A GIS-Based Approach to Microclimate Monitoring in Singapore's High-Rise Housing Estates

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Abstract

Surface temperature data of urban areas derived from satellite thermal sensors are under-utilized in planning applications due to the inability to demonstrate meaningful relationships between the satellite-derived data and the urban microclimate. The study uses GIS operations to demonstrate such relationships for high rise housing estates in a tropical city where climate control is of paramount importance. The procedure for emissivity correction decreased the pixel size to 30 metres and enhanced the spatial characteristics of vegetated areas to approximate the high spatial frequency of the urban environment. This gave a high correlation between satellite derived surface temperature and biomass indices, as well as similarity with air temperature data. While noting the limitations of the data for obtaining absolute quantitative values for ambient air temperature, the study suggests specific planning contexts in which image-derived values can be input into planning models.

Introduction

Climatic characteristics of urban areas have been examined using relatively low resolution thermal sensors on satellites, including the NOAA AVHRR with a spatial resolution of 1.1 km (Balling and Brazell, 1988; Roth *et al.*, 1989) and the HCMR sensor with a 0.6-km pixel size (Carlson and Boland, 1978; Carlson *et al.*, 1981; Vukovitch, 1983; Henry *et al.*, 1989).

In these studies, the authors cite the coarse spatial resolution of the data compared with the high spatial frequency of urban surfaces as responsible for the inability to derive accurate and meaningful relationships between ground temperatures calculated from corrected sensor radiance values and those measured on the ground (Balling and Brazell, 1988; Desjardins *et al.*, 1990; Roth *et al.*, 1989). In this context, Desjardins *et al.* warn against using satellite derived-data, even including the much higher resolution data of Landsat Thematic Mapper (thermal band, 120 metres) for the acquisition of precise ground temperatures for areas other than those characterized by large isotropic surfaces such as lakes, oceans, and deserts.

While Carnahan and Larson have utilized Landsat's thermal band to observe meso-scale temperature differences between urban and rural areas in Indianapolis, no significant attempts have been made to investigate its application to microclimate monitoring.

Yet accurate and spatially detailed information relating to the urban heat island would be invaluable to the urban planner, particularly in tropical cities where human comfort is subject to effective landscaping of areas where people live and work. Because near surface climates are known to be intimately related to those of the active surface (Chandler, 1967; Goldreich, 1985; Price, 1979; Roth *et al.*, 1989; Carlson and Boland, 1981), surface temperature data derived from satellites are under-utilized in urban planning for the evaluation of existing, and formulation of future, landscaping policies.

Effective "greening" campaigns may ameliorate the heat island effect. This is the strategy adopted by environmentally conscious planning authorities in Singapore since 1967 in order to mitigate the effects of a high rise lifestyle in the densely populated nation state.

However, such greening campaigns are expensive and can only be judged empirically by their direct impact on microclimate modification, for which data on spatial aspects of the urban heat island would be of obvious value.

Objectives

The objective of the present study is to evaluate Landsat Thematic Mapper's thermal waveband for indicating temperature differences in Singapore's high-rise municipal housing estates. Bearing in mind the close relationship between surface temperature (**Ts**) and the climate near the ground, the following specific questions are addressed:

- Can the satellite data indicate temperature differentials at meso- and micro-scales in Singapore, as represented by temperature differences between and within housing estates?
- Is the spatial resolution sufficient to accurately relate these patterns to individual parcels of land cover within the estates?
- Are such data sufficiently meaningful for use in urban planning, and can they be conveyed to planners at a scale compatible with city base maps, i.e., at the level of the individual land parcel?

Singapore's Environment

The combination of high temperature and high humidity in Singapore creates a human physioclimate characterized by some degree of thermal discomfort for approximately 40 percent of the hours of any one year (DeDear, 1989). Low wind speeds (mean wind speed <2 m sec^{-1}) accentuate the temper-

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ature related effects of land-use changes on human comfort by increasing the correspondence between the active surface and air temperature in the urban canopy layer (Oke, 1976), thus enhancing the potential usefulness of satellite derived values.

Existing studies of Singapore's urban climate (Singapore Meteorological Service, 1982; Toh, 1990), confirm the existence of land cover related temperature differences. In these cases, day- and night-time air temperature data were collected *in situ* using vehicle traverses over a period of several hours. Temperature differences of 5°C in the warmer mid-year months and 2.5°C during the January to February monsoon were observed between urban and "rural" situations on the island (Singapore Meteorological Service, 1982). This is small compared with heat islands in temperate zone cities, but is comparable to those of other tropical cities (Jauregui, 1984). Temperature differences were greatest around 10 PM to midnight.

The high moisture availability year-round in the humid tropics and immediate vegetation growth on all areas of bare ground would promote high evapotranspiration rates, especially on cloud-free days when humidity at the time of image acquisition can be as low as 70 percent. Under these conditions, latent heat energy is lost from all but the most densely built urban areas. This, as well as the Singapore government's urban planting campaign, diminishes the urban rural land-cover contrasts on thermal imagery. Plate 1 indicates that some areas in the Central Business District (A) and housing estates vicinity (B) are as cool as in the forested nature reserves (C).

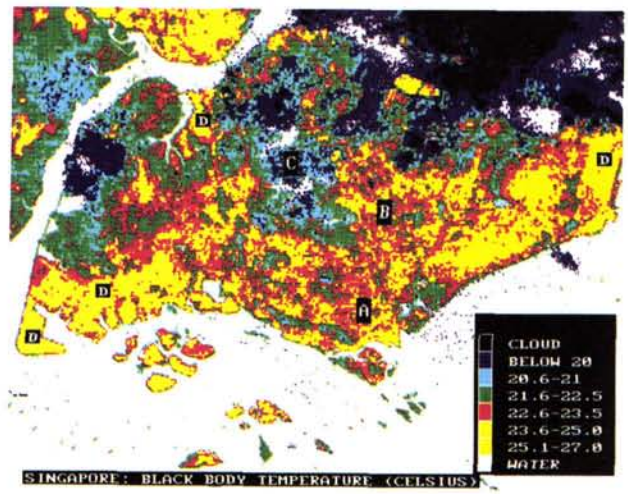

Plate 1. Thematic Mapper image of black body temperature of Singapore. Approximate locations: (A) Central Business District. (B) Housing Estates. (C) Forested Nature Reserves. (D) Industrial and Reclaimed Land.

Background

Remote Sensing of the Urban Heat Island

Satellite-derived thermal data correspond to Surface Temperature (**Ts**) for which rural-urban differences are said to be greatest during the daytime (Roth *et al.*, 1989). These differences in daytime **Ts** are not likely to correspond spatially to the conventional urban heat island based on measurements of air temperature by night-time traverse.

Oke's recognition of two distinct types of heat island (Oke, 1976) is relevant to the different methods of measurement. These are

(1) The *urban canopy layer heat island*, which consists of air between the roughness elements (mainly buildings and tree canopies) and whose upper boundary may be visualized as lying just below roof level, though in large open spaces it may be entirely absent. This layer consists of a distinctive combination of horizontal and vertical facets comprising building assemblages, in which roof areas alternate with urban street "canyons." Within the canopy layer there is convergence of sensible heat due to reduced wind speeds (Oke, 1979).

(2) The *urban boundary layer heat island*, situated above the former, whose characteristics are affected by the presence of an urban area at its lower boundary, and may advect downwind as an urban plume.

Satellite derived surface temperature corresponds more closely with canopy layer climate which may be discontinuous between urban structures. Thus, accurate representation requires discrete data, i.e., small pixel sizes.

A precise transfer function between **Ts** and the near-ground air temperature is not available. However, Carlson and Boland, using data from three mid-latitude cities, found that daytime **Ts** and surface flux are closely related to land-cover characteristics, of which moisture availability is dominant (Carlson and Boland, 1978). In their study, surface roughness was found to be the next most influential factor, but this, along with wind speed, conductivity, and other factors, accounted for an error of only 1 to 2°C in ground temperature estimates[1]. These findings support those of other workers (e.g., Morgan *et al.*, 1977; Schmidt, 1975) in suggesting the importance of vegetated surfaces, which retain and transpire moisture, for controlling and modifying the urban climate.

However, the surface as "seen" by the satellite is only a proportion of the active surface, particularly in high-rise urban developments, and this may not realistically represent active surface temperature. This effect is accentuated in tropical cities where high solar elevation means that horizontal surfaces, including roofs and tree canopies, may be significantly hotter than the mean temperature of the active surface. Thus, even assuming a close relationship between the temperature of the active surface (**Ts**) and air temperature, the satellite-derived **Ts** may be unrepresentative because in certain land-cover types the active surface is underrepresented and the "seen" surface may be disproportionately hot (Roth *et al.*, 1989).

On the other hand, the advantages of a satellite-based approach to urban micro-climatology include the "instantaneous" nature of the data collected over an urban area compared with the difficulty of synchronizing *in situ* field data. Secondly, in order to represent spatial temperature variations within a heat island, a dense sampling grid extending across an urban area, such as is provided by satellite sensors, is required. For large urban areas, high resolution synchronized field data collection would not be feasible.

[1]The same study found that thermal inertia was the most responsible factor for shaping night-time temperature patterns.

[2]In the 12 years prior to 1980, less than 2 percent of studies of the urban climate published in English were of tropical areas (Oke, cited in Jauregui (1984)).

The Relationship between Image Data and Surface Temperature (Ts)

Satellite derived observations of Earth surface temperature are affected by the complexity of interactions between electromagnetic radiation and the Earth surface and atmosphere within the field of view of the sensor. These interactions include differential emissivity of land-cover types and the absorption and emittance properties of water vapor and other atmospheric constituents. Both these effects are likely to be particularly pronounced in Singapore due in the first case to the heterogeneity of the urban land cover and secondly to the humid tropical climate where absorption and emittance of infrared radiation by atmospheric water vapor may account for as much as 10°C difference between actual surface temperatures and satellite data (Deschamps and Phulpan, 1980; Price, 1983).

Thus, although satellite-derived radiance values can readily be converted to equivalent black body temperatures (**Tb**) using Planck's law (Malaret *et al.*, 1985), this underestimates **Ts** if corrections for emissivity differences according to land cover are not carried out[2]. The resulting **Ts**, moreover, can only be considered accurate in clear, dry atmospheres, and a further correction using atmospheric data should be made, if absolute temperatures are desirable.

Low spatial resolution constitutes a further source of inaccuracy; thus, Desjardins *et al.* (1990, p. 1386) discovered that a difference between satellite-derived **Ts** and ground temperature data of 2°K using 120-metre spatial resolution data from Landsat TM improved to 0.6°K with airborne data of 11-metre resolution. This is attributed to the greater proportion of "pure" pixels using higher spatial resolution (Desjardins *et al.*, 1990).

In summary, among the parameters which contribute to error in the derivation of actual **Ts** from satellite radiance data, those which produce relative inaccuracy between land-cover types are the most serious for monitoring temperature variations within the urban heat island. Thus correction for emissivity (ϵ) is more important than atmospheric correction if only relative comparisons are to be made. Studies which utilize data from low resolution sensors such as HCMM, and correct for atmospheric factors but not for emissivity differences between surface materials, would appear to be ignoring two major sources of potential error while mitigating a minor source.

The Study Area

The study area corresponds to an image extract containing nine of Singore's high density municipal housing estates, located near the center of the island. The estates are spatially in close proximity but are of varying size, age, and proportion of built-up area. Individual housing blocks are typically 150 by 30 metres in area by 60 metres high. Spacing between blocks is typically 30 metres and spatial arrangement is in the form of parallel rows, or quadrangles with inner courtyards. Orthophoto measurements of the active:plan area ratio in a typical estate give the proportions listed in Table 1.

The table indicates that the active surface is 1.7 times the planimetric (satellite "seen") area. The "seen" surface is defined as that part of the active surface whose projection towards the satellite comprises the instantaneous field of view (IFOV).

Roofing material is concrete, as are walkways, forecourts, and carparks which occupy a substantial portion of the interstitial space between blocks. The remainder is occupied by grassy surfaces and trees which are well established in the older estates. Depending on the sun angle, substantial portions of ground may be in shadow at any time. Population density averages 37,500 per square kilometre, in a combined area of 17 square kilometres.

TABLE 1. RATIO OF MEASURED SURFACES TO PLANIMETRIC AREA IN A HOUSING BOARD ESTATE, SINGAPORE.

Roof area	0.17
Ground area	0.83
Total planimetric area	1.0*
Total planimetric area	1.0
Building sides	0.54®
Tree canopies	0.16®
Total active surface	1.70

* Corresponds to the satellite "seen" surface, of which built (hard) surfaces = 50%, vegetated surfaces = 50%.
® Corresponds to satellite "unseen" surfaces, including building sides and areas below tree canopies. These areas have no direct contribution to radiance at satellite altitudes.

Methods

The main source of temperature data was a 24 May 1989 Landsat TM image, and the local time of overpass at 10:40 AM corresponded to a sun elevation of 51 degrees and azimuth of 58 degrees, respectively. The thermal band (Plate 1) at 10.4 to 12.5 μm has a spatial resolution of 120 metres and a noise equivalent temperature difference of 0.5°C (Gibbons and Wukelic, 1989).

Because absolute temperature values are not required for the study, atmospheric correction was not carried out, though calibration with anniversary sea water temperatures which vary by less than 1°C from year to year (emissivity is assumed to be 1) suggest that **Ts** values derived for the present study are approximately 11°C lower than actual **Ts**. This estimate is likely to be at least as accurate as the use of radiosonde data, for which accuracies of ± 2 or 3°C are achievable (Price, 1979).

Conversion to **Ts** was carried out on a pixel-by-pixel basis using a simple FORTRAN program. First, radiance values were converted to **Tb** using a quadratic conversion (Malaret *et al.*, 1985). Second, emissivity correction (Equation 1) was carried out according to land cover, of which two main classes were recognized. These were areas comprising high rise apartment blocks and associated hard surfaced walkways, roads, and car parks, which were classified as non-vegetated surfaces, while the remainder, comprising grassy surfaces bordered by ornamental shrubs and trees, were classed as vegetated. These could easily be differentiated on Landsat TM reflective bands.

Surface Emissivity Values

Due to the significant variation in published values of ϵ for vegetated and man-made surfaces (e.g., Table 2) and in view of the importance of this parameter in deriving accurate relative values for **Ts**[3], field measurements were carried out in the study area. These comprised measurements of **Ts** using contact thermistors attached to a data logger, and measurements of effective radiant temperature using a Wahl Heat

[3]A variation of only 1 percent in ϵ results in a variation in **Ts** of approximately 0.4°K for a body whose temperature approaches the average value for the Earth's surface (Desjardins *et al.*, 1990).

Spy Thermal Radiometer. Mean values of ϵ for non-vegetated and vegetated areas respectively were 0.92 and 0.95.

In the absence of a detailed vegetation map of the housing estates, a density sliced vegetation index image was used to produce a Geographic Definition File (or template) of vegetated areas. The Normalized Difference Vegetation Index, (NDVI) was used. Pixels in this file representing vegetated surfaces were given the value $\epsilon = 0.95$ and those representing non-vegetated surfaces were given the value $\epsilon = 0.92$ (Figure 1). Vegetation index accuracy was assessed interactively by overlaying the image with an air photo scanned into the image processing system and registered to the image. From a sample of 200 randomly selected pixels, only 3.5 percent were misclassified.

Ts for all nine estates was then obtained by ratioing the Geographic Definition File of vegetated surfaces with **Tb** in the equation (Artis and Carnahan, 1992)

$$\mathbf{Ts} = \frac{\mathbf{Tb}}{1 + (\lambda \mathbf{Tb}/\alpha)\ln\epsilon} \quad (1)$$

where

λ = wavelength of emitted radiance,
$\alpha = hc/K$ (1.438×10^{-2} mK),
K = Stefan Bolzmann's Constant (1.38×10^{-23} J/K),
h = Planck's constant (6.26×10^{-34} J-sec), and
c = velocity of light (2.998×10^{8} m/sec).

The equation corrects for emissivity according to wavelength, for which the peak responsivity and average of the limiting wavelengths (λ=11.5 μm)(Palmer, 1984; Markham and Barker, 1985) was used.

Thus, **Ts** values for the study area between 21.0°C and 27.2°C were obtained.

The method effectively decreases the pixel size of the thermal data from 120 metres to the 30-metre pixel size of the TM visible wavebands, while correcting for differential emissivity within the 120-metre pixels according to vegetation status. Because vegetation is recognized as the main influence on daytime **Ts**, the method enhances the spatial resolution and spectral accuracy of the data[4].

Data Analysis

The boundaries of the nine housing estates were screen digitized from a TM false color composite image to create a polygon overlay which, when rasterized, provided a Geographic Definition File for the production of data summaries, e.g., mean **Ts**, using the IDRISI Extract program. Data available for these polygons include, **Ts**, **Tb**, NDVI, Estate Area, percent of Built Area, and a Leaf Area Index value (LAI), (Table 3 and Figure 2). The latter value is derived from field data collection and is based on the following parameters (after Toh, 1990):

$$\text{LAI} = \text{I} * (\text{VA}/\text{TA}) \quad (2)$$

where **I** = foliage density from randomly sampled sites,
VA = area covered by vegetation (including trees, shrubs, and grass), and
TA = total area of each estate.

I is derived from a consideration of the total ground surface area covered by tree and shrub canopies (tree density and canopy size) combined with the ratio of pyranometer measurements of solar radiation above and below the canopy.

Table 2. Published Emissivity Values

Concrete	Source	Vegetation	Source
ϵ		ϵ	
0.97	Buettner, 1965	0.99 (closed canopy)	Curran, 1985
0.71–0.88	Sellers, 1965	0.97–8 (closed canopy)	Henry *et al.*, 1989
0.93	Vlcek, 1982	0.96 (open canopy)	Henry *et al.*, 1989
		0.93–7 (varied crops)	Montieth, 1972
		0.90 (urban green space)	Morgan, 1977
		0.97–8 (grasslands)	Henry *et al.*, 1989

ϵ = Emissivity where 1 = emissivity of a black body

Results

Mean **Ts** was found to vary little between individual housing estates (Table 3 and Figure 3) with a range of only 0.9°C. Toh (1990), in a study of the heat island in the same nine housing estates using air temperature data from daytime vehicle traverse, found a mean heat island intensity difference

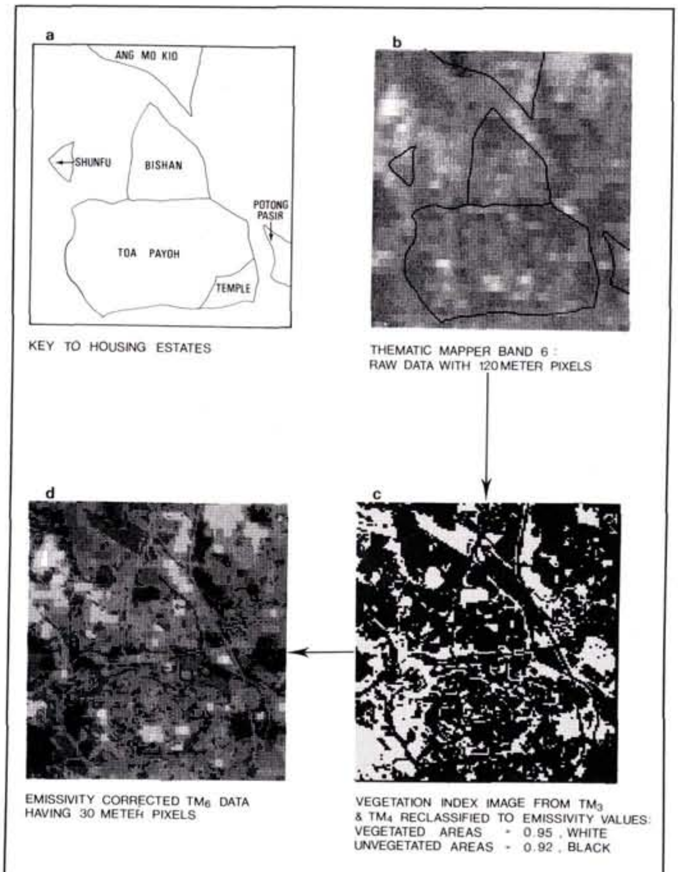

Figure 1. Procedure for emissivity correction.

[4]This correction is not equivalent to increasing the spatial resolution to 30 metres because the brightness temperature represents an average over a ground surface of 120 metres. However, there is an enhanced spatial and spectral accuracy within each 120-m pixel. The degree of enhancement depends on the amount of green biomass within each pixel and the extent to which **Ts** is biomass dependent. After the correction, single lines of trees along roadsides became readily discernible.

TABLE 3. ATTRIBUTE DATA FOR HOUSING ESTATE POLYGONS (MEAN VALUES)

Estate	1. TM6 DN	2. BB TEMP (°C)	3. SURF TEMP (°C)	4. AREA (HA)	5. BUILT (%)	6. LAI	7. NDVI
Ang Mo Kio	128.8	22.22	23.7	520	59	16	176.3
Bishan	129.2	22.39	24.4	128	41	2	168.9
Hougang	129.1	22.33	24.4	470	59	2.4	167.6
Potong Pasir	128.8	22.21	24.0	46	43	7.3	166.5
Serangoon C.	128.9	22.15	24.2	128	51	2	167.4
Serangoon N.	128.7	22.24	24.1	54	52	2.8	169.2
Shunfu	130.0	22.79	24.6	14	46	4.3	166.8
Temple	129.2	22.40	24.3	28	37	0.5	172.6
Toa Payoh	130.0	22.28	24.0	298	63	14.3	173.5

of 1°C. Additionally, the same three estates were found to be among the four warmest in both studies. This suggests a degree of correspondence between satellite measurements of **Ts** and near-ground air temperature during the daytime in spite of the fact that satellite measurements are from varying elevations above ground, whereas the air temperature data represent screen height.

Because 67 percent of the surface "seen" by the satellite is at ground level (Table 1), the remainder being at tree canopy (16 percent) and roof level (17 percent), and because ground temperature is taken by many authors as a surrogate for screen temperature (heat island)(Goldreich, 1985), and because in many cases horizontal surfaces are more radiatively active than vertical surfaces (Nunez and Oke, 1977), such a correspondence is not unlikely.

This correspondence is supported by other empirical results concerning the distribution of biomass related to **Ts**. Thus, the three warmest estates happen to be the most recently developed, with immature tree planting programs.

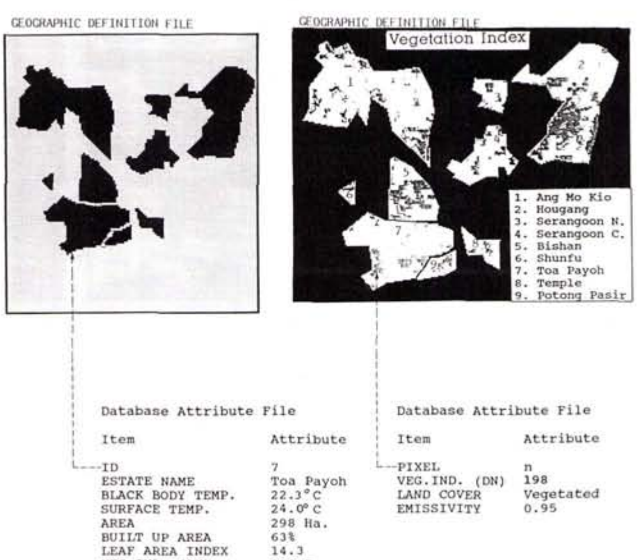

Figure 2. Geographic Definition File and Database Attribute File. (a) Housing estate polygons with associated attributes. (b) Vegetation Index image used as mask for emissivity correction.

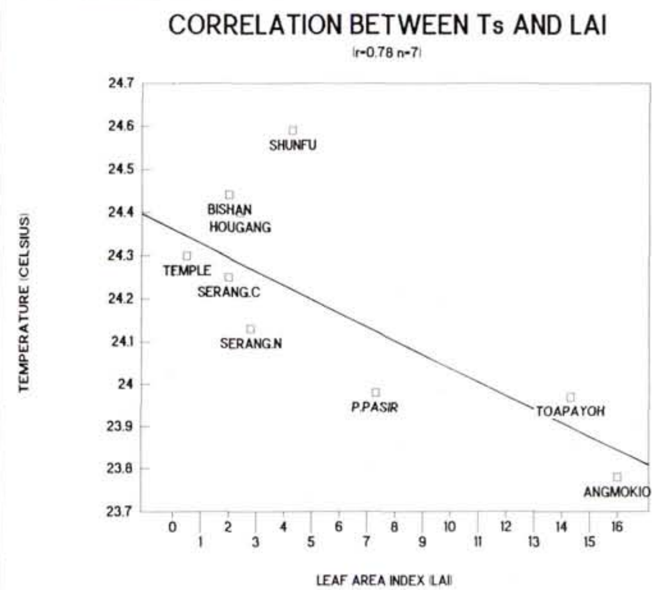

Figure 3. Mean surface temperature (°C) for nine housing estates related to leaf area index.

Additionally, for all the estates, a close inverse relationship was obtained between **Ts** and LAI ($r = -0.78$, $n = 7$) indicating that the presence of green biomass may effectively lower temperatures in this type of high-rise residential development (Figure 3). The correlation increases to -0.90 if Shunfu estate, which is very small in area, is omitted.

A higher correlation observed between the emissivity corrected mean temperatures and LAI, than for the uncorrected **Tb** ($r = -0.25$), was expected because the original data suffers from greater spatial averaging over each 120-m pixel of micro-scale temperature differences associated with surface materials as well as from apparent **Ts** differences due to differential emissivity.

In order to further investigate the correspondence between cool temperature and vegetation, pixels representing areas which were cool but unvegetated were identified using a Boolean overlay operation in IDRISI, e.g., by using IDRISI's OVERLAY (multiply) operation on a binary image of vegetated areas and a binary image representing areas below one standard deviation of mean temperature. Only 0.3 percent of pixels satisfied the two conditions. They correspond entirely to *shadows cast by high rise residential* buildings, e.g., inner courtyards and housing blocks oriented at right angles to the sun direction. At the time of the overpass, a sun angle of 51 degrees gives buildings 60 metres high a shortest shadow length (for buildings at right angles to sun azimuth) of 50 metres. Figure 4 shows Shunfu Estate with pixels representing unvegetated areas having **Ts** values *of less than* 22.5°C *in* areas shaded by tall buildings. Except for vegetated areas, much of the remainder of the estate has **Ts** values more than one standard deviation above mean temperature (i.e., above 25°C), with a very steep (almost vertical) temperature gradient existing between cool, shaded and much warmer, unshaded surfaces. The GIS overlay operation confirms the intimate relationship between the satellite-derived heat island and moisture availability as represented by vegetated surfaces, as well as the importance of the geometric arrangement of surfaces in relation to sun angle.

The potentially smoothing effects of meso-scale advective heat transport do not apparently affect **Ts**. A low rise housing estate immediately downwind of the cool, forested central catchment area (mean **Ts** 19.0°C, wind speed 3 km.p.h) had the same mean **Ts** of 24.6°C as the same type of estate downwind of Bishan New Town whose mean **Ts** is 24.4°C. A similar effect is observed across all major land-cover boundaries on the image. Thus, strong horizontal temperature gradients were maintained, with little apparent influence from adjacent surfaces upwind.

This finding accords with that of Chandler (1967) who found that urban-rural temperature differences were more closely related to local building density than to city size (and thus to fetch from upwind). Oke (1976) confirms this observation, stating that in Vancouver the canopy thermal climate appears to be governed by the immediate site character (especially building geometry and materials) and not by the accumulation of thermally modified air from upwind areas.

Studies by the Singapore Meteorological Service (1982) of Singapore's heat island based on night-time air temperature traverses found that Ang Mo Kio and Toa Payoh new towns constitute distinct heat islands separated by a more dispersed cool corridor of air along the Singapore river. This was true for both warm situation (May-August) and cool situation (January-February) models. The values obtained in the present study do not correspond to these observations, except for a localized "surface heat island approximately 25 ha in extent at Toa Payoh town center. In fact, Ang Mo Kio and Toa Payoh estates are the coolest of the nine high-rise housing estates studied as well as the most densely built (Table 3). Some adjacent, low-rise middle income estates with bungalow style development appear considerably warmer than all nine high rise estates. These differences are not surprising due to two main factors:

- *The distinct characteristics of the daytime satellite derived and night-time traverse derived heat islands.*
  In low-rise estates, because a greater portion of the active surface is horizontal, more of it is heated, thus giving a warmer mean active surface during the daytime. The short building shadows comprise only a minor portion of a pixel even at a 30-metre pixel size. Additionally, smaller buildings have both lower thermal inertia as well as form only shallow canyons defining the depth of the urban canopy layer. Thus, daytime heat is less effectively retained. Conversely, in high-rise areas the retention of daytime heat in large buildings and deep canyons would produce a marked night time heat island. Thus, Toa Payoh, being densely built (63 percent), as well as high-rise, would be expected to exhibit a marked night-time heat island whereas it may act as a heat "sink" relative to low-rise areas at times of day before the daily solar heating maximum, i.e., at the time of the satellite pass, 10:40 AM.
- *The satellite view of the active surface*
  The satellite views proportionally more of the active surface in low-rise estates with shorter building sides. These appear disproportionally hot relative to high-rise areas, due to more horizontal surfaces "seen."

Thus, areas dominated by high-rise residential buildings do not appear as particularly warm on Landsat TM thermal imagery even where buildings have been placed very close together. The high sun angle in low latitude cities means that shortwave radiation may be lost by direct reflectance (Arnfield, 1982) due to a high sky view factor. Additionally, the close spacing appears advantageous and ensures that the inter-building space is not greater than the shadow length; thus, shady canyons are maintained between blocks at most times during the day. The coolness of high-rise areas corresponds with the observations of Roth *et al.* (1989) on the heat island in the city of Vancouver, that the commercial core of the city, comprising many densely packed tall buildings, is not the warmest area on AVHRR imagery. They were surprised to observe that light industrial activities located in buildings large in plan area exhibited the highest surface temperatures.

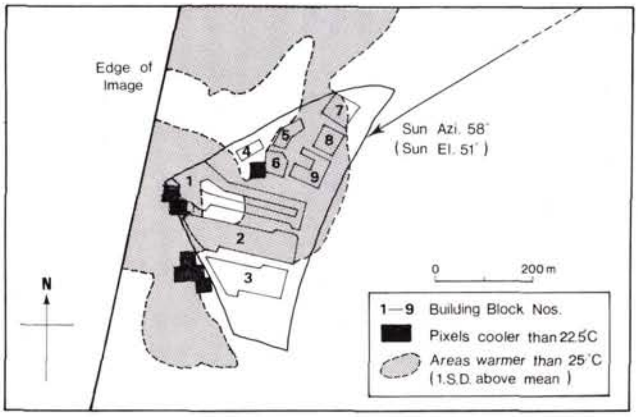

Figure 4. Influence of building layout and solar elevation and azimuth on surface temperature of Shunfu Estate.

The high degree of spatial precision obtained using 30-metre pixels is illustrated in Figure 5, which shows **Ts** values for two housing estates geometrically corrected to, and overlaid onto, a 1:20,000-scale air photo. Density slicing of the image has isolated areas over one standard deviation above mean **Ts** of 24°C (i.e., areas 25°C and above). The figure identifies specific buildings and building complexes with particularly warm surfaces. The warmest areas appear to correspond to town center commercial complexes, schools, hospitals, bus terminals, sports complexes, markets, and food centers, with schools overwhelmingly represented. They comprise low-rise buildings and building complexes often separated by extensive barren patches of concrete corresponding to car parks, playgrounds (in the case of schools), and forecourts (in the case of bus terminals).

Thus, the imagery is able to identify the potential heat generating surfaces responsible for modification of near-ground air temperatures, although the effects of those at rooftop level cannot be predicted without further investigation of the nature of heat exchanges between rooftops and canopy layer climate. However, rooftops are likely to contribute to micro-scale advective interaction within the canopy layer (Nunez and Oke, 1977), as well as impact on meso-scale climate of the lower boundary layer.

Conversely, a density slice of cool areas identifies specific features such as a double row of trees or a grassy border wider than 30 metres, though not all such features appear cool, i.e., not all tree plantings appear to be equally effective climatically.

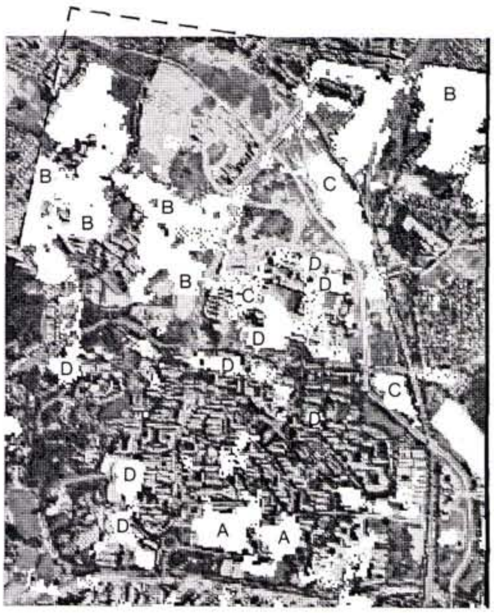

Figure 5. Density slice of surface temperature image overlaid on air photo showing areas over 25°C (one standard deviation above mean **Ts**). (A) Toa Payoh Town Center. (B) Low-rise medium density housing estates. (C) Transport depots/car parks. (D) Schools.

Conclusion

The overriding importance of green biomass for climate control in a humid tropical city is evidenced by the strong correlation between the high resolution temperature patterns and daytime air temperatures in housing estates.

This confirms the applicability of TM thermal data to studies of the urban microclimate during the daytime, when thermal stress on human activity is likely to be greatest.

Because most significant urban features or feature classes influencing near-ground temperatures are larger than 30 metres[5], the correction for emissivity using 30-metre resolution gives a more realistic representation of the potential contribution of specific urban surfaces to adjacent air temperatures.

Limitations to the use of the data for microclimate monitoring in urban areas result from the incomplete representation of the active surface, as well as the incorporation of surfaces at differing elevations above ground. These constraints are offset to some extent by the ability to identify specific features or buildings at or near ground level and thereby judge their individual contribution to climate modification.

Ts observed in the present study appears to be site specific with near vertical temperature gradients across landcover boundaries (and, thus, of sensible heat flux into the adjacent air). No meso-scale advective influences from neighboring surfaces were detected. This, as well as the inability to detect meso-scale patterns associated with the dominant trends in Singapore's night-time heat island, asserts the unique nature of the data and determines its limitations and optimum usefulness, as follows:

(1) The high resolution thermal data used in this study indicate a mosaic of potential micro-climates in the urban canopy layer at or below rooftop level, influenced by the thermal characteristics of the immediate active surface, and not by horizontal advection which is more characteristic of the night-time heat island. Because it is these individual active surfaces which are sensed by a high resolution satellite sensor, the concept of a "satellite-derived heat island" is inappropriate for high resolution daytime imagery, suggesting, as it does, a continuous layer or island of higher temperatures surrounded by a "sea" of lower rural temperatures. This is particularly true for humid tropical cities or those with well developed planting campaigns which have areas of potentially high latent heat loss within the urban fabric. In this context, the term, "temperature patterns" seems more appropriate, and can refer to both surface and near surface temperature.

Thus, in the context of the present study, Goldreich's (1985) assertion that

> " ... satellite images are only adequate for comparing urban and rural temperatures, and to date no solutions have been found for studying the inner structure of urban heat islands ... ."

can be qualified in terms of spatial and temporal aspects of the imagery. In fact, Landsat's thermal data have been found suitable for examining the spatial aspects of the urban microclimate but would require resampling at coarser resolution for urban rural temperature comparisons.

(2) Due to different patterns of day- and night-time heating between high- and low-rise developments, temperature reversals may occur on a diurnal time scale. Thus, daytime heat islands observed by satellite should not be equated with those at night.

Planning Implications

Planning objectives in a humid tropical city such as Singapore differ from those in temperate cities in that heat loads always need to be minimized. Methods include consideration of the high sun angle causing faster heating of urban canyons, thus a need to minimize solar penetration to street level. The following recommendations arise from the present study:

- The study noted a minimum difference of 2°C between shaded and unshaded surfaces, which demonstrates the importance of avoiding street and building alignments at right angles to the dominant east-west solar angle.
- In a humid tropical city such as Singapore, low-rise, medium density, private housing developments, followed by the newer high-rise estates, appear to constitute the warmest daytime living environments, indicating the need for more rigid environmental controls in these areas.
- The data indicate cool areas, and in conjunction with vegetation index images from TM visible wavebands, or corrected to maps or air photos showing vegetation distribution, can be used to evaluate the effectiveness of greening campaigns. Using 30-metre pixels, a tree-lined road appearing as a cool linear feature is potentially a corridor for the dispersal of warm, polluted air masses or may interrupt spatially extensive heat generating surfaces.
- The effectiveness of costly greening campaigns can be evalu-

[5]The size of urban features in Singapore is large, resembling cities in the developed world rather than many tropical cities in the Asian region. Thus, a pixel size approximating 30 metres would be appropriate (Welch, 1982).

ated because not all tree-lined roads and grassy areas are equally cool.

- Overlay of the imagery onto maps or air photos in a GIS may permit modeling of the impact of proposed land-cover changes in terms of the topological arrangement of warm and cool polygons. Thus, the optimum location of green corridors and buffer zones can be suggested.
- Satellite data can contribute to the understanding of the role of the type and spatial arrangement of different surface materials in urban microclimatology, as well as indicate potential areas of energy interaction with the overlying boundary layer for modeling of air pollution dispersal.

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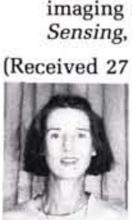

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