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Rapid cooling of urban surfaces during rainfall: physical basis, dominant energy fluxes, and sensitivity to pavement and rainfall properties

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ABSTRACT

Using model for the heat transfer between pavements and runoff during rainfall, we investigate the importance of different pavement and rainfall properties, as well as crucial energy budget terms that drive the cooling processes. The results indicate that the pavement and runoff temperature and energy fluxes are very sensitive to the rain temperature. In addition, pavement albedo has a significant effect on the simulated temperature since it modifies the initial pavement temperature before the rain starts. The results also indicated that among the different energy budget terms, evaporation and long wave radiation are the main cooling terms, while the shortwave radiation dominates energy input into the runoff-pavement system.

KEYWORDS

Pavements, rainfall, surface energy budget

INTRODUCTION

There are a variety of phenomena in the atmosphere that are affected by earth surface temperature such as urban microclimatology, turbulent transport, and surface energy budgets. In urban areas, the materials of which the pavements are made (i.e. impervious pavements with low albedo values), as well as other urban canopy properties, result in hotter surfaces than rural areas. This is the main reason for urban heat islands in metropolitan areas. However, during rainfall, hot ground surfaces cool down very fast, mainly due to the runoff advection and/or infiltration of heat. Previous investigations have proposed runoff-pavement heat transfer models to predict the surface and runoff temperature during rainfall [*Van Buren et al.*, 2000; *Herb et al.*, 2009; *Janke et al.*, 2009; *Kertesz and Sansalone*, 2014]. A few of these studies have reported the sensitivity of the cooling to the input and model parameters; however, these analysis either were conducted on limited ranges of target parameter or were not extended to indicate the influence of model inputs on the energy budgets of pavement-runoff [*Herb et al.*, 2009]. Therefore, a lack of extensive analysis still hinders the understanding of how different input parameters, especially the pavements properties, alter the heat transfer between the runoff and pavement during rainfall, and what is their effects on surface temperature and on the driving energy budget terms (such as evaporation and sensible heat) before, during and after rainfall. A more detailed sensitivity analysis of the runoff-pavement heat transfer model helps us to determine, which input parameters need to be carefully measured. In addition, determining the influence of different energy budget terms on key model outputs (such as ground surface temperature) would allow the identification of the dominant heat transfer processes in the problem, and can lead to the development of simpler and more computationally efficient models. Such reduced models would be more suitable for implementation in coarser geophysical models, such as Urban Canopy Models (UCMs), or Weather Research Forecast (WRF) models.

In this paper, we use a runoff-pavement heat transfer model to investigate the sensitivity of different temperatures and fluxes to various pavement and rain properties. In addition, we evaluate the effects of various energy flux terms on the ground surface temperature. First the model is briefly explained, and then a metric for comparing the model sensitivity to different input parameters is introduced. Finally, we present the results, and conclude the paper with a discussion and future directions.

METHODS

Model description

The model used in this paper is a 2D heat transfer model (validated by experimental data) to solve for the runoff and pavement temperature and energy fluxes during rainfall [*Omidvar et al.*, 2018]. In this section, we summarize the main model elements. The model has two parts:

1- The runoff dynamics part, which solves for the runoff velocity and depth by combining the shallow water continuity equation and the kinematic wave approach for laminar flows [*Brutsaert*, 2005]. With a boundary condition of zero velocity at the upstream boundary, and an initial condition of dry ground, the solution of the horizontal (u) and vertical (v) velocities inside the runoff, and of the runoff depth (h) are as follows:

$$u(x,y,t)=\frac{gs_0}{\nu}\left(hy-y^2/2\right)\quad;\quad v(x,y)=\begin{cases}0 & \text{for } x\geq\dfrac{t^3s_0gi^2}{3\nu}\\ -\dfrac{s_0ghy^2}{6\nu x} & \text{for } 0<x<\dfrac{t^3s_0gi^2}{3\nu}\end{cases}\tag{1}$$

$$h(x,t)=\begin{cases}it & \text{for } x\geq\dfrac{t^3s_0gi^2}{3\nu}\\ \left(\dfrac{3x\nu i}{s_0g}\right)^{\frac{1}{3}} & \text{for } x<\dfrac{t^3s_0gi^2}{3\nu}\end{cases}\tag{2}$$

where in equations (1) and (2), s_0 is pavement slope; ν is runoff kinematic molecular viscosity ($m^2\ s^{-1}$); h is runoff depth (m); i is the rain intensity ($m\ s^{-1}$); and t is time (s).

2- The heat transfer part, which uses the advection- diffusion equation in order to solve for the runoff temperature (T_w), and a 2D conduction equation (assuming no infiltration) for solving the temperature of subsurface (T_g) as follows:

$$\frac{\partial T_w}{\partial t}=D_w\frac{\partial^2T_w}{\partial y^2}-\left(u\frac{\partial T_w}{\partial x}+v\frac{\partial T_w}{\partial y}\right)\quad;\quad\frac{\partial T_g}{\partial t}=D_g\left(\frac{\partial^2T_g}{\partial y^2}+\frac{\partial^2T_g}{\partial x^2}\right)\tag{3}$$

In equations (3), D_w ($m^2\ s^{-1}$) is the heat diffusivity of the runoff, which is modified from the molecular diffusivity to take into account the excess mixing due to the penetration of rain droplet into the runoff (an optimum value of 4 × molecular diffusivity is obtained from the experimental data); D_g ($m^2\ s^{-1}$) is the thermal diffusivity of the subsurface; and x and y are the horizontal and vertical distances. Surface energy budget equations are solved to get the temperature of the interfaces between the ground surface and the runoff (equation (4), left), and the interface between the runoff surface and the air (equation (4), right):

$$R_{sw}+Q_{wb}+G=0\quad;\quad R_{lw}+LE+Q_r+H+Q_{wt}=0.\tag{4}$$

where R_{sw} and R_{lw} are net shortwave and longwave radiation fluxes respectively; Q_{wb} is heat exchange flux between ground surface and runoff; G is ground heat flux; LE is latent heat flux; Q_r is net rain heat flux; H is sensible heat flux; and Q_{wt} is heat exchange flux between runoff and its surface (all in W m^{-2}). Among these energy terms, downwelling shortwave and longwave are the inputs of the model, and the rest are solved for.

A zero-heat flux boundary condition is considered for the bottom boundary of the subsurface, while a constant diffusive heat fluxes at the right and left of the subsurface domain are imposed. Equations (3) and (4) in conjunction with the discussed boundary conditions are solved numerically to obtain the ground surface and runoff temperatures as well as the energy budget fluxes during rainfall.

The downwelling radiative fluxes and other meteorological inputs of the model (i.e. air humidity, temperature, and pressure, wind speed) are obtained from an eddy covariance station at Princeton University (coordinates: 40°20'46.9"N, 74°38'36.5"W). A rainfall event starting from 2 PM local time on 30 of July 2016, with a duration of 3 hours, is chosen. The rain temperature is assumed to be equal to the air temperature. In addition, to get the ground surface temperature before and after rain, surface energy budget with similar terms as equation (4) are solved without any runoff model. The model for the dry surface is run for 12 hours before start of the rain (assuming a dry surface and no evaporation), then for 3 hours during rainfall, and, after rainfall stops, the model is run for an additional 2 hours and 20 minutes (until the downwelling shortwave radiation becomes zero).

Sensitivity analysis method

The model that we described in the previous section is used to conduct a set of sensitivity analyses with different pavement and rain properties. For an input (r) and output (z) of the model, we use the following metric in order to compare the sensitivity of the model to different inputs and outputs:

$$\gamma = \frac{\delta z}{\partial r / r}, \tag{5}$$

In this equation, the dimension of γ is as same as the dimension of the output (z), and indicates how much the output z changes for a 100 % change of input r. The model inputs we choose to conduct the sensitivity analysis are: (1) pavement thermal conductivity, k for the range of 0.3 - 3.1 (W m^{-1} K^{-1}) [*Côté and Konrad*, 2005; *Kodide*, 2010], (2) pavement albedo, α for the range of 0.01 - 0.23 [*Li et al.*, 2013; *Wang*, 2015], (3) rain intensity, i for the range of 5 - 105 (mm h^{-1}), and (4) rain temperature, T_{rain} for the range of T_{air}–5 ºC to T_{air}+5 ºC (as its deviation from equilibrium with air temperature (T_{air}), which is the baseline assumption). The average T_{air} during the rainfall is 23.3 ºC in the input data). The input ranges chosen represent the typical value of each input in the urban areas. Finally, γ values for each of the inputs are calculated for 8 model outputs: time averaged temperature of the ground surface during (T_{gs}^{r}) and after (T_{gs}^{ar}) rainfall, time averaged temperature of runoff during rainfall (T_w), initial temperature of ground surface temperature before rain starts (T_{gs}^{i}), time averaged latent heat flux during (LE^{r}) and after (LE^{ar}) rainfall, and time averaged sensible heat flux during (H^{r}) and after (H^{ar}) rainfall. All the output variables are averaged along the pavement except T_w, which is averaged both vertically and along the pavement. For each input, γ is averaged over the input range and the average value is reported ($\langle \gamma \rangle$).

RESULTS

Figure 1a shows the comparison of $\langle\gamma\rangle$ for different model inputs, and for the temperature outputs. Note that rain intensity and rain temperature do not affect the initial temperature of the ground surface, so their $\langle\gamma\rangle$ values are zero in the plot. As can be noted from this figure, except for T_{gs}^{i}, all other temperature outputs are strongly sensitive to the rain temperature such that with $\langle\gamma\rangle$ values for T_{gs}^{r}, T_w, and T_{gs}^{ar} are 11.0, 11.1, and 4.4 ºC respectively. This emphasizes the importance of determining the rain temperature accurately. The reason that T_{gs}^{ar} is less sensitive in comparison to the temperature outputs during the rainfall is that this temperature output is modified indirectly by the rain temperature because the final ground surface temperature during rainfall is the initial condition of the simulation after rainfall ends where T_{gs}^{ar} is solved for (similar justification can be made for the rain intensity as the input). The second input that the model outputs are most sensitive to is the pavement albedo. T_{gs}^{i} is the most sensitive temperature output to the pavement albedo in comparison to others because in the data we used in the model, the downwelling shortwave radiation is higher before the rainfall than during and after due to the cloudiness during and after rainfall. In addition, as we expected, the $\langle\gamma\rangle$ values corresponded to the pavement albedo are negative, meaning that if we increase of pavement albedo the temperature outputs decrease because of less available energy in the energy budget of the ground surface (which consequently leads to a cooler runoff temperature).

The $\langle\gamma\rangle$ value corresponding to the pavement heat conductivity has a negative sign for T_{gs}^{i}, but a it is positive for other temperature output. This can be attributed to the fact that, before rainfall, while the pavement is absorbing energy, the higher the conductivity of the pavement the more heat will be transfer from the pavement surface to the deeper parts of the subsurface. Therefore, the ground surface temperature remains cooler for the pavements with higher heat conductivity. However, during and after rainfall, while the heat is still being advected away by the runoff (or evaporation for after rainfall) at the surface, the pavements with higher conductivity have more stored heat and can transfer it more rapidly to the surface. Therefore, the higher conductive pavements have higher surface temperature than the lower conductive ones during and after rainfall.

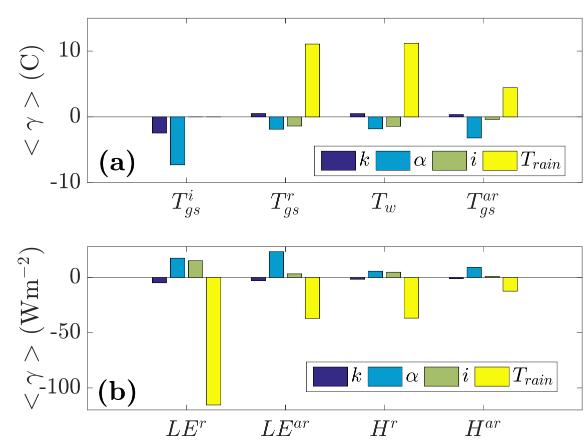

Figure 1. (a) Results of sensitivity analysis for temperature outputs, (b) for flux outputs

Figure 1b shows the sensitivity analysis for the evaporation and heat flux outputs. Similar to the temperature outputs, the flux outputs are very sensitive to the rain temperature specially the evaporation and heat fluxes during rainfall (with $\langle \gamma \rangle$ of –115 W m^{-2} and 37 W m^{-2} respectively). Although evaporation flux after rainfall is modified indirectly by the rain temperature, the $\langle \gamma \rangle$ for this flux is still comparable to the $\langle \gamma \rangle$ value for the heat flux during rainfall. Again, similar to the temperature outputs, pavement albedo rank as the second input to which the model outputs are most sensitive. The evaporation after rainfall (LE^{ar}) is the most sensitive output to the pavement albedo, then LE^{r} and H^{ar}, and finally H^{r} is the least sensitive to the pavement albedo. The sensitivity of the evaporation and sensible heat fluxes during rainfall to the rain intensity are higher than the corresponding sensitivity after the rainfall. This is expected since rain intensity directly modify the variables during rainfall, but indirectly modulates the ones after rainfall. Finally, the flux outputs are least sensitive to the thermal conductivity of the pavement among; this might be because the evaporation and heat fluxes are calculated at the interface between the runoff and air while the thermal heat conductivity of the pavement affects directly the subsurface and ground surface heat processes.

We are also interested in the effects of different surface energy budgets (here we just consider shortwave, longwave, evaporation and sensible heat fluxes) on the model outputs during rainfall. To investigate this, we choose T_{gs}^{r} as the target output, and evaluated how T_{gs}^{r} changes from its base value, $T_{gs}^{b,r}$ (the ground surface temperature during rainfall when all the energy budget terms are considered in the model), when we turn off (set to zero) a specific energy budget term in the model. Figure 2 shows the result of this analysis. It indicates that without considering the evaporation flux, the model predicts T_{gs}^{r} about 0.6 ºC higher. The longwave flux is the second most important term for predicting T_{gs}^{r} with $T_{gs}^{r} - T_{gs}^{r,b} = 0.4$ ºC. Without considering the shortwave flux, the model predicts T_{gs}^{r} 0.6 ºC cooler than its base value. Usually the shortwave radiation has bigger impacts on the surface temperatures; however, in our application since the shortwave radiation is small during the rainfall (because of cloudiness), it has a lower effect on the energy processes of the problem. Finally, the sensible heat flux has the least impact on T_{gs}^{r} with $T_{gs}^{r} - T_{gs}^{r,b} = 0.2$ ºC.

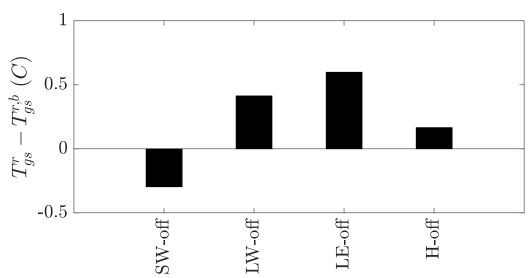

Figure 2. The effect of induvial energy budget terms on the ground surface temperature

DISCUSSIONS AND CONCLUDING REMARKS

In this paper, we conducted a set of sensitivity analyses for a runoff-pavement heat transfer model in order to determine how carefully one should determine different pavement and ambient properties that are needed inputs of the model. The analysis showed that the model is very sensitive to rain temperature. It is an important result because usually the models that predicts heat processes on the pavement during rainfall assume rain temperature is equal to air temperature (or previous models that assumed a dew point temperature as the rain temperature

[*Herb et al.*, 2009]). Therefore, considering the difficulties in measuring the rain temperature, more consideration is needed when choosing the value of rain temperature as the input of the model. Another important take away from the sensitivity results is the role of the pavement albedo in modifying the surface temperature and fluxes before, during and after rainfall. The results showed that albedo of the pavement mainly affects the temperature of the pavement before the rain starts. This leads the pavement to be hotter when the rain starts, which can then lead to a hotter effluent entering the storm drainage network that ultimately joins the streams and can then have advects effect on their health [*Nelson and Palmer*, 2007]. Finally, we showed that among the discussed energy budgets terms in this paper, evaporation and longwave radiation play an important role in cooling the hot ground surface during the rainfall, while the shortwave radiation has an opposite role although the magnitude of the net shortwave is typically smaller during the rainfall due to clouds. Using the results of the sensitivity analysis and important energy budget terms, one can develop a reduced runoff-pavement heat transfer model that predicts the important temperature and flux outputs accurately with reduced computational demands. Such a reduced model is more suitable for implementation in coarser geophysical models.

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