LAND USE, LAND COVER, and LOCAL CLIMATE

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INTRODUCTION

The tools of remote sensing can be used to monitor land cover and the climatic environment of the Earth's surface. It is also possible to use these tools to investigate the interaction between land cover and local climate. This lecture will focus upon the "urban heat island" phenomenon as observed through the use of digital Landsat thematic mapper image data, and will address questions concerned with the link between surface land cover and local climate. Exercise number one, of Volume 4, in the Remote Sensing Core Curriculum titled: "Identification of Urban Heat Islands Using Remotely Sensed Data: A Multi Sensor Approach" provides an extensive discussion of the urban heat island phenomenon. In exercise number one, Dr. Kevin Gallo and Tim Owen have provided illustrations of observed urban temperatures as compared to surrounding rural landscapes. In their examples, remotely sensed images from the one-kilometer resolution AVHRR imaging system are used.

For many years it has been reported that city centers are generally warmer than the surrounding countryside. This idea was first observed using a few insitu thermograph observations placed at points within the metropolitan regions. More recent use of coarse resolution thermal remotely sensed imagery (usually from satellite platforms) has shown that many cities are warmer near their center. (See Exercise #1 of this applications volume, and figures 1 and 2.) This pattern is generally true for cities in humid climatic regions, but not necessarily the case for cities in arid environments.

Moreover, this general "heat island" concept does not explain thermal variations within the city, and does not explain why the city is warmer. It is incorrectly thought, and stated in many textbooks, that urban materials of concrete, steel and asphalt absorb and hold more of the sun's radiant energy. In fact, city surfaces often reflect more energy away from the earth's surface, and they also emit greater amounts of terrestrial radiation. Thus, the city actually has a much lower net radiant energy level than the humid rural landscape, and is holding much less energy.

The answer to why the city is warmer lies in how radiant energy is used. Where moisture is available the majority of radiant energy will be used for evapotranspiration. Since most city centers have less biomass for evapotranspiration, and less open water, most of the radiant energy is used for heating the air and the ground in the city. Air takes on the characteristics of the surface below. Thus, city surface temperature controls the near-surface air temperature. Environmental planning to provide greater moisture availability within the city can control neighborhood temperature to a significant level. Works by Schmid and Oke (1992) and Hubble (1993) have shown that microclimatic spatial interaction at a sale of less that 200 meters is critical to explain urban thermal variations. Fine resolution remotely sensed data are necessary to monitor and analyze these phenomena. The coarse resolution "urban heat island" pattern is a valid generalization, but misses the important intricacies necessary to study and understand the environmental processes taking place within the city environment.

In this lecture we will look at cites in both humid and arid environments. First, Rochester, New York will be viewed as an example of a city in a humid climate. As a comparison, research conducted in the area of Phoenix, Arizona will be presented to illustrate the climate of a city in an arid climate. Figures 1, 2, and 3 are Landsat 5 images of Rochester, New York. Rochester is located just south of Lake Ontario, in the humid continental climate of the northeastern United States. These images were obtained in the month of June. Figure 1 is a color composite image where green vegetation is shown in shades of green, bare soil appears in shades of pink, water appears almost black, and urban pavement and rooftops appear in shades of dark blue. Figure 2 is a thermal image of Rochester, New York. Lighter tones in figure 2 represent warmer surface temperatures. It can be seen that these images portray a city in a humid climate displaying the classic thermal patterns of the urban heat island, with hotter surface temperatures found towards the center of the city. Figure number 3 is an image of the normalized difference vegetation index for Rochester, New York. In general, brighter areas of figure 3 depict areas of greater biomass. By comparing figures 1, 2, and 3, it can be seen that, for land areas, cooler temperatures are associated with regions having greater amounts of vegetation.

FIGURES 1,2,3 [*Refer to Web site for images*]

Urban centers in arid climates do not necessarily exhibit the classic pattern of an urban heat island, as discussed above. Figures 4 and 5 show landsat images of the Phoenix, Arizona metropolitan region. Figure 4 is a color composite image where green colors correspond to vegetated surfaces, while figure 5 shows the surface temperatures of this area. It is interesting to note that the hottest regions are in the desert outside of the Phoenix metropolitan area, and the coolest surface temperatures are associated with areas of irrigated agriculture. In Figure 4, beige tones correspond to barren landscape and desert; bluish tones represent pavement and urban impervious surfaces, while green depicts vegetation.

FIGURES 4,5 [*Refer to Web site for images*]

In this lecture we ll look at the surficial climate of Phoenix, Arizona at verious spatial scales. Figures 4 and 5 show the whole metropolitan area and its surroundings, while figures 6 and 7 show a smaller portion of the city, and environmental variation within this small area. The standard "urban heat island" concept also does not work well when viewing specific portions of a city closely. This lecture will utilize digital remotely sensed Landsat imagery focusing upon the metropolitan region of Phoenix, Arizona, and the suburb of Scottsdale, Arizona. Some neighborhoods are much hotter than others. This differential in temperature can be from a few degrees to as much as twenty degrees (deg. F). Hotter neighborhood temperatures are not only more uncomfortable in summer months, but demand much greater amounts of electrical energy for air conditioning. Figures 6 and 7 show Landsat images of Scottsdale, Arizona region, within the Phoenix metropolitan area. Figure 6 shows a color composite image similar to that of Figure 4, while figure 7 shows patterns of thermal emittanace (i.e., surface temperature) similar to figure 5. Past work has shown that much of the thermal variation of the city surface can be explained by the presence of moisture for evapotranspiration (Lougeay et. al., 1996). The more evapotranspiration that takes place, the cooler the neighborhood. Thus, irrigated parkland, open pools of water, and irrigated residential lawns and shrubbery reduce the energy demand. Environmental managers can literally trade water for electricity by controlling the land cover characteristics of a neighborhood. Currently Scottsdale, Arizona and the whole country of Singapore (Nichol, 1994) are using this information in their city planning

FIGURES 6,7 [*Refer to Web site for images*]

Images of Phoenix, AZ (figures 4, 5, 8, and 9) show a city which is actually cooler than the surrounding desert rural landscape. The coolest regions in the Phoenix metropolitan area are those regions of irrigated agriculture or well irrigated residential land use. Figure 8 displays surface temperatures for Phoenix. Figure 9 is an image showing variations in biomass across the Phoenix metropolitan area, with brighter area representing greater biomass and rates of evapotranspiration.

FIGURES 8,9 [*Refer to Web site for images*]

This lecture focuses upon the utilization of remotely sensed data provided by the Landsat thematic mapper thermal band, having a pixel resolution of 120 meters. This is an environmental scale experienced by the people who live in these cities. As stated above, there is interest, and a few active applications, in using these procedures of image analysis to control neighborhood thermal environments by planning for strategically placed green belts of irrigated landscape.

For further information concerning current research on the topic of urban climatology the reader may wish to consult the Urban Climate Network at the following Internet address: http://www.urbanclimate.org/

DISCUSSION:

Landsat digital image data are used to investigate the intraurban temperature patterns within the metropolitan area of Phoenix, AZ. (Figures 4 and 5). Landsat TM thermal data (Figures 5, 7, and 8) have a resolution of 120 meters, while the six spectral bands of reflected sunlight have 30 meter resolution. Schmid and Oke (1992), Brazel, et al. (1993) and Hubble (1993) have all shown that the spatial pattern of climatic variability within a city manifests itself at a resolution of less than 200 meters. Landsat TM data provide information well within this scale.

At the time of Landsat image acquisition for this study, weather observations two meters above an irrigated grass surface revealed an ambient air temperature of 37 degrees Celsius, with 24 percent relative humidity and wind velocity of less than four meters per second. Air temperatures two meters above a desert plot and an asphalt parking lot were 41 and 38.9 degrees Celsius respectively. Horizontal insolation values observed at all locations were 806 watts per square meter. [A parallel discussion of this study is presented in Lougeay, et. al., 1996.]

Surface temperature is closely related to the energy available at the earth's surface which, in turn, warms the near surface atmosphere. Observations associated with this work in Phoenix, Arizona found a significant correlation between surface temperature and near surface air temperature (Hubble, 1993 and Brazel, et al., 1993). Comparison of insitu observations of near surface air temperature with remotely sensed radiometric surface temperatures yielded an R^2 of .40, significant at the .05 level. Similarly, when data from mobile transects were compared with remotely sensed radiometric surface temperatures the R^2 equaled .39, significant at the .05 level (Hubble 1993). The surface temperature is actually a result of the net radiant energy budget of the surface and the various sinks for this energy. Since the incoming solar and atmospheric radiant energy flux is approximately equal for all surfaces within an imaged scene, the net radiant energy is a function of the surface reflectance and emittance.

Net radiant energy of various environmental surfaces is used, primarily, to warm the air, warm the ground, or is used in the process of evapotranspiration. This is especially true in the mid morning of a cloud free day, which is the case for scenes imaged with Landsat TM data. In general, an evapotranspirative heat sink is the most significant use of net energy. Thus, the presence of open water or transpiring vegetation is a strong independent variable controlling local surface temperature. This is especially important in arid environments such as those experienced during June in Phoenix, Arizona USA. On June 24, 1992, potential evapotranspiration rates in the Phoenix area were very high due to high net radiation values and low relative humidity. However, actual evapotranspiration rates were very low where moisture was unavailable, but high where moisture was available to the atmosphere. This difference in rates of evapotranspiration proved to be a very important variable in explaining surface temperature and near surface air temperatures within the urban environment.

Modern demands for electrical service and amounts of potable and irrigation water are directly related to ambient air temperature. In Phoenix, urban development tends to reduce the spatial extent of evapotranspiring surfaces in this extensively irrigated valley, modify surface albedo values, and significantly increase the surface temperature. The magnitude of climatic modification associated with human activity varies with different types of land use (e.g., commercial, parkland, and various densities and landscaping of residential neighborhoods).

Surface temperature values were extracted from the Landsat data following the procedures discussed in Lougeay, et al. (1994). In brief, the digital values of the Landsat thermal data were transformed to observed ground surface temperatures by first calculating the spectral radiance and then calculating the "at satellite" temperature of each pixel. The "at satellite" temperature is a calculated ground surface temperature of the pixel, assuming the surface is radiating as a black body (i.e., emissivity = 1.0).

A more detailed discussion of this study, with ground temperatures adjusted for emissivity, can be seen in Lougeay, et. al. (1996). Much of this discussion is taken from that article. However, the total image area analyzed is different, and in the case of images presented with this lecture, surface temperatures have not been adjusted for emissivity characteristics.

Ground level observations of climatic parameters were made at the time the landsat satellite acquired these images. Although the relative temperature difference among various categories of land use and land cover were of primary interest, ancillary ground observations were conducted to insure accuracy of radiometric data extracted from the remotely sensed data. Temperature values extracted from Landsat remotely sensed data were compared with ground observations at the time of satellite overpass to assess effects of atmospheric attenuation and to insure accuracy of extracted surface radiometric temperature values.

IMAGE PROCESSING AND ANALYSIS

Ambient air temperature is not directly observed by investigating surface temperatures. However, the near-surface atmosphere takes on the heat and moisture characteristics of the surface. Digital satellite image data of thermal emittance were overlaid upon digitally mapped land use data to assess climatic heat loads characteristic of various land use categories. An unsupervised multispectral classification (Figures 10 and 11) of reflected and emitted radiation was derived to develop a "climatically-driven" land use classification to be compared with more traditional methods of assessing land use. [See Volume 3, Module 7.2 of the Remote Sensing Core Curriculum for a more detailed discussion of unsupervised image classification.] The classification of this image scene employed the Landsat spectral bands of reflected solar energy and the thermal band. The five clusters identified in this classified image were statistically derived according to surface reflectance and emittance patterns. After comparing the unsupervised classified image with ground observation the classes were given titles according to predominant land use. Mountainous areas were masked from the classification to avoid thermal effects of varying slope and exposure angles. This was accomplished by creating a vector file of polygons covering mountainous areas of the image, and then masking these areas from analyzed image files using an overlay procedure.

FIGURES 10,11 [*Refer to Web site for images*]

Most image processing and GIS software packages have the capability to extract numeric data from one image given the categories of another. In this case, values of surface temperature (from Figure 8) were extracted for each unsupervised land cover category in Figure 10. Table 1 presents seven significant temperature categories within the 6569 square kilometer region imaged over Phoenix, Arizona. Heavily irrigated agricultural crops, parkland, and well-irrigated residential neighborhoods exhibited an average surface temperature which was 32.61° Celsius. This was just slightly higher than the observed surface temperature of open water surfaces (31.54 ^{o}C). Xeriscaped residential neighborhoods, characterized by natural desert landscaping in addition to residential building materials, averaged 39.12 ^{o}C, which was nearly 0.8 degrees warmer than commercial areas. Areas identified as primarily commercial land use, characterized by large areas of pavement and roofing materials with very little open water or vegetation, averaged 38.35 ^{o}C. Natural desert landscape averaged a surface temperature of 42.08 ^{o}C. Barren land, which was primarily comprised of construction areas and agricultural fields currently not covered with crops, exhibited a nearly identical temperature (42.07 ^{o}C). These results are consistent with findings of Carnahan and Larson (1990) who, using Landsat thermal data, observed warm barren dry agricultural soils surrounding Indianapolis, Indiana as compared to a cooler urban environment.

It is no surprise that the desert and barren landscape exhibits a much warmer temperature than well-irrigated land. However, it is interesting to note that the average surface temperature associated with much of the residential land use is nearly the same, and slightly warmer than commercial areas (See Table 1). The land use categorization does not determine the physical climate of urban neighborhoods, but the land cover certainly does. Well-irrigated residential neighborhoods, with lawn, shrubbery, and extensive stands of irrigated palm or citrus trees have a surface temperature as cool as that of irrigated golf courses and cropland. However, residential neighborhoods which have little moisture available for evapotranspiration are as warm as commercial districts, having an average surface temperature which is 6.5^{o} C (12.7^{o} F) hotter than irrigated residential areas. Thus, traditional categories of land use may not correlate well with the thermal zones of the city, but the unsupervised cluster categories for remotely sensed imagery do represent a climatically derived categorization of the physical environment of the urban area. The categories presented in table 1 are determined from patterns of solar reflectance and surface emittance.

Most of the moisture available to the atmosphere in this region of study comes from the vegetation present at the ground. There is very little area of open water surface. In fact, a supervised classification of the 30 meter resolution thematic mapper data revealed that water surfaces comprised only 0.2 per cent of the total image scene. To test the role of biomass in controlling observed surface temperature a regression analysis was performed comparing the thermal landsat image of Phoenix, AZ (Figure 8) with the normalized difference vegetation index image (Figure 9). In this case the normalized difference vegetation index image (Figure 9) is the independent variable while the thermal image (Figure 8) is the dependent variable. Figure 12 presents a graph of this regression analysis. The R^2 is 0.66 (i.e., the coefficient of determination is 66.55 per cent). This implies that approximately 66 per cent of the thermal variation in the imaged scene can be attributed to variations in the amount of biomass (and energy used for evapotranspiration) present in each pixel. The R value of –0.8158 is negative because temperature declines with increasing biomass. Each of the 307,719 pixels (120 m resolution) has been plotted on the graph in Figure 12. In this case 120 meter pixels are used because the original thermal sensor has a pixel resolution of 120 meters. The data points in the lower left of the graph, showing cool temperatures associated with relatively low biomass, were found to be metal roofs with highly reflective metalized paints and materials exhibiting very low emissivity characteristics.

Figure 12 [*Refer to Web site for images*]

Table 1

RADIATIVE SURFACE TEMPERATURES (10:00 A.M.) and AREAL COVERAGE

June 24, 1992

PHOENIX, ARIZONA

Surface Type	Surface Temp. Deg. C*	Min. Temp Deg. C*	Max. Temp Deg. C*	Standard Dev. Deg. C*	Area km^2	% of scene**
Irrigated Ag. & Res.	32.61	25	40	3.06	487	7
Dry Res.	39.12	34	44	2.10	1255	19
Commercial	38.35	41	49	1.29	409	6
Desert	42.08	37	46	1.92	1512	23
Barren	42.70	38	46	1.66	769	12
Unclassified (masked mountain slopes)	-----	--	--	--	2138	33

* Surface Temperatures extracted from Landsat Thematic mapper band 6.

** Total imaged area of Metropolitan Phoenix equals 6,572 square kilometers.

APPLICATION

The Phoenix Arizona metropolitan area has experienced extreme rates of growth and development in recent years. It is the fast rate of expansion in an area as large as Greater Phoenix that makes the Salt River Valley somewhat unique. Over half of the land use conversion is from irrigated agriculture to urban land use (Salt River Project, 1992), thus converting one of the coolest categories of land cover to much hotter categories of land use. In terms of human population expansion, Metro Phoenix grew from a 1970 population of 971,000 to a 1990 population of 2.1 million. This 20 year growth rate of more than 110 percent places Phoenix as the fastest growing of the top 30 American urban areas. Perhaps even more noteworthy is the Maricopa Association of Governments (MAG) predicts that Metro Phoenix will reach 4.0 million inhabitants by 2010 (Maricopa Association of Governments, 1985), and this is thought by many to be a significant under estimate. While past growth has been sprawling, the Salt River Project (the utility company providing all of the water and most of the electricity to this region) predicts that future growth will continue to convert still more land to urban uses, squeezing another 2.0 million people into the Salt River Valley in the next 20 years.

During the first half of the twentieth century much of the region surrounding Phoenix, Arizona was converted from natural desert to extensive irrigated agriculture. In recent decades, increasing rates of land use conversion have resulted in extensive change to urban categories of land use. According to Salt River Project projections, in the next 20 years residential uses will increase by about 30 percent while commercial and industrial uses will nearly double. All of this growth in the urbanized area of Greater Phoenix must come at the expense of other land uses. Not surprisingly, much of the irrigated agricultural acreage is being converted. This has the effect of warming the earth's surface, and near surface air temperature, in the metropolitan area as a function of land use development. This produces a daytime metropolitan temperature field much closer to that of the surrounding natural desert.

The relatively high resolution of Landsat remotely sensed thermal data have proven to be useful in assessing temperature patterns of urban environments at the neighborhood scale. In addition, this image analysis has observed a strong correlation between patterns of environmental temperature and surface rates of evapotranspiration, where these rates of evapotranspiration are portrayed, in large, part by biomass as represented in the normalized difference vegetation index. Spatial patterns of energy demand and human comfort associated with ambient temperatures did not correlate well with traditional categories of mapped land use (e.g., high, medium and low density residential). The use of a multispectral classification of remotely sensed data did prove useful in identifying categories of environmental surfaces which exhibit relatively homogenous temperature patterns within the city. These classified categories were found to be associated with identifiable biophysical surface conditions, and were associated with identifiable land use and land cover categories (e.g., irrigated residential, xeriscaped residential, etc.).

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FIGURE CAPTIONS: [Refer to Web site for images]

Figure 1: False color composite image of Rochester, New York. Image width equals 38.7 km. This Landsat thematic mapper image overlays three spectral bands of digital imagery with red for band 7, green for band 4, and blue for band 3. In general, green vegetation appears in tones of green; bare fields and open land are depicted in tones of pink and white; water is shown in black; and urban surfaces are shown in tones of blue. Image acquisition date is August 22, 1991.

Figure 2: Thermal image of Rochester, New York. Image width equals 38.7 km. This Landsat thematic mapper band 6 image displays energy emitted from the earth's surface as a function of surface temperature. Brighter tones show surfaces having hotter temperatures, while darker surfaces are cooler. The image acquisition date is August 22, 1991

Figure 3: Normalized Difference Vegetation Index image of Rochester, New York. [Landsat thematic mapper band 4 and 3 are used in the following way: (B4-B3)/(B4+B3).] Brighter tones depict surfaces of greater biomass. Image width equals 38.7 km, and the image acquisition date is August 22, 1991.

Figure 4: False color composite image of Phoenix, Arizona. Image width equals 92 km. This Landsat thematic mapper image overlays three digital images with red for band 6, green for the first principal component of bands 4, 5, and 7, and blue for the first principal component of bands 1, 2, and 3. In general, green vegetation appears in tones of green; barren desert appears in tones of beige and brown; and urban surfaces are shown in tones of blue and purple. The hot, and barren, runways of Sky Harbor airport appear in red, and can be seen near the center of the image. Image acquisition date is June 24, 1992.

Figure 5: Thermal image of Phoenix, Arizona. Image width equals 92 km. This Landsat thematic mapper band 6 image displays energy emitted from the earth's surface as a function of surface temperature. Brighter tones show surfaces having hotter temperatures, while darker surfaces are cooler. The image acquisition date is June 24, 1992.

Figure 6: False color composite image of Scottsdale and northern Tempe, Arizona. Image width equals 13.5 km. This Landsat thematic mapper image is a section of Figure 4. It overlays three digital images with red for band 6, green for the first principal component of bands 4, 5, and 7, and blue for the first principal component of bands 1, 2, and 3. In general, green vegetation appears in tones of green; barren desert appears in tones of beige and brown; and urban surfaces are shown in tones of blue and purple. The hot, and barren, runways of Sky Harbor airport appear in red, and can be seen near the lower left of the image. Image acquisition date is June 24, 1992.

Figure 7: Thermal image of Scottsdale and northern Tempe, Arizona. Image width equals 13.5 km. This Landsat thematic mapper image is a section of Figure 5. This Landsat thematic mapper band 6 image displays energy emitted from the earth's surface as a function of surface temperature. Brighter tones show surfaces having hotter temperatures, while darker surfaces are cooler. The image acquisition date is June 24, 1992

Figure 8: Thermal image of Phoenix, Arizona. Image width equals 92 km. This Landsat thematic mapper band 6 image displays energy emitted from the earth's surface as a function of surface temperature. Brighter tones show surfaces having hotter temperatures, while darker surfaces are cooler. The image acquisition date is June 24, 1992. Figure 8 is identical to Figure 5.

Figure 9: Normalized Difference Vegetation Index image of Rochester, New York. [Landsat thematic mapper band 4 and 3 are used in the following way: (B4-B3)/(B4+B3).] Brighter tones

depict surfaces of greater biomass. Image width equals 92 km, and the image acquisition date is 24, 1992.

Figure 10: Unsupervised classification image of Phoenix, Arizona. Image width equals 92 km. Areas of clouds and mountains have been masked from the input images, and are shown in black. This K-means unsupervised classification used three input image scenes (Landsat thematic mapper band 6, the first principal component image of thematic mapper bands 1, 2, and 3, and the first principal component image of thematic mapper bands 4, 5, and 7.) Five significant environmental surfaces were identified. Well-irrigated agriculture and residential areas are shown in green. Residential areas with less biomass are displayed with a magenta color. Commercial areas are shown in red. Natural desert is portrayed in beige while barren surfaces are colored yellow. Greater accuracy was achieved with the unsupervised classification by aggregating pixels to a resolution of 120 meters. This was necessary since the original pixel resolution of the thermal band of the landsat thematic mapper is 120 meters.

It must be emphasized that these separate areas of the unsupervised classification are derived from patterns of reflected sunlight and emitted thermal energy. Labels of land cover have been assigned to these regions, after the classification, based upon the interpreter's familiarity with the area under study.

Figure 11: Unsupervised classification image of Scottsdale and northern Tempe, Arizona. Image width equals 13.5 km. This K-means unsupervised classification used three input image scenes (Landsat thematic mapper band 6, the first principal component image of thematic mapper bands 1, 2, and 3, and the first principal component image of thematic mapper bands 4, 5, and 7.) Five significant environmental surfaces were identified. Well-irrigated agriculture and residential areas are shown in green. Residential areas with less biomass are displayed with a magenta color. Commercial areas are shown in red. Natural desert is portrayed in beige while barren surfaces are colored yellow. This image is a subset of Figure 10, and matches the area shown in Figure 6. Greater accuracy was achieved with the unsupervised classification by aggregating pixels to a resolution of 120 meters. This was necessary since the original pixel resolution of the thermal band of the landsat thematic mapper is 120 meters.

It must be emphasized that these separate areas of the unsupervised classification are derived from patterns of reflected sunlight and emitted thermal energy. Labels of land cover have been assigned to these regions, after the classification, based upon the interpreter's familiarity with the area under study.

Figure 12: This regression analysis graph shows the relationship between biomass, as represented by the NDVI digital values (Figure 9) on the X-axis, and surface temperature (derived from Figure 8) on the Y-axis. Over 300,000 sample pixel locations were used in the analysis. The Y-intercept of 43.99 ^{o}C is almost exactly the same as observed surface temperatures of a large barren parking lot at the time of image acquisition. Surface temperatures decline with increasing biomass. The data points in the lower left of the graph, showing cool temperatures associated with relatively low biomass, were found to be metal roofs with highly reflective metalized paints and materials exhibiting very low emissivity characteristics. The coefficient of determination for this analysis is 66.56 per cent, significant at the .05 level.