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Understanding pavement-surface energy balance and its implications on cool pavement development

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ABSTRACT

The idea of using cool pavements to mitigate the urban heat island has gained momentum recently. Many studies have focused on the temperature of a cool pavement, whereas limited studies have reported on the pavement's sensible heat to the surrounding air. This paper demonstrates the energy partition at the ground surface, with focuses on the sensible heat releasing from the pavement surface. The energy partition of a typical dry pavement is simulated and compared to that at an irrigated grass surface. Pavements with different surface albedos and different thermal inertia are simulated to demonstrate influences of surface modification and heat-storage modification on the releasing sensible heat. Instantaneous solar absorption by the pavement is prone to be partitioned into heat conduction. Most of the absorption is discharged as sensible heat and long-wave emission, whereas the daily cumulative heat conduction is roughly 5% of the absorption. Both increasing the surface albedo and enhancing the evaporative flux are effective to suppress the sensible heat and to promote cool pavements. Raising the thermal inertia of the pavement decreases the sensible heat during the daytime but increases this factor at nighttime. Therefore, it should be cautious to design cool pavements by varying their thermal inertia.

1. Introduction

The energy partition of an asphalt or concrete pavement differs considerably from that of natural soil surfaces because of the distinctive thermal and absorptive properties of these materials. Pavement surfaces are generally warmer than vegetated areas around them since these pavements reduce evaporative transpiration and have sufficient thermal inertia and solar absorptivity to keep the surfaces hotter than natural ground. As pavement comprises 20–40% of a typical urban fabric [1–3], these hot surfaces discharge sensible heat to the urban atmosphere and aggravate the urban heat island effect (UHI).

One strategy to the problem is to make pavements cooler than conventional pavements [4–6]. To accomplish this, the energy partition and energy budget at the pavement surface must be modified to suppress the elevated pavement temperatures. Techniques to keep pavements cooler include resurfacing with a higher reflective coating [7–20], building watered pavements for evaporation [21–28], and constructing the pavement with high thermal inertia to transfer the absorbed heat to deeper layers [29–32]. The observed temperatures confirm that these techniques can keep pavements cooler than conventional pavements and help contend with the UHI. However, as the cool pavement is intended to mitigate the UHI, the pavement surface temperature may not be indicative of a truly cool pavement. Whether a pavement stays cooler should be judged from the sensible heat, which heats up the urban air environment. Unfortunately, studies on the sensible heat releasing from pavements are limited [33].

To evaluate these effects, this study investigates the energy partition at the ground surface. Energy partitions of a typical pavement surface are compared with an irrigated grass surface to capture the role of evaporative flux on the sensible heat. Pavements with different albedo levels and different thermal inertia are simulated to identify the role of surface modification and heat-storage modification on the instantaneous and cumulative sensible heat. How the releasing sensible heat impacts the development of cool pavement is discussed.

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2. Methods

2.1. Heat balance at ground surface

The heat transfer between the ground and underlying layers can be treated as a one-dimensional transient heat transfer in a semi-infinite body obeying

$$c\varrho \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} \tag{1}$$

where T (K) is the temperature profile of the ground; c (J/K) and ϱ (kg/m^3) are the heat capacity and density of ground, respectively; t(s) is time; z(m) is the vertical coordinate that starts from the pavement surface with positive being downward; and k(W/(m K)) is the thermal conductivity of the pavement layers' material.

The temperature variation of the earth is driven by the solar radiation. A portion of solar radiation is reflected back into the sky, which is proportional to the surface albedo, ρ. The remaining solar radiation is absorbed and partitioned into conduction G (W/m^2), convection H(W/m^2), net long-wave emission L(W/m^2), and evaporation E(W/m^2). The balance of energy at the ground surface obeys Eq. (2):

$$(1-\rho)I = G + H + L + E \tag{2}$$

where I (W/m^2) is instantaneous solar irradiation. The heat storage, or thermal conduction, is the energy flux causing variations to the ground temperature.

$$G = -k\left.\frac{\partial T}{\partial z}\right|_{z=0} \tag{3}$$

The heat convection, or sensible heat, is:

$$H = h_c(T_s - T_a) \tag{4}$$

where T_s (K) is the surface temperature; T_a (K) is the air temperature; and h_c (W/(m^2 K)) is heat convection coefficient. According to [34], the following empirical formula can provide reasonable accuracy for h_c

$$h_c = \begin{array}{ll} 5.6\times 4.0v & v<5 \\ 7.2\times v^{0.78} & v\geq 5 \end{array} \tag{5}$$

where v(m/s) is wind speed measured at 9.0 m height.

The net long-wave emission, L, is determined by:

$$L = h_r(T_s - T_{sky}) \tag{6}$$

where h_r (W/(m^2 K)) is the irradiative coefficient defined as:

$$h_r = \varepsilon\sigma(T_s^2 + T_{sky}^2)(T_s + T_{sky}) \tag{7}$$

where ε is the surface emissivity and σ is the Stefan–Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}. The sky temperature, T_{sky} (K), can be estimated:

$$T_{sky} = \varepsilon_{sky}^{0.25} T_a \tag{8}$$

where the sky emissivity ε_{sky}:

$$\varepsilon_{sky} = 0.754 + 0.0044T_d \tag{9}$$

where T_d (°C) is dew point:

$$T_d = b_0\gamma/(a_0 - \gamma) \tag{10}$$

where $a_0 = 17.3$, and $b_0 = 237.7$, and $\gamma = a_0T_a/(b_0 + T_a) + \ln(RH/100)$ in which T_a is unit in °C [35].

The evaporation E is strongly governed by the moisture availability at the surface and by the vapor density difference between the ground surface and the air. According to [36], the evaporative flux obeys:

$$E = \lambda h_e \frac{\rho_a - \rho_{sat}}{r_s} \tag{11}$$

where λ is the enthalpy of vaporization of water, 2260×10^3 J/kg; ρ_a is the vapor density of the air, kg/m^3; ρ_{sat} is the saturated vapor air density, kg/m^3; an $d\,h_e$ is the evaporative heat-transfer coefficient relative to wind speed; r_s (s/m) expresses the bulk evaporative resistance representing the water vapor to diffuse from the source to the air immediately above the pavement. r_s can be computed using Eq. (12) [36]:

$$r_s = ae^{b\theta} \tag{12}$$

where a (s/m) and b are two regression coefficients. b is negative because when the water content θ (%) decreases, the surface resistance increases and further evaporation is suppressed.

It is noteworthy to compare the heat convection coefficient h_c and the irradiative coefficient h_r. In Eq. (5), for a typical wind speed of 0–6 m/s, h_c varies approximately from 5.6 to 30 W/(m^2 K) [37]. h_r depends on surface emissivity, surface temperature, and the sky temperature. Assuming the surface temperature of a pavement varies from 10 to 70 °C during a typical summertime, sky temperature varies from 0 to 50 °C, and an emissivity of 0.90, h_r can range from 4.5 to −7.5 W/(m^2 K). Therefore, the net long-wave emission is relatively less insensitive to the temperature variation than the convection, especially in windy weather.

2.2. Analytic solution to the energy partition at the ground surface

Once the energy flux to the ground is known, the temperature profile of the ground can be solved. But as the weather fluctuates, the flux to the ground is not constant. For simplicity, the solar absorption is assumed to be a sinusoidal function described by:

$$A = (1-\rho)I_o\cos(\omega t - \varphi) \tag{13}$$

where I_0 (W/m^2) is the daily zenith solar irradiation; and ω (1/h) is the period angle, $2\pi/24$ h; and φ (rad) is the phase term and it is $\pi/2$ for local standard time.

Because A is zero at nighttime but the temperature of the ground still varies at nighttime, it is better to deem the net radiation R_n as the driving force for the energy balance at the ground surface as

$$R_n = (1-\rho)I_o\cos(\omega t - \varphi) - L \tag{14}$$

So Eq. (2) can be rewritten as:

$$R_n = G + H + E \tag{15}$$

According to the hysteresis effect of the surface energy budget at ground surface, the net radiation R_n and G obeys [38]

$$G = a_1R_n + a_2\frac{\partial R_n}{\partial t} + a_3 \tag{16}$$

where a_1, a_2(h) and a_3(W/m^2) are regression coefficients. a_1 stands for the percentage of absorption to thermal conduction. a_2 is the hysteresis of the surface energy storage. a_3 is the regressed intercept between R_n and G, but its physical meaning is still unclear [39].

Using the same hysteresis effect, one can link the net radiation to E and H:

$$E = b_1R_n + b_2\frac{\partial R_n}{\partial t} + b_3 \tag{17}$$

$$H = c_1R_n + c_2\frac{\partial R_n}{\partial t} + c_3 \tag{18}$$