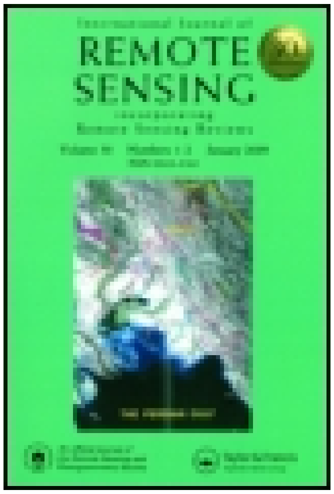

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The use of a vegetation index for assessment of the urban heat island effect

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The use of a vegetation index for assessment of the urban heat island effect

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Abstract. A vegetation index and radiative surface temperature were derived from NOAA-11 Advanced Very High Resolution Radiometer (AVHRR) data for the Seattle, WA region from 28 June through 4 July 1991. The vegetation index and surface temperature values were computed for locations of weather observation stations within the region and compared to observed minimum air temperatures. These comparisons were used to evaluate the use of AVHRR data to assess the influence of the urban environment on observed minimum air temperatures (the urban heat island effect). AVHRR derived normalized difference vegetation index (NDVI) and radiant surface temperature data from a one week composite product were both related significantly to observed minimum temperatures, however, the vegetation index accounted for a greater amount of the spatial variation observed in mean minimum temperatures. The difference in the NDVI between urban and rural regions appears to be an indicator of the difference in surface properties (i.e., evaporation and heat storage capacity) between the two environments that are responsible for differences in urban and rural minimum temperatures.

1. Introduction

Differences between air temperatures observed at weather stations located in urban areas and temperatures in surrounding rural regions have been well documented (Landsberg 1981). The influence of urbanization on long-term temperature records (i.e., the urban heat island, UHI, effect) has been the subject of numerous studies and has even been detected for cities with populations less than 10 000 (Karl *et al.* 1988). Changnon (1992) presents a review of additional climatic modifications attributed to urbanization.

Satellite-derived surface temperature data have been utilized for urban climate analyses in several studies (Rao 1972, Carlson *et al.* 1977, Matson *et al.* 1978, Roth *et al.* 1989, Kim 1992). Roth *et al.* (1989) utilized Advanced Very High Resolution Radiometer (AVHRR) thermal data (10·5–11·5 μm) to assess the UHI intensities of several cities on the west coast of North America. Daytime thermal patterns of surface temperature were associated with land use; higher surface temperature were associated with land use; higher surface temperatures were located in industrial areas compared to cooler temperatures in vegetated regions. Night-time observations revealed little difference in surface temperatures of urban and rural regions.

The greatest urban and rural air temperature differences are typically observed at night, while differences in surface radiant temperature are greatest at midday (e.g., Roth *et al.* 1989). Additional land surface properties, beyond surface temperature, may provide more information related to the factors that contribute to the observed UHI effect.

The reduced amount of heat stored in the soil and surface structures in rural areas covered by transpiring vegetation, compared to the relatively unvegetated urban areas, has been cited as a significant contributor to the UHI effect (Carlson *et al.* 1981). AVHRR-derived vegetation indices, have been demonstrated to be indicators of the presence and density of green vegetation and have been used successfully to monitor seasonal vegetation activity (Goward *et al.* 1985, Malingreau 1986, Gallo and Flesch 1989). Thus, the difference in urban and rural values of a vegetation index may be an indicator of those differences in the two environments that are related to observed differences in minimum air temperature.

The objective of this study was to evaluate the use of a AVHRR-derived vegetation index, and surface radiant temperature, for assessment of the difference in urban and rural air temperature due to the UHI effect.

2. Data analysis

The daily minimum air temperatures (Tmin) for 28 June through 4 July 1991 were obtained for urban and rural weather stations located within a 1° square centered on Seattle, WA (table 1). Each weather station was manually classified based on population and the environment that surrounded the station. Selected weather stations were located within cities with populations greater than 50 000 or less than 10 000. Stations were classified as urban if located in cities with populations greater than 50 000, or if the city was adjacent to an urban area. Stations in cities with a population less than 10 000, and not adjacent to urban areas, were considered rural.

AVHRR-derived data used in this study included full spatial resolution (1·1 km at nadir), daytime (1330 LST) single date scenes acquired by the AVHRR onboard the NOAA-11 satellite from 28 June through 4 July 1991. A weekly composite product was computed for the same interval. The data were acquired, and processed, and products produced, at the U.S. Geological Survey (USGS) EROS Data Center (EROS 1990). Daily AVHRR scenes that were primarily 'cloud-free' were geometrically registered to a Lambert Azimuthal Equal Area map projection. Each map cell of the georegistered products represents 1 square km. The normalized difference vegetation index (NDVI):

Table 1. Weather stations within Seattle, WA region utilized for assessment of urban heat islands. Stations are classified as urban (U) or rural (R).

ID	CLASS	NAME
1	R	MC MILLIN RESERVOIR
2	R	MUD MOUNTAIN DAM
3	R	BUCKLEY 1 NE
4	U	PUYALLUP 2 W EXPERIMENTAL STATION
5	R	PALMER 3 ESE
6	R	LANDSBURG
7	R	CEDAR LAKE
8	U	KENT
9	U	SEATTLE-TACOMA
10	R	SNOQUALMIE FALLS
11	U	BREMERTON
12	U	SEATTLE PORTAGE BAY
13	R	MONROE
14	U	TACOMA 1
15	U	SEATTLE SAND POINT

$$\mathrm{NDVI} = (\text{near-IR} - \text{visible}) \,/\, (\text{near-IR} + \text{visible}) \tag{1}$$

was computed from visible (0·58–0·68 μm) and near-IR (0·72–1·1 μm) data of the AVHRR. The visible and near-IR data were calibrated with modified prelaunch calibration coefficients recommended by Holben *et al.* (1990).

Surfaces features such as water or clouds, which have no vegetation, have low or negative NDVI values. The NDVI computed for the daily AVHRR scenes was used to screen the data for each map cell such that the 'greenest' or most 'cloud-free' data value of each week was retained in the composite products.

Calibrated thermal-IR data of channels 4 (T4; 10·3–11·3 μm) and 5 (T5; 11·5–12·5 μm) on the NOAA-AVHRR were used to estimate apparent surface temperature (Tsfc; equation (2)) as

$$\mathrm{Tsfc} = \mathrm{T4} + 3{\cdot}3\ (\mathrm{T4} - \mathrm{T5}) \tag{2}$$

for a surface emissivity of 1·0, as described by Price (1990). Roth *et al.* (1989) estimated that the suppressed differences in Tsfc, due to unaccounted differences in emissivity, could be as much as 1·5°C. Roth *et al.* (1989) suggested, based on Carlson (1986), that the error in relative temperature differences due to horizontal differences in atmospheric properties between urban and rural regions was approximately 1°C or greater. The visible, near-IR, and thermal-IR data were not adjusted for atmospheric properties because relative, rather than absolute, differences in the vegetation index and Tsfc were computed.

The visible, near-IR and thermal-IR data were sampled for 3 by 3 pixel windows centred on the weather stations included in the study. Data acquired over water bodies, as defined by USGS digital data (USGS, 1991), were excluded from analyses. No additional attempts, beyond the use of composite products, were made to screen the daily data for cloud contamination.

Three days with cloud-free conditions were identified and Tmin values observed on these dates were compared with the derived Tsfc and NDVI for these dates.

Additionally, the mean Tmin for a one week interval that included the three cloud-free dates was compared to the Tsfc and NDVI of the coincident one-week composite product.

3. Results and discussion

Relationships between minimum air temperature (Tmin), radiative surface temperature (Tsfc), and the NDVI were examined for each cloud free single date and compared to the weekly composite (figure 1) data of Tsfc, NDVI, and mean weekly Tmin. Generally, the relationship between Tmin and Tsfc for individual observation dates was the inverse of the relationship between Tmin and NDVI (figure 2). Lower values of Tsfc were associated with lower values of Tmin (figure 2 (*a*)), while lower values of NDVI were associated with greater values of Tmin (figure 2 (*b*)). The Tsfc values (figure 2 (*a*)) were generally lower for rural observation locations compared to urban locations while the NDVI values (figure 2 (*b*)) were lower for urban locations and greater for rural locations. Similar results to those of the single observation dates were observed for the weekly composite data (figures 1, 3 (*a*), and 3 (*b*)).

The inverse relationship between Tsfc and NDVI displayed in figure 1, and implied in figures 2 and 3, has been observed by others (e.g., Price 1990) and is related to the partitioning of the latent and sensible heat fluxes associated with the land surface features. The surface features associated with the urban environment typically exhibit greater sensible heat flux than latent heat flux while the surface features of the rural environment exhibit greater latent heat flux than sensible heat flux.

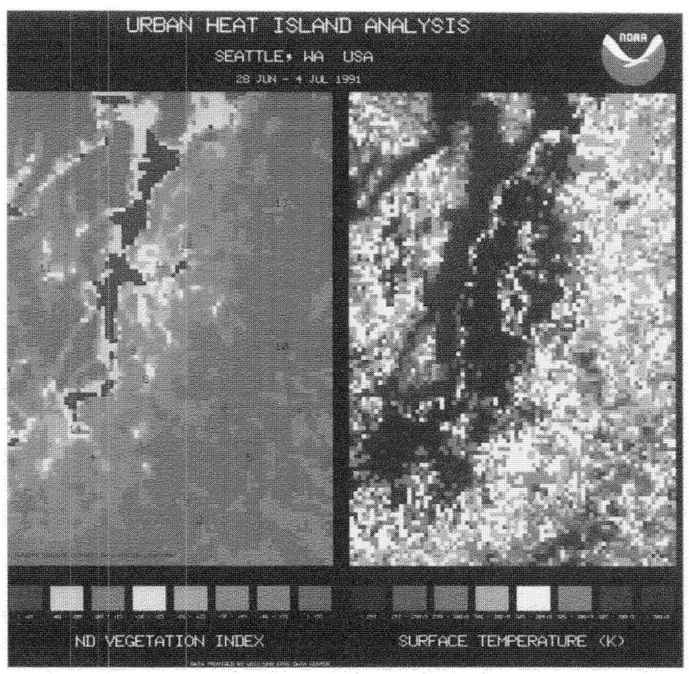


Figure 1. Normalized difference (ND) vegetation index and radiant surface temperature derived from a one week (28 June–4 July 1991) composite of NOAA-11 AVHRR data for the Seattle, WA, region.

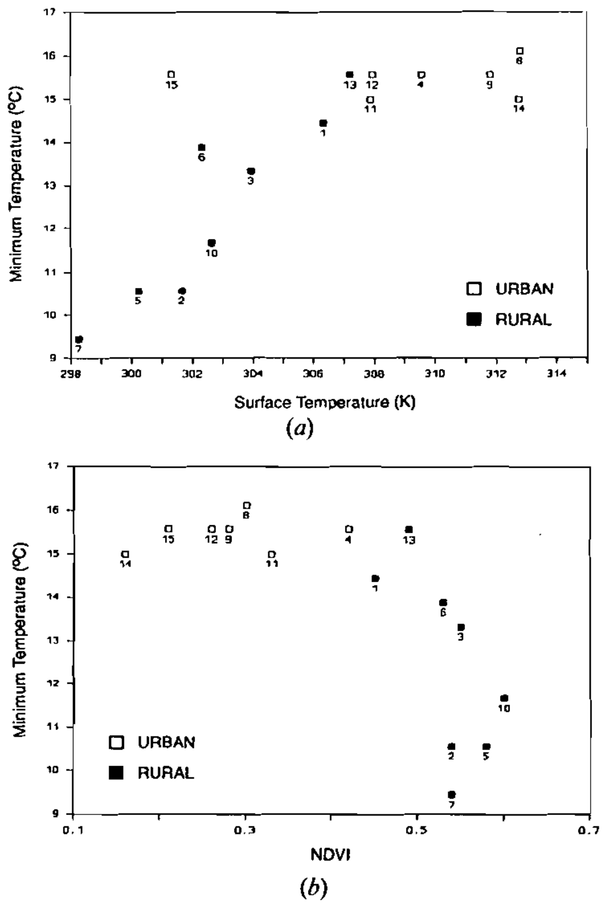
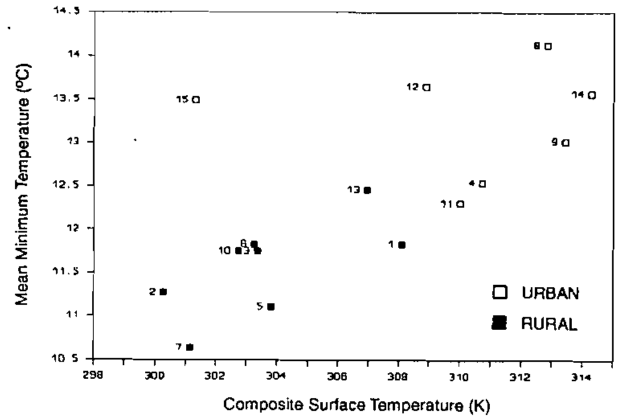


Figure 2. Relationship between minimum air temperature and (*a*) radiant surface temperature and (*b*) the NDVI for 1 July 1991 for observation locations in the Seattle, WA, region. Numbers indicate weather stations as identified in table 1; urban and rural location are indicated by open and closed boxes.

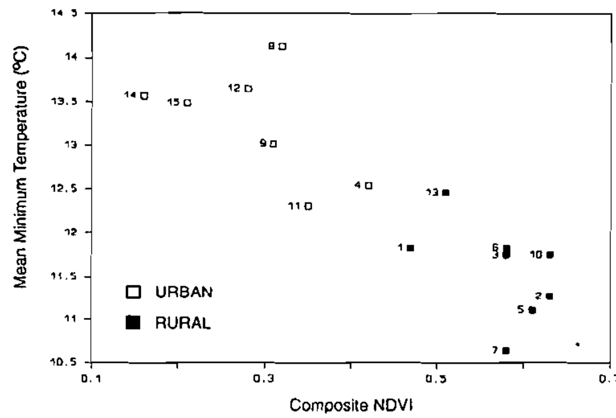
The NDVI accounted for a greater portion of the spatial variation in Tmin on a weekly compared to daily basis (table 2). Similar results were obtained when Tsfc was examined, although on one of the three dates (1 July) the daily Tsfc data accounted for a greater amount of variation in Tmin than did the weekly composite of Tsfc (table 2).

The greater percentage of variation in Tmin associated with the weekly composite of NDVI was not unexpected as the UHI development varies with day-to-day meteorological conditions. The establishment of an UHI, and the greatest differences between urban and rural conditions, usually occurs under clear and calm conditions (Landsberg 1981). The differences decrease in cloudy and windy conditions (Landsberg 1981).

One explanation for the relatively low spatial variation in mean Tmin associated with the composite of Tsfc might be due to the process used to produce the weekly composite. The composite utilized was based on maximum values of the NDVI. Thus, the weekly thermal data were compiled from individual dates with the



(a)



(b)

Figure 3. Relationship between mean minimum air temperature and one-week composite data of (a) radiant surface temperature and (b) the NDVI, for the 28 June through 4 July 1991 interval, for observation locations in the Seattle, WA region. Numbers indicate weather stations as identified in table 1; urban and rural location are indicated by open and closed boxes.

greatest value of the NDVI. The relationship between mean Tmin and Tsfc may have been different if the weekly composite utilized was based on maximum Tsfc values.

The mean value for Tmin observed at the urban locations was consistently greater than the mean observed at rural stations. Urban-rural differences in mean Tmin were 3·1, 1·8, and 2·0°C for 1, 3, and 4 July, respectively. The urban-rural difference in mean Tmin for the 28 June through 4 July interval was 1·6°C. Tsfc sampled over urban areas was consistently greater than Tsfc from rural regions (table 2). NDVI values of the rural locations were consistently greater than those of urban locations (table 2).

4. Conclusions

AVHRR-derived normalized difference vegetation index and surface radiant temperature data, sampled over urban and rural regions, were linearly related to the

Table 2. Comparison of single date and composite relationships between Tmin, Tsfc, and NDVI (n = 15), and urban-rural differences in mean values of Tsfc (°C) and NDVI.

Tmin observation date	r^2	RMSE†	urban-rural difference
		Tsfc	
1 JUL 91	0·62	1·4	6·4
3 JUL 91	0·20	1·5	6·3
4 JUL 91	0·28	1·1	8·6
composite	0·46	0·8	6·5
		NDVI	
1 JUL 91	0·53	1·6	−0·26
3 JUL 91	0·31	1·4	−0·32
4 JUL 91	0·62	0·8	−0·35
composite	0·77	0·5	−0·28

†RMSE = root mean square error

observed urban and rural minimum temperatures. Urban locations generally exhibited greater values of surface temperature and lower values of a vegetation index than rural locations. The difference in the NDVI between urban and rural regions appears to be an indicator of the difference in surface properties (evaporation and heat storage capacity) between the two environments responsible for the differences in urban and rural minimum temperatures (the urban heat island effect). The NDVI of a one-week composite accounted for a greater amount of the variation observed in mean minimum temperatures than did radiant surface temperature.

Satellite-derived surface temperature data, sampled similarly to the vegetation index data, were minimally related to observed differences in urban and rural minimum temperatures. This result may be due to the composite process utilized and further investigation is recommended.

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