The Heat Budget Mini-Project

August 18, 2009

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1. Theoretical background

We consider the energy budget at the soil surface (equation 1). Energy flux components absorbed or emitted by the soil surface are: net radiation, latent heat flux, sensible heat flux and ground heat flux. Net radiation is comprised of solar radiation (minus the reflected fraction), longwave radiation from the atmosphere and the emitted longwave radiation from the surface (equation 2).

$$R_N - SH - LH - G = 0$$

Equation 1.

$$R_N = S(1 - a) - LW \uparrow + LW \downarrow$$

Equation 2.

Where R_n denotes net radiation (positive downwards), SH is sensible heat flux, LH is latent heat flux, G is ground heat flux, S is the solar radiation, *a* is albedo, and LW denotes upward (↑) and downward (↓) longwave black body radiation. Upward black body radiation is emitted by the surface, whereas downward black body radiation is emitted by the atmosphere.

When all of the radiation components are considered, the equation 1 should sum up to zero. In the following analysis, we will try to close the energy budget for seven different types of surfaces.

1.1 Shortwave radiation

The intensity of incoming solar radiation at the top of the atmosphere is called the solar irradiance, S. It is given in units of $W*m^{-2}$. Some of this radiation is attenuated by scattering, absorption and reflection from clouds on the way down to the surface. When the sun is lower in the sky, the radiation will also be attenuated by its longer path through the atmosphere en route to the surface. In our experiment, we measure the solar irradiance at the earth surface, after some of the radiation has been attenuated by the aforementioned processes. The measurement is done in two ways – using an Eppley pyranometer and using an RCR spectrometer.

In order to estimate the intensity of the absorbed solar radiation we used the expression *Absorbed Solar* $= S \cdot (1 - a)$. "*a*" denotes surface albedo, and it differs for each surface.

1.2 Thermal infra-red radiation

2.2.1 Upward long wave radiation (LW↑)

The emitted long wave radiation from the earth's surface is given by

$$F_s = \varepsilon_s \sigma T_s^4$$

$$Equation\ 3.$$

Where T_s is the surface temperature, ε_s is the surface emissivity and σ is the Stefan-Boltzmann Constant. In the TIR part of the spectrum, the emissivity is usually close to unity; in our experiment, we used $\varepsilon_s = 0.95$.

2.2.2. Downward long wave radiation (LW↓)

The earth's atmosphere also emits long wave radiation, because of the presence of greenhouse gases such as carbon dioxide and water vapor. The downgoing long wave radiation plays a significant role in the surface heat budget. It is estimated from

$$F_a = \varepsilon_a \sigma T_a^4$$

$$Equation\ 4.$$

Where T_a is the lower atmosphere temperature and ε_a is the atmospheric emissivity. Several different methods have been proposed to estimate ε_a, we will use a single value at sea level: $\varepsilon_a = 0.67$.

1.3 Turbulent heat transfer

1.3.1 Sensible heat (SH)

A fraction of heat that is received by the earth's surface is transported to the atmosphere by conduction, convection and evaporation. These turbulent heat fluxes can be measured only by a fully instrumented flux tower using the eddy-covariance method. However, flux towers are very expensive and not portable, so for our experiment we used estimates of heat fluxes using an empirical exchange equation. For sensible heat

$$SH = \rho C_p C_{DH} U (T_s - T_a)$$

Equation 5.

where r is air density at sea level ($r = 1.2\ \mathrm{kg \cdot m^{-3}}$), C_p is specific heat capacity for air ($C_p = 1004$ J/kg·K) and C_{DH} is the exchange coefficient. C_{DH} depends on the wind speed, surface roughness and on the difference between air and surface temperatures. In our experiment C_{DH} is somewhat of a fudge coefficient; we are taking it to be constant and equal to $C_{DH} = 0.00495$.

1.3.2 Latent heat (LH)

When the surface is moist (e.g. forest and water surfaces) evapotranspiration plays a large role in the heat budget: evaporation of water from the surface cools the surface. Also, water vapor flux into the atmosphere transfers latent energy upwards (latent heat flux). This energy can be turned into sensible heat if the water vapor condenses.

In our experiment, latent heat flux is neglected in all surfaces except grass. That is because water is essential for latent heat flux, and the only moist surface was grass – water is contained within a living plant and it evaporates during a hot sunny day. Latent heat flux is difficult to measure, so in our case we scale it with NDVI:

$$LH = 10\left(\frac{NDVI - 0.2}{0.6}\right) T_s(°\mathrm{C})$$

Equation 6.

This approximation is valid for NDVI >0.2, otherwise $LH = 0$. The uncertainty in this formulation will be one of the sources of error in our calculations.

1.3.3 Total turbulent heat flux

The total turbulent heat flux is the sum of the sensible and latent heat fluxes:

$$F_t = SH + LH$$

Equation 7.

2. Surfaces

Heat budget was calculated for a variety of surfaces, differing in albedo, texture and physical properties:

1. **Foam sheet (painted gray)**

Styrofoam was chosen as a control surface because it is not a good heat conductor. We are assuming that it conducts no heat into the soil; therefore the “imbalance” term has to be close to zero. Also, it is dry, so the latent heat component is non-existent.

2. **Stone**
   Stone surface is in fact a stone pavement in front of the Environmental Sciences Center (ESC). It is brighter than asphalt, but darker than concrete. It is also dry, so the latent heat is assumed to be zero. However, since its physical properties are different than foam, it conducts heat so the “imbalance” term is not zero.

3. **Grass**
   Grass is essentially a patch of clovers in front of the ESC. Because of its surface heterogeneity it introduces some uncertainty into the value of the exchange coefficient. Also, the latent heat term is expected to be significant here because of the water contained inside the plants. This is especially true in the early morning, when there is also dew on the leaves.

4. **Soil**
   Bare soil in front of the ESC. Again, it is taken to be completely dry, so the latent heat term is zero. Other than having slight differences in albedo, it is expected to behave similarly to stone.

5. **Dark Asphalt**
   Dark asphalt is a part of the asphalt path in front of the ESC building. It has very low albedo so it is expected to absorb, and consequently, emit a lot of radiation. It is dry, so the latent heat term is taken to be zero. It is also a non-negligible heat conductor, so the imbalance term is not zero.

6. **Light asphalt**
   Also a part of the asphalt path in front of the ECS, although somewhat brighter in color. Other than the higher albedo value, it is expected to behave similarly to dark asphalt.

7. **Concrete**
   Concrete surface is a part of a sidewalk next to ESC. The sidewalk is constructed of concrete panels and for the experiment we picked the brightest one. It has the highest albedo of all the surfaces and because of it is expected to have a reversed (negative) heat flux very early after sunset. It is also dry, so the latent heat component is zero.

5. Results

Insolation (Eppley):

Insolation was measured in two ways: using the Eppley pyranometer and using the spherical head of the spectrometer (RCR). When measured with Eppley, it was expressed in millivolts and converted into W/m^2. The insolation should be the same above all surfaces if measured at the same time of day and during the same atmospheric conditions (i.e. no scattered clouds passing over). However, due to non-ideal conditions of our measurements (a building or trees blocking sections of the sky), insolation varied from surface to surface.

Insolation shows a very visible diurnal cycle: it has very small values just after sunrise (at 0600 only the diffuse component was measured because the building was blocking the sun), it reaches maximum at 1200 (due to the smallest solar zenith angle) and it falls to zero at night.

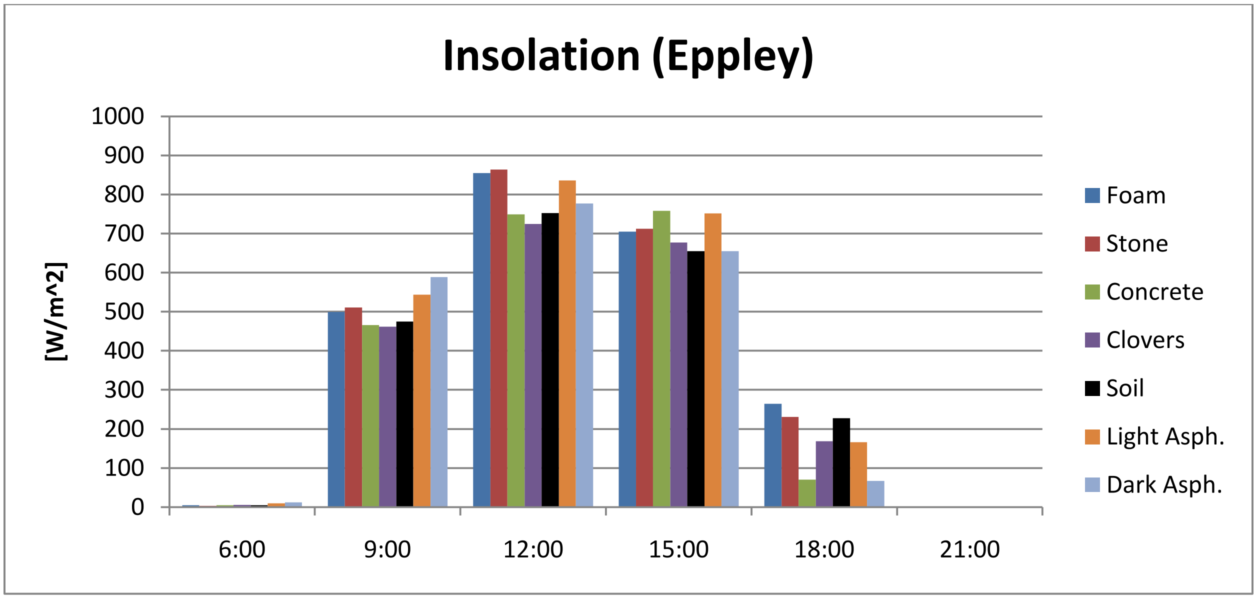

Figure 1: Insolation measured by Eppley pyranometer. For a given time, insolation is supposed to be the same for all surfaces. The variations observable here are due to non-ideal measuring conditions (something blocking the sun, or a part of the sky thus reducing diffuse radiation).

Insolation (RCR):

Insolation was calculated using the spectrometer by summing up the irradiances above each surface across all wavelengths. These results are somewhat different than the ones obtained by the pyranometer. Even though the data sets show the same qualitative features (e.g. prominent diurnal cycle), individual measurements differ significantly. For example, the Eppley and RCR insolations measured at noon, differ by up to 80 W/m^2.

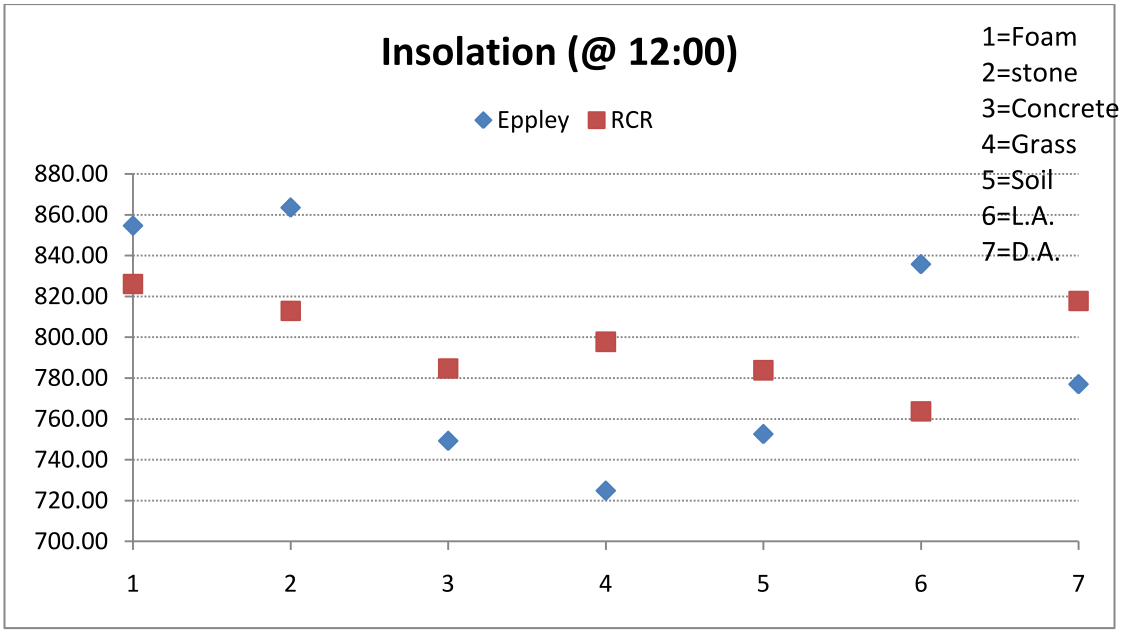

Figure 2: A plot showing differences in noon insolation due to different instruments. The insolation differs significantly depending whether a pyranometer or a spectrometer was used. Because of this discrepancy, in the following analyses it will be specified which method was used.

Albedo

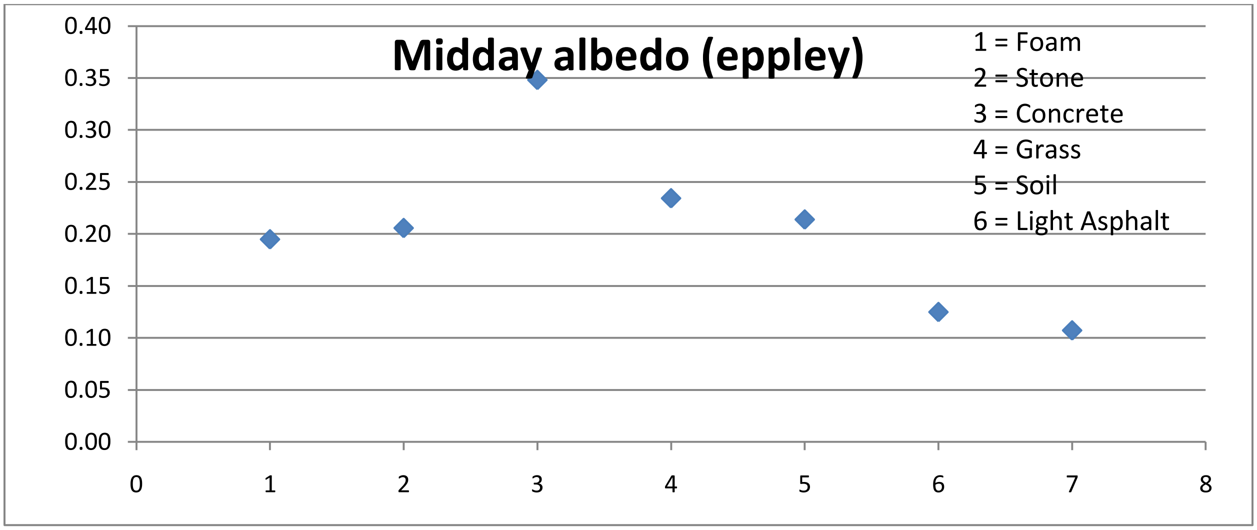

Figure 3: Noon albedo of all surfaces as measured by Eppley pyranometer.

Albedo of various surfaces is not expected to vary much during the day, therefore I am presenting only noon albedo here. As expected, due to its white color, concrete has the highest albedo (0.35). Surprisingly, grass has a somewhat higher albedo than soil, which is not consistent with theoretical expectations. This could be explained by a relatively large "fetch" that the instrument has, and a relatively small size of the bare soil patch. With this in mind, it is possible that the albedo for soil is actually a mixed signal of soil and grass albedo. Dark asphalt has the lowest albedo (about 0.11) of all surfaces.

Air temperature:

Air temperature was measured approximately 2 meters above each surface at the time of performing other measurements. Theoretically, it is expected to be the same for each surface. The differences in air temperature observed at times 0900, 1200, 1500 and 1800 are probably due to the instrument not being entirely shaded from the sun, which may have influenced the measurements. The values (in Kelvins) are given in Table 1:

time	Foam	Stone	Concrete	Clovers	Soil	Light Asphalt	Dark Asphalt
6:00	296	296.2	296.2	296	296.1	296	296
9:00	298.9	299.6	301	301	301.3	301.1	301.4
12:00	302.6	303.3	306	305.1	304.8	305.1	305.8
15:00	305.8	306.9	306.5	304.5	306.8	305.5	306.2
18:00	301.4	302.1	302.6	302.7	302.7	304	303.4
21:00	298.6	298.8	298.9	299.1	299.1	299.2	299.1

Table 1.

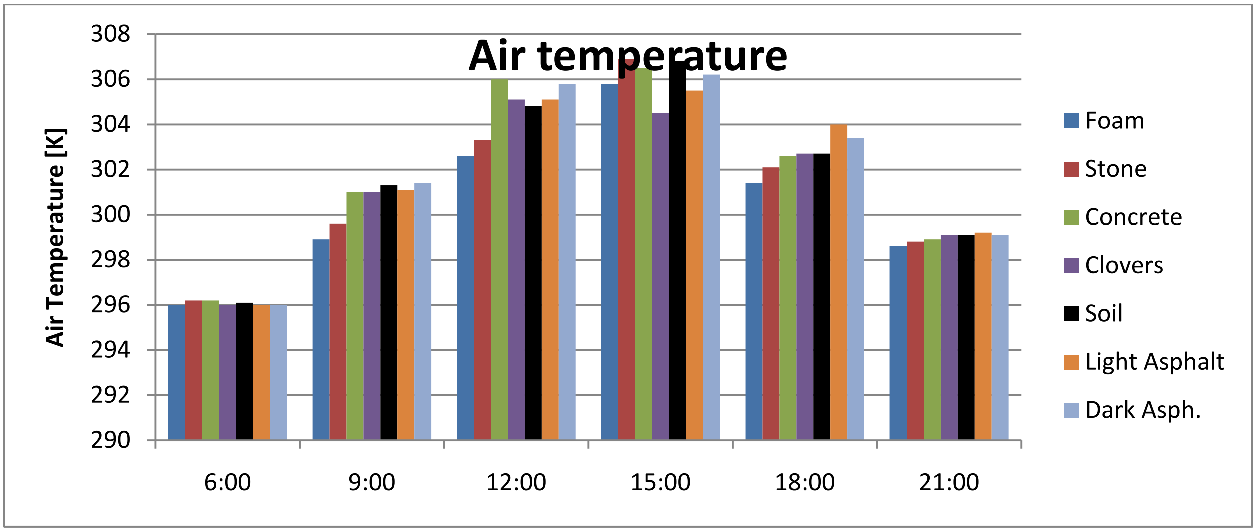

Figure 4: Air temperature throughout the day, measured over all surfaces. Due to a large inhomogeneity of the area, air temperature is expected to be the same over all surfaces for a given time. Variations are due to non ideal measurement conditions (sun hitting the Kestrel, etc.).

As visible from the Figure 2, the air temperature clearly follows a diurnal cycle with minimum temperatures just before sunrise and maximum temperatures in the afternoon.

Surface temperature:

Surface temperatures were measured for each surface, using a Raytek infra-red thermometer. All surfaces had temperatures higher than air temperature during the day. However, at 0600, surface temperatures were generally lower than air temperature. At 2100 surface and air temperatures were about the same.

During the day, foam continually had the highest temperatures, indicating that our assumption about the lack of heat conduction was correct. Grass, on the other hand, had the lowest temperatures throughout our measurements. This result was expected - the relatively low temperatures are a consequence of evaporation of water through the stomata.

Also, an interesting result for the man-made surfaces: concrete, being brighter, had considerably lower temperatures during the day than light and dark asphalt.

time	Foam	Stone	Concrete	Clovers	Soil	Light Asphalt	Dark Asphalt
6:00	293.2	295.4	297.6	294.2	294.4	296.2	297.2
9:00	315.4	303.2	304.6	307.6	311.4	309.6	312.2
12:00	339.2	320.3	318.2	313.4	317.6	327	327.8
15:00	335.8	326.6	323.2	311.8	320	331.2	331.8

18:00	313.6	313.6	308.8	302.6	309.6	317.8	312.8
21:00	298.8	301.6	303.4	298.2	300	303.2	303.8

Table 2: Surface temperatures (in Kelvins) for all surfaces

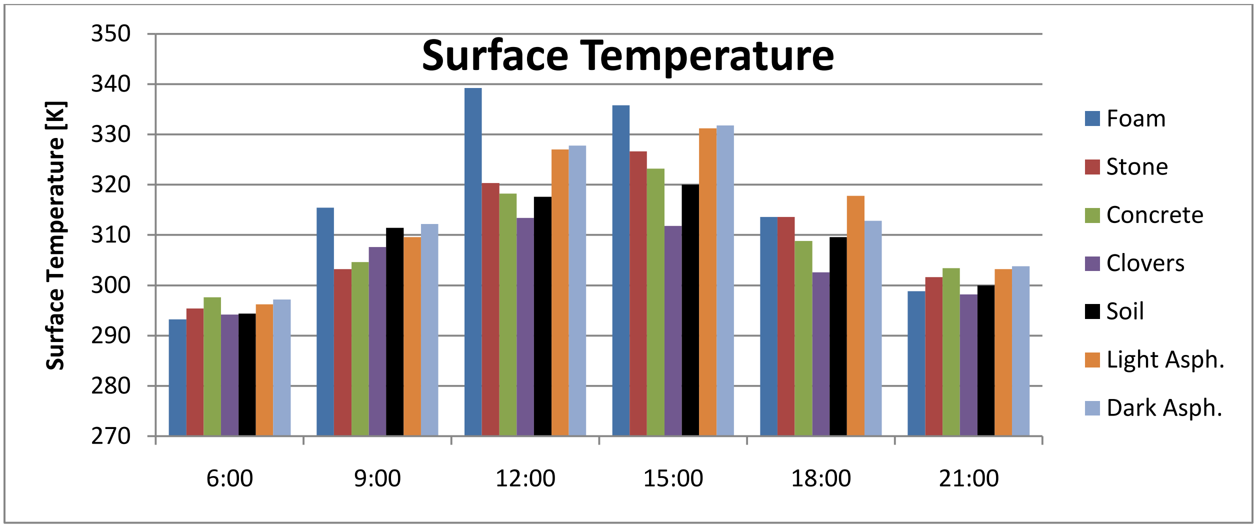

Figure 5. Surface temperature measured throughout the day for each surface.

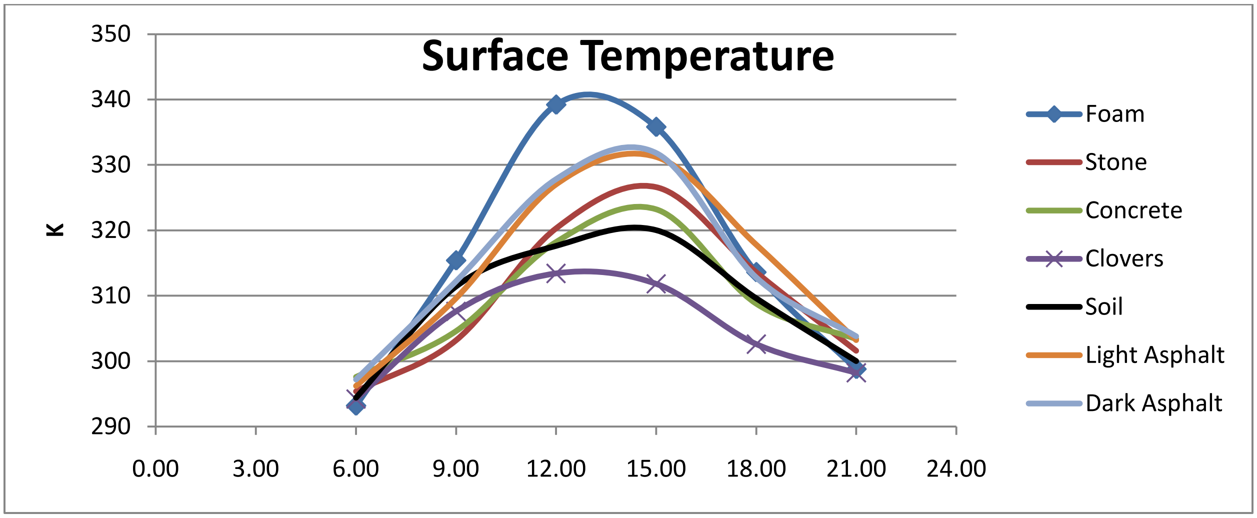

Figure 6: Surface temperature diurnal cycle for each surface.

Foam and grass reach their highest temperature at noon, whereas other surfaces reach their maximum temperature at 1500. The maximum temperature was measured after the maximal insolation due to thermal inertia of the surfaces like stone, concrete, soil etc. The reason why grass reached its maximum temperature at noon could possibly be explained by evaporative cooling that occurred during the maximum temperatures of the day, thus counteracting the temperature increase. Foam was not left outside in between measurements. Instead, it was carried outside some time before the measurement and left to equilibrate, which generally took about 5 minutes. Given its very limited ability to store heat, it was expected to reach its highest temperature during the maximal insolation.

Furthermore, foam reached the highest temperature of all surfaces. Among other, non-test surfaces, asphalt (both dark and light) reached highest temperatures. Concrete, surface with the highest albedo, was still warmer than bare soil at 1500 hrs. Concrete was also the only surface that was shaded at 1800 hrs (a building was blocking direct radiation) which explains its rapid decrease in temperature from 1500 hrs to 1800 hrs.

Net radiation:

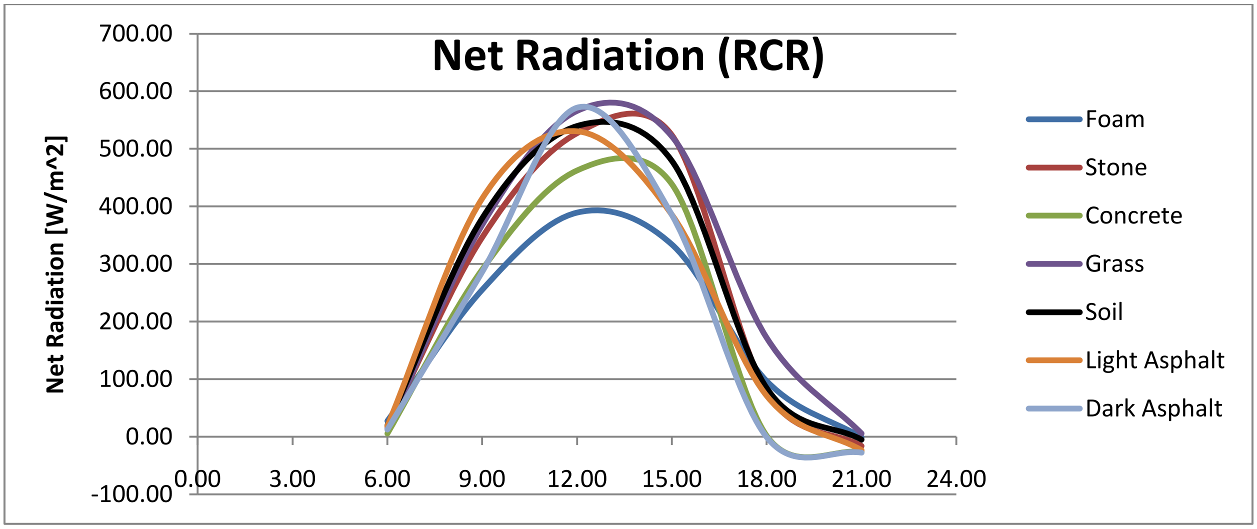

Figure 7: Diurnal cycle of net radiation for each surface.

Net radiation measured by RCR method generally shows the expected diurnal cycle: it peaks during midday and reverses sign in the evening. Net radiation becomes negative (negative = upwards) around 1800 for dark asphalt and concrete, whereas for most other materials that occurs around 2100. The reason for this early reversal could be the large amount of black body radiation emitted by dark asphalt during the day due to its high temperature. For concrete, the early reversal occurs due to a lack of incoming direst solar radiation at 1800hrs (there is a physical obstacle obscuring the sun). For other surfaces, net radiation reaches zero around 2100 hrs. This means that around that time, net radiation is upwards – from the ground, which cools off the ground surface. This cooling continues until sunrise.

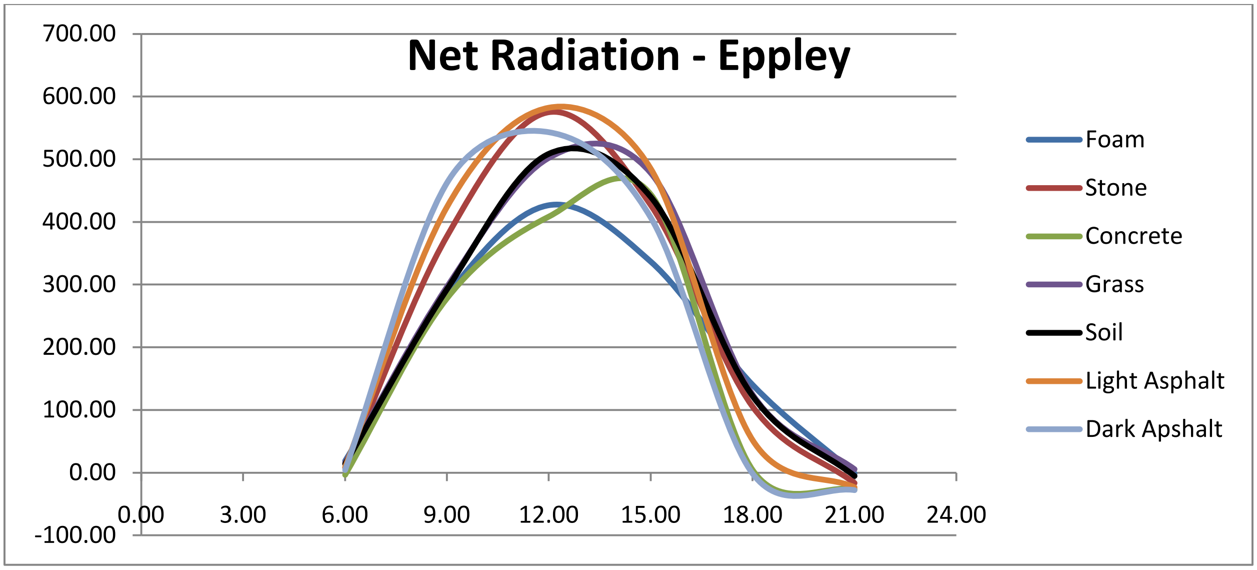

Figure 8: Diurnal cycle of net radiation for each surface.

Net radiation computed from insolation measured by Eppley is generally very similar to the one obtained by RCR. Here also net radiation for dark asphalt and concrete reverses signs at 1800hrs, whereas for other surfaces that occurs later. The only difference is observed for concrete: when measured by Eppley, net radiation for concrete peaks at 1500hrs instead of at 1200hrs.

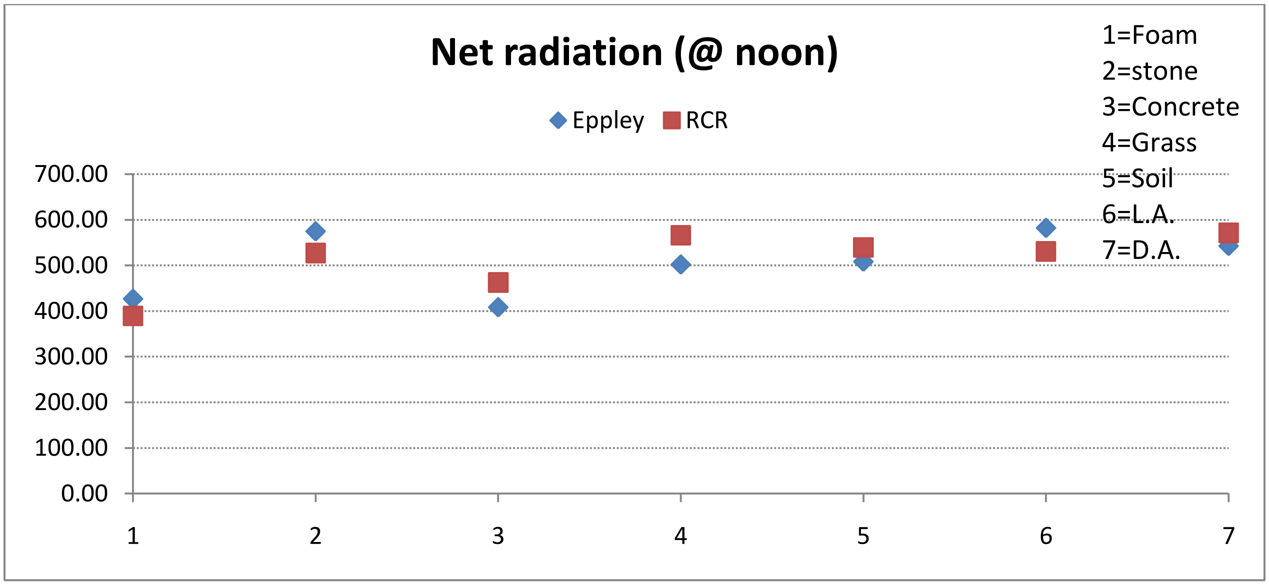

Figure 9: Comparison of midday net radiation measured by different instruments.

Sensible Heat Flux

In our experiment, sensible heat flux was computed based on the temperature differences between ground surface and air. This means that at a given time (air temperature is roughly constant above all surfaces) sensible heat flux will be the largest above the surface that has the highest surface temperature. In our case that was almost always foam (control surface), due to its limited ability of heat conduction.

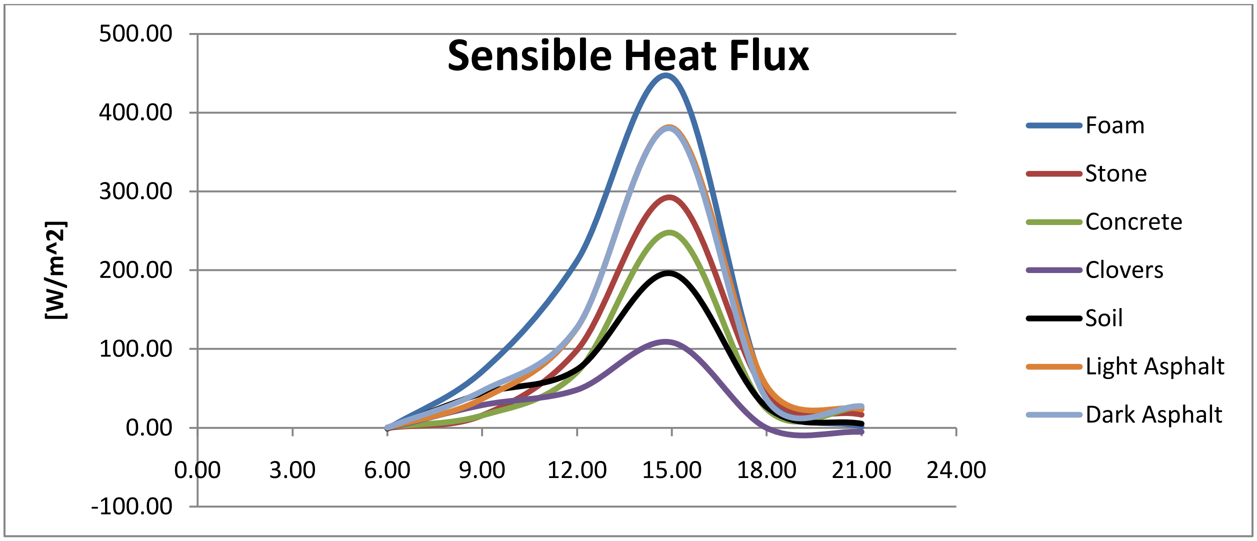

Figure 10: Diurnal cycle of sensible heat flux for all surfaces

Among non-control surfaces, sensible heat is largest for both dark and light asphalt. Natural surfaces (soil and grass) have the lowest sensible heat flux due to their lower temperatures. Grass has the lowest sensible heat flux of all surfaces, but not the lowest total turbulent flux (due to latent heat).

Latent Heat Flux

Latent heat was computed using equation 6. Since latent heat is scaled with NDVI, only vegetated surfaces are assumed to have latent heat flux in our experiment. (A hot, dry summer day was chosen for the experiment in order to minimize latent heat flux from other surfaces and thus reduce the error introduced by our assumption.)

Latent heat flux for grass is plotted in figure (11):

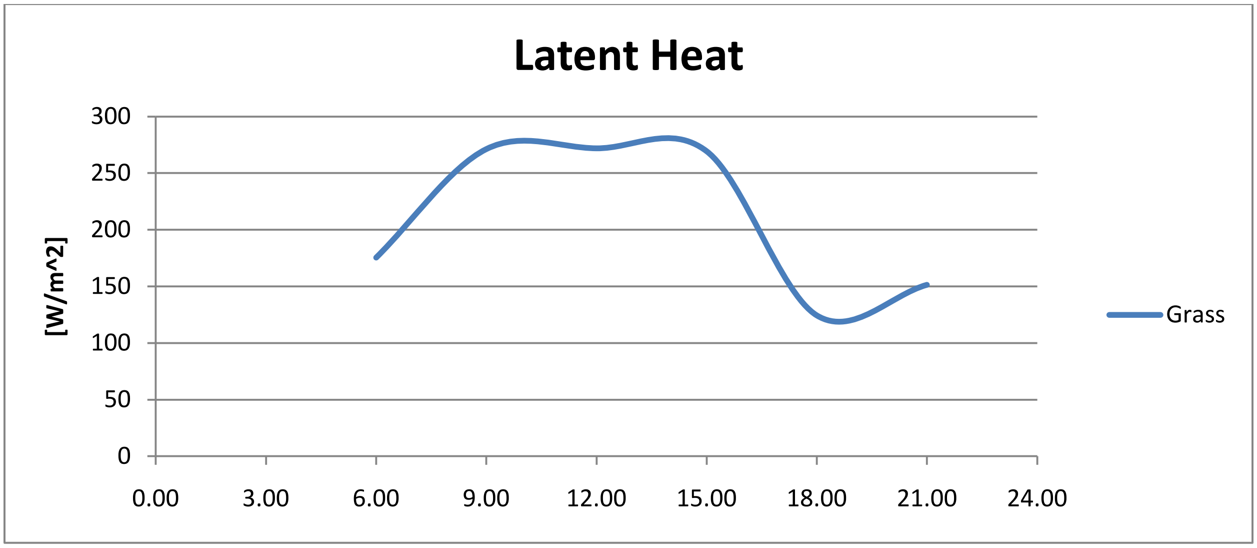

Figure 11: Diurnal composite of latent heat flux for grass.

Latent heat flux computed this way shows only a hint of a diurnal cycle. It is generally highest from 0900 to 1500. It reaches its minimum at 1800. The maximum values of latent heat are rather high (around 300 Wm^{-2}) meaning that latent heat flux dominates over sensible heat flux over grass.

Ground Heat Flux (Imbalance)

Since we do not have measurements of ground heat flux, we are assuming that the entire heat budget residual is in fact ground flux.

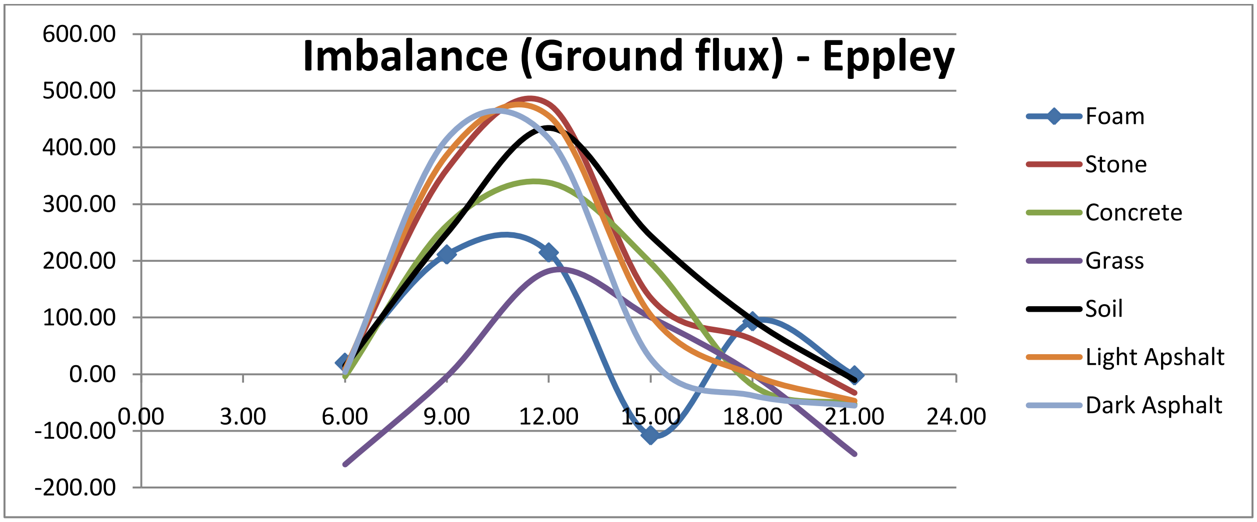

Figure 12: Diurnal cycle of imbalance (assumed to be equal to ground flux) for all surfaces.

Ground heat flux is generally highest at noon, when the net radiation is most intense. Dark asphalt, light asphalt and stone have a similar ground heat flux. It is zero at sunrise, reaches about 500 Wm^{-2} at noon and then falls back to zero around 1500 (dark asphalt), 1800 (light asphalt) and 2100 (stone). Among man-made materials, concrete has the lowest ground heat flux. It is about 320 Wm^{-2} at noon and falls to zero at 1800. Among the tested surfaces, grass has the lowest ground heat flux. It is negative at sunrise and reaches about 200 Wm^{-2} at noon. Around 1800 hrs, it changes sign and becomes negative again.

If our measurement errors and errors introduced through our assumptions were very small, the imbalance for the control surface (foam) would be close/equal to zero. However, that is not true. The imbalance for foam is actually rather large (up to 200 Wm^{-2}) and inconsistent with the diurnal cycle – it positive at noon, then negative at 1500, then positive again at 1800. This suggests that the errors introduced through our assumptions and non-ideal measurement conditions are large.

6. Conclusions

The heat budget experiment produced results that were in accordance with theoretical expectations: All of the energy components show a diurnal cycle which is directly related to solar insolation cycle. Furthermore, the net energy flux changes sign in the evening after sunset (1800 – 2100) thus changing from downward flux (into the soil) to upward flux (from the ground to the atmosphere).

Albedo was measured as a part of the experiment. As expected, visually brightest surface (concrete) had the highest albedo and consequently lower surface temperatures. There were some inconsistencies: bare soil had lower albedo than grass, but that is probably due to a mixed signal coming from both grass and soil. (The bare soil patch was very limited in size.)

We lacked instrumentation for measuring ground heat flux, so the heat budget residual term was assumed to be equal to ground heat flux. As a test of our assumptions and calculations, we used the heat budget measured for a gray piece of Styrofoam. Styrofoam has virtually no ability to conduct heat, therefore, the ground heat flux for that surface should be zero. However, the imbalance term for Styrofoam was very large (up to 200 Wm^{-2}). The reasons for this error are plentiful, but we suspect that parameterization of latent and sensible heats was the main source of inaccuracies.