Supporting Information for

Sensitivity of surface temperature to land use and land cover change-induced biophysical changes: the scale issue

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Introduction

This supporting information contains four text files, one table, and one Figure. Text S1-S3 describe the formulations of three models for studying land use and land cover change (LULCC)-induced surface temperature anomalies, respectively. Text S4 describes the model inputs, which are provided in Table S1. Figure S1 presents the sensitivity tests on the initial boundary layer height and the integration time used in the convective boundary layer model.

Text S1: The TRM model

The first model to be used in this paper is the so-called two-resistance mechanism (TRM) model [*Rigden and Li*, 2017]. In this model, the atmospheric properties (air temperature and specific humidity) are provided as top boundary conditions for solving the surface energy balance equation and are assumed to be identical over the reference and the perturbed patches. That is, perturbations at the land surface only affect the surface temperature but not the atmospheric properties. In addition to the air temperature and specific humidity, the incoming shortwave and longwave radiation, as well as the surface pressure, are assumed to be identical over the reference and the perturbed patches.

The surface energy balance equation, which forms the basis of the TRM model, can be written as:

$$R_n = S_{in}\,(1-\alpha) + \varepsilon L_{in} - \varepsilon\sigma T_s^4 = H + LE + \mathrm{G} \tag{S1}$$

where R_n is the net surface radiation, S_{in} is the incoming shortwave radiation, L_{in} is the incoming longwave radiation, α is the surface albedo, ε is the surface emissivity, σ is the Stephan-Boltzmann constant, T_s is the land surface temperature, H is the sensible heat flux, LE is the latent heat flux, and G is the ground heat flux. The ground heat flux is not treated as a function of surface temperature and hence it does not alter the solution qualitatively. For simplicity, it is set to be zero throughout the paper, especially considering that the TRM model is forced by long-term averaged atmospheric conditions.

Sensible heat flux is parameterized using the aerodynamic resistance concept, as follows:

$$H = \frac{\rho c_p}{r_a}(T_s - T_a) \tag{S2}$$

where ρ is the air density, c_p is the specific heat of air at constant pressure, r_a is the aerodynamic resistance, and T_a is the air temperature. In the original TRM method, the latent heat flux is parameterized using the aerodynamic and surface resistance concept (i.e., the big-leaf model):

$$LE = \frac{\rho L_v}{(r_a + r_s)}\left(q_{sat}^*(T_s) - q_a\right) \tag{S3}$$

where L_v is the latent heat of vaporization, r_s is the surface resistance, q_{sat}^* is the saturated specific humidity, and q_a is the atmosphere specific humidity. However, in order to compare to the advection-diffusion equation (ADE) model to be discussed later, we modify the parameterization of latent heat flux by replacing the surface resistance (r_s) concept by the surface water availability (β), which is defined as the surface specific humidity normalized by its saturation counterpart (i.e., the surface relative humidity). As a result,

$$LE = \frac{\rho L_v}{r_a}(q_s - q_a) = \frac{\rho L_v}{r_a}\left(\beta q_{sat}^*(T_s) - q_a\right) \tag{S4}$$

Substituting equations S4 and S2 into equation S1, and linearizing the outgoing longwave radiation and saturated specific humidity terms yield,

$$S_{in}\,(1-\alpha) + \varepsilon L_{in} - \varepsilon\sigma T_a^4 - 4\varepsilon\sigma T_a^3(T_s - T_a) = \frac{\rho c_p}{r_a}(T_s - T_a) + \frac{\rho L_v}{r_a}\left(\beta q_a^*(T_a) + \beta \left.\frac{\partial q^*}{\partial T}\right|_{T_a}(T_s - T_a) - q_a\right) + G \tag{S5}$$

namely,

$$T_s - T_a = \frac{R - \varepsilon\sigma T_a^4 - \frac{\rho L_v}{r_a}\left(\beta q_{sat}^*(T_a) - q_a\right) - G}{4\varepsilon\sigma T_a^3 + \frac{\rho c_p}{r_a} + \frac{L_v}{r_a}\beta \left.\frac{\partial q^*}{\partial T}\right|_{T_a}} \tag{S6}$$

where $R = S_{in}\,(1-\alpha) + \varepsilon L_{in}$ is the sum of absorbed shortwave and longwave radiation. Further denoting $r_o = (\rho c_p)/(4\varepsilon\sigma T_a^3)$, $\Delta = \left.\frac{\partial e^*}{\partial T}\right|_{T_a}$, and $\gamma = \frac{c_p P}{0.622 L_v}$ leads to

$$T_s - T_a = \frac{\frac{1}{\rho c_p}\left[R - \varepsilon\sigma T_a^4 - \frac{\rho L_v}{r_a}(\beta q_{sat}^*(T_a) - q_a) - G\right]}{\frac{1}{r_o} + \frac{1}{r_a}(1 + \beta\frac{\Delta}{\gamma})} \tag{S7}$$

It is clear that the inputs of the TRM model are the radiative forcing (S_{in} , L_{in}), atmospheric properties (T_a, q_a), and surface properties ($\alpha, \beta, r_a, \varepsilon$). The direct output is the surface temperature (T_s). Once T_s is obtained from equation S7, the sensible and latent heat fluxes, as well as the outgoing longwave radiation can be also obtained.

Text S2: The CBL model

The second model to be used in this paper is the convective boundary layer (CBL) model [*Porporato*, 2009] coupled to the surface energy balance equation. In this model, the atmospheric properties above the reference patch are assumed to be only affected by the reference patch, while those above the perturbed patch are only affected by the perturbed patch. Namely, perturbations at the land surface are 'felt' by the whole CBL.

The CBL model is based on the integrated budget equation for potential temperature (θ_a) and specific humidity (q_a) in the CBL of depth (h), assuming that potential temperature and specific humidity are uniform throughout the CBL:

$$h\frac{d\theta_a}{dt} = \frac{H}{\rho c_p} + (\theta_f - \theta_a)\frac{dh}{dt} \quad \text{(S8)}$$

$$h\frac{dq_a}{dt} = \frac{LE}{\rho L_v} + +(q_f - q_a)\frac{dh}{dt} \quad \text{(S9)}$$

where θ_f and q_f are the potential temperature and specific humidity of the free atmosphere just above the CBL top ($z = h$). Thus $\theta_f - \theta_a$ indicates the temperature jump at the top of the CBL. Potential temperature and specific humidity in the free atmosphere are assumed to follow linear profiles:

$$\theta_f = \theta_{f0} + \Gamma_\theta h \quad \text{(S10)}$$

$$q_f = q_{f0} + \Gamma_q h \quad \text{(S11)}$$

where Γ_θ and Γ_q are the slopes of the linear profiles, and θ_{f0} and q_{f0} are the intercepts at $z = 0$.

To close the equations system, we need to know the growth of the CBL height, which is closely related to entrainment and thus the temperature jump at the top of the CBL. Assuming that entrainment sensible heat flux is a fraction ($\beta_{entrain}$) of the surface sensible heat flux and ignoring the contribution of water vapor to buoyancy, the growth of the CBL height can be described by the following equation:

$$\frac{dh}{dt} = \frac{(1+2\beta_{entrain})H}{\rho c_p \Gamma_\theta h} \quad \text{(S12)}$$

Equations S8-S12 provide a way to model the atmospheric properties in the CBL. It is clear that compared to the TRM method, θ_a and q_a are no longer forcing variables, but are internal variables governed by CBL dynamics.

The surface energy balance equation remains the basis for providing surface boundary conditions for the growth of the CBL. In order to compare to the TRM method, we solve the surface energy balance equation in the same way as the TRM method with radiative forcing (S_{in}, L_{in}), atmospheric properties from the CBL model (T_a, q_a), and surface properties ($\alpha, \beta, r_a, \varepsilon$). We assume $\theta_a = T_a$ given that that the CBL extends to regions near the surface.

In summary, the major difference between the CBL model and the TRM model is that the dynamics of T_a and q_a are described by equations S8-S12 in the CBL model instead of being prescribed as in the TRM model. In addition, the CBL model is time-dependent by design. Hence, the initial boundary layer height and the integration time need to be prescribed, in addition to the free atmospheric conditions ($\theta_{f0}, q_{f0}, \Gamma_\theta, \Gamma_q$). The initial values of θ_a and q_a are assumed to be identical to those used in the TRM model.

Text S3: The ADE method

The third model to be used in this paper is the advection-diffusion equation (ADE)-based model [*Li and Bou-Zeid*, 2013]. In this model, an internal boundary layer gradually develops due to perturbations introduced by the perturbed patch. Similar to the CBL model, the atmospheric properties are affected by the perturbations. However, the whole boundary layer column has not reached equilibrium with the perturbed patch.

The ADE model is based on the advection-diffusion equations describing temperature (T) and humidity (q) dynamics in the internal boundary layer:

$$u\frac{\partial T}{\partial x} = \frac{\partial}{\partial z}\left(K_h \frac{\partial T}{\partial z}\right) \tag{S13}$$

$$u\frac{\partial q}{\partial x} = \frac{\partial}{\partial z}\left(K_q \frac{\partial q}{\partial z}\right) \tag{S14}$$

where u is the mean wind velocity along the streamwise direction, and K_h and K_q are turbulent diffusivity for heat and vapor, respectively. The two turbulent diffusivities are assumed to be identical. In addition, the mean wind velocity and the turbulent diffusivity are assumed to follow power-law functions near the surface, as follows:

$$u = az^m \tag{S15}$$

$$K_h = K_q = bz^n \tag{S16}$$

where (a, b, m, n) are constants for given conditions of surface roughness and atmospheric stability. While power law functions are only approximations, they are much better suited in an analytical context than the logarithmic profile and the stability correction functions in Monin-Obukhov similarity theory. The values of *m* and *n* have been extensively studied and their values are chosen to be 1/7 and 6/7 [*Brutsaert and Yeh*, 1970]. The values of *a* and *b* are calculated following [*Brutsaert and Yeh*, 1970] and [*Brutsaert*, 1982], as follows:

$$a = 5.5u_*/z_o^m \tag{S17}$$

$$b = u_*^2/(ma) \tag{S18}$$

where u_* is the friction velocity and z_o is the momentum roughness length assumed to be 0.1 m. It is thus clear that the role of (a, b, m, n) is similar to the aerodynamic resistance concept used in the TRM and CBL models and parameterizes the effects of mean velocity and turbulent transport. In the spirit of a consistent comparison among models, the friction velocity is further derived from the aerodynamic resistance (r_a) through [*Garratt*, 1992]

$$u_* = \ln{(z/z_{oh})}/(\kappa r_a) \tag{S19}$$

where *z* is the height at which the aerodynamic resistance is defined (assumed to be 10 m), z_{oh} is the thermal roughness length and is assumed to be (1/10)z_o, κ is the von-Karman constant (= 0.4).

The two partial-differential equations S13-S14 can be solved provided with two boundary conditions at the surface ($z = 0$), as well two boundary conditions at $x = 0$. In order to compare to the TRM model, the surface boundary conditions are provided by the surface energy balance equation:

$$S_{in}\,(1-\alpha) + \varepsilon L_{in} - \varepsilon\sigma T_s^4 = H + LE + G \tag{S20}$$

and the surface water availability (β) concept linking the surface specific humidity to its saturated counterpart:

$$q_s = \beta q_{sat}^*(T_s) \tag{S21}$$

The H and LE are linked to the vertical gradients of temperature and specific humidity, respectively. It should be pointed out that longwave radiation feedbacks, which were neglected in our previous study [*Li and Bou-Zeid*, 2013], are considered here in order to compare to the other two models. Similar to the TRM model, G is assumed to be not a function of surface temperature and is simply set to zero.

The boundary conditions at $x = 0$ are given as the temperature and specific humidity profiles over the reference patch, namely, $T = T_r$ and $q = q_r$ when $x = 0$.

The equation system is now closed provided with radiative forcing (S_{in}, L_{in}), surface properties ($\alpha, \beta, \varepsilon$), as well as the temperature and humidity profiles at the reference patch (T_r, q_r). Note that the outputs from this equation system are $T_p(x, z)$ and $q_p(x, z)$. However, it is difficult to develop a sensitivity theory since the temperature and humidity profiles at the reference patch need to be a prior prescribed in order to obtain T_p and q_p. It would be better if T_r and q_r can be related to the surface properties of the reference patch. To do so, it is further assumed that the reference patch is infinitely long so that 1) T_r and q_r are only functions of z and 2) the dynamics of T_r and q_r can be described by

$$0 = \frac{\partial}{\partial z}\left(K_h \frac{\partial T}{\partial z}\right) \tag{S22}$$

$$0 = \frac{\partial}{\partial z}\left(K_q \frac{\partial q}{\partial z}\right) \tag{S23}$$

Equations S22-23 are equipped with the similar surface boundary conditions as equations 20-21 except with values of α, β, and ε that are specific to the reference patch. This tactic further allows the perturbed patch to be of a finite size (e.g., $0 < x < x_o$) provide that when $x > x_o$ the surface becomes the reference patch again (i.e., the perturbed patch is surrounded by the reference patch).

The solution of this problem when $\beta_p = 1$ is provided in *Yeh and Brutsaert* [1971]. The introduction of β addressed a major limitation of the solution in *Yeh and Brutsaert* [1971], which was only applicable when the surface temperature is lower than the air temperature (i.e., under stable conditions) over the perturbed patch (see discussions in *Brutsaert* [1982]). This tactic was also used by *Rao et al.* [1974] in their numerical study. With this important correction, the surface temperature difference between the perturbed patch ($T_{s,p}$) and the reference patch ($T_{s,r}$) can be obtained as follows:

$$T_{s,p} - T_{s,r} = (1 - f_{ADE})(\beta_r - \beta_p)T_1^* + f_{ADE}(\alpha_r - \alpha_p)T_2^* \tag{S24}$$

where the first term represents the surface temperature difference as a result of the difference in terms of water availability (controlled by β), while the second term represents the surface temperature difference as a result of the difference in terms of energy availability (controlled by α). The two temperature scaling factors are

$$T_1^* = \frac{L_v q_r^{sat}}{c_p\left(1+\frac{\Delta}{\gamma}\beta_p\right)} \tag{S25}$$

$$T_2^* = \frac{S_{in}}{4\epsilon\sigma T_{s,r}^3} \tag{S26}$$

where q_r^{sat} is the saturated specific humidity at the reference patch, $\Delta = \left.\frac{\partial e^*}{\partial T}\right|_{T_{s,r}}$ is the derivative of the saturated water vapor pressure evaluated at the surface temperature of the reference patch, $\gamma = c_p p/(0.622\, L_v)$ is the psychrometric constant.

The f_{ADE} is a function of x resulting from the complex parameterizations of the mean wind and turbulent transport (a, b, m, n), as follows:

$$f_{ADE} = \omega x^\nu \sum_{i=0}^{\infty} \frac{(-\omega x^\nu)^i}{\Gamma(1+\nu+\nu i)} \tag{S27}$$

where $\nu = \frac{1-n}{2+m-n} = \frac{1}{9}$, Γ is the gamma function, and $\omega = \frac{4\epsilon\sigma T_{s,r}^3}{c_p(1+\frac{\Delta}{\gamma}\beta_p)} \frac{\Gamma(\nu)\nu^{1-2\nu}}{\Gamma(1-\nu)\rho b\left(\frac{a}{b}\right)^\nu (1-n)^{1-2\nu}}$

Text S4: Model inputs

The input parameters needed by the three models are listed and explained in Table S1. In this study, we primarily use observational data from flux tower and radiosondes at (or close to) the open land site of pair three in *Liao et al.* [2018] as forcing. The results over the other sites/pairs in are similar qualitatively and hence are not shown.

In this study, we consider the sensitivities of surface temperature to changes in surface albedo and surface water availability. To do so, we systematically vary the surface albedo value from 0.1 to 0.3, with a reference value of 0.2. We also vary the surface water availability value from 0.25 to 0.75, with a reference value of 0.5. For all three models, the aerodynamic resistance, the emissivity, and the surface pressure are set to be 30 s/m, 1, and 10^5 Pa, respectively, over both the reference and perturbed patches.

The TRM model requires forcing parameters such as incoming shortwave radiation, incoming longwave radiation, atmospheric temperature, and specific humidity. These parameters are directly taken from the previously mentioned flux tower measurements in *Liao et al.* [2018] and the long-term summer daytime mean values are used (see Table S1).

The CBL model also uses the measured incoming shortwave radiation and incoming longwave radiation as forcing, but treats the measured atmospheric temperature and specific humidity as their initial values and allows them to evolve according to CBL dynamics. This further requires the potential temperature and specific humidity profile slopes/intercepts in the free atmosphere, the initial boundary layer height, and the integration time. The potential temperature and specific humidity profile slopes/intercepts in the free atmosphere are estimated from the nearest radiosonde measurements. The initial boundary layer height is set to be 100 m and the integration time is set to be 12 hours. Sensitivity tests on the initial boundary layer height and the integration time are conducted.

The ADE model also uses the measured incoming shortwave radiation and incoming longwave radiation as forcing. It allows the atmospheric temperature and specific humidity to evolve according to the advection-diffusion equations, which further requires specifications of parameters in the parameterizations of the mean wind and turbulent transport. As mentioned earlier, in the spirit of a consistent comparison we use the aerodynamic resistance, together with the momentum/thermal roughness lengths that are set to be 0.1 m and 0.01 m, respectively, to determine the parameters needed by the complex parameterizations of the mean wind and turbulent transport in the ADE model (equations S17-S19).

Table S1: Parameters used in the models and their values

	Parameters	Names	Values
Common to all models	S_{in} (W m^{-2})	Incoming shortwave radiation	459.1
	L_{in} (W m^{-2})	Incoming longwave radiation	400.7
	r_a (s m^{-1})	Aerodynamic resistance	30
	z (m)	Height where r_a is defined	10
	α_r	Albedo of the reference patch	0.2
	β_r	Water availability of the reference patch	0.5
	α_p	Albedo of the perturbed patch	0.1-0.3
	β_r	Water availability of the perturbed patch	0.25-0.75
	ε	Surface emissivity	1
	P (Pa)	Surface pressure	10^5
TRM	T_a (K)	Air temperature	300.8
	q_a (kg kg^{-1})	Specific humidity	0.0147
CBL	θ_{f0}(K)	Free atmosphere temperature profile intercept	300.3
	q_{f0}(kg kg^{-1})	Free atmosphere humidity profile intercept	0.0148
	Γ_θ(K m^{-1})	Free atmosphere temperature profile slope	0.0042
	Γ_q(m^{-1})	Free atmosphere humidity profile slope	-1.325e-06
	$\beta_{entrain}$	Ratio of entrainment heat flux to surface flux	-0.2
	h_{init} (m)	Initial boundary layer height	100
	T (h)	Integration time	12
ADE	m	Mean velocity power-law exponent	1/7
	n	Turbulent diffusivity power-law exponent	6/7
	a	Mean velocity parameter	4.40
	b	Turbulent diffusivity parameter	0.53
	z_o (m)	Momentum roughness length	0.1
	z_{oh} (m)	Thermal roughness length	0.01

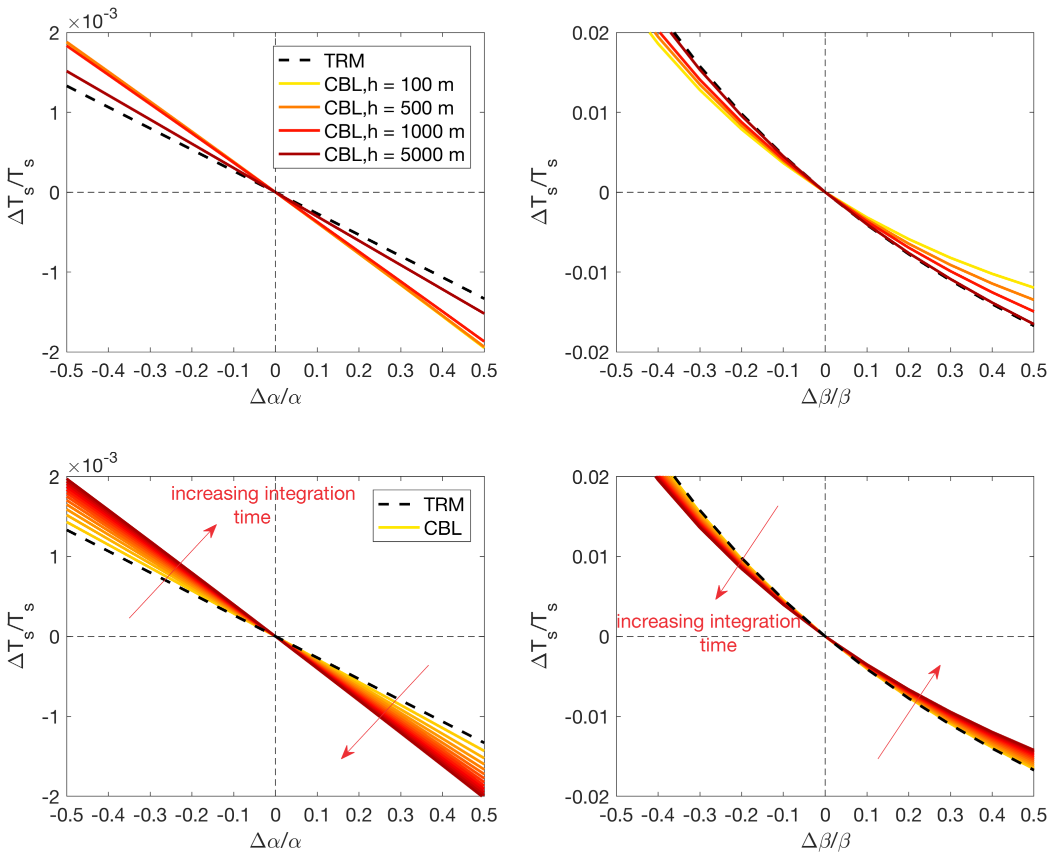

Figure S1: Similar to Figure 3 but only showing the TRM and CBL model results. The CBL model results with (top panels) different initial boundary layer height (h) values and (bottom panels) different integration time from 1 hour (yellow line) to 12 hours (red line) are shown. Note the difference in the y-axes between left and right panels.

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