EFFECTS OF WATER ON THE ENERGY BUDGET OF PAVEMENTS IN THE URBAN ENVIRONMENT

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Abstract. Urban areas are proven to have a disproportionately high temperature in relation to surrounding rural areas. This effect is compounded by the rising temperatures due to climate change. If this trend continues as expected, human health could be threatened, energy resources strained, and economic productivity compromised (Summer in the City 2014). The higher temperature in cities is due to several factors, including a high concentration of engineered materials. In order to assess a material's contribution to the higher temperature of urban areas, it is necessary to understand how energy is absorbed and emitted from these surfaces. Data on materials in a moisture rich state, such as that which occurs after rainfall, is limited. This is a dangerous knowledge gap, as the escalating temperature of cities, their unique structures, and the high density of pollution all interact to influence rain patterns, usually to the effect of increasing rainfall (Riebeck 2006). Experiments were conducted on concrete and asphalt surfaces in wet and dry conditions, and these data was used to determine how components of the energy budget were altered by the presence of water. Results showed that sensible heat flux was noticeably lower in asphalt when wet, and molecular ground flux was lower in both concrete and asphalt.

INTRODUCTION

Cities currently contain 54% of the global population, with predictions showing that this number will increase to 68% by the year 2050 (The World Bank 2015). The density of cities, however, is predicted to decrease, and it is anticipated that the current land area of cities could nearly triple in the next 30 years (United Nations 2014). In building these new urban areas, we are presented with an exceptional opportunity to implement more environmentally sustainable practices, hopefully reducing their atmospheric temperature. A concerning trend among metropolitan areas is their tendency to have a higher temperatures than surrounding rural environments. This phenomenon is called the "Urban Heat Island Effect," and is attributed to several different causes. Of specific interest are urban land surfaces, which are largely made up of impervious pavements, such as concrete and asphalt. It is estimated that 29% to 45% of the surface area in cities is covered with pavements, and this proportion is expected to increase (Golden 2004). Because they do not absorb water, rainfall collects on these surfaces, and is moved only through evaporation or runoff.

The tendency of cities to retain large amounts of thermal energy presents an additional set of problems. First, it leads to an increased cooling energy demand for homes, commercial buildings, and vehicles in urban areas during the warmer seasons. In addition, the runoff generated after a rain event allows heat to be transferred to surrounding bodies of water through advection, which can be detrimental to those ecosystems.

A study conducted by Steve Burian from the University of Utah and Marshall Shepherd from the University of Georgia shows increasing trends in rainfall in urban areas. Their research used past precipitation records to determine that areas downwind of cities received more rainfall than they would if the cities were not there. Moreover, findings from an urban growth model suggest that as urban surface area increases, the area affected by city-induced precipitation will shift from downwind towards the center of the city (Riebeck 2006). In other words, the predicted rapid urban expansion will also lead to more rain in those areas.

While previous research has been conducted to assess energy transfer in and out of these engineered materials, it has neglected to address atypical scenarios, such as rain events. As new materials are being engineered, and techniques for improving existing infrastructure are introduced, understanding how wet materials behave in comparison to their dry counterparts is essential information. The best way to obtain this information is through experimental methods.

We performed experiments in dry conditions, as well as during periods of rain, in order to examine energy transfer into and out of the surface in each scenario. Each experiment lasted two days, allowing us to compare measurements from the wet surface to the dry surface at the same time of day. We took measurements of surface temperature, air temperature, air pressure, relative humidity, rain amount, and net radiation. Additionally, the temperature close to the surface was measured at seven 1 mm intervals as a way of finding the temperature gradient. Each of these measurements was necessary for calculating the components of the energy budget.

METHODS

We gathered data over a 48 hour time span, with a period of rain occurring during each experiment. The rainfall was natural, as opposed to simulated, so the duration, timing, and intensity were not consistent between experiments. We used a net radiometer to measure incoming and outgoing radiation from the surface, a thermocouple to measure surface temperature, and a Vaisala weather transmitter to measure wind speed and direction, relative humidity, and rain intensity. We used these data to calculate the components of the energy budget for each material.

The Energy Budget

The energy budget consists of four components: net radiation (Rn), sensible heat flux (H), latent heat flux (LE), and molecular flux into the ground (G). Rn encompasses shortwave radiation coming in from the sun, the incoming longwave radiation from the atmosphere, as well as the short and long wave radiation reflected back into the atmosphere and emitted by the surface. H is energy that causes variations in temperature without changes in phase, while LE is responsible for phase change (evaporation) without altering the temperature. G is the measure of the difference in temperature between the surface and the subsurface. These variables can be related through the following equation.

$$R_n = H + G + LE \qquad \text{(Eq 1)}$$

Sensible Heat Flux

Fluid flow over a surface is generally dominated by inertial forces, causing turbulence. However, in the distance particularly close to solid surfaces, the flow is dominated by viscous effects, and is therefore more orderly. The heat flux over this space, call the viscous sublayer, is primarily a result of intermolecular collisions that transfer the molecular kinetic energy, much like diffusion. It can therefore be expressed in terms of the spatial temperature gradient and the thermal conductivity of air. A sensor developed by recent Princeton graduate, Ingrid Yen, was used to measure the spatial temperature differential immediately above the surface. The sensor is a 3D printed rod with seven grooves at 1 mm intervals so that thermocouple wires can be wrapped around them, measuring the temperature gradient close to the surface. Here the flow is assumed to be viscous, instead of turbulent. H is calculated using this temperature gradient, multiplied by the conductivity, k, of air.

$$H = -k\frac{\partial T}{\partial Z} \qquad \text{(Eq 2)}$$

Molecular Ground Flux

With Rn measured by the net radiometer, and H found using the temperature gradient, G can be calculated with the energy budget equation (Eq 1) during dry periods, when LE is negligible. To verify the accuracy of the recently developed temperature gradient sensor, we also calculated G using the following force-restore equation:

$$-G = C_{GA}\left(\frac{\partial T_G}{\partial t}\right) + \left[\frac{2\pi}{\mathbb{P}} C_{GA}\right] [T_G - T_M] \qquad \text{(Eq 3)}$$

Latent Heat Flux

When the surface is wet, and LE is not negligible, it must be calculated using specific humidity at the surface, q_s and of the air, q_{air}.

$$LE = C_E(q_s - q_{air}) \qquad \text{(Eq 4)}$$

We used the surface temperature to solve for saturated vapor pressure and then converted it to specific humidity at the surface, while the measured air relative humidity to was used to calculate air specific humidity.

When the surface is smooth, the heat transfer coefficient, C_H, can be substituted for the water vapor coefficient, C_E. We found C_H using the temperature instead of the specific humidity of the surface and of the air.

$$H = C_H(T_s - T_{air}) \qquad \text{(Eq 5)}$$

Calclating C_H in dry conditions, and using this value for C_E in wet conditions, we were able to calculate LE. To determine how long the surface was wet for, we compared the measured values from the top thermocouple on the temperature sensor to the air temperature recorded by the weather transmitter. Theoreticall,y these values should be close; however, the thermocouples lose accuracy when wet, so when those measurements were different from the weather transmitter's we assumed the surface was not dry.

RESULTS

The graphs below show the values of each component of the energy budget taken over time. The periods of rain, in addition to the time it took for the surface to dry, are represented by the dotted line. To compare the dry and wet periods, we looked at the the same time period on the day it rained, as well as as the day it did not. In Figure 1, it is clear that the net radiation is much lower on the day that it rained. This can be attributed to cloud cover from the storm, or lower temperatures on that day.

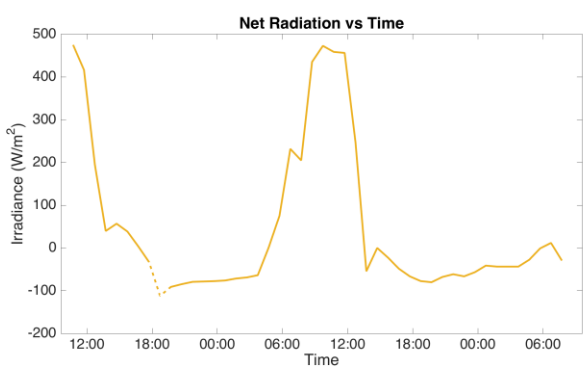

FIGURE 1. Net Radiation over time on concrete

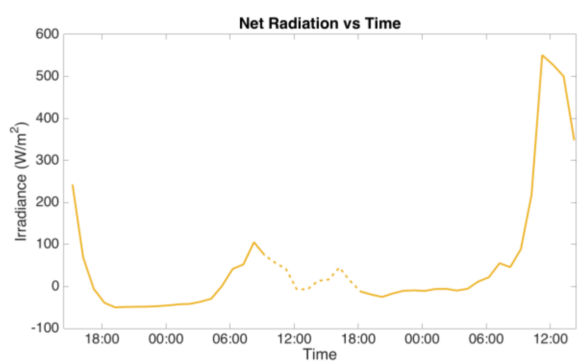

FIGURE 2. Net Radiation over time on asphalt

Figure 3 shows a sharp increase in heat flux during rainfall, which is most likely due to the inaccuracy of the sensors when wet. In the asphalt data, there is a clear dip in the heat flux (Figure 4), and although the exact values are not reliable, the overall trend is evident.

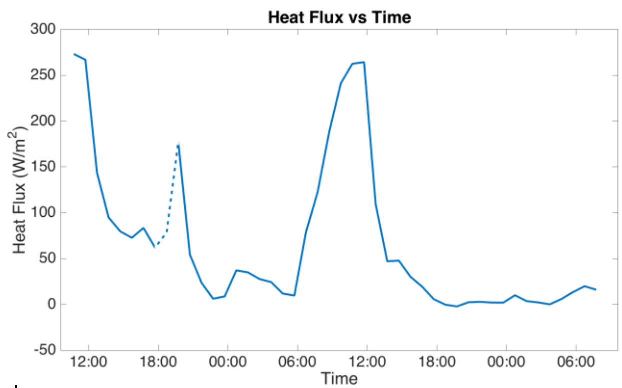

FIGURE 23. Heat flux over time on concrete

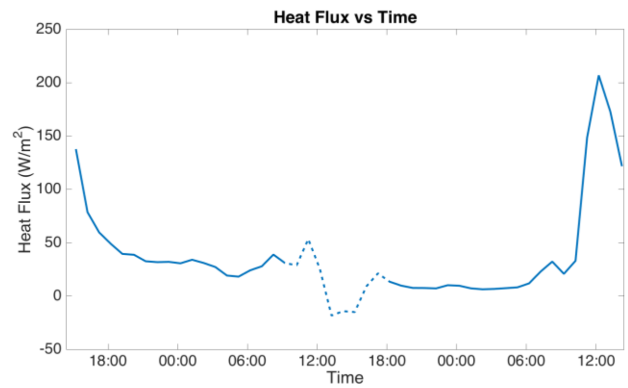

FIGURE 4. Heat flux over time on asphalt

Both the concrete and asphalt data show much lower ground flux responses when the surface is wet (Figure 5, Figure 6).

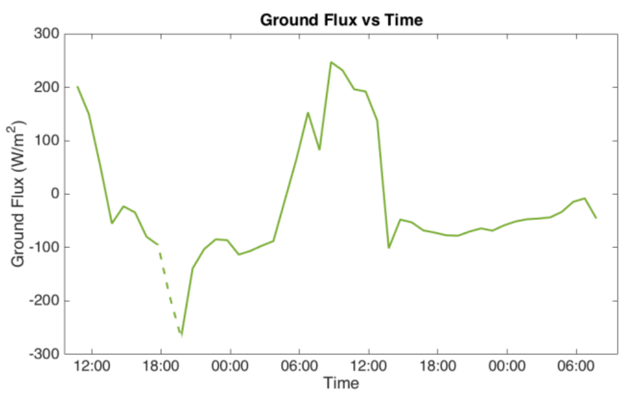

FIGURE 5. Ground flux over time on concrete

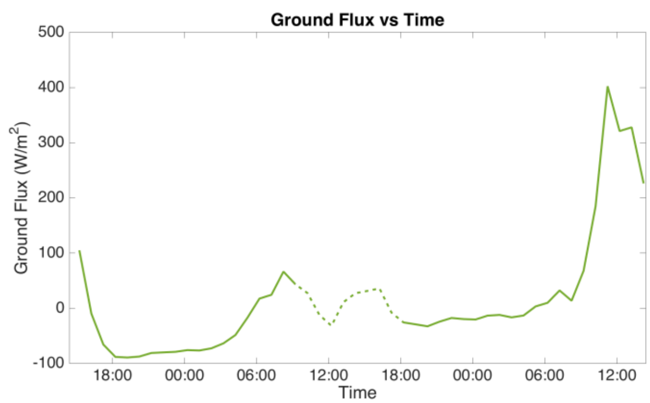

FIGURE 6. Ground flux over time on asphalt

The latent heat flux is only present when the surface is wet, so there is no data for the dry periods of each experiment (Figure 7, Figure 8).

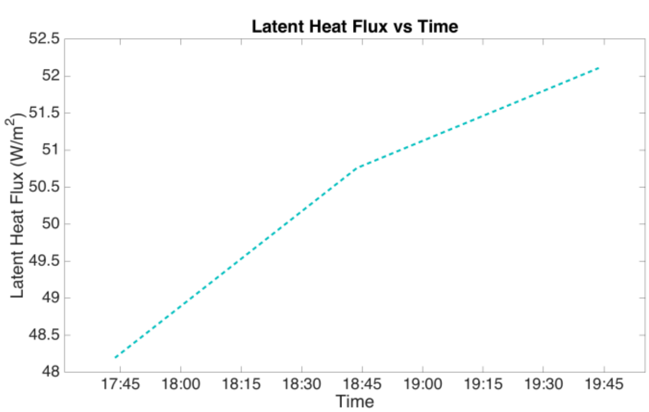

FIGURE 7. Latent heat flux over time on concrete

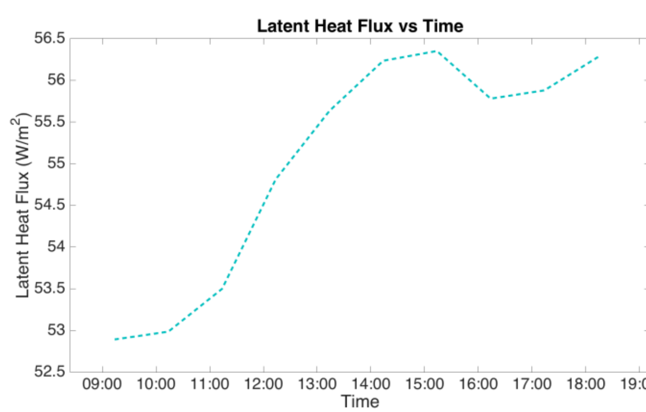

FIGURE 8. Latent heat flux over time on asphalt

The force-restore equation used to find G was highly sensitive to the input values: conductivity, heat capacity, specific heat, and density of the ground surface. These variables had a wide range of variability, so it was difficult to obtain accurate results. Figure 9 shows how changing the conductivity from one end of the accepted range to the other can has a large impact on the output.

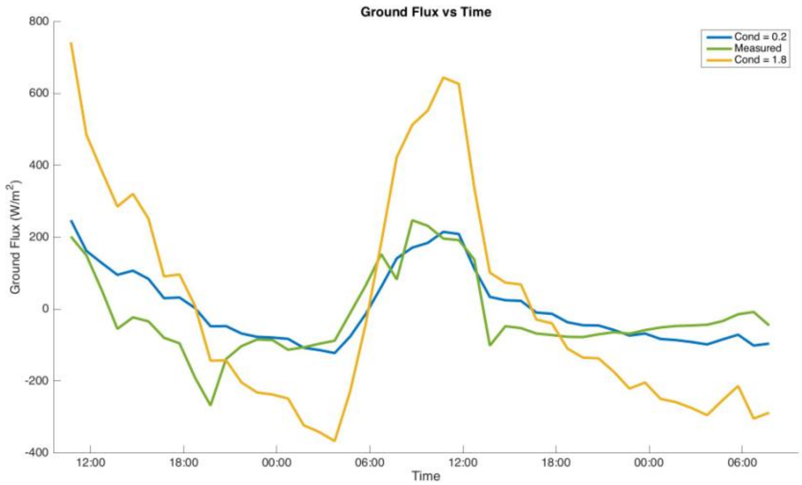

FIGURE 9. Ground flux over time for different values of conductivity

To account for this variability, we calibrated the input variables to dry conditions, and then applied them over wet conditions.

DISCUSSION

LE is responsible for the process of water evaporating into the atmosphere. Phase changes from liquid or solid to vapor are the main energy transfer mechanisms from Earth's surface to the atmosphere on a global scale. It follows, then, that the heat flux and molecular ground flux are lower than expected when the surface is wet. The evaporation that occurs is responsible for most of the heat transfer in this case, and if the net radiation stays constant, the result is less energy transferred through heat and ground flux.

Water vapor is the most abundant greenhouse gas, trapping solar radiation that would otherwise escape into space. This leads to a positive feedback loop, wherein higher temperatures result in increased evaporation, adding more water vapor into the atmosphere, which increases temperatures, starting the loop over again. The measurement of LE is therefore extremely important, since higher LE diverts energy from H, and consequently reduces the urban heat island effect. Because urban surfaces, such as the ones tested in this study, are impervious, rain water accumulates on the surface, and escapes only as evaporation or runoff.

The findings support the hypothesis that rain has a noteable effect on the transfer of heat into and out of materials found in an urban environment. Experiments should be repeated, to determine how variability in rain patterns, cloud cover, and temperature affects the results. Trials should also be done with simulated rain for consistency. These experiments relied on naturally occurring rain to wet the surface, which is beneficial in replicating real world conditions. However, this also allowed for variability between the concrete and the asphalt experiments. Results were likely altered by the fact that rain occurred in the morning for the concrete, and in the middle of the day in the case of the asphalt. Although we accounted for the increased drying time that occurred after the sun went down, other conditions such as rain intensity and duration, may have had an impact on each surface's response.

The accuracy of the sensors was a major limitation in this research. While overall trends could be observed, exact numbers could not be relied upon until the sensors dried off. More sophisticated sensors would be useful in providing more accurate data during wet periods. It would also be informative to get data on the thermal properties of the urban materials being tested, such as the conductivity, albedo, and heat capacity. These aspects are not well documented in existing research, and can vary widely, so finding this data experimentally would increase accuracy, building confidence in the calculations of energy budget components that rely on these input values. Ultimately, the goal of future research is to find ways to build more sustainable cities. Data collected should inform future decisions on building materials and techniques, taking into account the atypical scenarios that may occur.

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