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Role of soil moisture in the determination of urban heat island intensity in different climate regimes

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ABSTRACT

A precipitation pattern scheme was combined with Koppen climate classes to form a five-class Global Climate Scheme for Urban Climate Studies (GCS/UCS) that explains observed diurnal variations of urban heat island (UHI) magnitude in different climatic zones. The validity of this scheme was demonstrated using urban/rural micrometeorological field measurements obtained during summer and winter in four cities.

Nighttime UHI magnitude was found to increase monotomicly with increasing population, independent of season, climate type, or causal mechanism. Daytime UHI magnitude versus population values, however, showed an interesting dichotomy between results for dry and wet rural soils. Wet-soil rural sites produced daytime UHIs larger than their corresponding nighttime values due to high rural latent heat flux values and high rural thermal inertia values (relative to those of urban materials).

With dry rural soils, daytime UHIs were smaller than corresponding nighttime values due to the low thermal inertia of the rural soil (relative to that of urban materials). This produces a rapid daytime rural warming/nighttime cooling and hence weak daytime/strong nighttime UHIs.

INTRODUCTION

Much work has been done in recent years in the field of urban climatology. However, most studies of UHI intensity and their causal mechanisms have been concentrated in mid-latitude cities, with few in tropical cities (low-latitude cities).

Results from mid-latitude climatological studies generally show nighttime UHI magnitudes larger than daytime values. Some show winter nocturnal UHIs stronger than those in summer, while others found the opposite results. Strong nighttime winter values are explained by anthropogenic heat production in cold cities, e.g., Dbf Edmonton, Canada. Strong nighttime summer values are explained by the release of stored solar energy in warm cities, e.g., Cs Rome and Athens. A complete reference for each study associated with each city named in this paper is found in Imamura [1].

Fewer such long-term climatological studies have been carried out in the tropics. In Aw Ibadan, Nigeria, the UHI was again strongest in nighttime minimum temperatures in both the dry and wet seasons, with larger values during the dry season. Day-time values were, however, reversed from the mid-latitude pattern, i.e., larger during the wet season.

Long-term climatological studies can document UHI development at a particular site within a growing city. On the canopy scale, however, the UHI is not a monolitic thermal plateau, but a patchwork of interlaced pockets of cool and warm temperatures correlated with land use types. Since long-term temperature records are only available at a few sites, it is necessary to use short-term intensive mobile field studies to document horizontal 1.5 m UHI structure, including its location of the maximum UHI peak value.

Observed spatial distributions from such studies in mid-latitude cities in different climate regimes are consistent with those from long-term climatological studies, i.e., they show nighttime UHI magnitudes generally larger than daytime values, e.g., in Cbf London, Dbf Montreal, and H Mexico City.

Fewer 1.5 m mobile studies have been carried out in tropical cities, but their results are inconsistent with those from the mid-latitudes, i.e., UHI values are not always stronger at night. Examples of tropical cities with daytime maximum UHI include Aw Nairobi and Af Rio de Janeiro, while those with nighttime maximum include Aw Ibadan and Lagos, Aw Puna and Bombay and BSh Delhi.

Recent UHI studies have utilized surface radiative temperature distributions obtained from satellite or aircraft thermal-band radiometric observations. Early investigations were able to detect mid-latitude nocturnal surface UHIs, but did not compare with 1.5 m air temperature values (Rao [2], Matson et al [3], Tsuchiya [4]).

Studies using daytime and nighttime satellite images (although not adjacent day-night pairs) show daytime surface UHI values generally greater than

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nighttime values (Carlson et al [5], Kiddler and Wu [6], Roth et al [7]).

Vukovich [8] both analyzed an adjacent day-night pass pair in St. Louis and correctly compared satellite UHI values with observed 1.5 m fixed site network values (i.e., only near the fixed network sites). Results showed satellite UHI values during all seasons and during all hours, but with largest values during daytime warm season periods. Daytime surface values were up to five times greater than corresponding 1.5 m values, while nighttime surface UHI magnitudes were smaller than 1.5 m values. Daytime surface UHI distributions showed a strong dependence of the small scale land use features than nighttime distributions.

METHODOLOGY

The global urban heat island literature reveals that maximum UHI values are not confined to any one season or time of day. Causal mechanisms for seasonal and diurnal UHI variations should be consistent with the climate class of the specific city. Local UHI formation factors can include the seasonal variations of solar insolation and precipitation (which determines atmospheric moisture levels and rural soil moisture content), as well as city morphology and anthropogenic heat production.

Each of these factors is not equally important in every climate region, e.g., the small seasonal surface insolation variations in tropical cities are not as important as the larger variations in mid-latitude cities. Seasonal variations in tropical precipitation patterns (and resulting rural soil moisture content variations) thus assume a greater importance in controlling UHI cycles.

The traditional Koppen global climate divisions, however, are not precise enough in two cases to understand seasonal and diurnal 1.5 m UHI magnitude variations. First, the lack of a seasonal surface insolation variation in the equatorial zone implies that seasonal precipitation patterns (and resulting seasonal variations of soil moisture content) will be the dominant factor controlling seasonal and diurnal UHI magnitude variations.

Second, the seasonal variation in insolation (and not anthropogenic heat) in the subtropics is the dominant factor determining seasonal 1.5 m UHI magnitude variation. In fact, subtropical summer surface insolation is greater than in the equatorial zone. Subtropical areas will thus have a diurnal summer UHI variation dependent on soil moisture content (as in the tropics). Wintertime subtropical (low solar radiation period) diurnal UHI distributions, however, will be like that in higher latitudes and not like that of the tropics.

For urban climate studies, it is thus necessary for a re-grouping of some Koppen climate divisions, i.e., the Summer Dry Tropics As must be considered separately from the remaining tropical sub-groups and the Summer Dry Subtropics Cs must likewise be treated separately from the remaining subtropical classifications.

The following six annual precipitation patterns of Miller and Thompson [9] recognize these proposed new sub-groups, as they consider General Circulation effects on precipitation: (a) Equatorial, (b) Tropical, (c) Monsoon, (d) Subtropical, (e) Mid-latitude, off winter storm tracks, and (f) Mid-latitude, on winter storm tracks. The last two classes have been slightly generalized from their original topographic and marine classifications.

The Miller and Thompson [9] and Koppen climate classes were combined to form a new Global Climate Scheme for Urban Climate Studies (GCS/UCS), which consists of five classes (Table 1).

Cities in the Equatorial class are located in the Inter Tropical Convergence Zone (ITCZ) where maximum precipitation occurs at the equinox. The uniformly high monthly insolation values and high soil moisture content for cities in these zones will produce two maximum daytime UHI at the equinoxes (e.g., Nairobi), since a larger fraction of rural solar energy is used for evaporation (in contrast with hot urban fabrics).

Cities in the Tropical class (small seasonal variation in insolation) have summer wet and winter dry seasons. High daytime insolation and the surface wetness during the summer wet season also produces daytime UHIs (e.g., Ibadan and Rio de Janeiro). In the winter dry season, however, formation of a nighttime UHI will dominate over daytime values, due to the lack of daytime moisture. The formation mechanism for these nighttime UHIs is thus related to the large solar storage in the urban fabric and its slow nocturnal release (e.g., Lagos, Pune, Bombay).

Cities in the Arid class are generally hot and dry throughout the year. Their similar urban and rural thermal properties prevent daytime UHI formation, and thus the UHI is mainly a nighttime phenomenon in which the rural radiative cooling process and the large urban heat release are the dominant formation mechanisms (e.g., Delhi and Kuwait).

Cities in the Subtropical dry class have their maximum insolation at the summer solstice, with summer dry and winter wet seasons. At the summer solstice a large amount of heat is again stored in the urban fabric by day and slowly released at night. UHI values will thus again be strong at nighttime during this summer dry season (e.g., Rome and Athens).

Cities in the High latitude class have large seasonal insolation variations (as compared with Equatorial or Tropical classes), hot or cool summers, and moisture throughout the year. Anthropogenic heat production is the main mechanism for the formation of nighttime UHIs (e.g., Edmonton and Toronto).

Highland cities have a small seasonal variation in their temperature fields due to altitude. Mexico city, in the Tropical zone, is an example of Highland climate with a dry winter and a wet summer. It has a maximum UHI at night in its winter dry season [10].

To test the validity of the above UHI-climate scheme, urban/rural micrometeorological, energy balance, and moisture balance field measurement programs were carried out in six cities in different climatic zones in Brazil, Japan, and U.S. Measurements were obtained during all phases of the diurnal cycles and during summer and winter seasons.

RESULTS

Urban/rural micrometeorological, energy balance, and moisture balance field measurement programs were carried out in four cities in three countries (Japan, Brazil, and the USA) to determine surface and 1.5 m air temperatures urban heat island (UHI) characteristics in different climatic zones. Measurements were obtained during all phases of the diurnal cycle during summer and winter seasons.

Results show city-wide surface UHI values significantly larger than traditional 1.5 m air temperature UHI values during both daytime and nighttime periods [3]. Surface radiative temperatures were also highly correlated with corresponding 1.5 m values, and hence predictable by statistical methods [1].

The relationship between population and 1.5 m UHI was investigated using the day and night results from all six cities (Fig. 1). Nighttime UHI magnitude is seen to increase monotomicly with increasing population, independent of season, climate type, or UHI causal mechanism, e.g., the Shimozuma winter nighttime UHI causal mechanism is anthropogenic heat, while the Sacramento summer nighttime UHI mechanism is urban heat storage.

Daytime UHI magnitude versus population values, however, show an interesting dichotomy between the results for the dry and wet rural soil cases, consistent with the different daytime formation mechanisms. Dry daytime UHIs are smaller than corresponding nighttime values, due to the low thermal inertia of the dry rural soil (relative to that of urban materials). This produces a rapid daytime rural warming/nighttime cooling and hence weak daytime/strong nighttime UHIs.

Wet rural sites produce daytime UHIs that are larger than their corresponding nighttime values, due to the high rural soil moisture content. This is associated with a high rural latent heat flux and a high rural thermal inertia (relative to that of urban materials). This lowers daytime and raises nighttime rural temperatures, thus producing strong daytime/weak nighttime UHIs.

CONCLUSION

The Miller and Thompson [9] and Koppen climate classes were combined to form a five class Global Climate Scheme for Urban Climate Studies (GCS/UCS). The validity of the new scheme was demonstrated using urban/rural micrometeorological, energy balance, and moisture balance data from six cities in different climatic zones in Brazil, Japan, and U.S during all phases of the diurnal cycles and during summer and winter seasons.

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I-B*	Climate	Koeppen	M-T**	Max UHI	Mechanism	e.g. 1.5 m UHI
Equatorial	Uniformly high rad., max precip. at equinoxes	Am	Equatorial	Daytime max at equinoxes	Large rural Q_E	Nairobi
Tropical	Global summer max at solstice summer wet, winter dry	Am, Af, Aw	Tropical, Monsoon	Daytime max at summer solstice, winter solstice	Large rural Q_E Large urban Q_S	Rio, Ibadan, Lagos, Pune, Bombay
Arid	Dry and warm all year	B		Nighttime, all year	Large urban Q_S	New Delhi, Kuwait
Subtropical	Warm, summer dry, winter wet	Cs	Subtropical	Summer nights	Large urban Q_S	Rome, Athens
Higher latitude	Cool summer wet all year	D, E	Middle-latitude	Winter nights	Large urban Q_A	London, Edmonton

* - Imamura-Bornstein
** - Miller-Thompson

Table 1. Global climate scheme for urban climate studies (GCS/UCS).

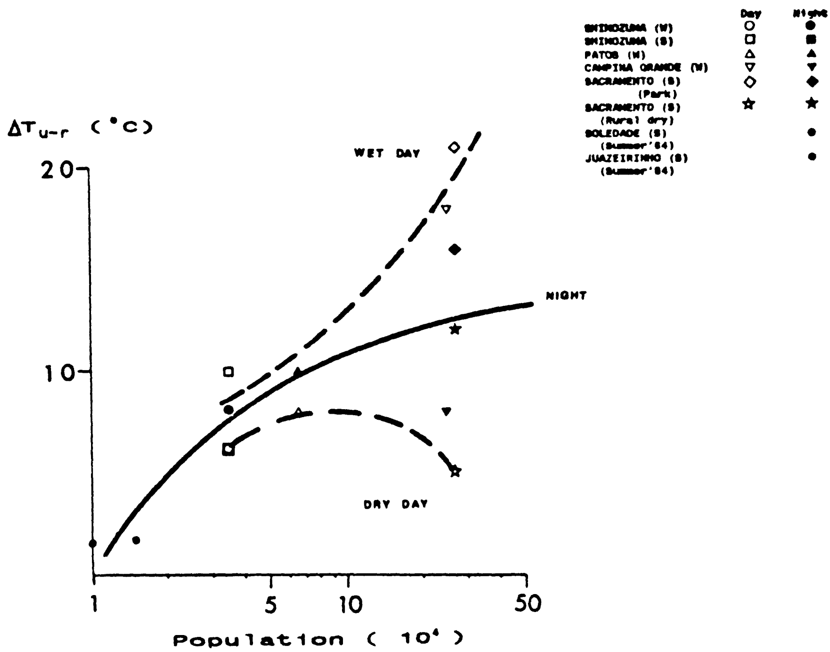

Fig. 1. Urban heat island at 1.5 m and population.