Environmental Research Laboratories

Air Resources
Atmospheric Turbulence and Diffusion Laboratory

Oak Ridge, Tennessee

A NUMERICAL STUDY OF THE URBAN HEAT ISLAND

Carmen J. Nappo, Jr.

U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

A NUMERICAL STUDY OF THE URBAN HEAT ISLAND

Carmen J. Nappo, Jr.
Air Resources
Atmospheric Turbulence & Diffusion Laboratory
National Oceanic & Atmospheric Administration
Oak Ridge, Tennessee

(Published in Proceedings of Conference on Urban Environment and Second Conference on Biometeorology held in Philadelphia, Pa., October 31 - November 2, 1972.)

ATDL Contribution File No. 67

A NUMERICAL STUDY OF THE URBAN HEAT ISLAND

Carmen J. Nappo, Jr.

Air Resources Atmospheric Turbulence & Diffusion Laboratory
National Oceanic & Atmospheric Administration
Oak Ridge, Tennessee

Recent interest in urban climatology has brought the attention of many researchers to the heat island effect. Myrup (1969) was one of the first to numerically investigate the phenomenoa. He used a single layer one-dimensional model and differentiated between urban and rural environments by adjusting the surface roughness, surface humidity, wind speed and soil thermal diffusivity between their urban and rural values. Tag (1969), McElroy (1971), and Pandolofo (1971) attempted heat island simulations using much more sophisticated models but arrived at about the same conclusions. All of these authors have examined the sensitivity of the heat island to surface conditions, but none have done so in depth. Here a detailed examination is made of the sensitivity of the diurnal surface temperature and the urban heat island to variations in surface roughness, surface moisture and soil thermal diffusivity.

The numerical model used is a modified version of that used by Delsol et al. (1971) to test various formulations of eddy exchange coefficients for possible use in large scale prediction experiments. This time-dependent, one-dimensional model contains a transition or Ekman layer composed of nine vertical levels extending from 75 to 3400 meters, a constant flux layer of 75 meters, and a soil layer composed of eight levels extending to a depth of 10 meters. The fluxes within the constant flux layer are determined by similarity theory (Monin and Obukhov (1954)), and are given by integrals of non-dimensional wind shear and lapse rate which are empirical functions of $|z_t/L|$ and $|z_o/L|$, where z_t is the height of the constant flux layer, z_o is the surface roughness and L is the Monin length. To close the system of equations in this layer, the surface energy balance is used, giving as a byproduct the surface temperature for each time step. Initial conditions are taken from the fifth observational period of the O'Neill, Nebraska field data (Lettau and Davidson (1957)).

The surface moisture, Q_S, is given by the relation

$$Q_S = SRH*Q_{SS}$$

where Q_{SS} is the saturation mixing ratio and SRH is defined to be the surface relative humidity and is held constant. As in Tag (1969), the vapor flux is set to zero when it is directed downward.

Whether or not an urban heat island exists depends on the relative amplitudes and phases of the diurnal surface temperature waves for the rural and urban areas. These are investigated by running the model 64 times, each run representing a possible combination of z_o, SRH and K_S. Each parameter took on in turn one of the following values:

Surface roughness, z_o: 1, 10, 100, 1000 cm.

Surface relative humidity, SRH: .25, .50, .75, 1.00

Soil thermal diffusivity, K_s: .0015, .0075, .015, .020 cm^2/sec.

Figures 1, 2, and 3 show the results of these runs when only one of the parameters is allowed to vary. In figure 3, there is so little change in temperature with K_s that only the extreme cases are shown.

In figure 1 it is seen that with increasing surface roughness the amplitude of the diurnal surface temperature wave decreases, the time of temperature maximum increases and the time of temperature minimum remains unchanged. It is also seen that the mean surface temperature over this period is relatively insensitive to changes in z_o. From figure 2, it is evident that the amplitude as well as the mean of the diurnal wave is very sensitive to surface moisture, a result reached by all the authors mentioned above. In addition, an increase in SRH decreases the time of temperature minimum while the time of maximum temperature remains unchanged. From figure 3, it is seen that the soil thermal diffusivity has a small effect on the amplitude and mean of the diurnal wave and time of temperature maximum but has a marked effect on the time of temperature minimum. From the above observations it can be concluded that high values of roughness, moisture, and soil diffusivity lead to small amplitudes of the diurnal wave, while small values lead to large amplitudes. This is clearly shown in figure 4, where the diurnal surface temperatures are plotted for extremely small, case A(z_o = 1cm,

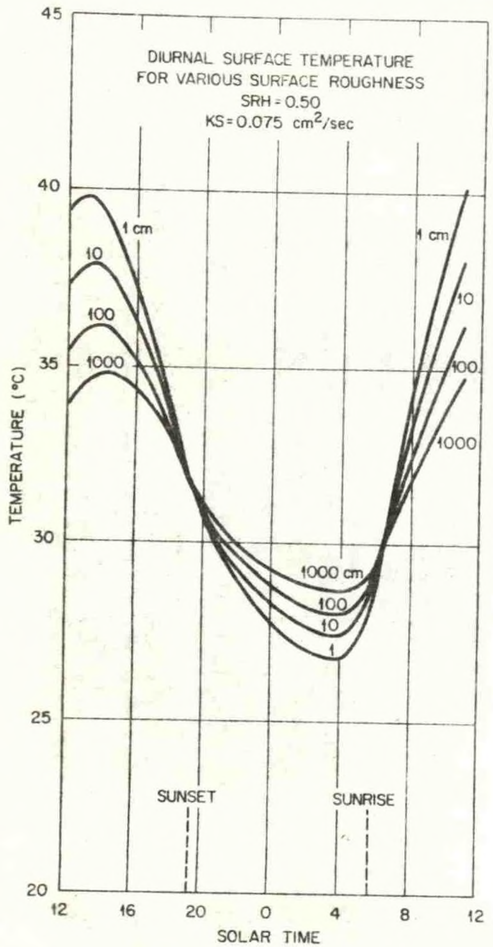


Figure 1

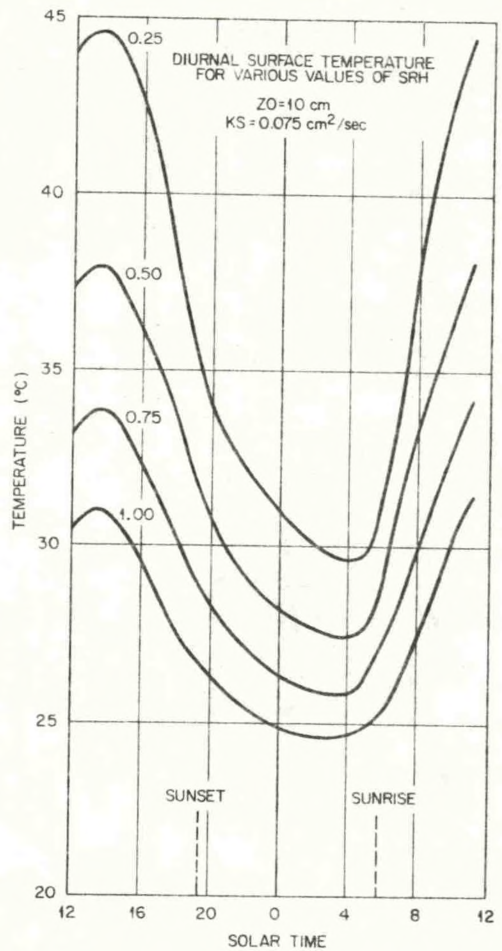


Figure 2

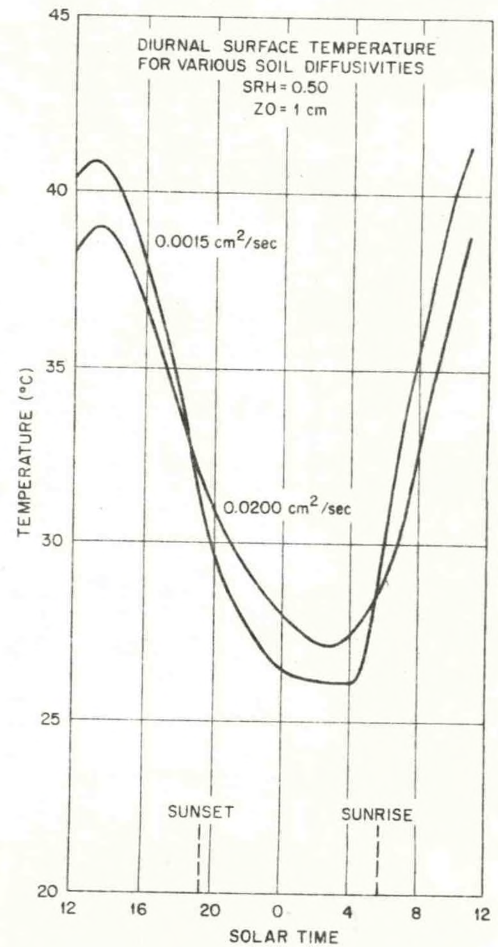


Figure 3

SRH = 0.25, K_s = $0.0015cm^2/sec$), and extremely large, case B (z_o = 1000cm, SRH = 1.00, K_s = $.020cm^2/sec$) values of the surface parameters. The amplitude of the diurnal wave is seen to range from 20.9 C° for case A to 3.7 C° for case B. The amplitudes for all 64 cases lie between these extremes.

Figures 1, 2, and 3 also show that a heat island can be achieved by changing only a single parameter from its rural to its urban value. It is seen that two types of heat island are possible: type 1, with rural temperature greater than urban temperature during the day and the reverse at night; and type 2, with urban temperature always greater than rural temperature. Myrup (1968) discusses these types. Mitchell (1961) shows that a type 1 heat island exists in Vienna during July, and a type 2 during February, and the recent study of the Edmonton, Alberta heat island by Hage (1972) also shows the presence of both types, type 1 in winter and type 2 in early summer.

The type 1 heat island is predicted to exist when there is little difference between rural and urban surface moisture. Such situations could exist in a city surrounded by desert, or a city with much vegetation and water surrounded by farm land. Possible examples are Albuquerque and Minneapolis. Figure 5 shows such a heat island. The urban roughness increases the turbulent fluxes so that the city is relatively cooled during the day but relatively warmed at night. In this example, the ratio of the urban to rural sensible heat flux is 0.79 during the day (upward fluxes) but is 1.51 during the night (downward fluxes).

The type 2 heat island will result where there are differences between urban and rural surface moisture, as well as between roughness and diffusivity. Such a case is shown in figure 6, where we have also considered the intermediate case of the suburbs. The maximum temperature difference between rural and urban areas occurs

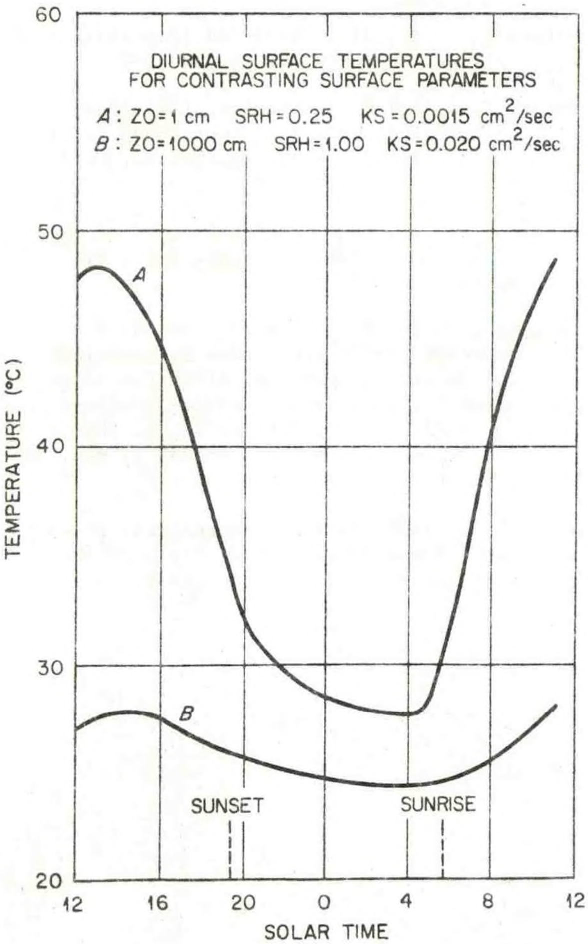
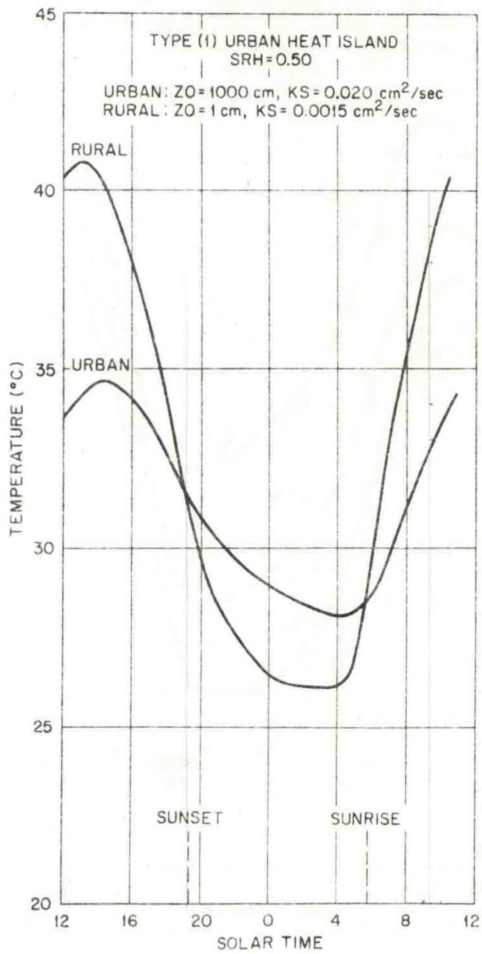


Figure 4



38

33

Figure 5

at about 2100 hours which is in keeping with the observation of Hage (1972). For this case, the ratio of the urban to rural sensible heat flux is 3.16 during the day and 2.24 during the night.

From figures 5 and 6 it can be seen that for the type 1 case urban and rural areas begin warming at the same time, while for type 2 the rural area begins warming about 3 hours before the urban area.

While the above predictions are interesting, they are only approximations. What is needed is a more physically realistic model of at least two spatial dimensions to properly simulate the heat island effect, as well as actual measurements in several metropolitan regions for comparison.

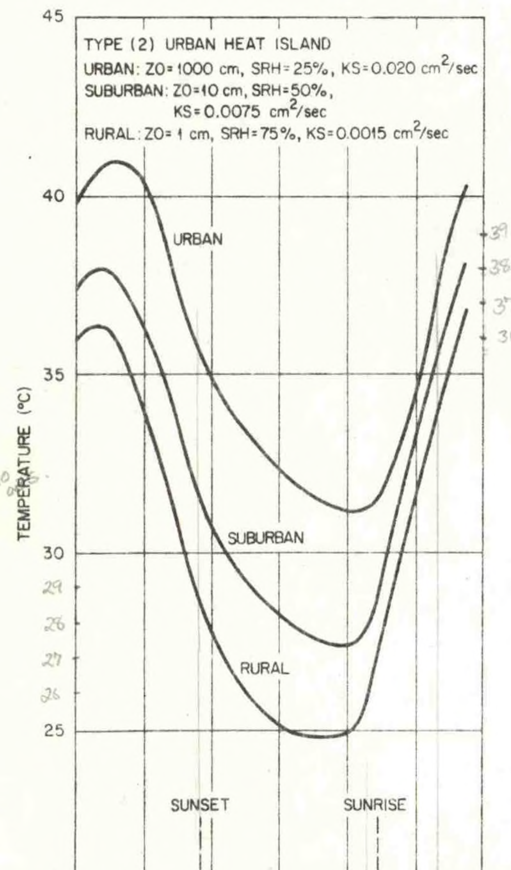


Figure 6

References

Delsol, F., K. Miyakoda, and R. H. Clarke, 1971: Parameterized processes in the surface boundary layer of an atmospheric circulation model. Quart. J. R. Met. Soc., 412, pp 181-208.

Hage, K. D., 1972: Nocturnal Temperature in Edmonton, Alberta, J. Appl. Met., 11, pp 123-129.

Lettau, H. H. and B. Davidson, 1957: Exploring the Atmosphere's First Mile. Vol. 2, Pergamon Press, New York.

McElroy, J. L., 1971: An experimental and numerical investigation of the nocturnal heat-island over Columbus, Ohio, Ph.D. Thesis, Dept. of Met. Penna. State Univ.

Manabe, S., S. Smagorinsky, and R. F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrolocial cycle. Mon. Weath. Rev., 93, pp 769-798.

Mitchell, J. M., Jr., 1961: The temperatures of cities. Weatherwise, 14, 224-229.

Monin, A. S. and S. M. Obukhov, 1965: Basic laws of turbulent mixing in the ground layer of the atmosphere, Akad, Nauk, SSSR, Geofz. Inst. Turdy 151, 163-87.

Myrup, L. O., 1969: A numerical model of the urban heat island, J. Appl. Met., 8, pp 908-918.

Pandolfo, J. P., M. A. Atwater, and G. E. Anderson, 1971: Prediction by numerical models of transport and diffusion in an urban boundary layer, Sponsor Contract No. -CPA 70-62, CEM Contract No. 4082, The Center for the Environment of Man, Inc., Hartford, Connecticut.

Tag, P. M., 1969: Surface temperatures in an urban atmosphere. Part I, Rep. 15, NSF Grant GA-3956, The Penna. State Univ.