Evaluating Thermal Comfort in City Life and Its Relation to Socio-Economic Activities

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Abstract

In this study, we developed methods for calculating Wet Bulb Globe Temperature (WBGT) and Wind Chill Temperature (WCT) from Multi-functional Transport Satellite (MTSAT) data (IR1~IR2), and tried to improve the methods, so that we can evaluate thermal comfort in Asia-Pacific region by satellite remote sensing in near real time. As a result, it was found that our WBGT formula could express the tendency of WBGT change and detect the risk value (WBGT over 25). That enabled making thermal comfort image mappings in 4km resolution. About formula of WCT, we needed further study to get accuracy. In addition, as one of the indices of socio economic activity, we examined the relationship between WBGT and GDP per capita of each country in this study. As a result it was found that high WBGT countries tend to have low GDP per capita. From this research, hourly evaluation of thermal comfort in whole hot area and its visualization became possible, and the database from this calculation would be useful in analyses about relationships between thermal comfort and socio economic activities.

Key words: Wet Bulb Globe Temperature (WBGT), Wind Chill Temperature (WCT), Multi-functional Transport Satellite (MTSAT).

1. Introduction

1.1 Background of This Research

Heat island is one of the urban problems in recent years. Satellite remote sensing is widely used for evaluating its effect. For example algorithms have been developed for land surface temperature retrieval from Multi-functional Transport Satellite (MTSAT) [Oyoshi *et. al*, 2009]. However, human's health and thermal comfort are affected by not only the temperature but also other factors including humidity, wind speed and solar radiation. So we usually use composite temperatures, which are indexes expressing sensible climate, for assessing environment. Measuring sensible climate by satellite remote sensing is useful for evaluating thermal comfort in city life in large area in real time. In previous study, we developed a method for calculating Wet Bulb Globe Temperature (WBGT), a composite temperature used to prevent heat disorder, from thermal infrared data of MTSAT [Okamura *et. al*, 2012]. It enabled evaluating thermal comfort in large hot area by satellite remote sensing. It was found that the formula could be applied when actual WBGT was over around 25, but it was over estimated when WBGT was lower. So we needed to other method for cool season.

1.2 Objective of This Research

The objective of this study is to develop a method for evaluating thermal comfort all year around in both hot and cold seasons. We used Wind Chill Temperature (WCT), a cold index used to avoid injuries from the cold, in cold

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season as well as WBGT in hot season. Firstly we prepared WCT calculated from in-situ measurement data and then did regression analysis with 2 bands of MTSAT data. From that, a formula expressing relations between WCT and MTSAT data was derived. Next we calibrated the expression, using data except hot days' so that it became best suited to cold season. Finally we used this formula together with WBGT's formula. The result enabled evaluating real-time thermal comfort with MTSAT data all year around. The database should be effective for comparative analysis of large area and we could make thermal comfort image mappings in 4km resolution. In addition, regional thermal comfort's relevance to various statistical data about social life could be examined.

2. Methodology

2.1 Data Used in This Study

The dataset we have used in this study consists of surface data at four observation stations and MTSAT data of same points.

Surface data (atmospheric temperature, dew point, atmospheric pressure and wind speed) of following four cities in Asian-Pacific region were downloaded from NNDC Climate Data Online provided by National Climate Data Center (NCDC)

(http://hurricane.ncdc.noaa.gov/pls/plclimprod/cdomain.abbrev2id).

MTSAT thermal infrared data was archived by IIS, The University of Tokyo (http://webgms.iis.u-tokyo.ac.jp/). IR1 and IR2 channels were used in this caluculation in reference to the algorithms for land surface temperature retrieval from MTSAT data[Oyoshi *et. al*, 2012]. IR1 and IR2 are brightness temperature, and it was indicated that the influence of the atmosphere can be eliminated by using the difference between IR1 and IR2 of coefficient of atmospheric transmission.

Wet bulb globe temperature (WBGT) is a composite temperature used to estimate the effect of temperature, humidity, and visible and infrared radiation on humans. It is widely used to determine appropriate exposure levels to high temperature (Table 3), and is derived from the following equation (1). (C.P.Yaglou and Minard,1957).

$$WBGT = 0.7Tw + 0.2Tg + 0.1Td \qquad (1)$$

Where, Tw=wet-bulb temperature(^{o}C), Tg=globe temperature(^{o}C), Td=dry-bulb temperature(^{o}C)

In this study, the following simple estimate formula(2) was used. The equation(2) was derived with a relation between Tg and Td, "Tg = 1.45Td – 7.09" (Niigata Agricultural Research Institute, Horticultural Center, 2004).

$$WBGT = 0.7Tw + 0.4Td - 1.4 \qquad (2)$$

WCT (Wind Chill Temperature) index is used to provide a formula for calculating the dangers from winter winds and freezing temperatures. It is based on the rate of heat loss from exposed skin caused by the effects of wind and cold as below.

$$WCT = 13.12 + 0.6215 \cdot T - 11.37 \cdot V^{0.16} + 0.3965 \cdot T \cdot V^{0.16} \qquad (5)$$

Where, T=air temperature(^{o}C), V=wind speed(km/h)

Table 1. Station data.

Station	**Tokyo**	**Taipei**	**Sapporo**	**Urumqi**
Latitude	35.683	43.06	25.033	43.8
Longitude	139.767	141.329	121.517	87.65
Data	hourly	3 hourly	Hourly	3 hourly
	2011/1/1-12/31	2011/1/1-12/31	2011/1/1-12/31	2011/1/1-12/31

Table 2. MTSAT technical specifications.

Channel	Wavelength	Spatial Res.
IR1	10.5-11.5μm	4km
IR2	11.5-12.5μm	4km
IR3	6.5-7.0μm	4km
IR4	3.5-4.0μm	4km
VIS	0.55-0.90μm	1km

Table 3. Risk level of heat disorder.

WBGT(℃)	**Level** (proposed by the Japan Amateur Sports Assosiation, 1994)
>31	Danger
28-31	Alert
25-28	Advisory
21-25	Caution

Table 4. Risk level of frostbite.

WCT	Level
0- -9	Low
-10 - -27	Low
-28 - -39	Risk: exposed skin can freeze in 10 to 30 minutes
-40 - -47	High risk: exposed skin can freeze in 5 to 10 minutes
-48 - -54	Very high risk: exposed skin can freeze in 2 to 5 minutes

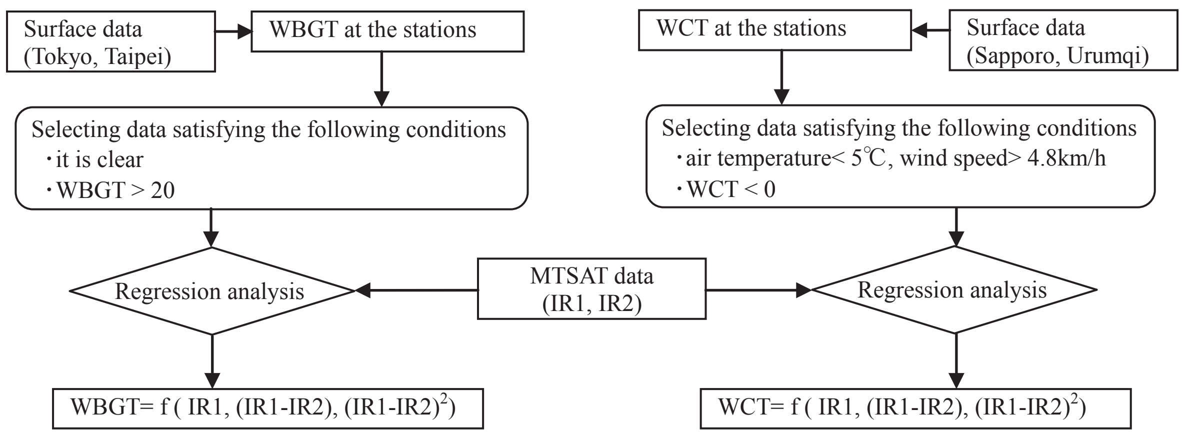

Figure 1. Flow chart of making relational expression between composite temperatures and MTSAT data.

2.2 A Method for Calculating WBGT and WCT Proposed in This Study

Figure 1 is a flow chart of making regression equations between WBGT and MTSAT data, and WCT and MTSAT data.

Firstly we calculated WBGT with surface data of Tokyo and Taipei in use of equation (2) with surface data. Wet-bulb temperature(Tw), needed to use (2), was calculated by following formulas.

$$es = 6.1078 \cdot 10^{(7.5T/T+237.3)} \quad (3)$$

Where, es=saturation vapor pressure(hPa), T=air temperature(^{o}C)

(Tetens, 1930)

$$e = e's - 0.000662 \cdot P(Td-Tw) \quad (4)$$

Where e=vapor pressure(hPa), e's=saturation vapor pressure at Tw(hPa), P=atmospheric pressure(hPa)

(Sprung, 1855)

We chose and used WBGT data over 20 and of clear points so that there is no influence caused by cloud cover. Then regression analysis (least squares method) was conducted to derive relational expressions between WBGT and MTSAT data. We used IR1, (IR1-IR2) and $(IR1-IR2)^2$ as terms of equations.

Secondly,WCT were calculated in use of equation(5) with surface data of Sapporo and Urumqi, and regression analysis was conducted to derive relational expressions between WCT and MTSAT data. In the analysis, we used WCT data under 0 and of points in time when the air temperature was under 5^{o}C and the wind speed was over 4.8km/h because WCT can be used when it satisfys the condition(air temperature<5^{o}C, wind speed>4.8km/h). IR1, (IR1-IR2), $(IR1-IR2)^2$ were used as terms of equations.

3. Results and Discussion

3.1 Result of Regression Analysis of WBGT

The following relational expressions were derived as the results.

From the data of Tokyo,

$$WBGT= 0.322IR1 +0.977(IR1-IR2) -0.252(IR1-IR2)^2 -69.4 \quad (6)$$

From the data of Taipei,

$$WBGT= 0.0299IR1 +3.27(IR1-IR2) -0.343(IR1-IR2)^2 +12.6 \quad (7)$$

From the data of the two cities,

$$WBGT= 0.0209IR1 +2.58(IR1-IR2) -0.272(IR1-IR2)^2 +16.1 \quad (8)$$

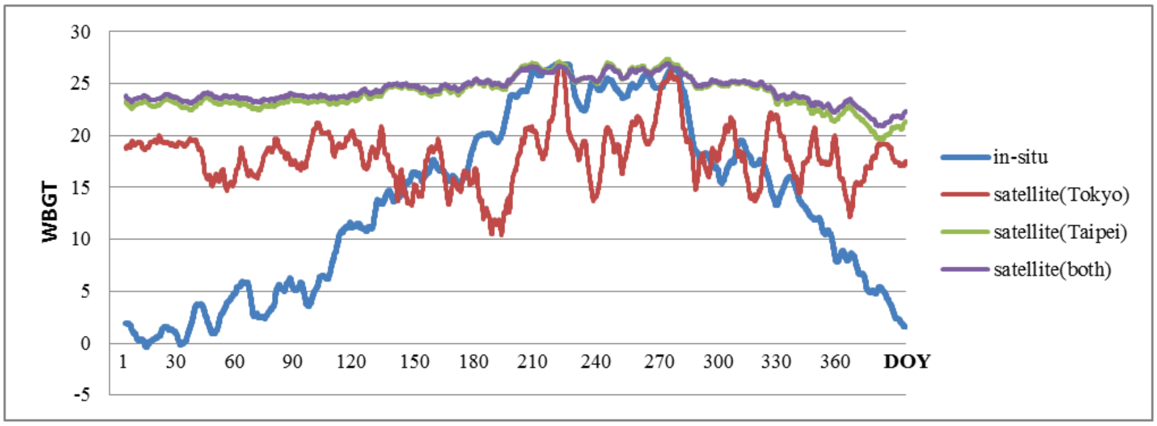

Figure 2. WBGT annual change in Tokyo (2011).

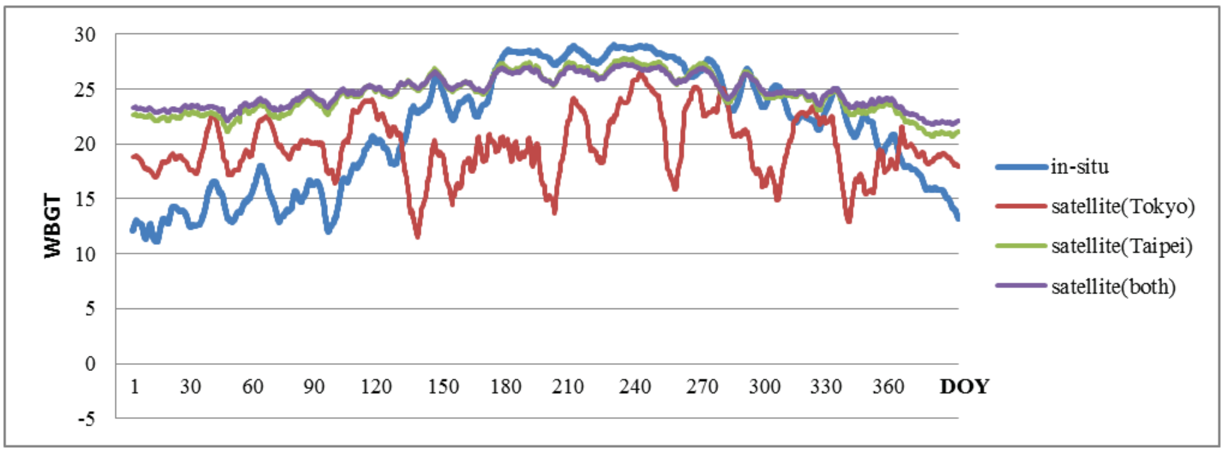

Figure 3. WBGT annual change in Taipei (2011).

Table 5. RMSEs between "in-situ" WBGT and each "satellite" WBGT.

		formula		
		Tokyo	**Taipei**	**Both**
City	**Tokyo**	11.7 (1.02*)	13.3 (1.39*)	13.7 (0.980*)
	Taipei	7.68 (5.51*)	5.74 (1.58*)	6.09 (1.79*)

*The numbers inside the parentheses are the RMSE of data used for regression analysis

Following Figures 2, 3 show WBGT annual change in Tokyo and Taipei in 2011, showing a WBGT in a vertical direction and day of year in lateral direction. In Figure 2~3, "in-situ" shows annual change of WBGT calculated with surface data, and "satellite(Tokyo)", "satellite(Taipei)" and "satellite(both)" show that calculated from equation(6),(7),(8). Table 5 shows Root Mean Square error (RMSE) between WBGT by in-situ measurement and WBGT by calculation using formulas derived by least squares method.

From Table 5, formula(6), "satellite(Tokyo)", had the smallest RMSE 11.7 with in-situ WBGT in Tokyo, and formula(7), "satellite(Taipei)", had the smallest RMSE 5.74 with in-situ WBGT in Taipei. However it can be said that formula(8), "satellite(both)", was the best when one formula was applied to both cities in hot season. RMSE of data satisfying the condition ,that it was clear and WBGT was over 20, between WBGT by in-situ measurement and WBGT calculated by formula(8) in Tokyo was 0.980 and that in Taipei was 1.79.

From Figure 2 and Figure 3, it can be said that WBGT by in-situ measurement and WBGT calculated based upon the "satellite(both)" formula take the value over 25 in almost same period. It shows a possibility of that we can evaluate thermal comfort by the number of days when WBGT takes critical value(over 25) of each city.

3.2 WBGT Image Mapping and Its Spatial Characteristics

This calculation also enabled making WBGT image mapping.

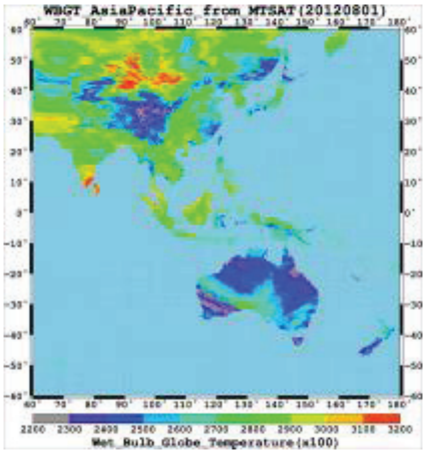

Figure 4. WBGT daily mean map (2012.8.1).

Figure 4 shows daily mean of WBGT distribution on 1 January, 2012. Each 4 kilometers square is color-coded by height of WBGT as shown by the figure at the bottom. The approximate situation of WBGT in Asia Pacific is clear immediately from this image. We can make the daily image map from October, 2006 to now using the relational expression between WBGT and MTSAT data.

3.3 Relation to Socio Economic Activity

As one of the indices of socio economic activity, we examined the relationship between WBGT and GDP per capita of each country. Figure 5 shows the relation between WBGT and GDP per capita. In the map in the left side of Figure 5, circles are color-coded by the height of yearly average of WBGT in each city, and the size of circles expresses amount of GDP per capita of countries of these cities. The relations between WBGT and GDP are plotted in the right side graph in Figure 5 showing yearly average of WBGT in a vertical direction and GDP per capita in lateral direction. It cannot be said the rule, however high WBGT countries tend to have low GDP per capita.

3.4 Result of Regression Analysis of WCT

The following relational expressions were derived as the results.

From the data of Sapporo,

$$WCT= -0.0237IR1 +0.122(IR1-IR2) +0.129(IR1-IR2)^2 -0.0290 \quad (9)$$

From the data of Urumqi,

$$WCT= 0.0782IR1 +0.965(IR1-IR2) +0.904(IR1-IR2)^2 -33.7 \quad (10)$$

From the data of the two cities,

$$WCT= 0.0788IR1 +1.95(IR1-IR2) -0.149(IR1-IR2)^2 -29.6 \quad (11)$$

Following Figures 6, 7 show WCT annual change in Sapporo and Urumqi in 2011, showing a WCT in a vertical direction and day of year in lateral direction. In Figure 6~7, "in-situ" shows annual change of WCT calculated with surface data, and "satellite(Sapporo)", "satellite(Urumqi)" and "satellite(both)" show that calculated from equation(9),(10),(11). Table 6 shows Root Mean Square error (RMSE) between WCT by in-situ measurement and WCT by calculation using formulas derived by least squares method.

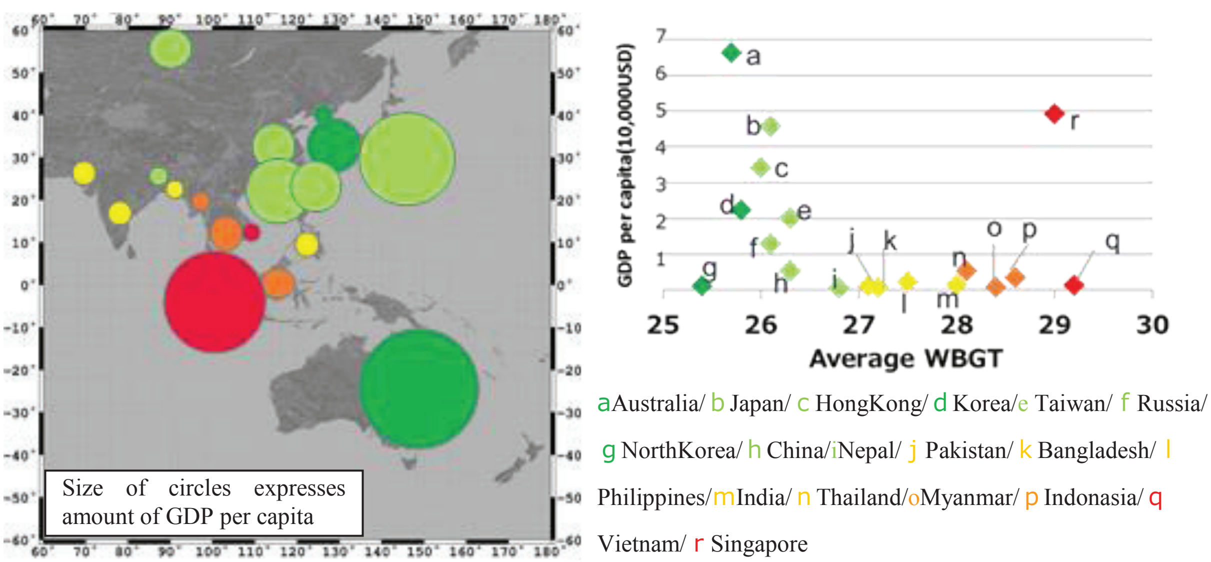

Figure 5. Relation between WBGT and GDP per capita.

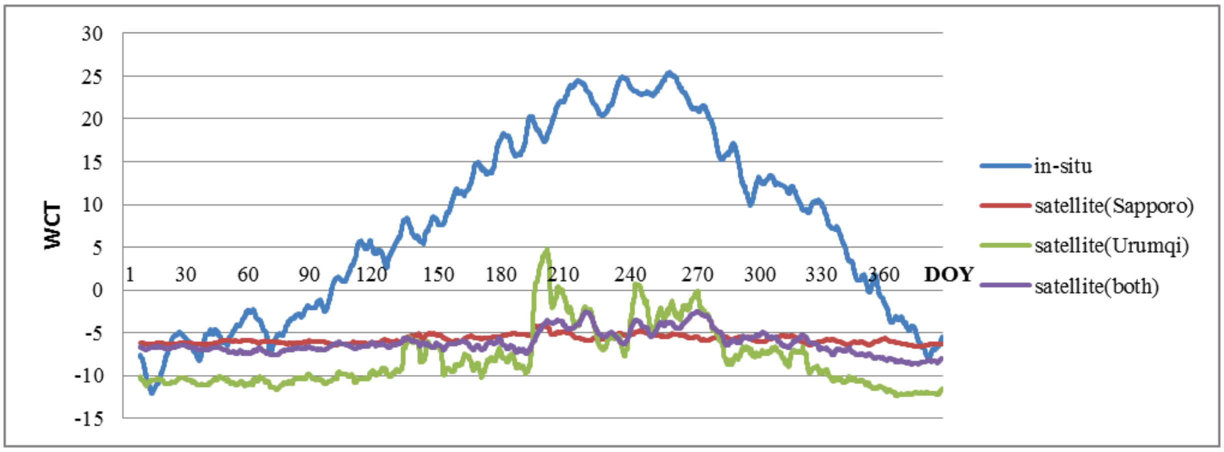

Figure 6. WCT annual change in Sapporo (2011).

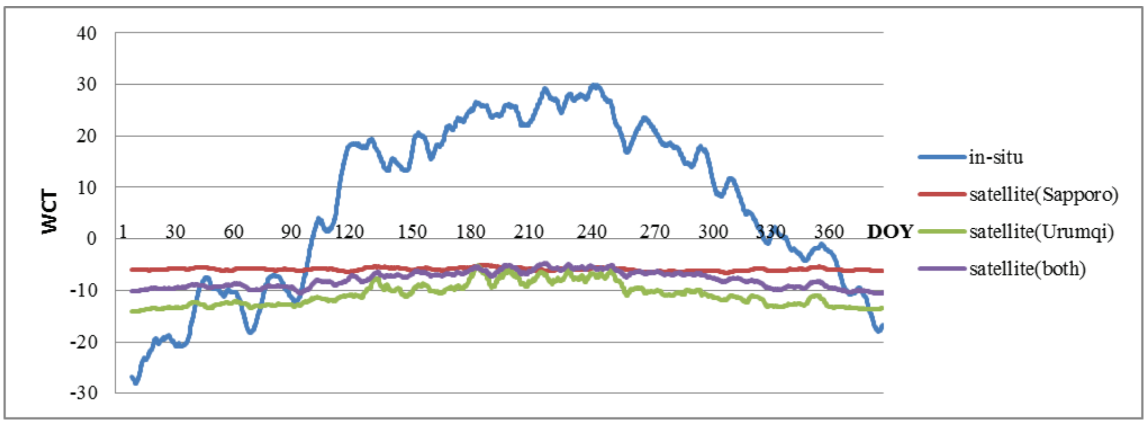

Figure 7. WCT annual change in Urumqi (2011).

Table 6. RMSEs between "in-situ" WCT and each "satellite" WCT.

		formula		
		Sapporo	**Urumqi**	**Both**
City	**Sapporo**	17.3 (3.53*)	20.3 (6.37*)	17.3 (4.01*)
	Urumqi	22.6 (10.4*)	52.1 (7.59*)	55.8 (15.8*)

*The numbers inside the parentheses are the RMSE of data used for regression analysis

From Table 6, RMSE of data satisfying the selection criteria between "in-situ"WCT and "satellite(both)" WCT was 4.01 and 15.8 in each city. In addition, from Figure 6 and Figure 7, it cannot be said that the formula express the tendency of WCT changes cold season. From this result, further study is required to derive more appropriate relational expression for evaluating thermal comfort in cold season.

4. Conclusion and Future Works

This study demonstrated a method for evaluating thermal comfort by calculating WBGT and WCT using MTSAT data. Selection of data and Regression analyses were conducted and relational expressions between the composite temperatures and MTSAT data were derived. From the results, it could be said that we could evaluate thermal comfort in hot season by the number of days when WBGT takes critical value(over 25) of each city by satellite remote sensing. In addition, it enabled making image mappings of WBGT distribution. However our formula of WCT could not express the annual change of WCT accurately. Further study was needed to improve the formula. Next, as one of indices of socio economic activity, we examined the relationship between WBGT and GDP per capita of each country and made the result visible as a figure. It could be said that high WBGT countries tend to have low GDP per capita.

As the future works, further study for getting accuracy of WCT formula and analyses of relationships between thermal comfort and each industry will be proceeded.

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