High-Resolution Surface Temperature Patterns in a Complex Urban Terrain

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ABSTRACT: In this investigation, the polar-orbiting AVHRR thermal scanner is used to produce one-kilometre resolution surface temperature patterns of Phoenix, Arizona. The resulting map shows realistic, high-resolution temperature variations across the metropolitan area. The derived surface temperatures covary with incidence of residential, commercial, and industrial land use and indirectly covary with the vacant land cover. The AVHRR system appears to provide the capability of significantly increasing the spatial resolution of thermal fields across an urban area. The results of the study are being used by a local utility in their analyses of water and power consumption.

INTRODUCTION

 $\mathbf{A}_{\text{PORAL}}^{\text{NALYSES OF TEMPORAL}}$ and spatial patterns of urban temperature structures serve a variety of theoretical and practical functions (Oke, 1982; Lee, 1984; Brazel, 1987). Variations of surface and air temperatures within an urban heat island reveal the impact of complex landscapes upon surface energy budgets and resulting temperature patterns. Information on the shape of a heat island can help decision-makers in the formulation of policies regarding spatial differences in energy and water demands throughout a metropolitan area. However, the lack of sufficiently dense surface and air temperature observation networks in most cities prohibits an accurate representation of heat island patterns. Without detailed inputs on the physical properties of the urban surface (Marotz and Coiner, 1973; Goward, 1981; Arnfield, 1982), existing numerical simulation models of urban climates (e.g., Myrup, 1969; Outcalt, 1972; Terjung and Louie, 1973; Nunez and Oke, 1980) are incapable of generating high-resolution temperature fields over large metropolitan areas. Alternate systems, such as the AVHRR technology, must be applied to the measurement of high-resolution temperature patterns in urban settings.

One heat island receiving considerable attention in the recent literature is associated with the expanding Phoenix, Arizona urban area (Brazel and Johnson, 1980; Cayan and Douglas, 1984; Hsu, 1984; Brazel and Balling, 1986; Balling and Brazel, 1986a, 1986b, 1986c, 1987a, 1987b; Balling and Cerveny, 1987; Brazel *et al.*, 1988). The interest in the Phoenix heat island can be attributed to (a) the rapid growth of the city during recent decades, (b) the quality of the temperature records during the period of growth, (c) clear skies and light winds accentuating the climatological impacts of land-use changes, and (d) the unusual water and power demand problems associated with the desert setting of the city. The limited number of observation stations (approximately 30 stations over the metropolitan area) has forced broad interpolations that may not accurately depict the temperature patterns across the city (Balling and Brazel, 1986c).

A relatively new satellite-based thermal scanning system (operational since the late 1970s) called the Advanced Very High Resolution Radiometer (AVHRR) provides a promising means of greatly increasing the resolution of surface and near-surface temperature fields. In this investigation, data from the AVHRR system are used to construct surface temperature patterns in the Phoenix area at approximately a one-kilometre resolution. Specific objectives in this study are to evaluate the general feasibility of using AVHRR data to determine realistic surface temperatures across the city, compare variations from day to day in the shape of the AVHRR-derived temperature field, and assess the impact of various land-use types on the resulting surface temperature patterns.

THE AVHRR SYSTEM

The surface temperature data for this project were generated by measurements made with the AVHRR sensor onboard the NOAA-9 polar orbiting satellite. The orbital period of this satellite is approximately 102 minutes, resulting in 14.1 orbits per day. The ascending node of the satellite (northbound equator crossing) occurs at 1420 Local Solar Time (LST) and the descending node (southbound equator crossing) occurs at 0220 LST. The measurement resolution is approximately 1.1 km at the nadir point of the sensor (Dozier, 1981).

The AVHRR sensor records the "aperture radiance," representing a combination of radiant emittance from the surface, modifications of this emittance within the atmosphere, and thermal radiance from the atmosphere. This aperture radiance is recorded within five selected bands of the electromagnetic spectrum, including the Band 4 (10.3 to 11.3 μ m) data used in this study. An apparent temperature (also known as brightness temperature or radiant temperature) is calculated from the radiance data using Planck's Law. This apparent temperature is an equivalent black-body temperature defined as the temperature at which a black body would emit the same amount of radiation as the surface in the sensor's field of view. According to Dozier (1981), the apparent temperature, although they can be higher where there are warm, moist inversion layers."

Interpreting meaningful relationships from these apparent temperatures is further complicated by the complex physical interactions of the Earth's surface and atmosphere within the sensor's field of view. Such factors may include complexity of surface types and their associated emissivities, surface roughness and shading, soil moisture level, vegetation canopy characteristics, relative humidity, atmospheric turbulence, presence of clouds, and absorption and emittance of thermal radiation by aerosols, water vapor, and other gases in the atmosphere (Artis and Carnahan, 1982; Short and Stuart, 1982; Price, 1983; Njoku, 1985; Barton and Takashima, 1986). However, in spite of these difficulties, many researchers believe that the use of thermal radiance data can be of assistance in the analysis of temperature patterns within urban areas (e.g., Outcalt, 1972; Pease et al., 1976; Carlson et al., 1977; Matson et al., 1978; Carlson et al., 1981; Dozier, 1981; Short and Stuart, 1982; Barton and Takashima, 1986).

PHOENIX AVHRR IMAGES

With the aid of scientists at NOAA's National Satellite Data Services (NSDS) in Washington, D.C., five summer days were selected from 1986 for our analyses. These five days (5 June, 15 June, 12 July, 31 July, and 9 August) were selected based upon (a) generally clear skies in the Phoenix area before and during

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the time of the afternoon orbital pass (ranging from 1436 to 1450 LST), (b) a near-nadir position of the Phoenix area, (c) an approximate two-week spacing of the images, (d) general similarity in the concurrent and antecedent weather conditions (Table 1), and (e) the availability of the satellite data.

After selecting the five test dates, magnetic tapes containing the raw AVHRR data were prepared at NSDS. The Center for Applied Land Management Information Technologies (CALMIT) at the University of Nebraska-Lincoln provided the necessary processing of the raw satellite data into a more usable form. CALMIT scientists used a series of in-house and NASA software packages (Applied Land-Resources Remote-Sensing Group, 1986) to calculate estimates of one-kilometre apparent temperatures from the raw satellite images.

For each test day, satellite measurements in Band 4 were converted into apparent temperature estimates assuming blackbody emission. The apparent temperatures for one-kilometre grid cells were estimated and geometrically rectified to a Universal Transverse Mercator (UTM) projection using a nearest neighbor resampling algorithm. These procedures resulted in the construction of a 96- by 96-pixel matrix for each of the five test days, representing the apparent temperatures throughout a square centered on the Phoenix metropolitan area (Figure 1).

Each of the five 96- by 96-pixel matrices was examined to determine the presence of local cloud cover. On several days, isolated large temperature depressions (often by more than 20°C) that were unrelated to elevation changes were identified as cloud features and the values for the affected pixels were interpolated from surrounding temperature levels. The daily mean apparent temperature value of all cells showed substantial variation from one test day to the next (Table 2). The standard deviations, indicating spatial diversity in the temperatures, were more consistent through time, although the standard deviation on 9 August (a day with some cloud interference) was substantially higher than on the remaining test days. The spatial correlations between the five days revealed values ranging from 0.54 to 0.75; rarely was more than half of the variance from one day shared with the spatial variance from another day.

An additional 96- by 96-pixel matrix was constructed by averaging the apparent temperatures from the five test days. Map correlations between the mean pattern and the daily temperature patterns ranged from 0.52 to 0.82 (Table 2). A principal components analysis (Rummel, 1970) was conducted on the temperatures of the five selected test days and the mean temperature pattern. The matrix subjected to principal components analysis consisted of six columns, one for each of the five test days and one for the mean pattern, and 9,216 rows representing the pixels from the 96- by 96-pixel grid.

This analysis revealed one component in the data accounting for 58.6 percent of the variance in the 9,216 by 6 matrix. The loadings for this dominant component in the apparent temperature fields were nearly equivalent to the correlations between

TABLE 1. PHOENIX AIRPORT 1500 LST CONDITIONS FOR FIVE 1986 TEST DATES

Variable	June 5	June 15	July 12	July 31	Aug. 9
Air Temperature (C)	38.8	42.8	39.4	45.6	41.1
Relative Humidity (%)	18	11	13	7	22
Dew Point (C)	10.0	6.1	7.2	2.2	15.0
Wind Speed (m/s)	0	4.1	2.1	4.1	3.1
Wind Direction	-	320	240	270	260
Cloud Cover (tenths)	0	0	1	2	4
Pressure (mb)	969	968	970	969	967
Antecedent Precip. over previous 3 days	None	None	None	None	Scat-



FIG. 1. Surface temperatures (average of five dates) in the Phoenix metropolitan area determined from the AVHRR data.

TABLE 2. SELECTED STATISTICS FOR THE 1986 AVHRR APPARENT TEMPERATURE DATA

Test		Std.	Intercorrelations						
Day	Mean	Dev.	June 5	June 25	July 12	July 31	Aug. 9	Ave.	
5 Jun	43.08	3.84	1.00	0.75	0.66	0.69	0.60	0.74	
15 Jun	47.43	3.83		1.00	0.68	0.73	0.61	0.76	
12 Jul	45.22	3.65			1.00	0.68	0.68	0.82	
31 Jul	47.53	3.70				1.00	0.54	0.52	
8 Aug	40.28	4.31					1.00	0.72	
Ave.	44.71	3.21						1.00	

the spatial patterns for the individual days and the average temperature pattern (the righthand column in Table 2). The mean of the squared loadings for the five days equalled 0.52; these results indicate that the principal component (effectively equivalent to the mean temperature pattern) accounts for 52 percent of all spatial variance in the apparent temperature fields; the remaining 48 percent of the variance is related to the dayto-day fluctuations in the urban temperature pattern.

SURFACE TEMPERATURES

The data provided by the AVHRR sensing system represented the black-body apparent temperature estimates and did not account for thermal emissivity differences occurring at the surface. Land-use data at the one-kilometre resolution were assembled for the study area to correct the AVHRR apparent temperatures to a more accurate estimate of the true surface temperature. These land-use data were supplied by the utility funding the study (see acknowledgment) and had been determined from a series of 1986 aerial photographs.

The land-use data showed the portion of each square kilometre covered by residential, commercial, industrial, and vacant categories. The residential category included (a) light residential, (b) medium residental, (c) heavy residential (apartment complexes), and (d) mobile home parks. The commercial category included (a) low commercial (e.g., neighborhood food stores and small shopping centers), (b) medium commercial (e.g., strip developments), and (c) high commercial, including major regional retail shopping facilities, downtown areas, schools, hospitals, and churches. The industrial category included (a) light industrial areas (fairly common high technology facilities in Phoenix) and (b) relatively rare heavy industrial areas. The land in any one square kilometre area not included in residential, commercial, or industrial categories was considered vacant and included (a) vacant restricted land such as parks, lakes, and state land or (b) undeveloped desert areas.

Estimates of the appropriate grey-body infrared emissivity values for these four major categories were taken from Morgan *et al.* (1977) and Sellers (1965) and were consistent with emissivities provided by Buettner and Kern (1965) and Griggs (1968). These grey-body emissivities were specified as 0.87 for residential surfaces, 0.86 for commercial and industrial land, and 0.90 for the vacant land category.

Due to (a) the coarseness of the four-category land-use data, (b) the lack of local field measurements of emissivities in the Band 4 portion of the spectrum (Barton and Takashima, 1986), (c) the grey-body assumptions of the selected emissivity values, and (d) the lack of correction functions for atmospheric effects (e.g., Dozier and Warren, 1982; Price, 1984), the following simplistic procedure was used to refine the estimates of the surface temperature values from the satellite derived apparent temperatures. The true surface temperature, T_s , was estimated from the apparent temperature, T_a , as

$$\sigma T_a^4 = \epsilon \sigma T_s^4$$

where σ is the Stefan-Boltzmann constant and ϵ is the greybody emissivity of the surface. Within each pixel, the T_s values were determined for each land-use category with an assumption of constant radiance within the pixel. The resulting T_s values were then area-averaged based upon land-use coverage to arrive at the T_s estimate for the pixel. Errors associated with the assumption of constant radiance with each 1 km² were minimized due to the propensity of cells to be dominated by one land-use type. Over 75 percent of the pixels had at least 90 percent coverage by one land-use type; 82 percent of the pixels had over 80 percent coverage by only one of the land-use categories.

The resulting map (Figure 1) displays the estimated surface temperature patterns in Phoenix from the near one-kilometre resolution data. Although no actual surface temperature data are available for the summer of 1986, the values are generally consistent with the field measurements described by Brazel and Marcus (1987) and Marcus *et al.* (1988). The surface temperature patterns ranged from 39°C in a mountainous area in the northeast to 61°C along the runways of several Air Force bases in the city. Most of the many residential areas showed a surface temperature level in the mid-50s, while the major irrigated agricultural areas to the south and to the west of the downtown revealed temperatures near or below 50°C. The mountainous area to the northeast of the city was generally cooler than the other portions of the study area.

A preliminary, quantitative assessment of the interrelationship between the land-use patterns of Phoenix and the estimated mean surface temperatures from the AVHRR images is difficult because of the integration of land-use patterns into the computation of the surface temperature estimates. Assuming the surface temperatures to be accurate, several north-south and east-west transects were drawn across the city and 77 onesquare-kilometre grid cells were selected for analysis. For each grid cell, the estimated surface temperature, mean elevation above sea level, and portions of residential, commercial, industrial, and vacant land were determined. Given the lack of normality in the data, the Spearman Rank-Order Correlation was computed to illustrate the interrelationships within the data (Table 3). The results showed the surface temperature estimates to be positively and significantly related to residential (r=0.32) and commercial coverage (r=0.47), and negatively and significantly related to the vacant land coverage (r=0.38). Elevation differences, which ranged from 297 to 915 m above sea level for the 77 cells, showed no relationship with the temperature values.

Average surface temperature for each land-use category was determined by selecting only those cells where more than 80 percent of the land area fell into one of the four categories. The results (Table 4) showed the vacant land to be much cooler than the residential, commercial, or industrial grid cells. Residential and commercial land appeared to have similar surface temperatures; industrial land produced the highest temperatures. The values within the land-use categories appeared to be consistent with the measured surface temperatures published by Brazel and Marcus (1987) and Marcus *et al.* (1988).

The mean apparent temperatures (all emissivities are assumed to be 1) were also determined for the pixels dominated by one of the land-use categories. The results (Table 4) indicated that the industrial land-use category is warmer than the residential, commercial, or vacant land categories. These other categories showed mean apparent temperatures to be within 0.6°C of one another. The similarity in these apparent temperatures for the three land-use categories indicates the importance of accurately representing emissivities across an urban area when attempting to use AVHRR in producing surface thermal patterns. The coarseness of the category selection in Phoenix may be responsible, in part, for the inability to account for more of the spatial variance in the observed temperature structure.

CONCLUSIONS

Use of AVHRR data showed complex and realistic surface temperature variations at a one-kilometre resolution throughout the Phoenix, Arizona metropolitan area. Surface temperature patterns were shown to be directly related to residential, commercial, and industrial coverage and indirectly related to the coverage in the vacant land category. The residential and commercial area appeared to be over 2.0°C warmer in the summer afternoon period than the surrounding vacant land. Grid cells dominated by the industrial category were over 5.0°C warmer than vacant land and several degrees warmer than the residential or commercial parcels.

The existing AVHRR capabilities appear to hold considerable promise in detailed urban climatological studies. Modeling and

TABLE 3. SPEARMAN RANK-ORDER CORRELATION COEFFICIENTS

	T_s	Elev	Res	Com	Ind	Vac
Surface Temp	1.00	0.04	0.32	0.47	0.20	-0.38
Elevation		1.00	-0.01	-0.06	-0.15	0.07
Residential Land			1.00	0.68	0.20	-0.92
Commercial Land				1.00	0.28	-0.80
Industrial Land					1.00	-0.38
Vacant Land						1.00

Note: Absolute values \geq 0.22 are statistically significant at the 0.95 confidence level.

TABLE 4. MEAN SURFACE AND APPARENT TEMPERATURES (C) BY LAND-USE CATEGORIES

Land-Use Category	Emissivity	N	Surface Temp.	Std. Dev.	Apparent Temp.	Std. Dev.
Residential	0.87	310	55.17	1.38	44.17	1.37
Commercial	0.86	10	55.70	3.43	44.00	2.98
Industrial	0.86	30	58.10	2.50	46.13	2.40
Vacant	0.90	7152	53.07	3.17	44.62	2.80

empirical studies are presently needed to (a) better establish the connection between thermal patterns and more detailed landuse classifications, (b) provide the transfer functions between AVHRR temperature patterns and air temperatures, (c) determine the influence of various meteorological conditions on AVHRR patterns, (d) evaluate diurnal patterns in the thermal data, and (e) determine the feasibility of projecting future heat island patterns given anticipated land-use changes. Over the past eight years, the AVHRR technology has been valuably utilized in landuse, geologic, oceanographic, and agricultural studies (e.g., Schneider *et al.*, 1981; Heilman and Moore, 1982; Norwine and Greegor, 1983; Shih and Chen, 1984; Njoku, 1985; Fung *et al.*, 1987; Woodwell *et al.*, 1987). This study has demonstrated that the AVHRR imagery should prove to be an equally valuable tool in future urban climatological studies.

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REFERENCES

- Applied Land-Resources Remote-Sensing Group, 1986. In-House Technical Memoranda. Nebraska Remote Sensing Center, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.
- Arnfield, A. J., 1982. An Approach to the Estimation of the Surface Radiative Properties and Radiation Budgets of Cities. *Physical Geography*, Vol. 3, pp. 97–122.
- Artis, D. A., and W. H. Carnahan, 1982. Survey of Emissivity Variability in Thermography of Urban Areas. *Remote Sensing of Environment*, Vol. 12, pp. 313–329.
- Balling, R. C., Jr., and S. W. Brazel, 1986a. 'New' Weather in Phoenix? Myths and Realities. Weatherwise, Vol. 39, pp. 86–90.
 - —, 1986b. Temporal Analysis of Summertime Weather Stress Levels in Phoenix, Arizona. Archives for Meteorology, Geophysics, and Bioclimatology. Series B., Vol. 36, pp. 331–342.
 - —, 1986c. Time and Space Characteristics of the Phoenix Urban Heat Island. Journal of the Arizona-Nevada Academy of Science, Vol. 21, pp. 75–81.
 - —, 1987a. Recent Changes in Phoenix, Arizona Summertime Diurnal Precipitation Patterns. Archives for Meteorology, Geophysics, and Bioclimatology. Series B., Vol. 38, pp. 50–54.
 - —, 1987b. The Impact of Rapid Urbanization on Pan Evaporation in Phoenix, Arizona. Journal of Climatology, Vol. 7, pp. 593–597.
- Balling, R. C., Jr., and R. S. Cerveny, 1987. Long-Term Associations between Wind Speeds and the Heat Island of Phoenix, Arizona. *Journal of Climate and Applied Meteorology*, Vol. 26, pp. 712–716.
- Barton, I. J., and T. Takashima, 1986. An AVHRR Investigation of Surface Emissivity near Lake Eyre, Australia. *Remote Sensing of Envi*ronment, Vol. 20, pp. 153–163.
- Brazel, A. J., 1987. Urban Climatology. Encyclopedia of Climatology (J. E. Oliver and R. W. Fairbridge, eds.), New York: Van Nostrand Reinhold, pp. 889–901.
- —, S. W. Brazel, and R. C. Balling, Jr., 1988. Recent Changes in Smoke/Haze Events in Phoenix, Arizona. *Theoretical and Applied Climatology*, in press.
- —, and D. M. Johnson, 1980. Land Use Effects on Temperature and Humidity in the Salt River Valley, Arizona. *Journal of the Arizona-Nevada Academy of Science*, Vol. 15, pp. 54–61.
- Brazel, A. J., and M. G. Marcus, 1987. Heat Enhancement by Longwave Wall Emittance. *Geographical Review*, Vol. 77, pp. 440–455.
- Brazel, S. W., and R. C. Balling, Jr., 1986. Temporal Analysis of Long-Term Atmospheric Moisture Levels in Phoenix, Arizona. *Journal of Climate and Applied Meteorology*, Vol. 25, pp. 112–117.
- Buettner, K. J. K., and C. D. Kern, 1965. The Determination of Infrared Emissivities of Terrestrial Surfaces. *Journal of Geophysical Research*, Vol. 70, pp. 1329–1337.

- Carlson, T. N., J. N. Augustine, and F. E. Boland, 1977. Potential Application of Satellite Temperature Measurements in the Analysis of Land Use over Urban Areas. *Bulletin of the American Meteorological Society*, Vol. 58, pp. 1301–1303.
- Carlson, T. N., J. K. Dodd, S. G. Benjamin, and J. N. Cooper, 1981. Satellite Estimation of the Surface Energy Balance, Moisture Availability and Thermal Inertia. *Journal of Applied Meteorology*, Vol. 20, pp. 67–87.
- Cayan, D. R., and A. V. Douglas, 1984. Urban Influences on Surface Temperatures in the Southwestern United States during Recent Decades. *Journal of Climate and Applied Meteorology*, Vol. 23, pp. 1520–1530.
- Dozier, J., 1981. A Method of Satellite Identification of Surface Temperature Fields of Subpixel Resolution. *Remote Sensing of Environment*, Vol. 11, pp. 221–229.
- Dozier, J., and S. G. Warren, 1982. Effect of Viewing Angle on the Infrared Brightness Temperature of Snow. Water Resources Research, Vol. 18, pp. 1424–1434.
- Fung, I. Y., C. J. Tucker, and K. C. Prentice, 1987. Application of Advanced Very High Resolution Radiometer Vegetation Index to Study Atmosphere-Biosphere Exchange of CO₂. *Journal of Geophysical Research*, Vol. 92, pp. 2999–3015.
- Goward, S. N., 1981. Thermal Behavior of Urban Landscapes and the Urban Heat Island. *Physical Geography*, Vol. 2, pp. 19–33.
- Griggs, M., 1968. Emissivities of Natural Surfaces in the 8- to 14-Micron Spectral Region. *Journal of Geophysical Research*, Vol. 73, pp. 7545– 7551.
- Heilman, J. L., and D. G. Moore, 1982. Evaluating Near-Surface Soil Moisture using Heat Capacity Mapping Mission Data. *Remote Sens*ing of Environment, Vol. 12, pp. 117–121.
- Hsu, S. I., 1984. Variation of an Urban Heat Island in Phoenix. *The Professional Geographer*, Vol. 36, pp. 196–200.
- Lee, D. O., 1984. Urban Climates. Progress in Physical Geography, Vol. 8, pp. 1–31.
- Marcus, M. G., C. Kelly, A. J. Brazel, and S. W. Brazel, 1988. Urban Surfaces: How Hot are They? Arid Lands Today and Tomorrow pp. 561–569. Proceedings of an International Research and Development Conference (E.E. Whitehead et al., eds.) Boulder, Colorado, Westview Press.

, University of Arizona, October, 1985, in press.

- Marotz, G. A., and J. C. Coiner, 1973. Acquisition and Characterization of Surface Material Data for Urban Climatological Studies. *Journal* of Applied Meteorology, Vol. 12, pp. 919–923.
- Matson, M., E. P. McClain, D. F. McGinnis, Jr., and J. A. Pritchard, 1978. Satellite Detection of Urban Heat Islands. *Monthly Weather Review*, Vol. 106, pp. 1725–1734.
- Morgan, D., L. Myrup, D. Rogers, and R. Baskett, 1977. Microclimates within an Urban Area. Annals of the Association of American Geographers, Vol. 67, pp. 55–65.
- Myrup, L. O., 1969. A Numerical Model of the Urban Heat Island. Journal of Applied Meteorology, Vol. 8, pp. 908–918.
- Njoku, E. G., 1985. Satellite-Derived Sea Surface Temperature: Workshop Comparisons. Bulletin of the American Meteorological Society, Vol. 66, pp. 274–281.
- Norwine, J., and D. H. Greegor, 1983. Vegetation Classification based on Advanced Very High Resolution Radiometer (AVHRR) Satellite Imagery. *Remote Sensing of Environment*, Vol. 13, pp. 69–87.
- Nunez, M., and T. K. Oke, 1980. Modelling the Daytime Urban Surface Energy Balance. *Geographical Analysis*, Vol. 12, pp. 373–386.
- Oke, T. R., 1982. The Energetic Basis of the Urban Heat Island. Quarterly Journal of the Royal Meteorological Society, Vol. 108, pp. 1–24.
- Outcalt, S. I., 1972. A Reconnaissance Experiment in Mapping and Modeling the Effect of Land Use on Urban Thermal Regimes. *Journal of Applied Meteorology*, Vol. 11, pp. 1369–1373.
- Pease, R. W., J. E. Lewis, and S. I. Outcalt, 1976. Urban Terrain Climatology and Remote Sensing. Annals of the Association of American Geographers, Vol. 66, pp. 557–569.
- Price, J. C., 1983. Estimating Surface Temperatures from Satellite Ther-

mal Infrared Data - A Simple Formulation for the Atmospheric Effect. *Remote Sensing of Environment*, Vol. 13, pp. 353–361.

- —, 1984. Land Surface Temperature Measurements from the Split Window Channels of the NOAA 7 Advanced Very High Resolution Radiometer. *Journal of Geophysical Research*, Vol. 89, pp. 7231–7237.
- Rummel, R. J., 1970. Applied Factor Analysis. Evanston: Northwestern University Press.
- Schneider, S. R., D. F. McGinnis, Jr., and J. A. Gatlin, 1981. Use of NOAA/AVHRR Visible and Near-Infrared Data for Land Remote Sensing. NOAA Technical Report NESS 84. Washington, D. C.: National Earth Satellite Service, NOAA, Department of Commerce.
- Sellers, W. D., 1965. Physical Climatology. Chicago: The University of Chicago Press.

Shih, S. F., and E. Chen, 1984. On the Use of GOES Thermal Data to

Study Effects of Land Use on Diurnal Temperature Fluctuation. *Journal of Climate and Applied Meteorology*, Vol. 23, pp. 426–433.

- Short, N. M., and L. M. Stuart, Jr., 1982. The Heat Capacity Mapping Mission (HCMM) Anthology. NASA SP-465. Washington, D.C.: Scientific and Technical Information Branch.
- Terjung, W. H., and S. S-F. Louie, 1973. Solar Radiation and Urban Heat Islands. Annals of the Association of American Geographers, Vol. 63, pp. 181–207.
- Woodwell, G. M., R. A. Houghton, T. A. Stone, R. F. Nelson, and W. Kovalick, 1987. Deforestation in the Tropics: New Measurements in the Amazon Basin using Landsat and NOAA Advanced Very High Resolution Radiometer Imagery. *Journal of Geophysical Research*, Vol. 92, pp. 2157–2163.
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