Parameterization of Heat Island Effect Due to Urbanization and Implications on Energy Use

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ABSTRACT

Heat Island index is one of the most important parameters in renewable energy application design and development. Scientific evidences indicate that Heat Island Effect can no longer be attributed to biased temperature readings. It influences Global Climate Changes to an extent, which cannot be neglected. Besides, it remains a major consideration in predicting energy demand for thermal comfort, city planning, green area creation, etc. and even in conceptualization of Very Large Scale Photo Voltaic System (VLSPV) installation in deserts for future energy supply. In this paper, long term meteorological data for major cities and its sub urban areas of Japan were collected and analyzed to ascertain its impact at local level. Mathematical expressions are proposed for Parameterization of Heat Island Index and degree of urbanization. Tokyo city is considered as a benchmark and other cities (Fukuoka and Sendai) are evaluated to find out degree of urbanization. Finally its implication on city expansion/planning and energy use has been discussed.

Keywords: *Heat island, Energy use, Degree of urbanization, VLSPV.*

1. INTRODUCTION

Solar thermal energy absorption by high heat capacity construction materials significantly influences temperature and humidity profile in urban areas [1]. This process of urban warming has strong bearing upon energy efficiency and energy consumption for thermal comfort in buildings, which is fourth largest energy consuming sector today. Heat Island Effect is referred to extreme conditions of urban warming, having long term increasing trend of temperature due to unabated concretization and expansion of cities [2]. They are also driven by some of the same factors that create greenhouse gas warming. Heat Island Effect was initially attributed to biased temperature readings and was quite often meticulously squeezed by using physical proxy meteorological data measured at points far from cities under various topographical influences. Climatic changes at regional level are necessarily compounded effect of global warming and heat island effect in that region. The Intergovernmental Panel on Climate Change [3], in its Third Assessment Report has projected a 1.4 to 5.8°C increase in globally averaged surface temperature between 1990 and 2100.

The loss of vegetation in urban areas, compared to that in rural areas, reduces the natural cooling provided by evapo-transpiration. Several studies show that land cover changes create warming effect [4]. The effect is governed by physiological mechanisms rather than vegetation morphological mechanisms, especially in tropics and sub-tropics. Besides, building materials such as asphalt, cement and roofing tile absorb more thermal energy than the vegetation that existed prior to urbanization. This energy is released into the air late in the day and into the evening, keeping the city warmer than it would normally be. The combination of heat island effect and green house effect significantly raised the mortality from heat waves and the larger warming trend is not a statistical error [5]. The paradox is that, population may have decreasing trend (as observed in some mega cities) but the concretization once done cannot be undone. Heat island effect, therefore, is likely to have wider ramification on global warming, energy use and city planning. Reversal of this trend for example would mean either developing suburbs or green area formation in and around cities would have wider than expected cooling effect on long term mean global temperature profile.

There is hardly any quantitative study on ‘Heat Island Effect’ so far, which could be used by planners and policy makers for imposing moratorium (or considering alternative strategies) on further development of cities in terms of concretization and expansion. To show the effect of urbanization, concretization and related developments contributing to heat island effect, Tokyo has been selected for study. Its several suburbs, for which long term meteorological data is available, are included in analysis to show that the trend of rise in temperature profile due to ‘Heat Island Effect’ is definite and alarming, even in cities far away from equator. Heat Island Index (H.I.I.) parameter is defined and proposed as a measure of urbanization.

Results indicate that the Heat Island effect in long term has increased average local temperature by two degrees in a century in case of Tokyo and has still an increasing trend. Other cities are following the trend. The methodology developed to parameterize Heat Island Effect and degree of urbanization has immense potential for application in planning cities’ capacity, expansion ability and location since, it is likely to contribute to the reduction of overall energy efficiency and increase in energy consumption for thermal comfort. Besides, VLSPV installation in deserts [6] can be well evaluated for its impact on global climate changes. Projection of changes in ambient temperature can be used as a tool in land-surface models, such as, Land Surface Model (LSM) [7], Community Land Model (CLM-3.0) [8, 9], RAMS, LRAMS, and GEMRAMS etc.

2. TREND OF URBANIZATION

Industrial Revolution in the 18^{th} century changed demographic balances all over the world. Today, urban areas shelters 47% of the world’s population. The figure is likely to touch 60% by 2030. There are 411 cities with a population of over 1 million people and is expected to touch 600 in 15-20 years. The trend is more visible in developing countries, where economic developments are picking up. Population pressure and limited resources in these countries have compelled governments to introduce and improve civil amenities in high density urban areas on priority basis, which in turn precipitate more influx from rural and sub-urban areas. These political compulsions have made a vicious circle, where migration of population from rural to semi urban, semi urban to urban and, urban to mega cities is a stark reality.

The loss of vegetation in urban areas, compared to that in rural areas, reduces the natural cooling provided by evapo-transpiration in cities [10] and transforms cities into heat island. Humidity and precipitation profile of last century corroborates the fact. precipitation and humidity profile of Tokyo, Fukuoka and Sendai city for the last century is shown in Fig. 1. Precipitation is almost constant or have slightly increased but humidity shows decreasing trend. These indicate the effect of vegetation loss and subsequent loss in evapo-transpiration with urbanization, which turns the city into heat island.

3. PARAMETERIZATION OF H.I.I.

The greenhouse effect would act most effectively at night, as the gases impede radiation from escaping into space. However, it represents combined effect of concretization (Heat Island) and Green House Effect. To show the effect of concretization (urbanization) and related developments contributing to heat island effect, three mega cities (Sendai, Tokyo and Fukuoka) and several suburban areas in vicinity of each city, for which long term meteorological data is available, are selected for the present study. Data were obtained from Japan Meteorological Agency for over a century. Table 1 shows the coordinates (lat, long, elevation and distance from nearest city) of these sub urban areas.

It is further assumed that except heat island effect, other climatological parameters solar intensity received, wind movement, effect of global warming etc. of the city-suburban couplets remain same. It is observed from the data obtained that mean minimum ambient temperature during winter and summer season have been increasing. However, their differential increase over time is distinctly different for city and suburbs. To calculate Heat island effect summer and winter minimum temperature is considered, which show distinct differential increase in cities. The minimum ambient temperature has no effect of heat island in suburban areas. This typical behaviour is due to Heat Island Effect [11]. More the city is concretized/urbanized; more the change in minimum summer ambient temperature is visible due to land surface change [7,8,9]. Heat Island Index (H.I.I.) is defined as,

$$H.I.I. = \frac{(T_{m,s,u} - T_{m,s,su}) + (T_{m,w,u} - T_{m,w,su})}{2} \quad (1)$$

Where, $T_{m,s,u}$ ($T_{m,s,su}$) and $T_{m,w,u}$ ($T_{m,w,su}$) is ten years triangulated average minimum ambient temperature of city (sub urban area) in summer and winter respectively. In this equation, the effect of global warming is annulled due to subtraction process involved. Similarly, effect of other unknown complex variables is also minimized, since they do not vary considerably between urban and sub-urban areas in vicinity. Tokyo city is considered to have urbanization, which has achieved saturation level. Now it can only expand and engulf surrounding sub urban areas. Therefore, maximum temperature rise due to heat island effect is considered 100% urbanization. Degree of urbanization (DU) for other cities are measured as,

$$D.U. = \frac{\left[\frac{1}{n}\sum_{1}^{n} Change in\ H.I.I.\ per\ year\ of\ city\right] \times 100}{\left[\frac{1}{100}\sum_{1}^{100} Change in\ H.I.I.\ per\ year\ of\ Tokyo\right]} \quad (2)$$

Where, n represents change in H.I.I. for number of years for which data shows clear effect of Heat Island by sudden change in its trend line. Alternatively, a third order polynomial trend line can be used for extrapolating data for hundred years to calculate change in H.I.I. Since the methodology developed is vulnerable to unknown changes – manmade or natural – mean value of H.I.I. would provide a better insight in the whole process.

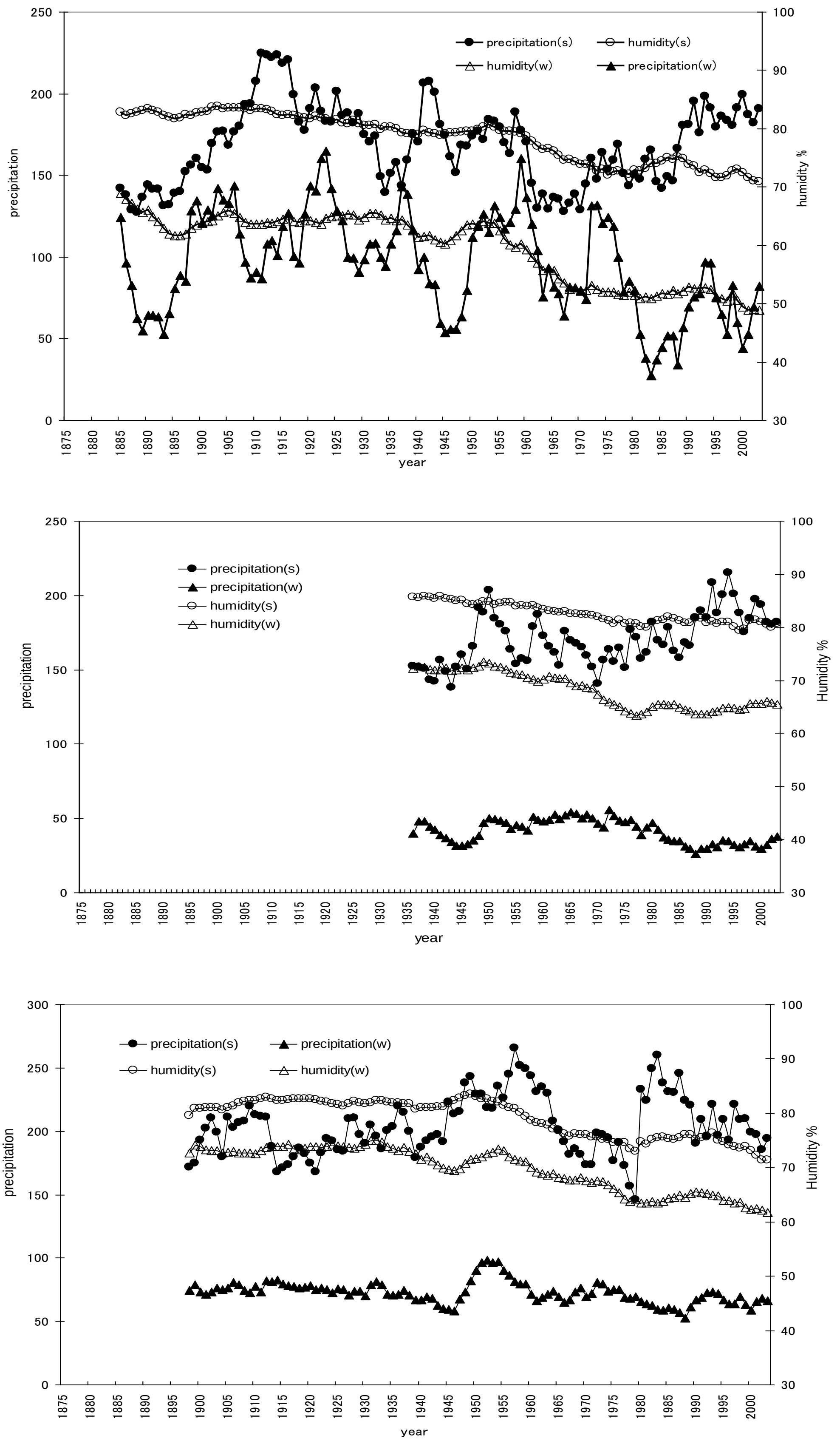

Fig. 1 Triangulated average trend of precipitation and humidity profile (Summer and Winter) of Tokyo, Sendai and Fukuoka.

Table 1 Geographical location of Mega cities and their suburbs.

City	Prefecture	latitude	longitude	Altitude (m)	Distance (km)	Nearest Mega city
Tokyo	Tokyo	N35 41.4'	139 45.6'	6		
Chichibu	Saitama	N35 59.4'	139 04.4'	232	70.4	Tokyo
Kumagaya	Saitama	N36 09.0'	139 22.8'	30	61.5	Tokyo
Maebashi	Gunma	N36 24.3'	139 03.6'	112	101.4	Tokyo
Kawaguchiko	Yamanashi	N35 30.0'	138 46.5'	860	93	Tokyo
Tateno	Ibaragi	N36 03.4'	140 07.5'	-	52.4	Tokyo
Choshi	Chiba	N35 44.3'	140 51.4'	20	99.4	Tokyo
Katsuura	Chiba	N35 09.0'	140 18.7'	12	78.1	Tokyo
Yokohama	Kanagawa	N35 26.3'	139 39.1'	39	29.6	Tokyo
Mishima	Shizuoka	N35 06.8'	138 55.5'	21	99.2	Tokyo
Mito	Ibaragi	N36 22.8'	140 28.0	29	99.6	Tokyo
Sendai	Miyagi	N38 15.7'	140 53.8'	39		
Ishinomaki	Miyagi	N38 25.6'	141 53.8'	43	39.6	Sendai
Morioka	Iwate	N39 41.8'	141 09.9'	155	161.2	Sendai
Miyako	Iwate	N39 38.8'	141 57.9'	43	179.4	Sendai
Sakata	Yamagata	N38 54.5'	139 50.5'	3	116.52	Sendai
Yanagata	Yamagata	N38 15.3'	140 20.7'	153	48.3	Sendai
Fukushima	Fukushima	N37 45.5'	140 28.2	67	67.3	Sendai
Fukuoka	Fukuoka	N33 34.9'	130 22.5	3		
Iizuka	Fukuoka	N33 39.1	130 41.6	37	30.5	Fukuoka
Hita	Ouita	N33 19.3	130 55.7	83	59	Fukuoka
Ouita	Ouita	N33 14.1	131 37.1	5	121.9	Fukuoka
Saga	Saga	N33 15.9	130 18.3	6	35.7	Fukuoka
Nagasaki	Nagasaki	N32 44.0	129 52.0	27	105.3	Fukuoka
Kumamoto	Kumamoto	N32 48.8	130 42.4	38	90.7	Fukuoka
Miyazaki	Miyazaki	N31 56.3	131 24.8	9	207	Fukuoka

4. RESULTS AND DISCUSSIONS

Heat Island Index is computed with respect to sub-urban areas in the vicinity of Tokyo, Fukuoka and Sendai, for which long term climatological data were available. Summer maximum ambient temperature variations have been found almost negligible. Results indicate that minimum winter ambient temperature variation is more glaring and steep as compared to maximum winter ambient temperature. Minimum ambient temperature in Summer depends upon heat island effect as well as global warming effect both in big cities, while, it is a strong function of global warming effect in suburban area. Subtracting the two minimizes the effect of global warming on ambient temperature trend. The same is true for winter data of the cities and sub-urban areas.

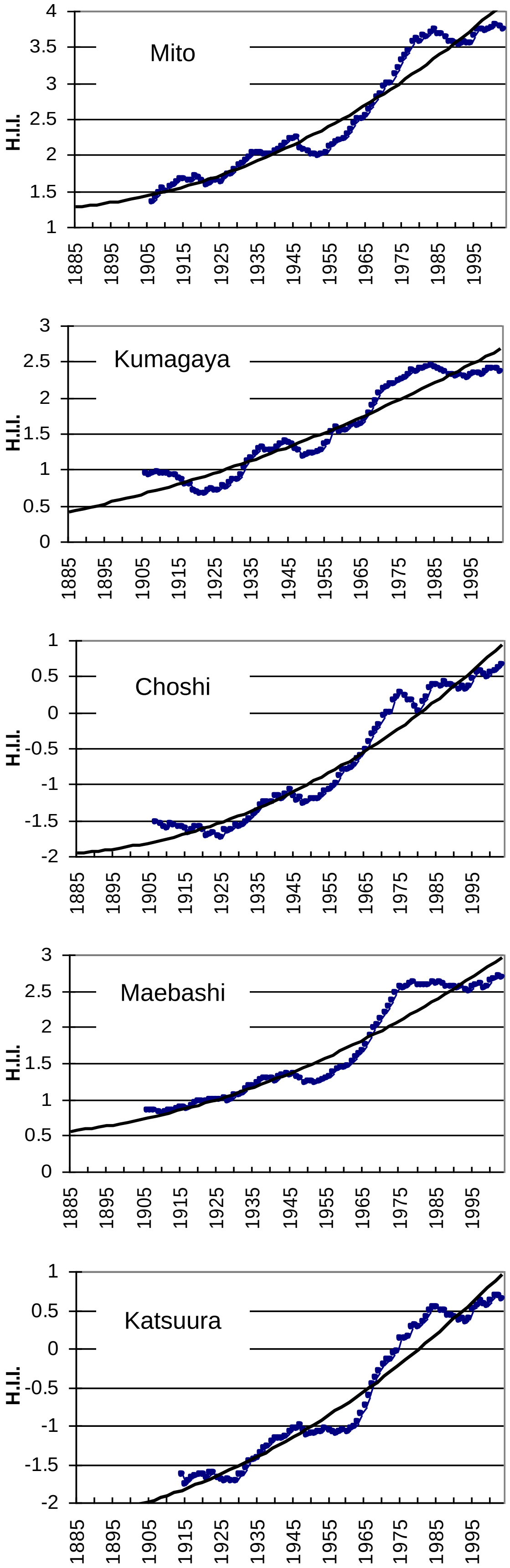

Fig. 2 H.I.I. for Tokyo with respect to Mito, Kumagaya, Choshi, Maebashi and Katsuura.

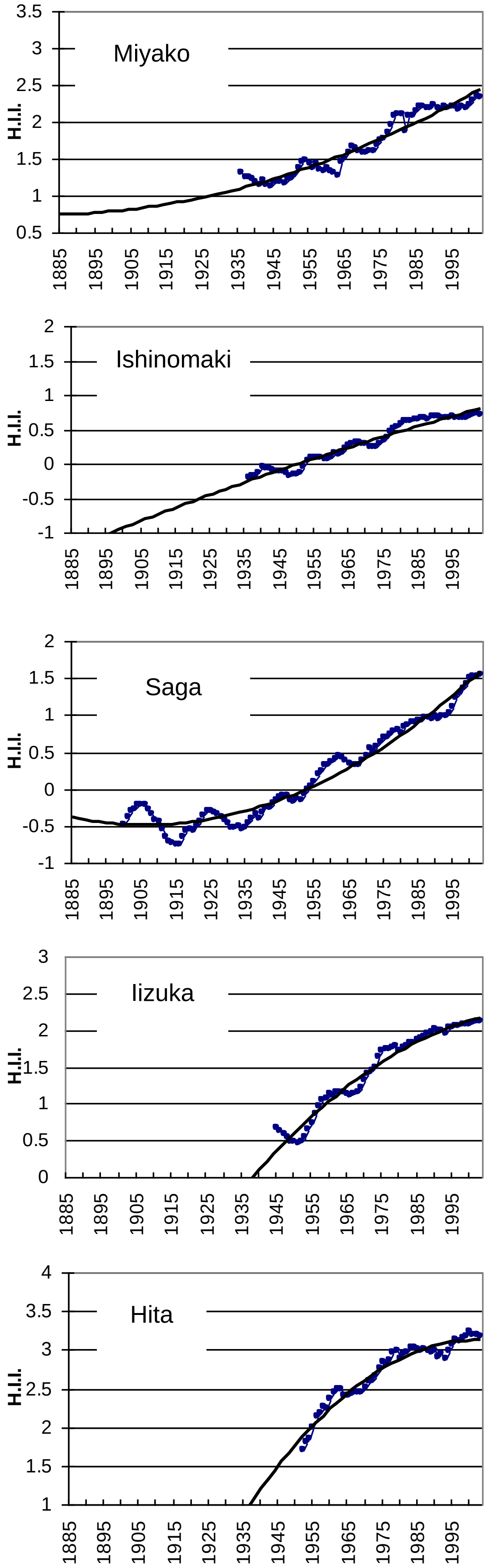

Fig. 3 H.I.I. for Sendai (with respect to Miyako and Ishinomaki) and Fukuoka (with respect to Saga, Iizuka and Hita).

Latitude, longitude, altitude and distance from the nearest city is shown in table 1. To see the clear trend of climatic data, triangulated average of data was considered. After experience as per eq 1, ten years triangulated average data were found more suitable than triangulated average based upon three, five and eight years. It removes noise and reduces the effect of unusual events. The transient variation of Heat Island Index (HII) is computed for the cities and its suburbs. Few of them are shown in Fig. 2 and Fig. 3. In case of Tokyo, mean value of Heat Island Index changes by an average of 2.5 as evident from computations using eq. 1 with respect to its suburbs Mito, Kumagaya, Choshi, Maebashi and Katsuura (Fig. 2). This is also a measure of average increase in temperature. In other words, it may be concluded that temperature has risen by 2.5 degree Centigrade due to massive concretization in Tokyo. The trend lines are drawn with third degree polynomial with correlation coefficient over 0.9. It clearly indicates the effect of Heat Island.

Similar studies for Sendai indicate Heat Island Index has increased by 1 with respect to its suburbs Miyako and Ishinomaki, i.e., temperature rise is almost 1degree Centigrade as shown in Fig. 3. In case of Fukuoka, Heat island Index changes by 1.5 with respect to its suburbs, Saga, Iizuka, Hita, i.e., a rise of temperature by 1.5 degree Centigrade (Fig. 3). The difference in the Heat Island Index indicates the degree of urbanization. Initial climatological/geographical advantages enjoyed by a city or its suburbs are annulled by the process adopted in the computation of Heat Island Index. That is why initial and final value of H.I.I. differs for different location i.e. near sea, mountain etc. but difference in H.I.I. remains the same for each sub-urban area near Tokyo. Similar results are obtained for Fukuoka and Sendai city.

Degree of urbanization for Fukuoka is computed as per eq. 2. It indicates that the degree of urbanization in case of Sendai is 40% while in case of Fukuoka, 60%. The result provides leverage as to which city should be selected for establishing new industry or economic activities. Besides, expansion of cities with green area patches can be created to minimize the effect. It also provides vital clues for avoiding construction of high rise buildings in areas where heat island effect is more visible. In a city, vulnerable to strong heat island effect, digital data processing technique of infrared band in remote sensing can be used to identify the area of construction. Increase in energy demand for air-conditioning systems in urban areas due to heat island effect can also be computed. Subsequently, the prediction of rate of increase in greenhouse gases into the atmosphere should be revised for more accurate climate prediction.

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