The Energetics of Urban and Rural Microclimates

John E. Frederick

The University of Chicago

Natural and Urban Environments

What Processes Determine their Surface Temperatures?

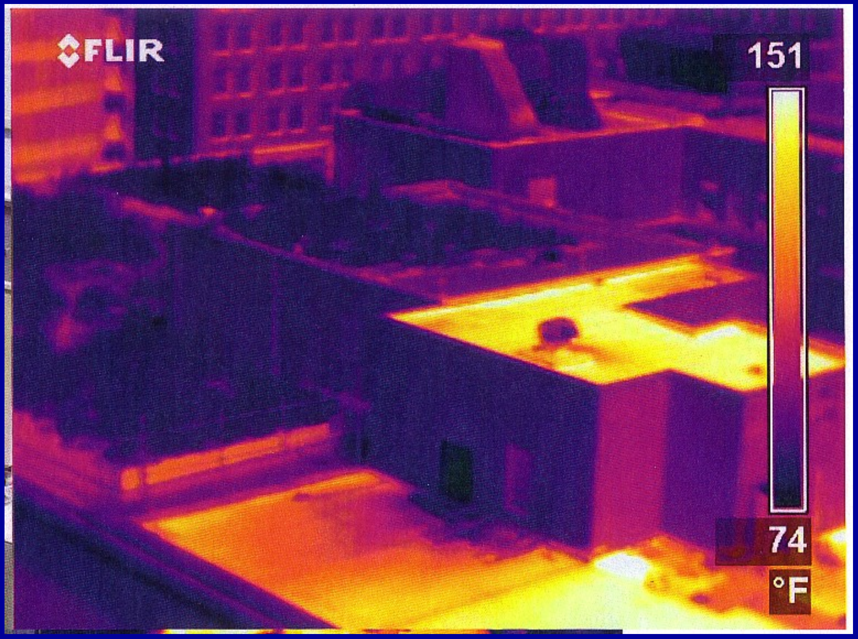
What Determines the Temperature of a Surface Exposed to the Atmosphere?

- Several different processes act simultaneously to heat and cool a surface (described by energy fluxes in watts m^{-2}) .
- Observed surface temperatures represent a balance between energy flowing into (heating) and out of (cooling) the surface.
- Some of the heating and cooling rates are functions of surface temperature.
- The temperature of a surface adjusts until the total energy flowing into the surface balances the total energy flowing out of the surface.

Origin of Temperature Differences: Natural versus Urban Environments

- **Anthropogenic Heat Release**
  - -Waste heat is released into urban air
- **Altered Surface Conditions**
  - -Reflectivity of surfaces
  - -Thermal Properties of materials
  - -Liquid water storage and evaporation
  - -Manmade structures alter wind flow

Temperature Contrast Between a Concrete and a Grass-Covered Rooftop – Chicago City Hall (Pictures from Chicago Dept. of the Environment)



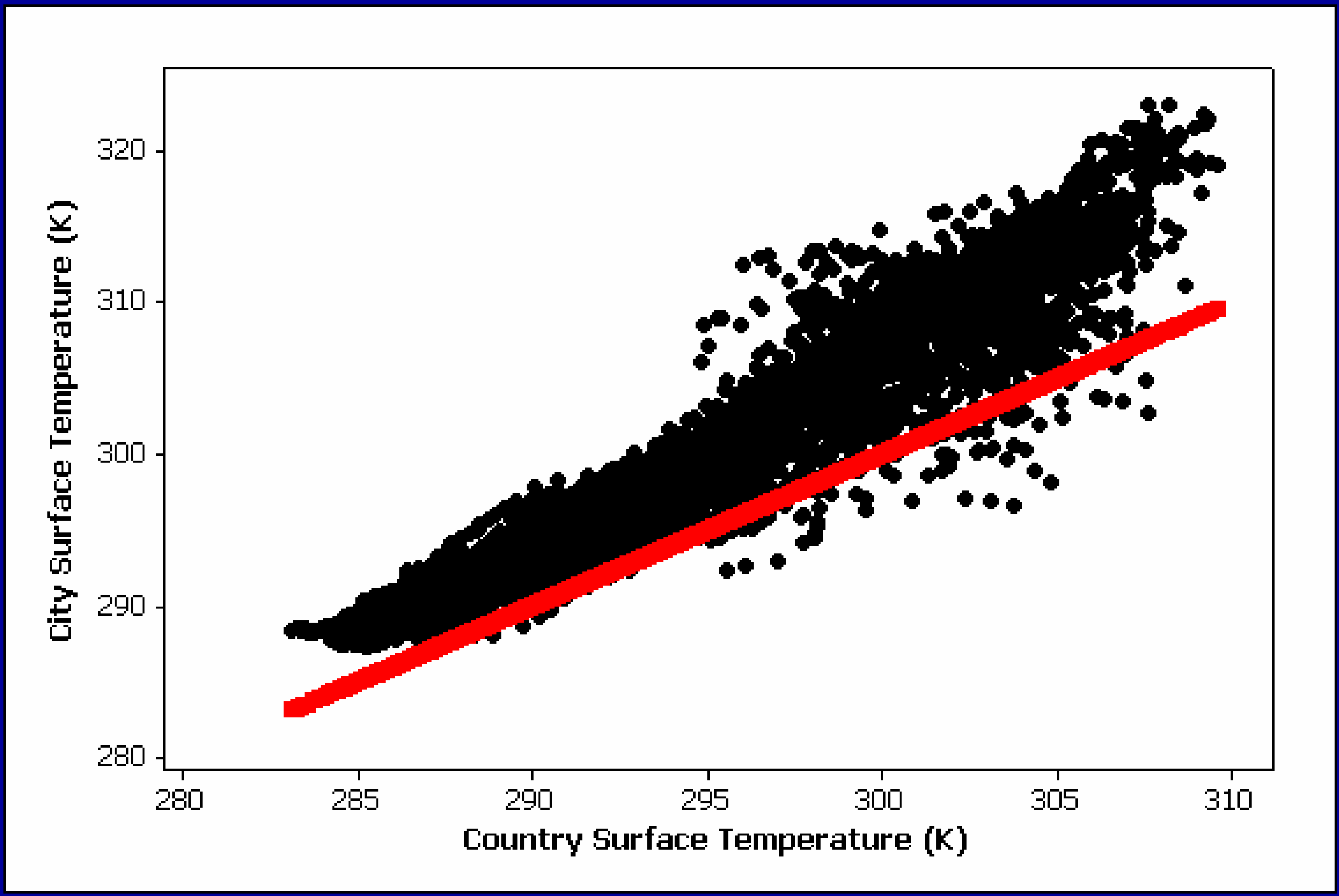
Observation Site – Illinois Countryside South of Chicago

Left: Net Radiometer Right: Weather Station

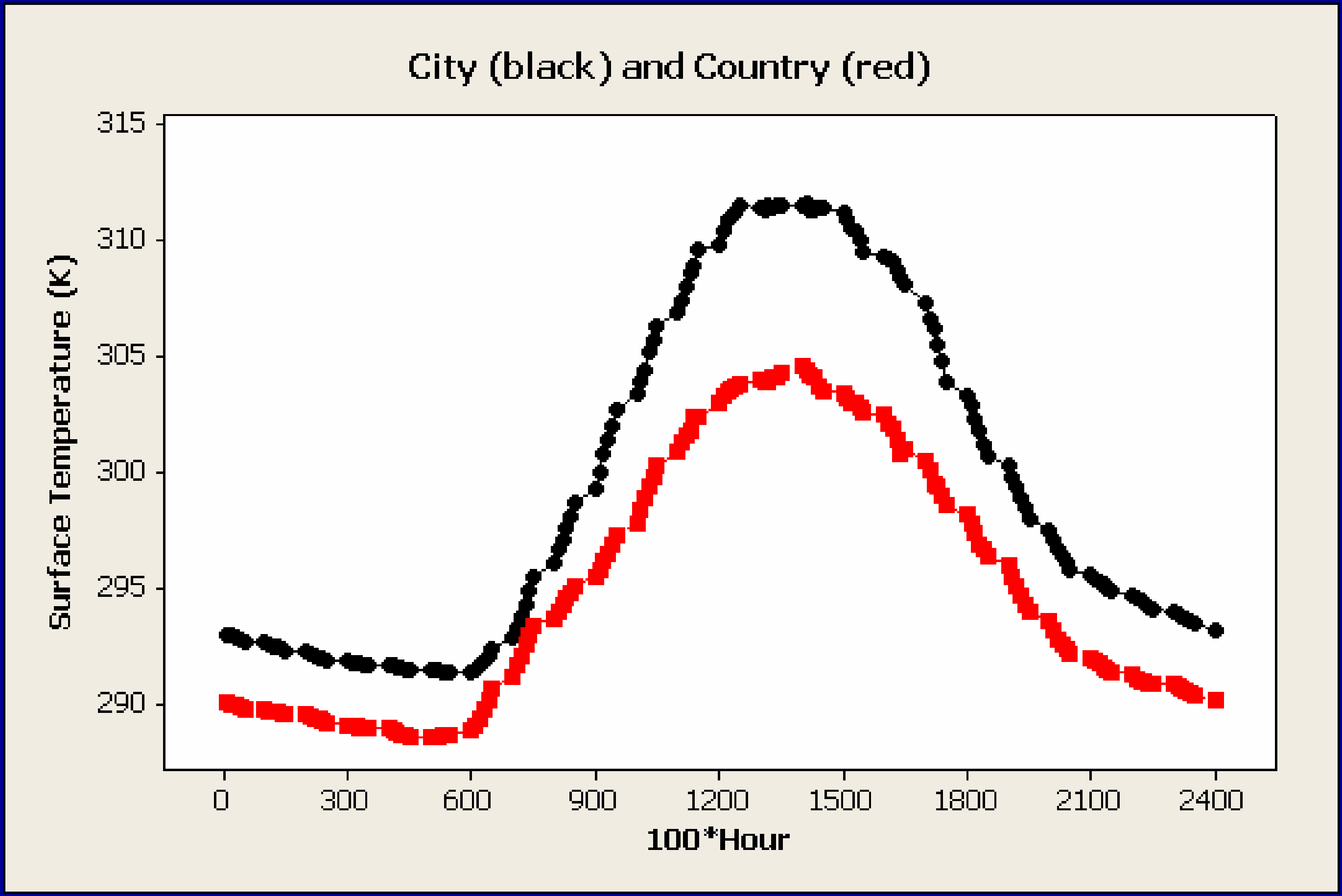
Net Radiometer

(2 solar sensors and 2 longwave radiation sensors)

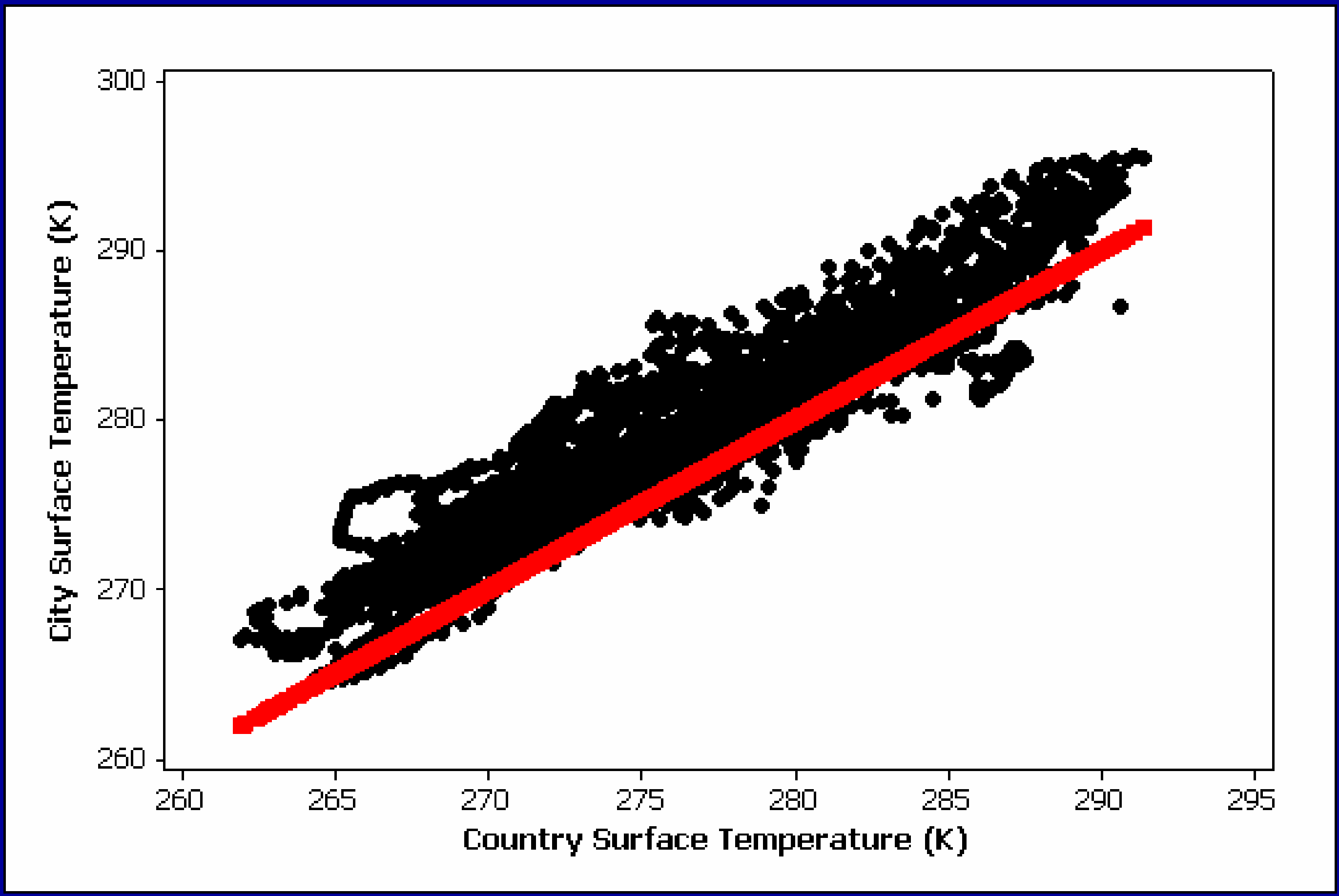
Surface Temperatures: July 2007 (City versus Country)



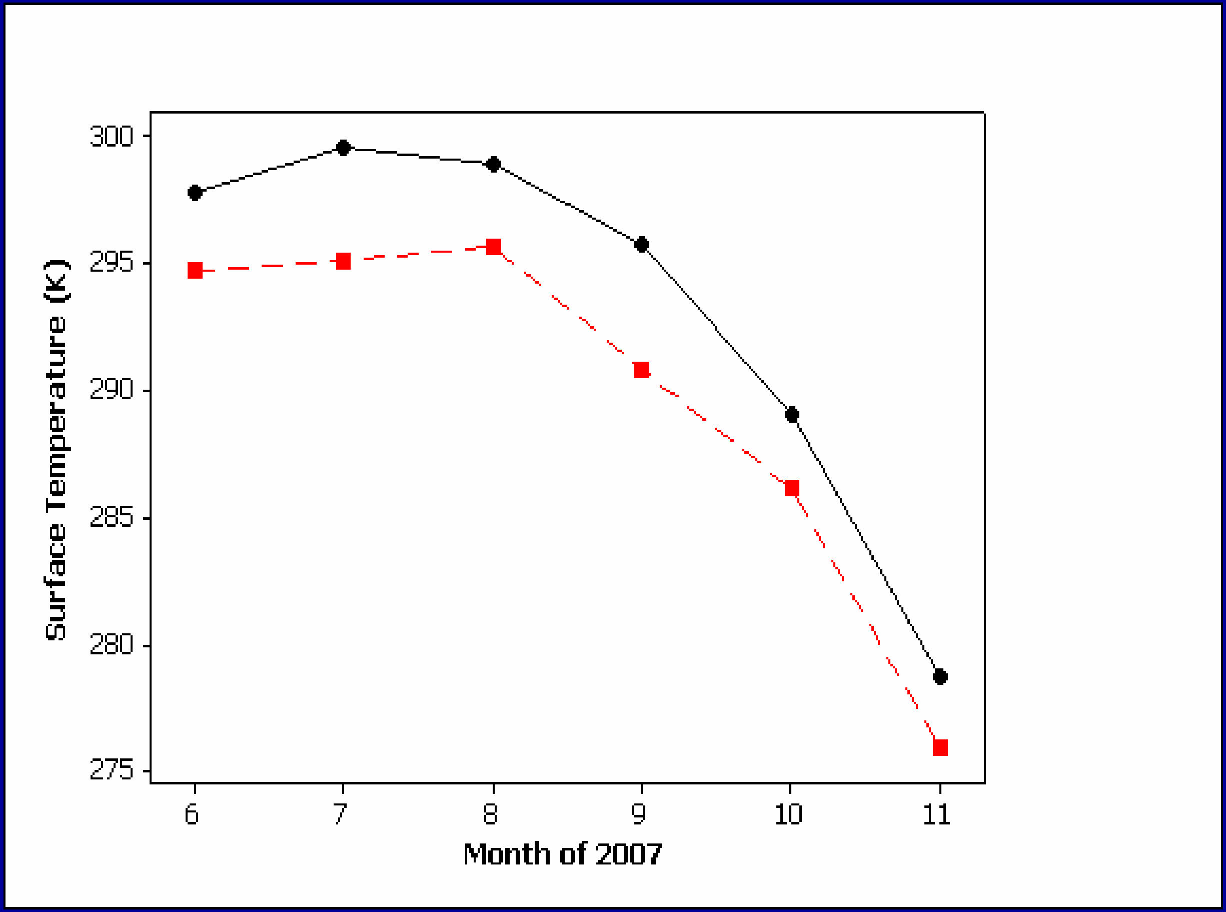
Monthly Mean Surface Temperature by Hour: July 2007



Surface Temperatures: November 2007 (City versus Country)



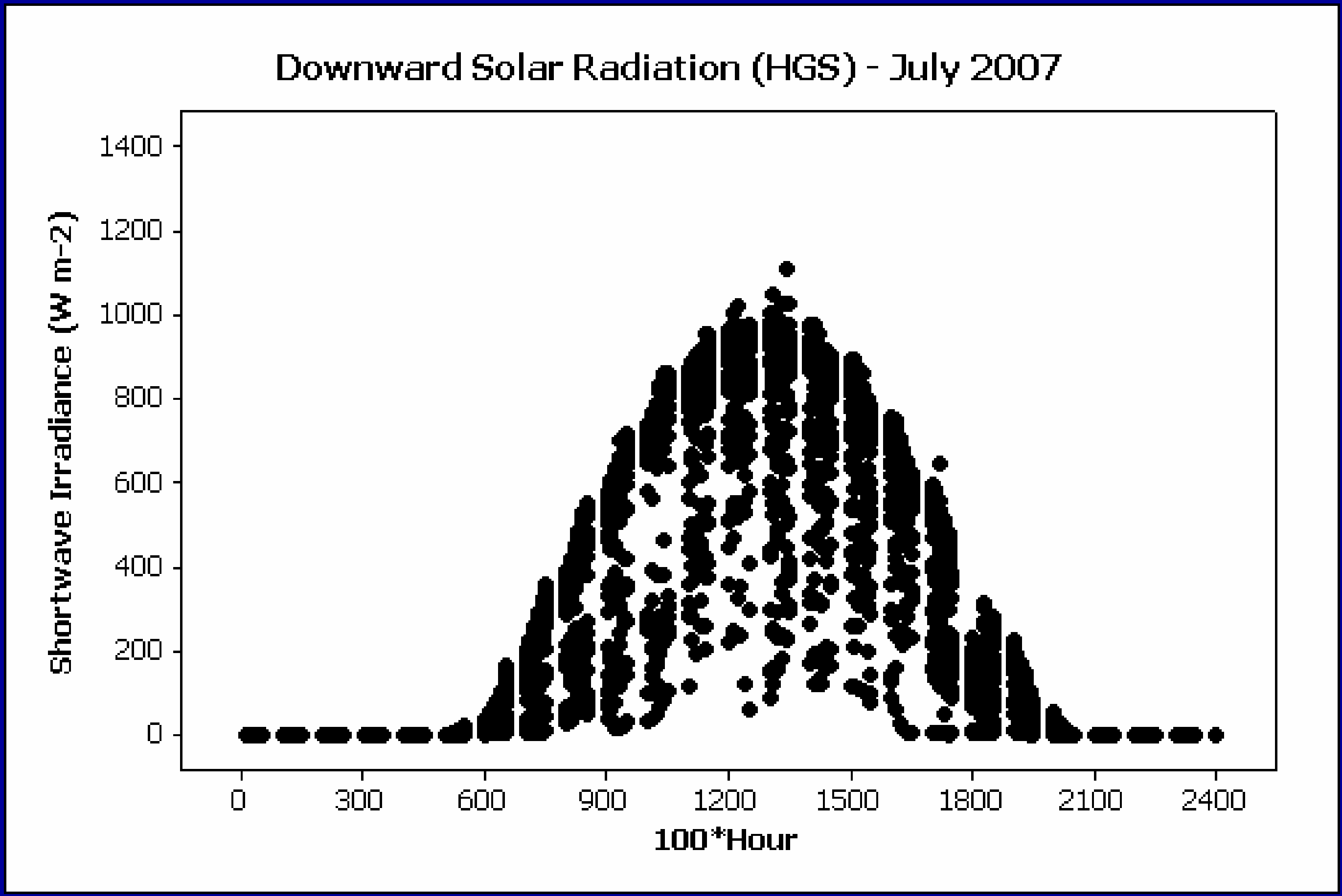
Monthly Mean Surface Temperatures: City (black) and Country (red)



How Do the Observed Temperature Differences Come About?

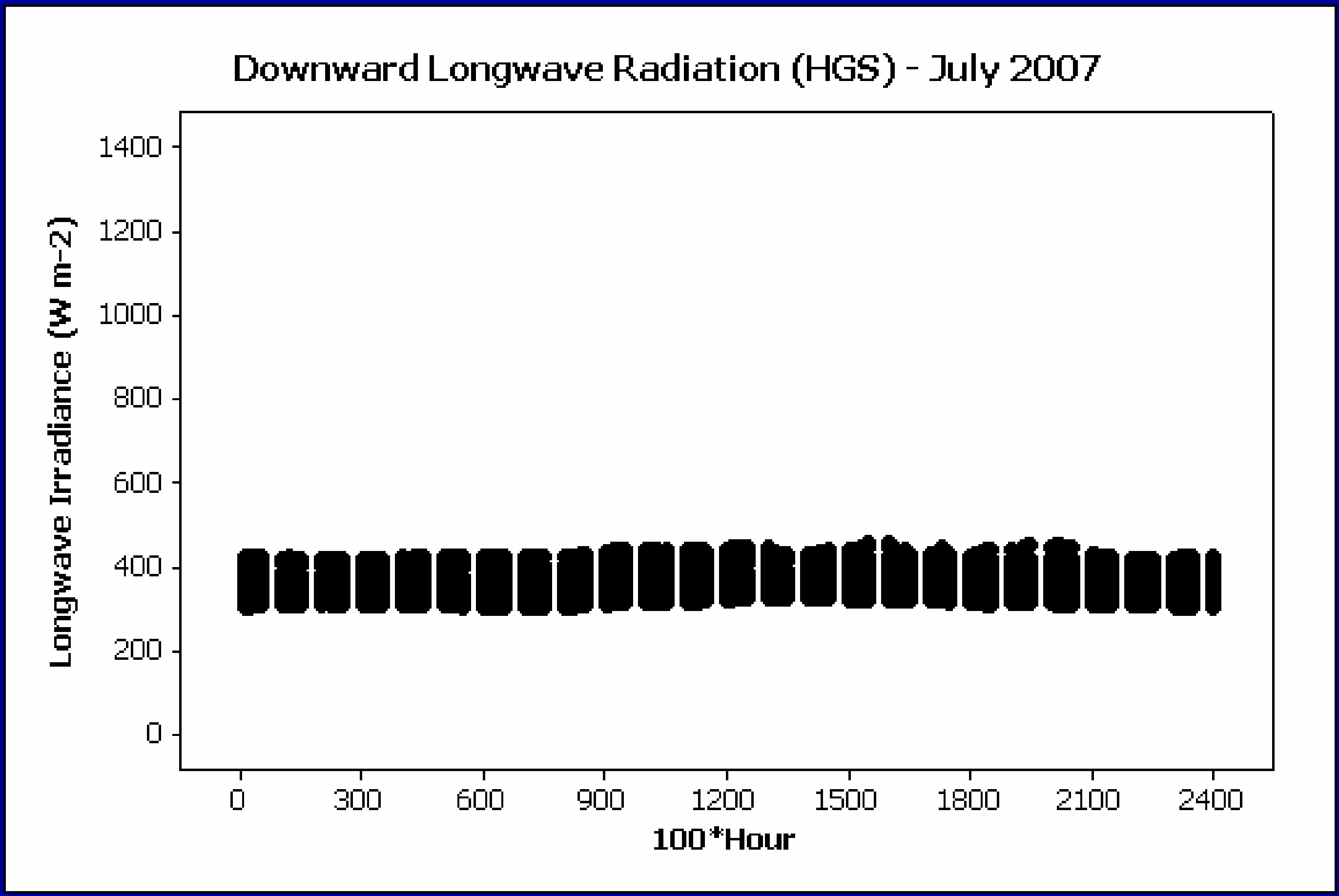
- Identify the physical mechanisms that act to heat and cool a surface.
- As a start, consider:
  - Solar (Shortwave) Radiation
  - Terrestrial (Longwave) Radiation
  - Radiative Heating
  - Net Radiation

Incoming Shortwave (SW) Irradiance – Urban Site



Incoming Longwave (LW) Irradiance: Urban Site

[Typical Wavelengths ~ 5-50 microns]



Relative Magnitudes of Shortwave (SW) and Longwave (LW) Irradiances: Country Site

Month	SW(dn)	LW(dn)	LW(dn)/SW(dn)
June	248.3	369.1	1.49
July	267.7	366.1	1.37
Aug	199.6	388.9	1.95
Sept	214.3	345.1	1.61
Oct	135.7	327.9	2.42
Nov	91.7	278.6	3.04

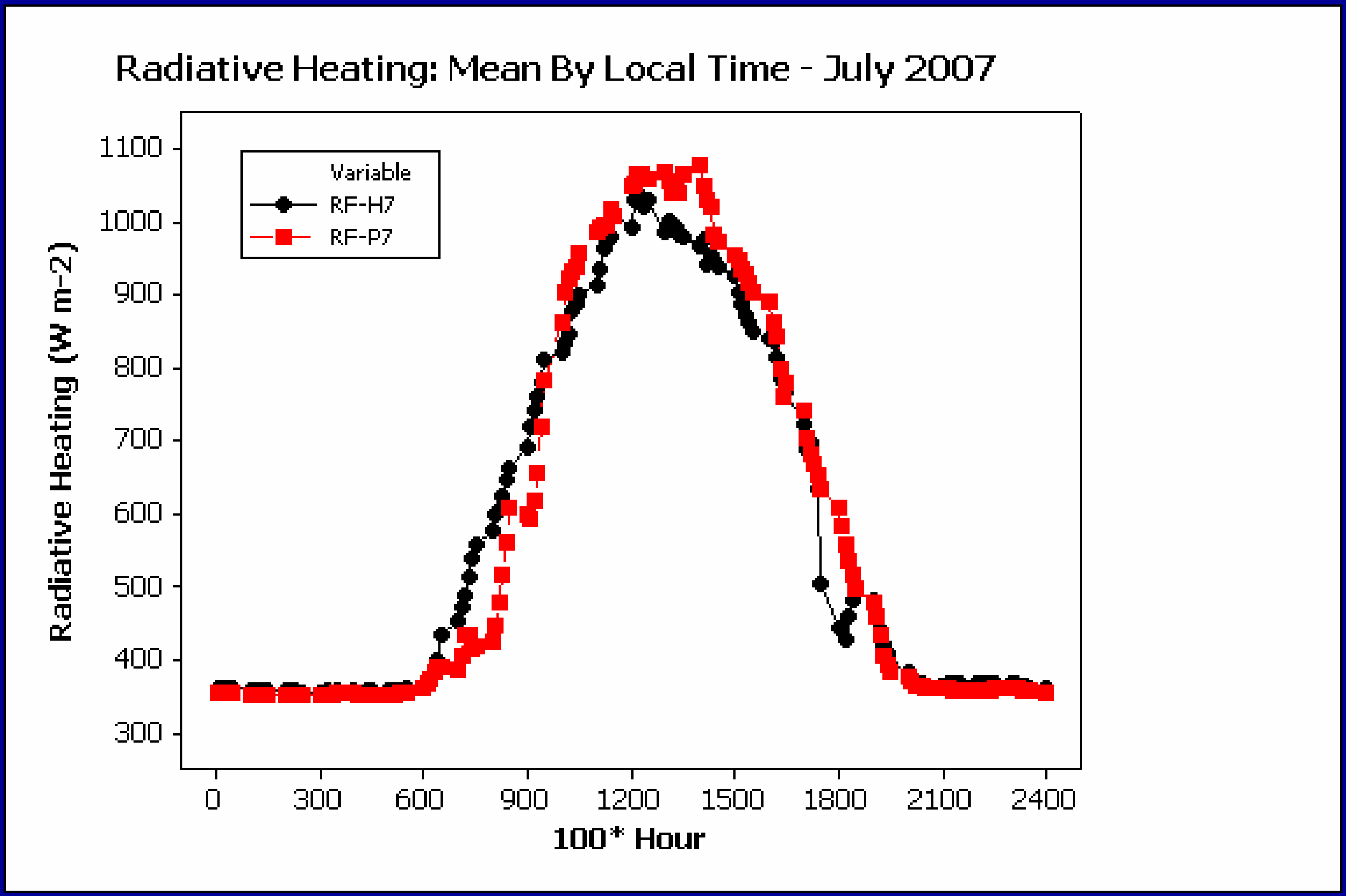
All irradiances are monthly averages in watts per square meter of horizontal area.

Radiative Heating (RH in W m^{-2})

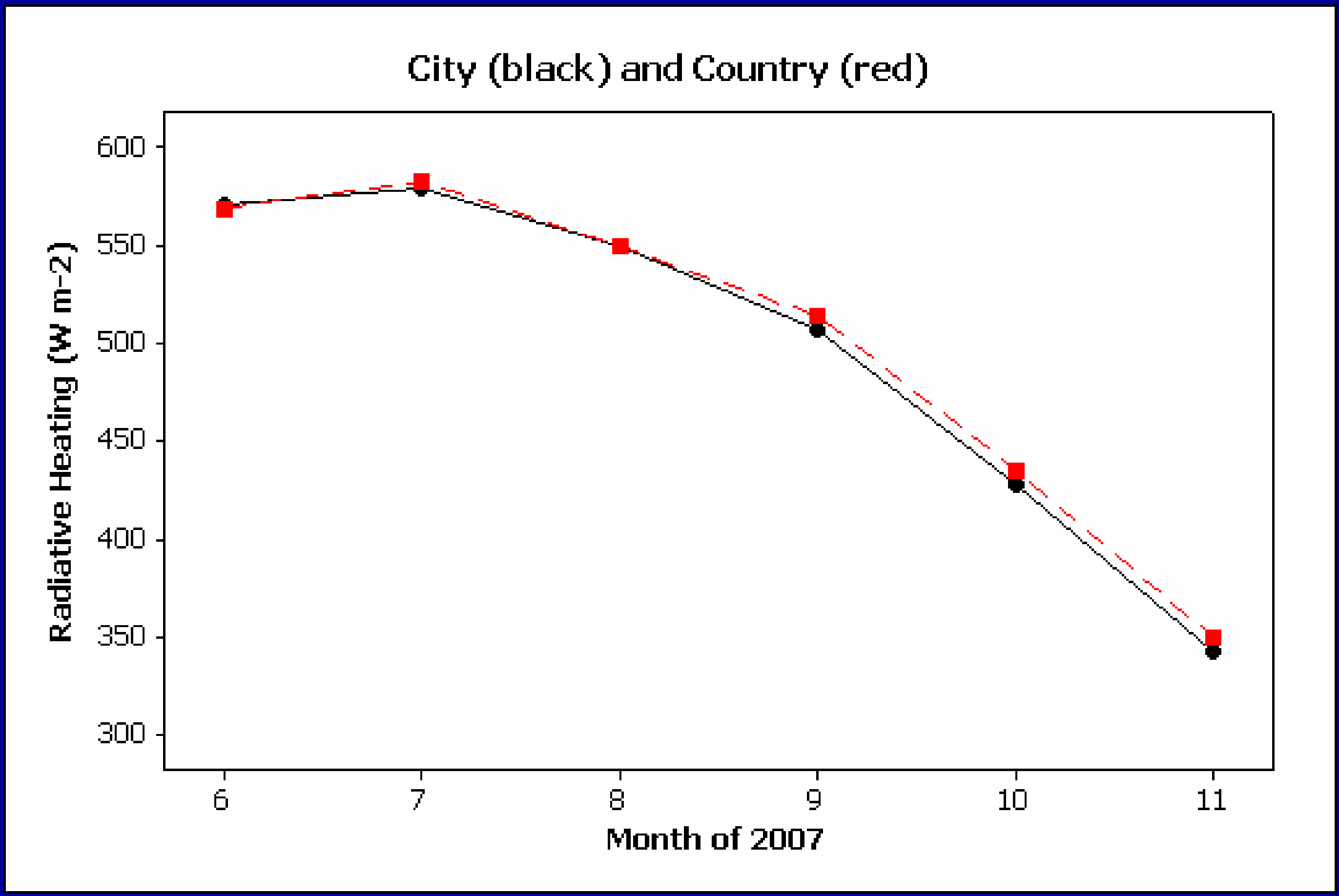
- RH = Total radiant energy absorbed by the ground per unit area per unit time
- RH = SW(dn) – SW(up) + LW(dn)
- Radiative heating must be offset by cooling mechanisms.

Local Time Dependence of Radiative Heating – July

[Black = City, Red = Country]



Monthly Mean Radiative Heating at the City and Country Site: June-November 2007



Findings (So Far)

- **The urban surface and the natural surface experience essentially the same radiative heating.**
- **But, in every month the urban surface is warmer than the natural surface.**
- **Conclusion #1 – Different cooling mechanisms must be important at the two sites.**
- **Conclusion #2: Cooling by means <u>other</u> <u>than</u> <u>radiation</u> must be more important for the natural surface than for the urban surface.**

Net Radiation (R_{NET} in W m^{-2})

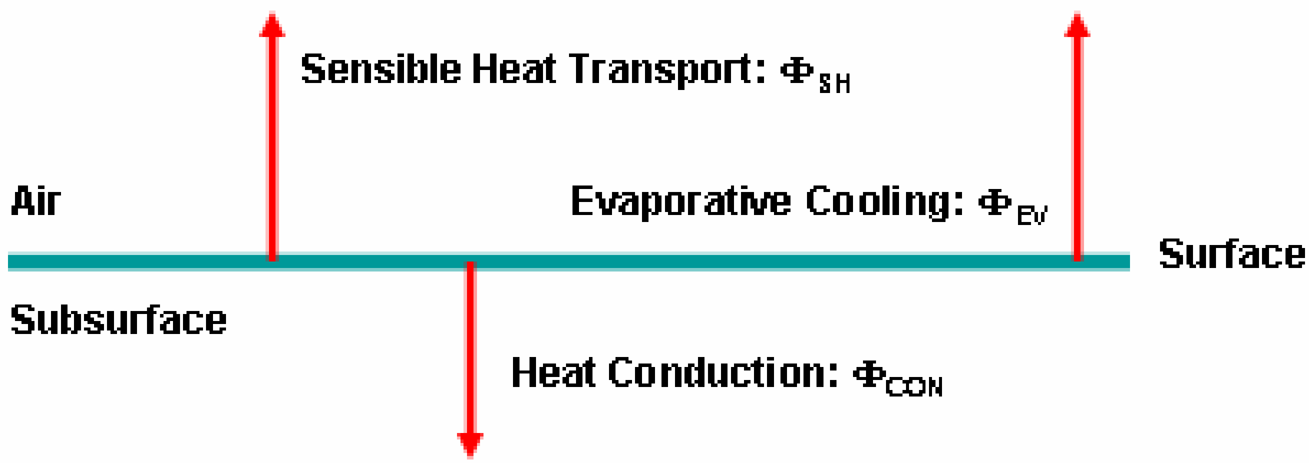
- **R_{NET} = SW(dn) - SW(up) + LW(dn) - LW(up)**
- **LW(up) = longwave radiation emitted by the ground.**
- **R_{NET} = RH - LW(up)**
- **R_{NET} = 0 means that cooling of the ground by longwave emission balances radiative heating.**
- **R_{NET}>0 means that radiation leads to a net heating of the ground. This heating must be balanced by non-radiative cooling processes.**

Conservation of Energy at the Underlying Surface

- Heating by net radiation (R_{NET}) must be balanced by cooling provided by non-radiative energy fluxes.
- Mathematically:
  R_{NET} = Net Non-Radiative Energy Flux Flowing Away from the Surface
- Direct measurements of R_{NET} show that the net non-radiative flux away from the natural surface is larger than for the urban surface.

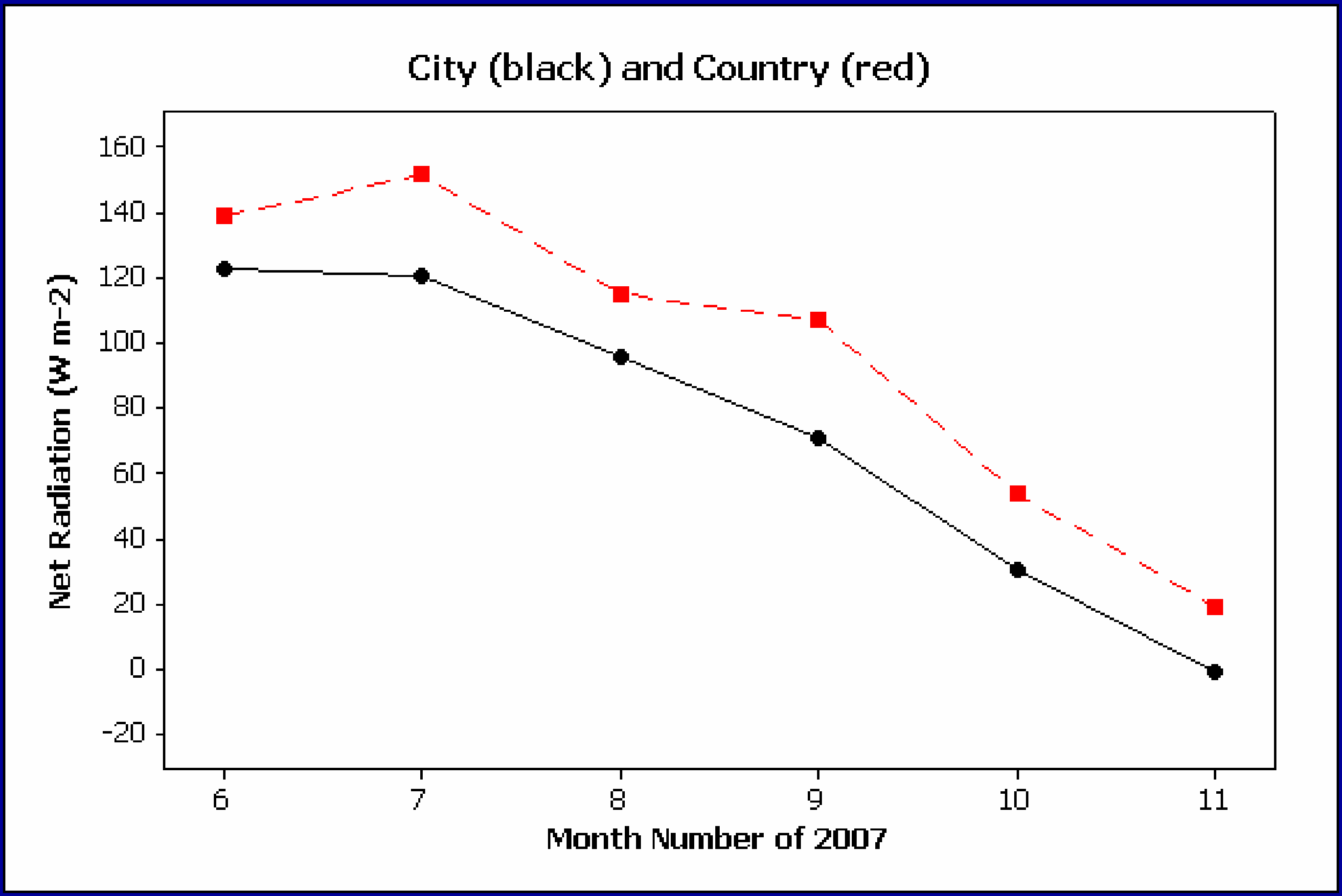
Non-Radiative Mechanisms for Transport of Energy:

(1) Sensible Heat Transport, (2) Evaporative Cooling & (3) Heat Conduction



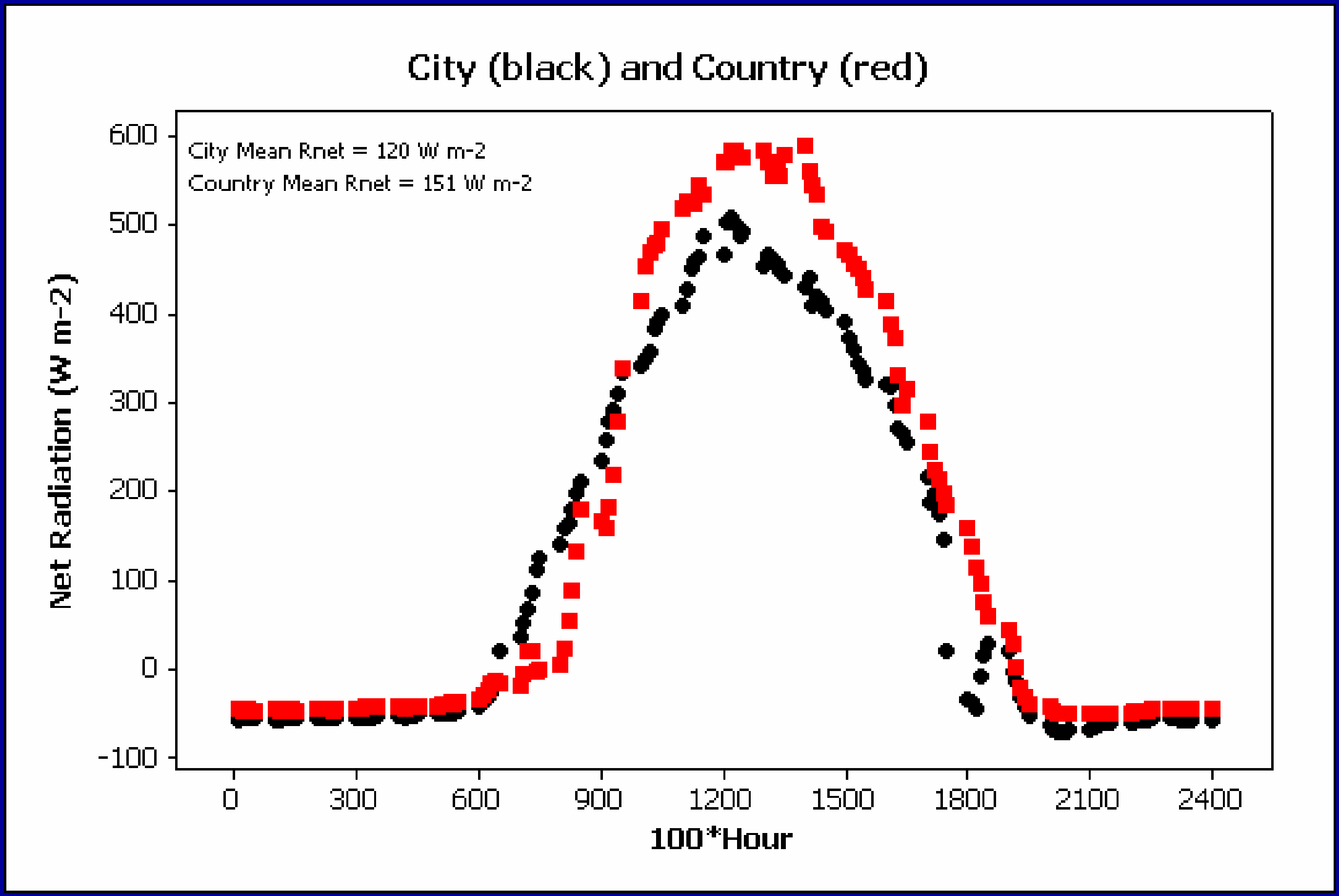
Monthly Mean Net Radiation at the City and Country Site: June-November 2007

[Note: Longwave radiative cooling is smaller at the country site. This leads to a larger value of net radiation here.]



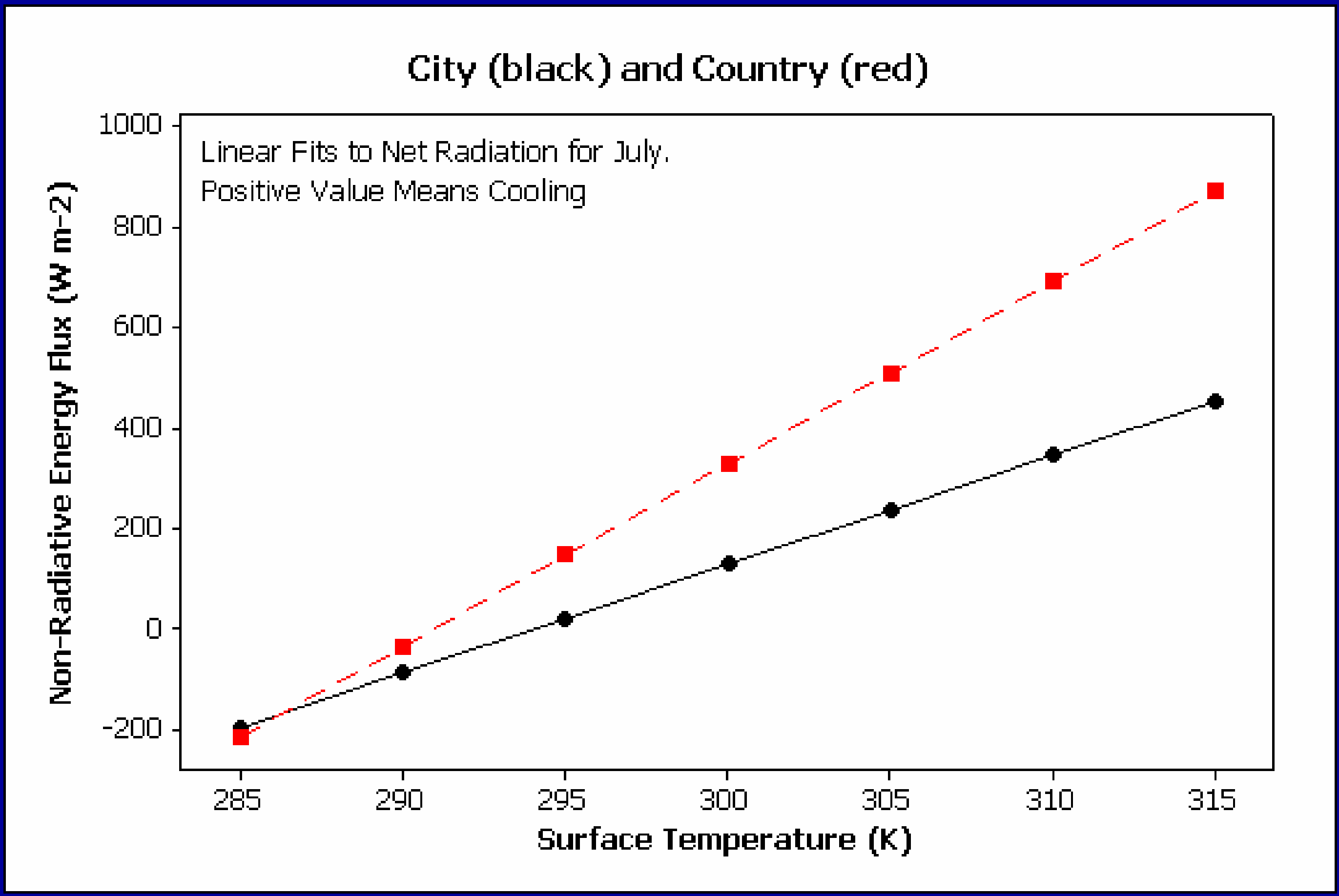
Required Non-Radiative Energy Fluxes – July 2007:

[Sensible Heat Transport + Evaporative Cooling + Conduction into the Subsurface Layer] = [Net Radiation]



Non-Radiative Energy Flux Required to Offset Net Radiation: July 2007

[At a given temperature, the grassy surface generates more cooling than the concrete surface.]



Estimate Non-Radiative Fluxes via Statistical Regression

- **Use conservation of energy to create a regression model:**

  $$R_{net} = \Phi_{CON} + \Phi_{SH}(T_S,T_A,v) + \Phi_{EV}(T_A,r,v)$$

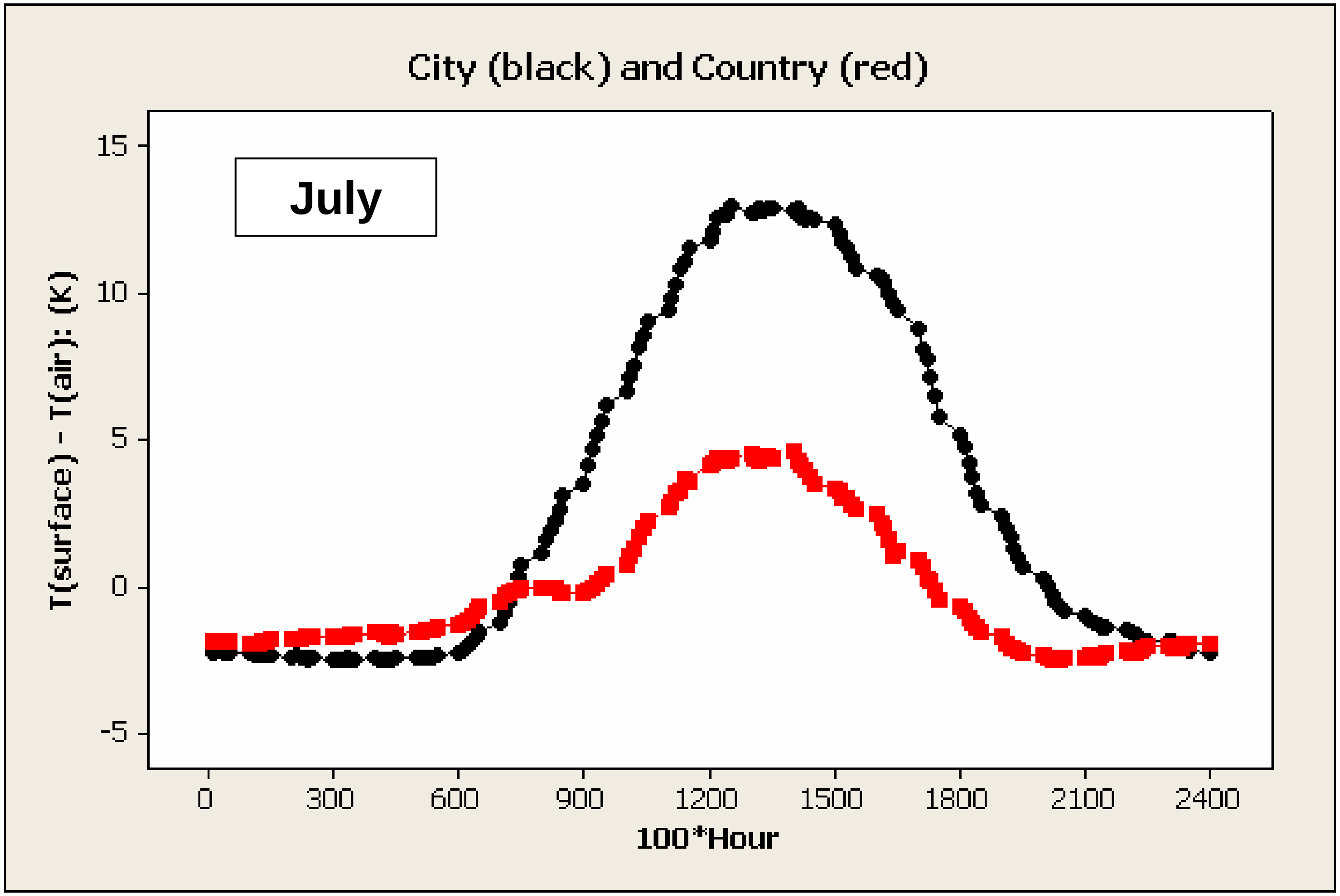
- **Compute Φ_{CON} (conduction of heat into or out of the subsurface layer) via the heat conduction equation.**

- **Sensible heat flux [$\Phi_{SH}(T_S,T_A,v)$] and evaporative cooling [$\Phi_{EV}(T_A,r,v)$] are parameterized using measured T_S,T_A, r and v with coefficients to be determined.**

- **Estimate coefficients by regression and use these to compute monthly mean fluxes.**

Sensible Heat Transport

- **Energy flux depends on temperature contrast between the solid surface and the air: $\Phi_{SH} = (S_0+S_1v)[T_s-T_a-\delta T]$**



Surface Energy Balance: Monthly Means for July

	Energy Flux	City ($W\ m^{-2}$)	Country ($W\ m^{-2}$)
Heating:	Net Radiation	120	151
Cooling:	Conduction	28	9
	Sensible Heat	92	17
	Evaporation	0	125

Warning: The above numbers contain considerable uncertainty, but they are of the proper magnitude.

Surface Energy Balance: Monthly Means for November

	Energy Flux	City ($W\ m^{-2}$)	Country ($W\ m^{-2}$)
Heating:	Net Radiation	----	19
	Conduction	79	42
Cooling:	Net Radiation	1	----
	Sensible Heat	78	7
	Evaporation	0	54

Warning: The above numbers contain more uncertainty than the numbers for July.

Why are Urban Surfaces Warmer than Natural Surfaces?

- **Urban Surfaces (e. g. concrete)**
  - Liquid water is not present – Evaporative cooling does not occur.
  - The surface must warm to the point where sensible heat transport is significant. A large surface-air temperature contrast is needed.

- **Natural Surfaces (e. g. grass-covered soil)**
  - Evaporative cooling is significant.
  - This cooling mechanism does not require a high surface temperature (for moderate relative humidities).

- **Natural surfaces have cooling mechanism that is not available to urban surfaces, and they can achieve the required cooling rate at a lower surface temperature.**

Implications for Urban Design

- **Models of energy exchange between manmade structures and their surroundings could contribute to urban planning with the goal of improved energy efficiency and summer urban heat island minimization.**
- **Reflectivity of surface materials could be manipulated to absorb more or less solar energy. Can surface reflectivity change with season?**
- **Green roofs can reduce demand for summertime cooling. White roofs or walls with liquid water present can increase passive cooling.**