 FLUXNET sites representing different vegetation types. The FLUXNET data consists of sensible and latent heat fluxes using the standard eddy covariance method and provides half hourly radiation and meteorological data (Baldocchi et al., 2001). The selected 51 sites contain data of the surface energy balance components and temperatures for more than four years. To avoid the effect of energy limitation on evaporation, only summer days are considered. Summer is defined here as days having [greater](#) daily mean incoming solar radiation at the surface than the median of the annual distribution. This approach standardizes the definition of summer days for sites at different latitudes and provides the days with comparable solar energy input for the individual sites.

Furthermore, among summer days, only clear sky days are considered to avoid the influence of clouds on temperatures. [A](#) filter to remove cloudy days is applied that is based on the quantile regression method using surface solar radiation and potential solar radiation (Renner et al., 2019). This method was applied only from morning to noon, so that the day with clouds [in the evening](#) is also considered as a clear sky day. This does not influence warming rates since they are calculated only from the morning to noontime variation of temperature.

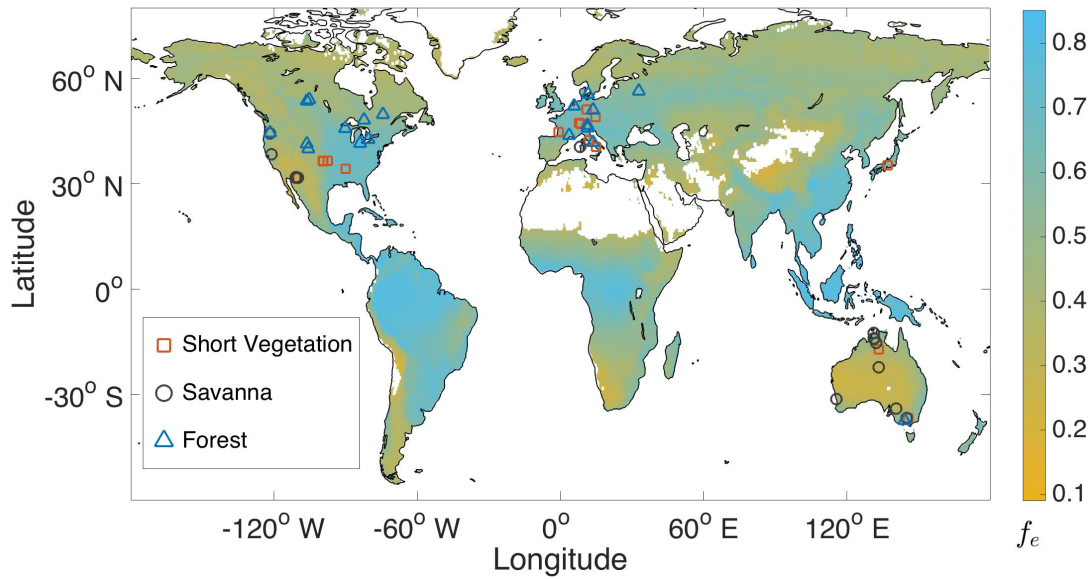


Figure 2 Geographical locations of FLUXNET sites used in this study. The vegetation type at each site is shown by the symbols. The color bar shows the mean annual evaporative fraction (f_e) derived from FLUXCOM data (year: 2001 to 2013).

The information on vegetation type is obtained from the FLUXNET land cover classification (Falge et al., 2017), which is based on the International Geosphere-Biosphere Programme (IGBP) Data and Information System. The IGBP land cover product is available at 1 km resolution and was derived from the Advance Very High Resolution Radiometer (Loveland and Belward, 1997). Detailed information of each site with their location, number of days used in the analysis, land cover type and references is provided in the Appendix (Table A2). Vegetation are classified into three types that is based on their typical height and coverage, see Table 1. Shorter vegetation like croplands, grasslands, and shrublands are grouped into the ‘short vegetation’ type. Savanna ecosystems are complex with heterogeneous vegetation height, which basically delineates the transition of short vegetation to forests, and are grouped into the ‘savanna’ type. All forest types, including deciduous broadleaf, evergreen broadleaf, evergreen needleleaf and mixed, are grouped in the ‘forest’ type.

The geographic location of the selected 51 sites is shown in Figure 2. The color bar represents the mean annual evaporative fraction derived from FLUXCOM data (Jung et al., 2019; Tramontana et al., 2016). Selected sites represent a wide range of ecosystems that is ideal for studying the generality of the response of warming rates to differences in evaporative conditions and vegetation type.

Table 1. Land cover types of the different sites considered here and their grouping into the short vegetation, savanna and forest types.

| Vegetation types | Land use type | Number of sites |
|------------------|---------------|-----------------|
| Short Vegetation | Cropland | 12 |

| | | |
|---------|------------------------------|---|
| | Grassland | 6 |
| | Shrubland | 5 |
| Savanna | Savanna | 4 |
| | Woody Savanna | 5 |
| Forest | Deciduous broadleaf forest | 4 |
| | Evergreen broadleaf forest | 1 |
| | Evergreen needle leaf forest | 9 |
| | Mixed forest | 5 |

Evaporative conditions are quantified by evaporative fraction. One of the advantages of the evaporative fraction is its stability for daylight hours such that it can be assumed to be constant over a day (Shuttleworth et al., 1989). The daily mean evaporative fraction is obtained by the linear regression of half hourly morning to noon values of latent heat flux to the total turbulent heat fluxes. Similarly, a linear regression of daily mean warming rates and daily mean evaporative fractions is used to quantify the sensitivity of the warming rate to evaporative fraction.

We use the term air temperature for the temperature measured above the canopy, which is typically at 2 meters height. Surface temperature is calculated from the upwelling flux of longwave radiation using the Stefan-Boltzmann law, such that it represents the skin temperature of the vegetated surface. The aerodynamic conductance (g_a) is obtained from the observed sensible heat flux from $g_a = H / (c_p \cdot \rho \cdot (T_s - T_a))$. Since aerodynamic conductance is not constant over the day, its diurnal variation is described by dg_a/dR_s , which is estimated from a linear regression of morning to noon half hourly values of g_a and R_s .

4 Results

4.1 Observational analysis

The primary advantage of the warming rate over DTR is its suitability to compare sites with different solar energy input. This is apparent from Figure 3, where we show the density distribution of the observed daily warming rates of (a) surface and (b) air temperatures for short vegetation, savanna, and forest. The warming rates of surface temperature for short vegetation, with a median value of $31.42 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$ are larger by almost a factor of two compared to the respective warming rates of forests with a median value of $15.47 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$. Savanna covers the range in warming rates of surface temperature with a median value of $27.09 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$, reflecting their characteristics being positioned between short vegetation and forests. Hence, the warming rates of surface temperature clearly show similar characteristics across different sites as well as a clear influence of vegetation type.

Surprisingly, this is not true for the warming rates of air temperature. All vegetation types show very similar distributions (Figure 3b). For short vegetation, this distribution is markedly shifted to smaller values, with a median of $12.32 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$, than the respective distribution for the warming rates

of surface temperature. Conversely, in forests, the distributions are similar (with a median of $11.13 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$), indicating the strong aerodynamic coupling between surface and air temperatures. The distribution for savanna has a median of $14.43 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$.

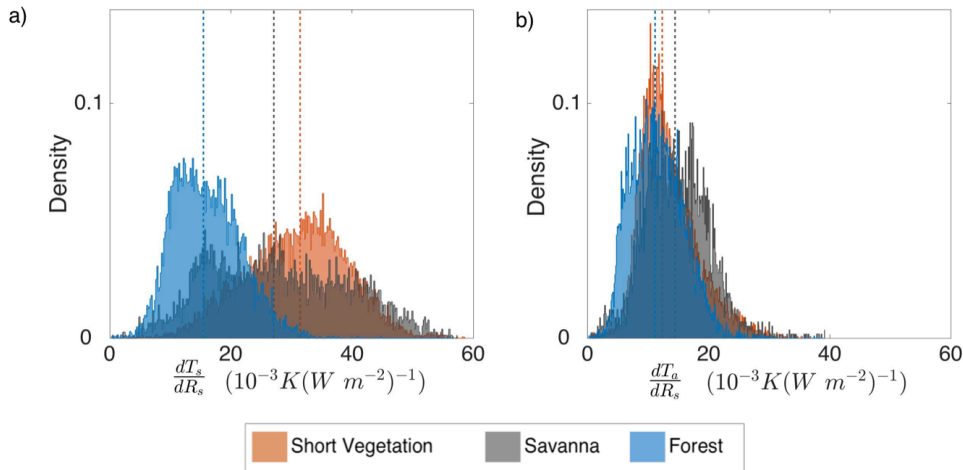


Figure 3 Density distribution of observed warming rates of (a) surface temperature and (b) air temperature for short vegetation, savanna, and forest. The vertical dashed lines indicate the median of each distribution in the respective colors of the vegetation types.

Within the short vegetation type, grassland and shrubland sites show much greater warming rates of surface temperature than cropland sites (Site-specific information on warming rates is provided in Figure A1 in the Appendix). This distinction could be attributed to site-specific evaporative conditions. Most of the shrubland sites are drier, while cropland sites are generally moister. Such an uneven distribution of evaporative conditions could impact the estimation of warming rates, such that it is higher for dry and lower for moist sites. On the other hand, despite these differences in the mean evaporative conditions, the sites contain days with a good range of evaporative fractions (see Figure A2 in Appendix). The range of evaporative fractions is important for the estimation of the sensitivity of the warming rates to evaporative fraction.

Next, we quantify the sensitivity of warming rates to evaporative fraction, $(dT/dR_s)'$, from the linear regression of the daily means. The value of this sensitivity represents the change in warming rate from dry ($f_e=0$) to moist ($f_e=1$) conditions, although we should note that these extreme values for the evaporative fraction are hypothetical. Figure 4 shows the mean sensitivity of the warming rates of surface (orange) and air (blue) temperature to evaporative fraction for short vegetation, savanna and forest (for site-specific responses, see Figure A2 in the Appendix). The sensitivity for short vegetation shows a strong decrease of $\sim 23 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$ for surface temperature, but a much smaller decrease by $\sim 5 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$ for air temperature. In our earlier work, similar responses were found for a cropland site (Figure A2, site no. 8). The savanna vegetation type shows a weaker decrease of $\sim 12 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$ for surface temperature, but the warming rate of air temperature is almost insensitive

to evaporative fraction. In forests, both warming rates show very weak to almost no sensitivity to evaporative fraction.

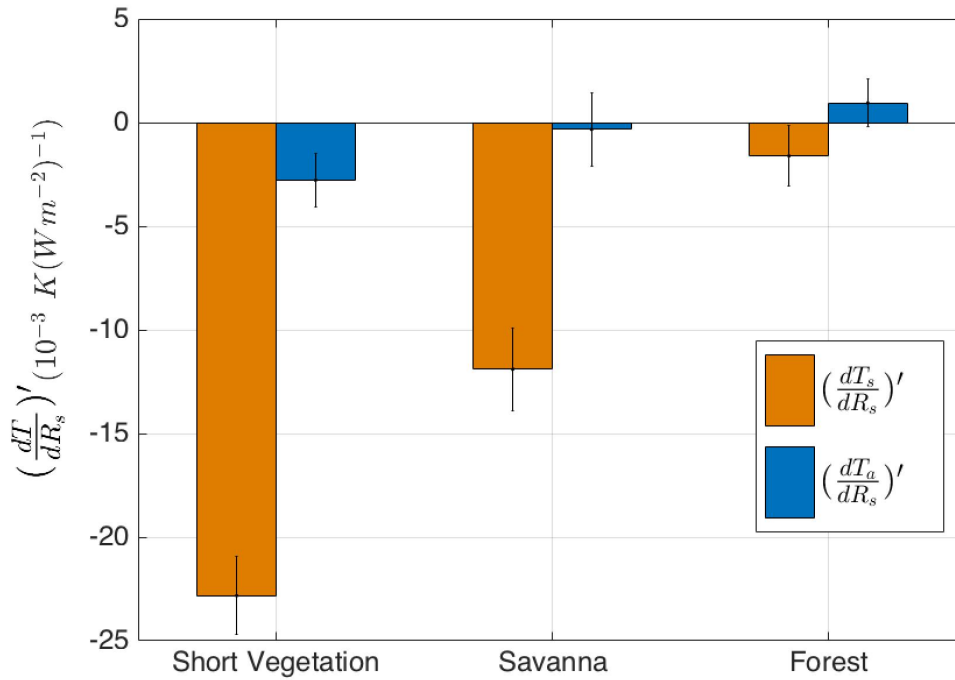


Figure 4 Bar plot of the sensitivity of warming rates of surface $(dT_s/dR_s)'$ and air $(dT_a/dR_s)'$ temperatures to evaporative fraction from observations for short vegetation, savanna, and forests. The error bars represent the standard error of the mean.

In addition to evaporative fraction, the aerodynamic conductance also influences the diurnal variation of temperatures. The aerodynamic conductance governs the ventilation of energy and mass from the surface to the atmosphere (Thom, 1972). Figure 5a shows the density distribution of morning to noon mean of aerodynamic conductance for the short vegetation, savanna, and forest sites. The mean aerodynamic conductance is usually a characteristic of vegetation height (Jones, 1992). We find that the aerodynamic conductance of short vegetation is much lower (median=0.022 m s⁻¹) than for forest (median=0.32 m s⁻¹). Savanna sites have similar aerodynamic conductance (median=0.023 m s⁻¹) as short vegetation but some woody savanna sites show relatively higher aerodynamic conductance (as shown by the second peak around 0.08 m s⁻¹ in the distribution in Figure 5a).

Aerodynamic conductance typically increases substantially during the day, increasing roughly linearly with absorbed solar radiation, which is captured by dg_a/dR_s (Figure 5b). The positive sign of dg_a/dR_s reflects the increase in g_a from morning to noon, which is found for all vegetation types. Forest sites show a stronger increase, but note that these sites also have higher mean aerodynamic conductance. Overall, the aerodynamic conductance at noon is ~2.5 times the mean value across all vegetation types (calculated with a $R_{s,max}=1000 \text{ W m}^{-2}$), indicating similar relative diurnal variations (see Table 2). In other words, the relative sensitivity of aerodynamic conductance, $1/\bar{g}_a \cdot dg_a/dR_s \approx$

$2.5 \times 10^{-3} (\text{W m}^{-2})^{-1}$ is about the same across the different sites. Because a greater aerodynamic conductance is expected to cool the surface more effectively, we expect that the diurnal increase in aerodynamic conductance shall reduce the warming rates of surface temperature (which can also be seen in Eq. 7, where the last term on the right-hand side is negative). Thus, in addition to the mean aerodynamic conductance, its diurnal variation is another important factor, which shapes the diurnal variation of temperatures.

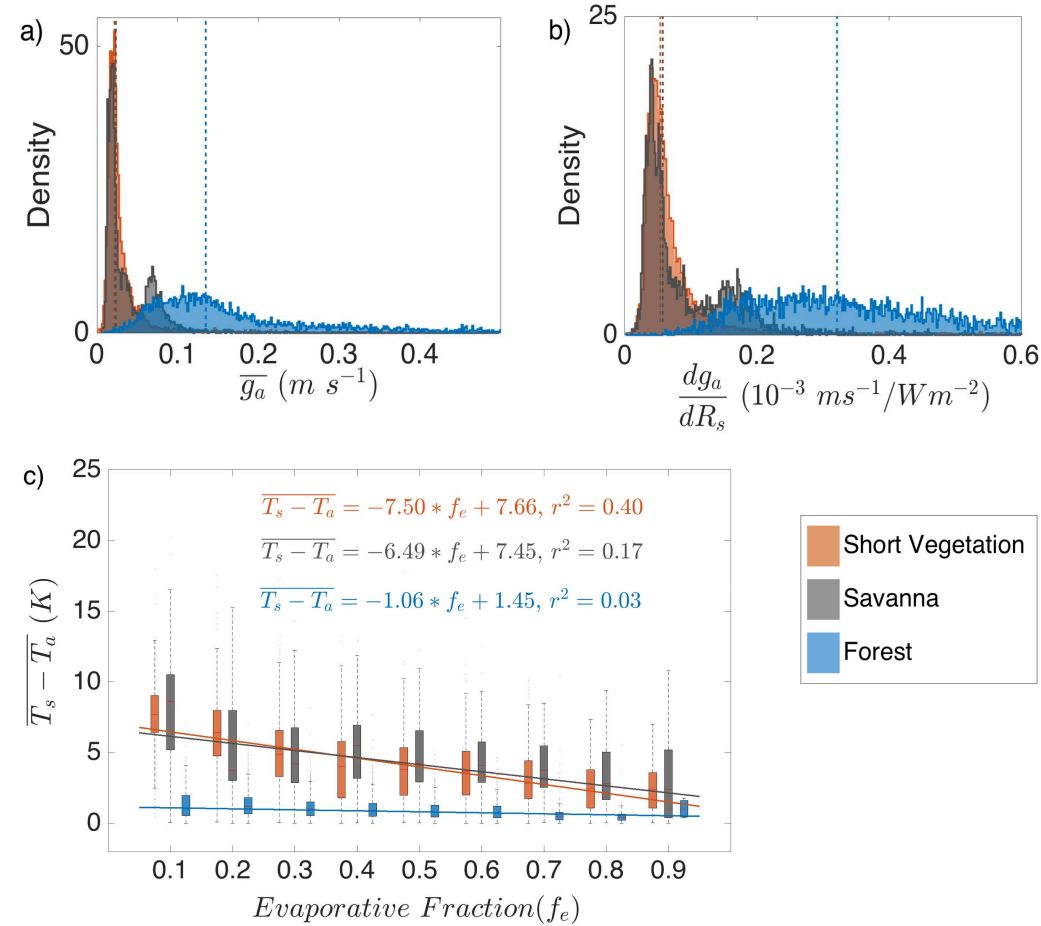


Figure 5 Density distributions inferred from observations of the morning to noon (a) mean aerodynamic conductance ($\overline{g_a}$), and (b) its sensitivity to solar radiation (dg_a/dR_s). The vertical dashed lines show the medians of the distributions. Also shown in (c) is the sensitivity of the morning to noon mean surface and air temperature difference ($\overline{T_s - T_a}$) to evaporative fraction, which is a sensitivity needed for the estimation of how the warming rate of surface temperature responds to evaporative fraction using Eq. (9). The bars indicate the 25th and 75th percentiles of the observations, respectively. The lines are the best fit for the linear regression of $\overline{T_s - T_a}$ and evaporative fraction for each vegetation type, with the equations and r^2 shown in the plot.

Table 2 First quartile (Q1), median, and third quartile (Q3) for the distributions of dT_s/dR_s , dT_a/dR_s , $\overline{g_a}$, and dg_a/dR_s for short vegetation, savanna and forest.

| Vegetation | dT_s/dR_s | dT_a/dR_s | $\overline{g_a}$ | dg_a/dR_s |
|------------|-------------|-------------|------------------|-------------|
|------------|-------------|-------------|------------------|-------------|

| | | $(10^{-3} \text{ K (W m}^{-2}\text{)}^{-1})$ | $(10^{-3} \text{ K (W m}^{-2}\text{)}^{-1})$ | (m s^{-1}) | $(10^{-3} \text{ m s}^{-1} / \text{W m}^{-2})$ |
|------------------|--------|--|--|---------------------|--|
| Short Vegetation | Q1 | 25.1 | 9.9 | 0.017 | 0.041 |
| | Median | 31.4 | 12.3 | 0.022 | 0.054 |
| | Q3 | 36.7 | 15.7 | 0.032 | 0.078 |
| Savanna | Q1 | 18.6 | 10.9 | 0.037 | 0.040 |
| | Median | 27.1 | 14.4 | 0.023 | 0.058 |
| | Q3 | 36.8 | 18.1 | 0.060 | 0.137 |
| Forest | Q1 | 11.8 | 8.1 | 0.093 | 0.229 |
| | Median | 15.5 | 11.1 | 0.135 | 0.321 |
| | Q3 | 19.7 | 14.3 | 0.204 | 0.444 |

To estimate the warming rate of surface temperature and its sensitivity to evaporative fraction using Eqns. 7 – 9, we also need to know the mean difference of surface and air temperature ($\overline{T_s - T_a}$). We find that $\overline{T_s - T_a}$ is higher in short vegetation and savanna compared to forest sites. Additionally, $\overline{T_s - T_a}$ decreases on days with high evaporative fraction in short vegetation and savanna, but not in forests. Betts and Ball (1995) showed a similar sensitivity of $\overline{T_s - T_a}$ to evaporative conditions in a grassland site. Unlike $\overline{T_s - T_a}$, we found no such sensitivity of $\overline{g_a}$ and dg_a/dR_s to evaporative fraction. This finding is different to the study by Rigden and Li (2017) who showed that the aerodynamic resistance depends on the Bowen ratio. This difference can be attributed to their way to estimate aerodynamic resistance from the frictional velocity and wind speeds, which assumes neutral conditions, whereas we obtain aerodynamic conductance from sensible heat flux.

Given that only the mean temperature difference, $\overline{T_s - T_a}$, is sensitive to evaporative fraction while $\overline{g_a}$ and dg_a/dR_s are not, the last term in Eq. (9) reduces to the sensitivity of this temperature difference to evaporative fraction. This sensitivity is shown in Figure 5c. The third term of Eq. (9) thus depends mostly on $(\overline{T_s - T_a})'$ because the relative diurnal variation of aerodynamic conductance ($1/\overline{g_a} \cdot dg_a/dR_s$) is similar for all vegetation types.

To summarize our analysis of observations, we found that the diurnal variation of surface temperature of short vegetation showed much stronger imprints of evaporative conditions than air temperature. In forests, the diurnal variations of both, surface and air temperature, were found to be insensitive to evaporative conditions. The mean aerodynamic conductance derived from observations confirm the characteristic high values for forests compared to short vegetation. Additionally, we found a strong diurnal variation of the aerodynamic conductance that in relative terms is comparable for all vegetation types.

To explain these findings, we hypothesize that the high aerodynamic conductance of forests lowers the diurnal increase in surface temperature, as it provides greater ventilation. Since air temperatures do not respond to evaporative fraction, we therefore expect the warming rate of surface temperature of forests

to be less sensitive. This can already be anticipated from Eq. 9, together with the values provided in Table 2 and the sensitivities shown in Figure 5c. Using these values, Eq. 9 yields an estimate for the sensitivity of the warming rate of surface temperature to evaporative fraction for short vegetation of about $-24 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$ and $-4 \times 10^{-3} \text{ K (W m}^{-2}\text{)}^{-1}$ for forests, similar to what is shown in Figure 4. In the following, we verify our model expression in greater detail.

4.2 Model application and interpretation

To estimate the warming rate of surface temperature using Eq. (7) in greater detail, we used daily values of observed f_e , $\overline{g_a}$, dT_a/dR_s , $\overline{T_s - T_a}$, and dg_a/dR_s . Since dT_a/dR_s is similar for all sites, the diurnal variation of air temperature does not seem to depend on the diurnal variation of surface temperature, and vice versa. Figure 6 a shows the comparison of the modeled warming rates to those derived from observations. The model performs very well for all sites for the given information, with coefficients of determination (r^2) of $r^2 = 0.69$ for short vegetation, $r^2 = 0.87$ for savanna, and $r^2 = 0.53$ for forests. Similarly, the slopes (m) of the regression between modeled and observed dT_s/dR_s are close to 1 for short vegetation (m = 0.85) and savanna (m = 0.90), meaning the dT_s/dR_s magnitudes are well captured by our model, although the slope is too low for forests (m = 0.77). However, at some sites with short vegetation, dT_s/dR_s is underestimated. We speculate that these are the sites with non-vegetated surfaces where the ground heat flux contribution to diurnal surface temperature variations can be significant (Saltzman and Pollack, 1977) which is currently neglected in our model.

It is apparent from Figure 6 a, that the warming rates for surface temperature are higher for short vegetation compared to that of forests. This is mainly due to the relatively high aerodynamic conductance of forest, which reduces the magnitude of the first and third term on the right-hand side of Eq. 7.

The greater aerodynamic conductance of forests also reduces the sensitivity of warming rates to evaporative fraction compared to short vegetation, which can be seen in Eq. (9). Note that the diurnal variation of the aerodynamic conductance is included here by the term dg_a/dR_s in our estimates. Eq. (9) reproduces the response of the warming rates to evaporative fraction quite well for all vegetation types (m = 0.88, $r^2 = 0.45$, Figure 6 b), including their ranges. Certain deviations exist because there are some biases in the number of moist and dry days in the observations that are reflected in the horizontal error bars. The other possible cause for bias is the large variation in the sensitivity of $\overline{T_s - T_a}$ to f_e in short vegetation and savanna (Figure 5c).

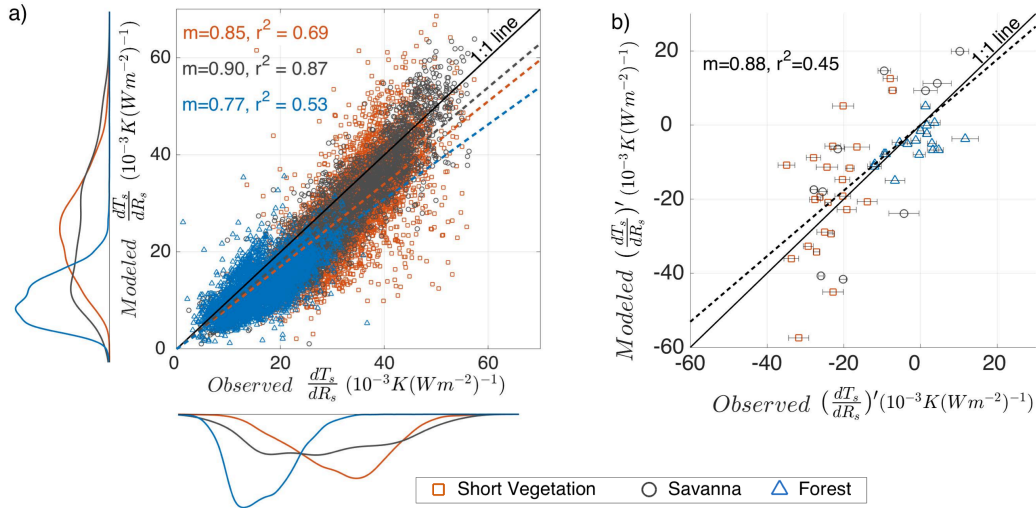


Figure 6 **a)** Modeled versus observed warming rates, dT_s/dR_s for each site, for the three vegetation types. The density distributions show the spread. The coefficient of determination (r^2) and slope (m) of the linear fit (dashed lines) are depicted for each vegetation type. **b)** Model evaluation of the sensitivity of the warming rates to evaporative fraction, $(dT_s/dR_s)'$, with those derived from observations for each site.

We next link our estimates for warming rates back to the diurnal surface temperature range (DT_sR) by multiplying the expression for the warming rate with the daily maximum of absorbed solar radiation, $R_{s,max}$ (see Eq. 8). To understand how solar radiation, evaporative fraction, and the mean aerodynamic conductance, and its diurnal variation contribute to DT_sR separately, we consider four cases. In first case, we assume that the diurnal variation in surface temperature is solely driven by solar radiation, such that there is no evaporation ($f_e = 0$) and the surface has a low and constant aerodynamic conductance of $g_a = 0.022 \text{ m s}^{-1}$, which is the median of the aerodynamic conductance of short vegetation (see Table 2). Figure 7 a shows that in this case, DT_sR is overestimated for all vegetation types (regression slope $m > 1$) with a low $r^2 \leq 0.3$. This greater warming indicates that vegetation and evaporation cools surface temperatures and reduces the diurnal surface temperature range.

In second case, we add the information on evaporative fraction (Figure 7 b). The DT_sR estimates for short vegetation ($m=1.26$, $r^2=0.55$) and to some extent for savanna ($m=1.37$, $r^2=0.46$) are considerably improved, but not for forests ($m=2.22$, $r^2=0.18$). Nevertheless, in this case, DT_sR is cooler and closer to the observed values than the previous case, indicating the importance of evaporation in cooling the diurnal temperature, although the values are still being too high, as indicated by the regression slopes being $m > 1$.

However, in forests, the information on evaporative fraction alone does not reduce DT_sR , because their high aerodynamic conductance is not accounted for. Therefore, in third case, in addition to absorbed solar radiation and evaporative fraction, we added the information on the mean aerodynamic

conductance ($\overline{g_a}$). The DT_sR in forests is now better captured ($r^2=0.35$) and the magnitude is closer to the observed ($m=0.98$), see Figure 7c. In short vegetation and savanna, however, DT_sR is still mostly overestimated. This can be attributed to the diurnal variation of the aerodynamic conductance, dg_a/dR_s , not being included in this case.

Finally, we add information on all components to our estimate (Figure 7d). DT_sR estimates are much closer to the observation with a good r^2 for all vegetation types and regression slopes are reduced to values $m < 1$, indicating a slight cold bias. Forest sites show a slight improvement in r^2 although the contribution of dg_a/dR_s is comparatively small because $\overline{T_s} - \overline{T_a}$ in the forest is small (~ 1 K).

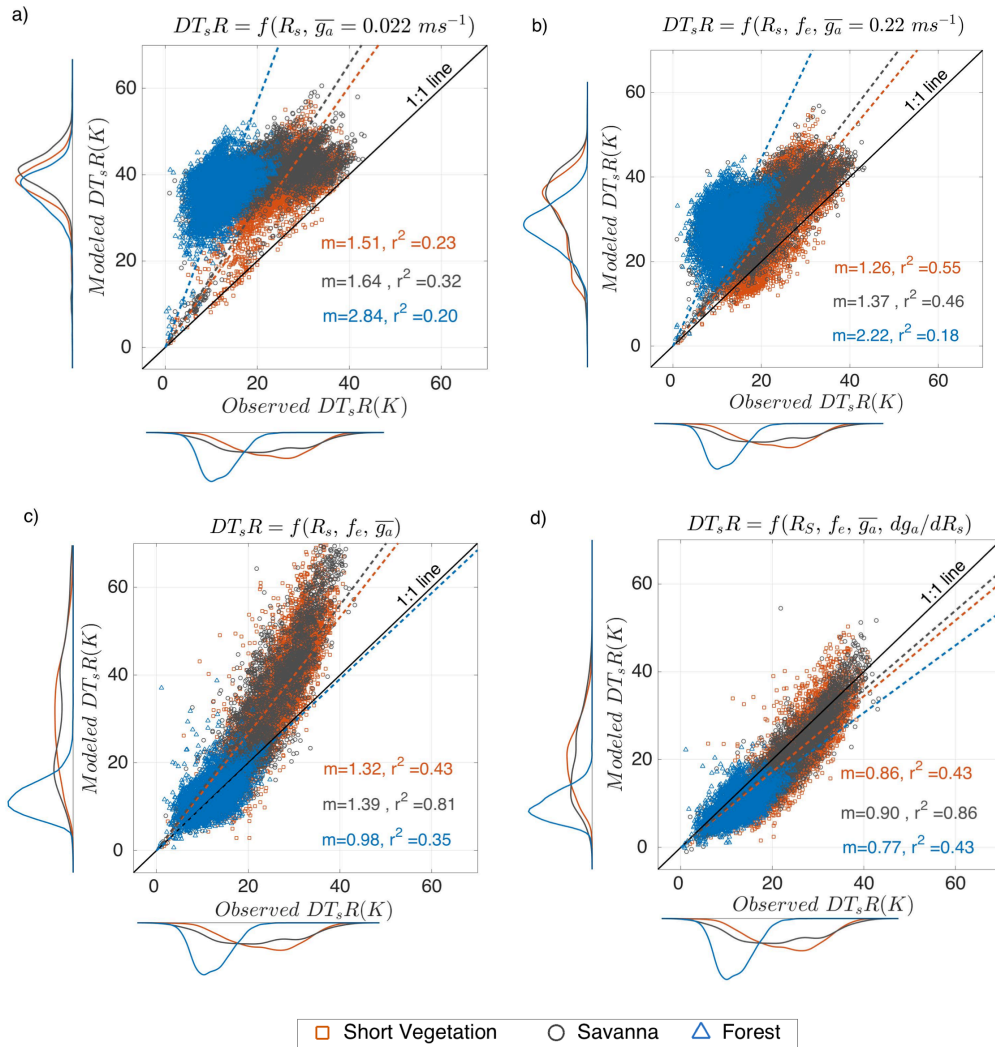


Figure 7 Comparison of the estimated diurnal surface temperature range (DT_sR) for short vegetation (red), savanna (grey) and forests (blue) with observations for four scenarios: a) DT_sR is only a function of solar radiation (R_s), b) DT_sR including the effect of evaporative fraction (f_e), c) DT_sR with the additional effect of differences in mean aerodynamic conductance between vegetation types ($\overline{g_a}$), and d) DT_sR additionally includes the effect of the diurnal variation in aerodynamic conductance,

(dg_a/dR_s). Dashed lines show the linear regression between model and observation with their slopes (m) and coefficient of determination indicated (r^2) in the plots.

These four cases show that vegetation type and evaporative conditions play significant roles in modulating the diurnal variation in surface temperature. Evaporative fraction is important to reduce the spread and magnitude (as indicated by the lower values of m and higher r^2) whereas differences in the mean aerodynamic conductance are important to capture the different magnitudes of DT_{sR} between short vegetation and forests.

The importance of these factors can be illustrated by how much they act to reduce the magnitude of DT_{sR} . This can be done by evaluating the extent to which the regression slope, m, is reduced by these factors, using the first case that only considers solar radiation as the reference case. Evaporation reduces DT_{sR} by ~18 % (short vegetation: $(1.26-1.51)/1.51 = -16.55$ %, savanna: $(1.37 - 1.64)/1.64 = -16.46$ %, and forest: $(2.22 - 2.84)/2.84 = -21.83$ %). On comparing Figure 7 b and 7c, we found that the high aerodynamic conductance of forests reduces DT_{sR} by 56 % ($(0.98 - 2.22)/2.22 = -56\%$). In other words, the higher aerodynamic conductance of forests causes a substantially larger cooling than evaporation. The diurnal variation of the aerodynamic conductance then reduces the DT_{sR} further, being stronger in short vegetation ($(0.86 - 1.32)/1.32 = -35\%$) and savanna ($(0.90 - 1.40)/1.75 = -35.25$ %) than in forests ($(0.77 - 0.98)/0.98 = -21\%$).

5 Discussion

We demonstrate a robust way of characterizing the diurnal variation of temperatures using their morning to noon warming rates, which are derived from the half hourly changes in temperatures and absorbed solar radiation. Warming rates are suitable for the analysis of other factors that affect temperatures, such as evaporation and vegetation, because the most dominant variation in temperatures caused by solar energy input is removed.

Our analytic surface energy balance model can reproduce the warming rates of surface temperature derived from observations quite well and shows the physical significance of evaporative fraction, aerodynamic conductance and its diurnal variation in shaping diurnal temperature variations. The approximations made in the derivation of Eqns. 7 and 9 can further be improved by a more detailed formulation of net longwave radiation (which could, for instance, include optical properties of the atmosphere) and the ground heat flux. Warming rates may also likely to be sensitive to clouds and might not capture the information of evaporative conditions and vegetation on cloudy days. These effects were not evaluated here because we focused the analysis on clear sky days. It may, however, very well be that the dominant effect of clouds is simply to reduce absorbed solar radiation, so that Eqns. 7 and 9 could also predict warming rates for those conditions. Also, we did not provide a way to estimate warming rates of air temperature. These could be topics for future research.

One of the main findings of our study is the contrasting response of [warming rates](#) of surface and air temperature to [evaporative fraction](#). The warming rate of air temperature does not contain any imprints of [evaporative fraction across all sites, irrespective of their](#) aerodynamic conductance and evaporative conditions. This finding is consistent with our previous work (Panwar et al., 2019), where we explained [this finding by the effect](#) of boundary layer growth [that](#) compensates [the effects](#) of different evaporative conditions. We anticipate that our hypothesis of the compensating effect of boundary layer growth might also [hold](#) for forests, but this would need further research.

The warming rate [of surface temperature is strongly sensitive to evaporative fraction](#) for short vegetation. [The mean sensitivity of \$\sim 23 \times 10^{-3} \text{ K \(W m}^{-2}\text{\)}^{-1}\$ is consistent with the reported sensitivity in Panwar et al. \(2019\).](#) This decrease is comparable for all sites with short vegetation and we anticipate that some of the spread is due to their somewhat different aerodynamic properties. Another source of uncertainty is the uneven distribution of days of different evaporative fractions, which may affect the [estimation of the sensitivity. This uncertainty could be reduced by](#) longer time series of observations to obtain a greater sampling range of [evaporative conditions](#).

The notion that surface and air temperature variations respond differently to [evaporative conditions was reported in previous research](#) (Cresswell et al., 1999; Fu et al., 2011; Hengl et al., 2012; Jang et al., 2004; Kilibarda et al., 2014; Zhu et al., 2013) [and is relevant](#) when air temperature products [are developed](#) from remotely sensed surface temperature. Typically, these products are primarily based on the assumption that surface temperature is [a](#) proxy of air temperature. Generally, these approaches overestimate daytime air temperature (Oyler et al., 2016; Zhang et al., 2011). This is consistent with our [analysis](#), which shows [markedly higher warming rates](#) of surface temperature [for non-forested vegetation than the warming rates of air temperature \(see Figure 3\). This overestimate can also be understood by the first term on the right-hand side of Eq. 7, which causes the stronger response of surface temperature compared to air temperature to changes in absorbed solar radiation.](#)

Our study shows that [the](#) warming rates of surface and air temperature are similar [at forest sites](#), which indicates the strong coupling between the two temperatures. This finding is in agreement with the previous study by Li et al., 2015 and Mildrexler et al., 2011, where evaporative cooling and [the](#) high aerodynamic conductance of forests were identified as the responsible factors for the strong coupling [between](#) surface and air temperature. [Additionally](#), we show that [the diurnal variation of surface and air temperature remains similar](#) irrespective of the evaporative conditions [in](#) the forest. [We can only speculate about the physical mechanism behind this finding. While it is well established that the greater aerodynamic roughness of the forest leads to a greater aerodynamic conductance for neutral conditions \(T.R. Oke, 2002\) we also find that the diurnal variation is much larger than the mean \(the term \$dg_a/dR_s\$ \). This enhancement is most likely related to buoyancy, which is produced when the surface is heated by the absorption of solar radiation during the day. The finding that the relative enhancement of aerodynamic conductance between forests and non-forests is the same, and that this enhancement is insensitive to evaporative fraction, seems to be surprising and would need further](#)

investigations about their physical explanations.

We then applied our analytical model to estimate the diurnal surface temperature range DT_sR and attributed the dominant factors that influence this range. It attributed the low DT_sR of forests mostly to their high aerodynamic conductance (~56 %), with evaporation playing only a secondary role (~22 %). This finding is consistent with studies that showed that the warming induced by deforestation to be mainly the consequence of changes in aerodynamic conductance rather than changes in evaporative conditions (Bright et al., 2017; Chen and Dirmeyer, 2016; Lee et al., 2011b; Zhao et al., 2014b). This aerodynamic effect is thus important for the cooling effect of forests (Ellison et al., 2017; Li et al., 2015; Tang et al., 2018), which our analysis and analytical model supports.

In addition to the role of the mean aerodynamic conductance, we find a strong diurnal variation of the aerodynamic conductance that is greater than the mean (as already reported by Mallick et al., 2013; Ronda et al., 2001; Steduto and Hsiao, 1998). This diurnal variation acts to reduce the diurnal variation in surface temperature further. While our findings show that the relative diurnal variation in aerodynamic conductance is about the same across the sites, this variation caused a stronger reduction in DT_sR (~ -35 %) in short vegetation and savanna compared to forests (~ -21%). It indicates that in forests, the greater mean aerodynamic conductance is much more important than its diurnal variation. This can be explained by $\overline{T_s} - \overline{T_a}$ being small (~1 K) in forests, although the reason for this small difference would need further evaluation.

Our model demonstrates a similar sensitivity of DT_sR to energy partitioning and aerodynamic conductance as a previous study by Diak and Whipple (1993), who used simulations with a boundary layer model. Our model can capture this sensitivity solely with surface energy balance information, but does not require information of the boundary layer (which is likely to be encapsulated in the warming rate of air temperature and its lack of sensitivity to evaporative fraction). This indicates that the diurnal variation in surface temperature is dominantly governed by the exchange at the surface, particularly regarding its aerodynamic conductance and the evaporative fraction.

To sum up this discussion, our findings are consistent with previously published research regarding the main factors that shape the diurnal variation of surface and air temperature across different vegetation types. The derived equations of the warming rate of surface temperature (Eq. 7) and its sensitivity to evaporative fraction (Eq. 9) appear to be useful to describe and quantify the primary factors that cause differences in the diurnal variation of surface temperature across different land cover types.

6 Conclusions

We used warming rates, the change in temperatures with a change in absorbed solar radiation from morning to solar noon, to identify the influences of evaporative conditions, and vegetation on diurnal temperature variations across 51 FLUXNET sites covering different vegetation types. We found that

the warming rates of air temperature are similar across the sites and are insensitive to evaporative fraction. The warming rates of surface temperatures of sites with short vegetation decreased with greater evaporative fraction, representing a stronger evaporative cooling. For forests, warming rates of surface temperature are almost the same as for air temperature and lacked sensitivity to evaporative fraction. Using an analytical description of the surface energy balance, we reproduced these findings and attributed the different response of forests primarily to their higher aerodynamic conductance.

From our analysis, we can draw several conclusions: First, we found that diurnal variations in air temperature reflect very little information of evaporative conditions, implying that these observations cannot be used to infer evaporation. Second, the diurnal variation of surface temperature, however, shows a clear sensitivity to evaporative fraction for short vegetation, so that evaporation may be inferred from surface temperature observations. Third, in forests, surface temperature is strongly aerodynamically coupled to air temperatures by their high aerodynamic conductance, so that these lack sensitivity to evaporative fraction. Hence, diurnal temperature variations of forested sites do not seem to carry a notable effect of evaporation. What this shows is that the effect of evaporative conditions on diurnal temperature variations delicately depends on the presence or absence of forests.

Data availability: For the map of evaporative fraction, we used the FLUXCOM monthly data of sensible and latent heat fluxes, available at <http://www.fluxcom.org/>. The observational analysis used FLUXNET data from 51 sites, available at <https://fluxnet.fluxdata.org/>. More description of each site is provided in the Appendix.

Author contribution: All authors conceived the study. AP analysed data, AK derived the energy-balance model that is further developed by AP. MR provided classification of cloud-free conditions. All authors interpreted results. AP wrote the manuscript with input of MR and AK.

Competing interests: The authors declare that they have no conflict of interest.

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827

828 Appendix

829 **Table A1** Abbreviation used

| Symbol | Full form | Unit |
|--------------------------------------|--|---------------------------------|
| σ | Stefan-Boltzmann constant | $\text{W m}^{-2} \text{K}^{-4}$ |
| ρ | Density of the lower atmosphere | Kg m^{-3} |
| LE | Latent heat flux | W m^{-2} |
| H | Sensible heat flux | W m^{-2} |
| G | Ground heat flux | W m^{-2} |
| DT_sR | Diurnal surface temperature range | K |
| DTR | Diurnal temperature range | K |
| DT_aR | Diurnal air temperature range | K |
| $(\overline{T_s} - \overline{T_a})'$ | Derivative of $\overline{T_s} - \overline{T_a}$ to evaporative fraction | K |
| T_s | Surface temperature, obtained from longwave radiation | K |
| T_{ref} | Reference temperature | K |
| T_a | 2 m air temperature | K |
| R_s | Surface solar radiation | W m^{-2} |
| $R_{s,max}$ | Maximum of surface solar radiation | W m^{-2} |
| R_o | Net radiation at reference temperature | W m^{-2} |
| $R_{l,net}$ | Net longwave radiation | W m^{-2} |
| k_r | Linearized constant | $\text{W m}^{-2} \text{K}^{-1}$ |
| g_a | Aerodynamic conductance | m s^{-1} |
| f_e | Evaporative fraction | - |

| | | |
|-----------------------------------|--|-------------------------------------|
| $\frac{dT_s}{dR_s}$ | Surface temperature warming rate | $\text{K (W m}^{-2}\text{)}^{-1}$ |
| $\frac{dT_a}{dR_s}$ | Air temperature warming rate | $\text{K (W m}^{-2}\text{)}^{-1}$ |
| $\frac{dg_a}{dR_s}$ | Morning ($20 \text{ W m}^{-2} \leq R_s \leq R_{s,\text{max}}$) derivative of aerodynamic conductance to solar radiation | $\text{m s}^{-1} / \text{W m}^{-2}$ |
| c_p | Specific heat capacity of the lower atmosphere | J/kg K |
| $\overline{T_s - T_a}$ | Morning ($20 \text{ W m}^{-2} \leq R_s \leq R_{s,\text{max}}$) mean surface and air temperature gradient | K |
| $\overline{g_a}$ | Morning ($20 \text{ W m}^{-2} \leq R_s \leq R_{s,\text{max}}$) mean aerodynamic conductance | m s^{-1} |
| $\left(\frac{dT_s}{dR_s}\right)'$ | Derivative of surface temperature warming rate to evaporative fraction | $\text{K (W m}^{-2}\text{)}^{-1}$ |
| $\left(\frac{dT_a}{dR_s}\right)'$ | Derivative of air temperature warming rate to evaporative fraction | $\text{K (W m}^{-2}\text{)}^{-1}$ |

830

831 **Table A2 Description** of sites used for this study
832

| Site no. | IGBP land use | Site ID | Site name | Location | | Number of days used | DOI |
|----------|--|---------|--------------------------------|----------|-----------|---------------------|---|
| | | | | Latitude | Longitude | | |
| 1 | Croplands (CRO) | AU-Rig | Riggs Creek | -36.65 | 145.57 | 237 | https://doi.org/10.18140/FLX/1440202 |
| 2 | | CH-Oel | Oensingel grass | 47.28 | 7.73 | 182 | https://doi.org/10.18140/FLX/1440135 |
| 3 | | CZ-wet | CZECHWET | 49.02 | 14.77 | 184 | https://doi.org/10.18140/FLX/1440145 |
| 4 | | DE-Geb | Gebesee | 51.10 | 10.91 | 285 | https://doi.org/10.18140/FLX/1440146 |
| 5 | | IT-BCi | Borgo Cioffi | 40.52 | 14.95 | 274 | https://doi.org/10.18140/FLX/1440166 |
| 6 | | IT-CA2 | Castel d'Asso2 | 42.37 | 12.02 | 143 | https://doi.org/10.18140/FLX/1440231 |
| 7 | | JP-SMF | Seto Mixed Forest Site | 35.25 | 137.06 | 164 | https://doi.org/10.18140/FLX/1440239 |
| 8 | | US-ARM | ARM Southern Great Plains site | 36.60 | -97.48 | 648 | https://doi.org/10.18140/FLX/1440066 |
| 9 | Croplands / Natural Vegetation (CRO/N) | CH-Cha | Chamau grassland | 47.21 | 8.41 | 188 | https://doi.org/10.18140/FLX/1440131 |
| 10 | | CH-Fru | Fruebuel grassland | 47.11 | 8.53 | 260 | https://doi.org/10.18140/FLX/1440133 |

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|----|----------------------|--------|---|--------|---------|------|---|
| 11 | V) | FR-LBr | Le Bray (after 6/28/1998) | 44.71 | -0.76 | 265 | https://doi.org/10.18140/FLX/1440163 |
| 12 | | US-Goo | 'Goodwin Creek' | 34.25 | -89.87 | 206 | https://doi.org/10.18140/FLX/1440070 |
| 13 | Grasslands (GRA) | AU-Stp | Sturt Plains | -17.15 | 133.35 | 532 | https://doi.org/10.18140/FLX/1440204 |
| 14 | | IT-MBo | Monte Bondone | 46.01 | 11.04 | 480 | https://doi.org/10.18140/FLX/1440170 |
| 15 | | US-AR1 | ARM USDA UNL OSU Woodward Switchgrass 1 | 36.42 | -99.42 | 242 | https://doi.org/10.18140/FLX/1440103 |
| 16 | | US-AR2 | ARM USDA UNL OSU Woodward Switchgrass 2 | 36.63 | -99.59 | 225 | https://doi.org/10.18140/FLX/1440104 |
| 17 | | US-SRG | Santa Rita Grassland | 31.78 | -110.82 | 696 | https://doi.org/10.18140/FLX/1440114 |
| 18 | | US-Wkg | Walnut Gulch Kendall Grasslands | 31.73 | -109.94 | 1074 | https://doi.org/10.18140/FLX/1440097 |
| 19 | Shrublands (SH) | AU-ASM | Alice Springs | -22.28 | 133.24 | 477 | https://doi.org/10.18140/FLX/1440194 |
| 20 | | US-SRC | Santa Rita Creosote | 31.90 | -110.83 | 621 | https://doi.org/10.18140/FLX/1440098 |
| 21 | | US-SRM | Santa Rita Mesquite | 31.82 | -110.86 | 1121 | https://doi.org/10.18140/FLX/1440090 |
| 22 | | US-Whs | Walnut Gulch Lucky Hills Shrubland | 31.74 | -110.05 | 558 | https://doi.org/10.18140/FLX/1440097 |
| 23 | | AU-Cpr | Calperum | -34.00 | 140.58 | 284 | https://doi.org/10.18140/FLX/1440195 |
| 24 | Savannas (SA) | AU-DaP | Daly River Pasture | -14.06 | 131.31 | 439 | https://doi.org/10.18140/FLX/1440123 |
| 25 | | AU-DaS | Daly River Savanna | -14.15 | 131.38 | 504 | https://doi.org/10.18140/FLX/1440122 |
| 26 | | AU-Dry | Dry River | -15.25 | 132.37 | 466 | https://doi.org/10.18140/FLX/1440197 |
| 27 | | AU-How | Howard Springs | -12.49 | 131.15 | 355 | https://doi.org/10.18140/FLX/1440125 |
| 28 | Woody Savannas (WSA) | AU-Gin | Gingin | -31.37 | 115.65 | 212 | https://doi.org/10.18140/FLX/1440199 |
| 29 | | AU-Whr | Whroo | -36.67 | 145.02 | 206 | https://doi.org/10.18140/FLX/1440206 |
| 30 | | IT-Noe | Sardinia/Arca di Noe | 40.60 | 8.15 | 555 | https://doi.org/10.18140/FLX/1440171 |

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|----|-----------------------------------|--------|--|--------|---------|------|---|
| 31 | | US-Me6 | Metolius New Young Pine | 44.32 | -121.60 | 270 | https://doi.org/10.18140/FLX/1440099 |
| 32 | | US-Var | Vaira Ranch | 38.40 | -120.95 | 1091 | https://doi.org/10.18140/FLX/1440094 |
| 33 | Deciduous Broadleaf Forest (DBF) | DK-Sor | Soroe- LilleBogeskov | 55.48 | 11.64 | 169 | https://doi.org/10.18140/FLX/1440155 |
| 34 | | IT-Col | Collelongo- Selva Piana | 41.84 | 13.58 | 343 | https://doi.org/10.18140/FLX/1440167 |
| 35 | | US-Oho | Oak Openings | 41.55 | -83.84 | 408 | https://doi.org/10.18140/FLX/1440088 |
| 36 | | US-WCr | Willow Creek | 45.80 | -90.07 | 237 | https://doi.org/10.18140/FLX/1440095 |
| 37 | Evergreen Broadleaf Forest | AU-Wom | Wombat | -37.42 | 144.09 | 180 | https://doi.org/10.18140/FLX/1440207 |
| 38 | Evergreen Needleleaf Forest (ENF) | CA-Obs | SK-Southern Old Black Spruce | 53.98 | -105.11 | 620 | https://doi.org/10.18140/FLX/1440044 |
| 39 | | CA-Qfo | Quebec Eastern Old Black Spruce (EOBS) | 49.69 | -74.34 | 194 | https://doi.org/10.18140/FLX/1440045 |
| 40 | | DE-Tha | Tharandt- Anchor Station | 50.96 | 13.56 | 268 | https://doi.org/10.18140/FLX/1440152 |
| 41 | | IT-Lav | Lavarone (after 3/2002) | 45.95 | 11.28 | 557 | https://doi.org/10.18140/FLX/1440169 |
| 42 | | IT-Ren | Renon/Ritten (Bolzano) | 46.58 | 11.43 | 362 | https://doi.org/10.18140/FLX/1440173 |
| 43 | | NL-Loo | Loobos | 52.16 | 5.74 | 401 | https://doi.org/10.18140/FLX/1440178 |
| 44 | | US-GLE | GLEES | 41.36 | -106.23 | 514 | https://doi.org/10.18140/FLX/1440069 |
| 45 | | US-Me2 | Metolius Intermediate Pine | 44.45 | -121.55 | 450 | https://doi.org/10.18140/FLX/1440079 |
| 46 | | US-NR1 | Niwot Ridge (LTER NWT1) | 40.03 | -105.54 | 600 | https://doi.org/10.18140/FLX/1440087 |
| 47 | Mixed Forest (MF) | CA-Gro | ON-Groundhog River Mixedwood | 48.21 | -82.15 | 339 | https://doi.org/10.18140/FLX/1440034 |
| 48 | | CA-Oas | SK-Old Aspen | 53.62 | -106.19 | 688 | https://doi.org/10.18140/FLX/1440043 |
| 49 | | CA-TP4 | ON-Turkey Point 1939 White Pine | 42.70 | -80.35 | 482 | https://doi.org/10.18140/FLX/1440053 |
| 50 | | FR-Pue | Puechabon | 43.74 | 3.59 | 535 | https://doi.org/10.18140/FLX/1440164 |
| 51 | | RU- | Fedorovskoje-drained | 56.46 | 32.92 | 257 | https://doi.org/10.18140/FLX/1440 |

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|--|--|-----|--------------|--|--|--|-----|
| | | Fyo | spruce stand | | | | 183 |
|--|--|-----|--------------|--|--|--|-----|

Observational analysis for each site

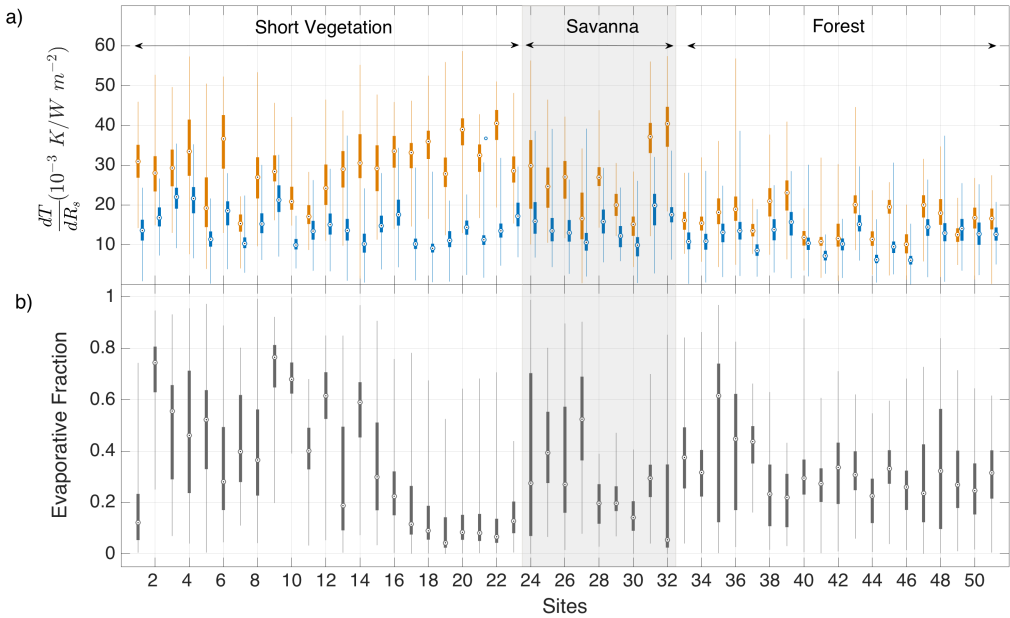


Figure A1 (a) Box plot of surface (T_s , orange) and air (T_a , blue) temperature warming rates (dT/dR_s), (b) Box plot of evaporative fractions. The vegetation types are separated by grey and white shades. The circle in the box plot indicates the median and the top and bottom edges indicate the 75th and 25th percentiles, respectively. The whisker covers the range in the observation.

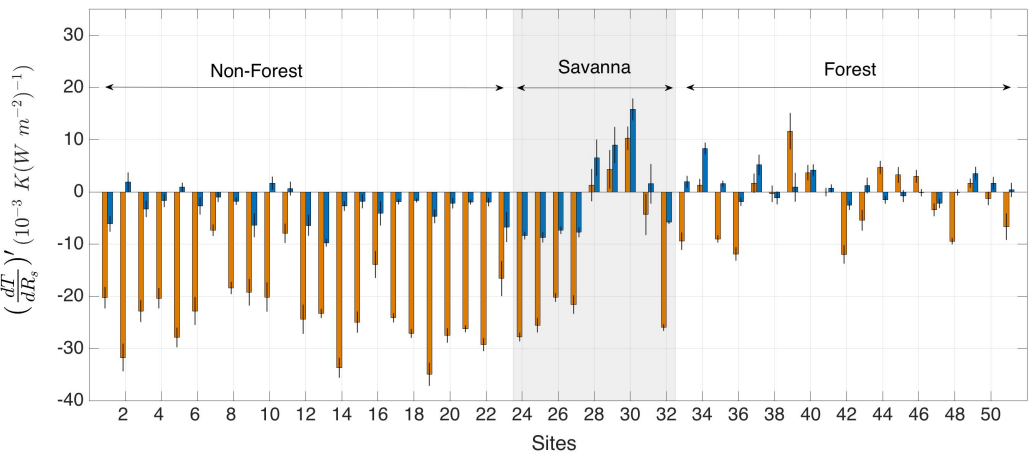


Figure A2 Warming rates response to evaporation, $(dT/dR_s)'$, for surface (T_s , orange) and air (T_a , blue) temperature. The vegetation types are separated by grey and white shades. The black bar represents the standard error in the linear regression of observed warming rate and evaporative fraction.

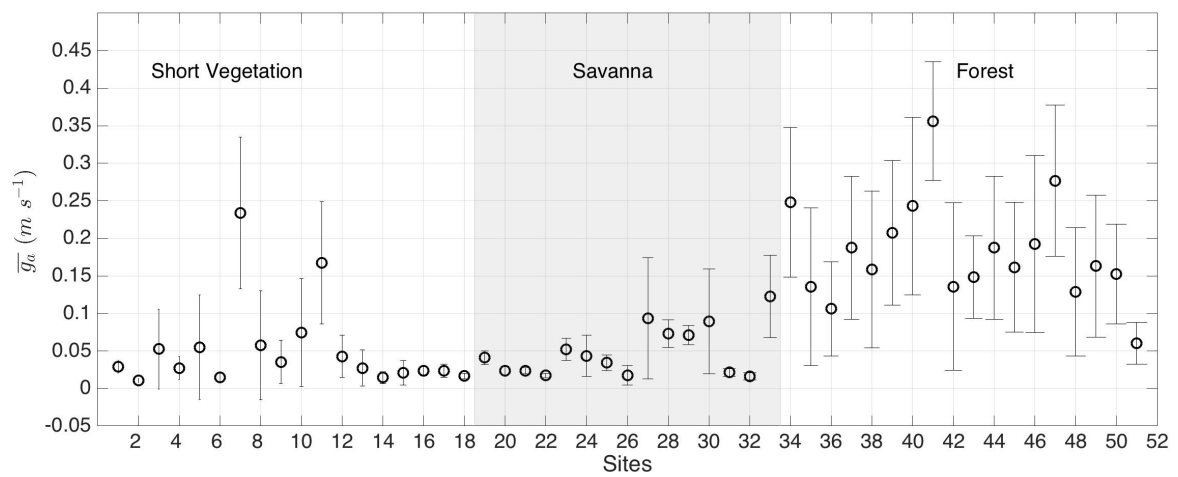


Figure A3 Morning time mean of aerodynamic conductance (g_a) for each site. The vegetation types are separated by grey and white shades. The error bar represents the standard deviation of the mean.