EFFECTS OF URBAN HEAT ISLAND ON VERTICAL ATMOSPHERIC STRUCTURE IN URBAN AREAS OF THAILAND

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ผลของปรากฏการณ์เกาะความร้อนของเมืองที่มีต่อโครงสร้างชั้นบรรยากาศในแนวดิ่งในเขตเมืองของประเทศไทย

นางสาวเย็นฤทัย จงถนอม

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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เย็นฤทัย จงถนอม: ผลของปรากฏการณ์เกาะความร้อนของเมืองที่มีต่อโครงสร้างชั้นบรรยากาศในแนวดิ่งในเขตเมืองของประเทศไทย (EFFECTS OF URBAN HEAT ISLAND ON VERTICAL ATMOSPHERIC STRUCTURE IN URBAN AREAS OF THAILAND) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ.ดร.ชาญวิทย์ โฆษิตานนท์, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: ผศ.ดร.สุรัตน์ บัวเลิศ, 105 หน้า

งานวิจัยนี้เน้นถึงปรากฏการณ์เกาะความร้อนของเมือง และผลของเกาะความร้อนของเมืองที่มีต่อโครงสร้างชั้นบรรยากาศในแนวดิ่งในพื้นที่เขตเมือง ได้แก่ เชียงใหม่ กรุงเทพฯ อุบลราชธานี สงขลา และภูเก็ต ข้อมูลที่ใช้ศึกษาเป็นข้อมูลอุตุนิยมวิทยา รายชั่วโมง ตั้งแต่ปีพ.ศ. 2547 – 2551 และข้อมูลอุตุนิยมวิทยาชั้นบนปีพ.ศ.2551 จากกรมอุตุนิยมวิทยา ข้อมูลอุตุนิยมวิทยาชั้นบนจากโครงการลักษณะของชั้นบรรยากาศและผลต่อการเปลี่ยนแปลงองค์ประกอบของมลสารทางอากาศสำหรับประเทศไทย (CAPE) ช่วงเดือนกุมภาพันธ์ 2551 ผลการศึกษาจากทุกพื้นที่พบว่า ค่าความเข้มสูงสุดของเกาะความร้อนเมืองมีค่าอยู่ระหว่าง 0.1°C - 4°C และมีการผันแปรตามช่วงเวลาระหว่างวัน รวมทั้งมีการผันแปรตามฤดูกาล และพบว่า ค่าความเข้มของเกาะความร้อนเมืองไม่มีความสัมพันธ์กับอัตราการเปลี่ยนแปลงอุณหภูมิหรือความเร็วลมตามระดับความสูง และไม่มีความสัมพันธ์กับความแตกต่างของอุณหภูมิหรือความเร็วลมระหว่างพื้นผิวกับระดับที่สูงขึ้น แต่พบว่าในพื้นที่ศึกษาตามโครงการ CAPE ค่าความเข้มของเกาะความร้อนเมืองมีความสัมพันธ์แบบแปรผันตามกับระดับความสูงผสม โดยมีค่าสัมประสิทธิ์การตัดสินใจ (R^2) ของเชียงใหม่และกรุงเทพฯ เป็น 0.49 และ 0.64 ตามลำดับ ซึ่งเป็นค่าที่มีนัยสำคัญสำหรับการศึกษาทางอุตุนิยมวิทยา จากการประมาณระดับความสูงผสมตอนช่วงเช้าตามวิธีการของ Holzworth พบว่า ค่าคงที่ของความเข้มเกาะความร้อนเมืองที่เหมาะสมสำหรับประเทศไทยในการประมาณค่าระดับความสูงผสมควรเป็น 3°C - 4°C

สาขาวิชา วิทยาศาสตร์สิ่งแวดล้อม ลายมือชื่อนิสิต..

ปีการศึกษา 2554 ลายมือชื่ออ.ที่ปรึกษาวิทยานิพนธ์หลัก..........................

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YENRUTAI JONGTANOM: EFFECTS OF URBAN HEAT ISLAND ON VERTICAL ATMOSPHERIC STRUCTURE IN URBAN AREAS OF THAILAND.
ADVISOR: ASST. PROF. CHARNWIT KOSITANONT, Ph.D.,
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This study focuses on urban heat island (UHI) effect and the effects of UHI on the vertical atmospheric structure in urban areas namely Chiang Mai, Bangkok, Ubon Ratchathani, Songkhla and Phuket. The data used were hourly meteorological data from 2004 to 2008 and the upper meteorological data of 2008 from Thai Meteorological Department and the upper meteorological data from the project of Characteristics of atmospheric profile and its effects on variation of air pollutions in Thailand (CAPE) during February 2008. The study results from all study areas showed that the maximum UHI intensity was 0.1°C - 4°C and there were the diurnal variation and seasonal variation. The study results were found that the UHI intensity did not correlate either with the rate of change of temperature or wind speed with height and the difference of temperature or wind speed between the surface and the higher levels. However, in the case study areas which followed CAPE project, there was the positive correlation between the UHI intensity and the mixing height which the coefficient of determination (R^2) for Chiang Mai and Bangkok was 0.49 and 0.64 respectively. These values were significant for meteorological study. From estimation of the morning mixing height by Holzworth method, the suitable constant of UHI intensity for Thailand should be 3°C - 4°C.

Field of Study Environmental Science Student's Signature..

Academic Year 2011 Advisor's Signature..

Co-advisor's Signature..

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ABBREVIATIONS

°C	Degree Celsius
CAPE	The project of characteristics of atmospheric profile and its effects on variation of air pollutants in Thailand
DOPA	Department of Provincial Admistration
°E	Degree East
EZ	Entrainment zone
JST	Japan Standard Time
K	Kelvin
km^2	Square kilometer
km	Kilometer
LST	Local Standard Time
m	Meter
max.	Maximum
mb	Millibar
ML	Mixing layer
ms^{-1}	Meter per second
MW	Megawatt
°N	Degree North
PBL	Planetary boundary layer
ΔQ_A	The heat advection
Q_E	The turbulent sensible heat
Q_F	The anthropogenic heat
ΔQ_S	The sensible heat storage
Q_N	The net all wave radiation
ΔT	The difference of temperature between the surface and the upper level
t	Ton
T_U	The urban air temperature
T_R	The rural air temperature

TMD	Thai Meteorological Department
TVI	Transformed vegetation index
UCI	Urban cool island
UCV	Urban cool valley
UHI	Urban heat island
USD	United States dollar
ΔW	The difference of wind speed between the surface and the upper level

CHAPTER I

INTRODUCTION

1.1 Background Information

Urbanization causes many problems in an urban area such as pollution, domestic and industrial waste and urban warming. Urban heat island is considered as one of the major problems in the 21st century as a result of urbanization (Zhou *et al.,* 2004; Rizwan *et al*., 2008; Zhang *et al*., 2009). This phenomenon referred to the temperature within an urban area tends to be much warmer than its rural or suburban area (Kim, 1992; Magee *et al.,* 1999; Kim and Baik, 2002, 2005). The causes of urban heat island can be divided into two factors: (1) city factors, such as city size, city topography, city morphology and anthropogenic heat sources (e.g. automobiles, power plants and air conditioner); (2) meteorological factors, such as cloud cover, wind speed and humidity (Rizwan *et al.,* 2008; Shahmohamadi *et al.,* 2010).

The effect of urban heat island was the urban warming which cause the deterioration of living environment and increase energy consumption (Konopacki and Akbari, 2002). The high temperature lead to the formation of low-level ozone from volatile organic compounds and nitrous oxides which already exist in the air, so these contribute to worse air quality (Rosenfild *et al*., 1998). In addition, urban heat island has the influence the human health due to extreme heat (Changnon *et al.,* 1996). Aside from the effects on temperature, urban heat island can produce secondary effects on local meteorology, including the altering of local wind patterns, the development of clouds, fog, humidity and the rates of precipitation (Arizona Board of Regents, 2006). Scientists have been interested in urban heat island due to its adverse environmental and economic impacts on the society and promising benefits associated with mitigating urban heat island effect (Rizwan *et al*., 2008). It has been studied all over the world with the objective of establishing urban heat island intensity which is determined as the spatially average temperature difference between an urban and its surrounding rural area (Magee *et al*, 1999; Kim and Baik, 2002, 2005). Oke (1973) addressed this issue, obtaining sufficiently important results to provide the basis for later studies. Since then, much work has been carried out in many different cities, with a view to establish and limit the increase in urban heat island intensity. The urban heat island intensity was established in many cities such as in Atlanta, USA (Hafner and Kidder, 1999), Salamanca, Spain(Alonso *et al*, 2003), Tokyo (Huang *et al*, 2005), Seoul (Kim and Baik, 2005), Beijing (Liu *et al*., 2007), New York (Gaffin *et al.,* 2008), Shanghai (Zhang *et al.,* 2009) etc. Many scientists have shown that the internal and external factors of the city influenced the urban heat island intensity, including city size, building density, land-use distribution, topography, weather conditions (Oke, 1982; Magee *et al.,* 1999; Montavez *et al*., 2000; Kim and Baik, 2005; Zhang *et al.,* 2009).

The cities in Thailand have been developed rapidly as the dominant center for economic activities, industrialization, social services, telecommunications and public welfare since the second half of the 20th century (Komonveeraket, 1998). The change of population and the change of land use in urban areas give rise to radiation, thermal, and aerodynamic modification of surrounding environment (Oke, 1988). Therefore, the cities in Thailand are facing higher risk on urban heat island effects. Komonveeraket (1998) used surface radiant temperature, transformed vegetation index (TVI), and land use type derived from Landsat TM to study urban heat island throughout Bangkok Metropolis and the results showed the surface radiant temperature in urban area was higher than those in rural area by 1.71°C and 1.53° C in 1988 and 1997. Bunyawatt *et al.,* (2000) used the weather data that derived from mobile surveys and the result showed the urban heat island intensity of 5°C in Bangkok Metropolis on February nights. However, the previous studies in Thailand focused on the urban heat island in a single city. The difference of this present study and the previous UHI studies in Thailand was that the urban heat island intensity of the cities from all parts of Thailand would be established by analyzing the meteorological data from urban and rural weather stations.

The planetary boundary layer is the part of the troposphere which is directly influenced by the presence of earth's surface and responds to surface forcing with a timescale of about an hour or less such as frictional drag, evapotranspiration, heat transfer, pollutant emission (Stull, 1988; Cooper and Eichinger 1994). The turbulent properties of this layer such as diffusivity, mixing, transport will rule whether pollutants are dispersed and diluted or whether they build up and led to pollution episodes (Piringer *et al*., 2004). So, the planetary boundary layer height or mixing height is a key parameter in dispersion of pollutants and depend on basic meteorological factors (Stull, 1988, Smith, 2005). The mixing height can often be inferred from vertical profile of temperature, wind speed and wind direction whose profiles are directly influenced by turbulent mixing (Benkley and Schulman, 1979). Many previous researches pointed that urban heat island related to the mixing height (Holzworth, 1967; DeMarrais, 1975). So, the details of the effects of urban heat island on the vertical atmospheric structure are important for the researchers who focus on the air pollution.

This present study is the first research to establish the urban heat island intensity of the cities from all parts of Thailand by analyzing the meteorological data from urban/rural weather station. The study results provided the basic information of urban heat island and its effect on vertical atmospheric structure for further urban planning to minimize urban warming or to avoid air pollution. In addition, this present study provided urban heat island intensity of the cities from all parts of Thailand which could be considered a replacement for the constant value of urban-rural temperature differences used for estimating morning mixing heights by Holzworth method.

1.2 Objective

The main objectives are to study urban heat island effect and its effects on the vertical atmospheric structure in urban areas of Thailand.

There are three aspects of this research:

1. Characterization of urban heat island in urban areas.
2. Characterization of vertical atmospheric structure in urban areas during the UHI events.
3. Study of the effects of urban heat island on vertical atmospheric structure.

1.3 Hypotheses

The hypotheses of this research are bases on:

1. The urban characteristics and the meteorological factors affect on the magnitude and characteristics of urban heat island.

2. The urban heat island affects the vertical atmospheric structure in urban areas.

1.4 Scope of the study

The works of this research are described as follow:

1. The study areas were Bangkok, Chiang Mai, Ubon Ratchathani, Songkhla, and Phuket.

2. The data series used in this study derived from two sources:

    1) The meteorology data were obtained from the urban weather station and the rural station in study areas operated by Thai Meteorological Department (TMD) for the 5-yr period from 2004 to 2008.

    2) The upper meteorological data were obtained from two sources; (1) the upper meteorological stations which were operated by TMD in study areas for the 1-yr period during 2008 (2) the project of characteristics of atmospheric profile and its effects on variation of air pollutants in Thailand (CAPE) during February 2008.

1.5 Expected benefits

1. The knowledge and basic information of urban heat island phenomenon.

2. The database of urban heat island intensity in urban areas can be applied to study the atmospheric characteristics and for urban planning and management to minimize or avoid the urban heat island effects.

CHAPTER II

LITERATURE REVIEWS

2.1 Urban heat island (UHI) phenomenon

The distinctions in the natural energy and hydrological balances in the city were associated by the changes in the atmospheric properties of a region by urbanization (Oke, 1987). Urban heat island (UHI) effect is one phenomenon which changes in the atmospheric properties and varies in time, meteorology, location and urban characteristics (Oke, 1987; Komonveeraket, 1998). This phenomenon referred to the temperature within an urban area tends to be much warmer than its surroundings rural area (Kim, 1992; Magee *et al.*, 1999; Kim and Baik, 2002, 2005). The unique character of each city greatly influenced UHI morphology (Shahmohamadi *et al.,* 2010). As displayed in Figure 2.1, air temperature varies along the distance crossing from the countryside to the center of an urban area.

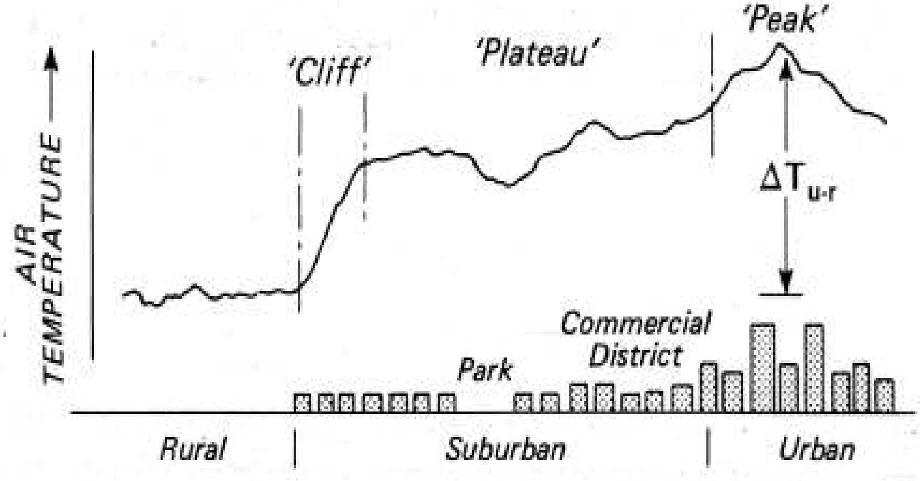

Figure 2.1 Generalized cross - section of a typical UHI (Available from: Oke, 1978)

Oke (1987) stated that in a large city with a cloudless sky and calm wind just after sunset, the boundary between the rural and the urban areas exhibits a steep temperature gradient or “cliff” to the UHI and then the rest of the urban area appears as “plateau” of increasing temperature towards the city center. The influence of distinct intra-urban land uses such as park, lakes, open areas, commercial, industrial and dense building areas modified the uniformity of the “plateau”. A “peak” in the UHI which referred to maximum temperature difference between an urban and rural temperature was found in the center of the urban. The difference of temperature between an urban and a rural area referred to the UHI intensity (Oke, 1973).

2.1.1 Physical basis of UHI

The surface energy balance gives an idea of the heat generated by an area, and can help us to understand the heat generated by various sources. The heat generated by and contained in an area could be given as the surface energy balance equation below (Oke, 1988).

$$Q_N + Q_F = Q_H + Q_E + \Delta Q_s + \Delta Q_A$$

Where Q_N is the net all wave radiation, Q_F, Q_E and Q_H are respectively the anthropogenic heat release, the turbulent sensible and turbulent latent heat flux densities, ΔQ_s is the sensible heat storage and ΔQ_A is the heat advection.

Munn (1966) represented the surface energy balances in an urban and a rural area that are shown in Figure 2.2. During the day a net daytime gain of energy through radiation at the earth-atmosphere interface results in a turbulent transfer of heat to the atmosphere(Q_H), conduction of heat into the ground (ΔQ_G), and evaporation (Q_E). During the night a net loss of energy through radiation at the interface results in decreasing of evaporation, turbulent transfer of heat from the atmosphere, and conduction of heat from the ground. In urban areas, associations of the above energy balance can result from any or all of the following: anthropogenic heat, limited amounts of surface moisture, urban structure and pollution. The decrease of surface moisture reduced the energy for evaporation (Q_E), therefore the energy transferred to the atmosphere (Q_H) and to urban surfaces (ΔQ_G). However, the urban temperature during daytime may be lower than the rural temperature in sometime due to the large heat capacity and high heat conductivity of urban building materials. These thermal properties prevent rapid warming after sunrise and cooling after sunset but allow the storage of large amount of solar energy and anthropogenic heat (Q_F) in an urban area,.

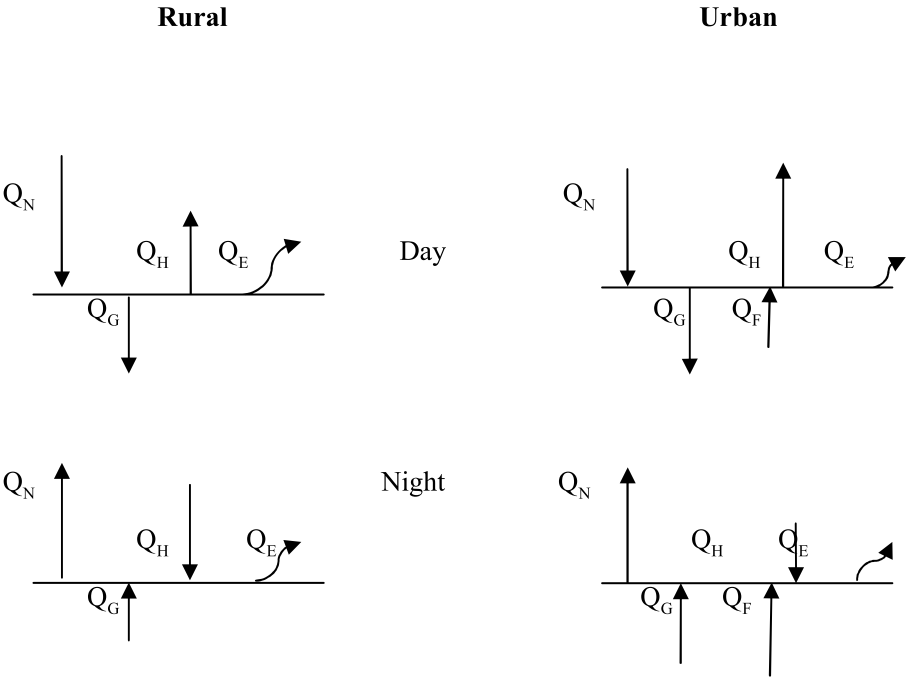

Figure 2.2 Schematic representation of the energy balances in rural and urban areas (Available from: Munn, 1966)

2.1.2 Generation of UHI

The factors that generate UHI can be considered as follows:

2.1.2.1 The physical characteristic of an urban

The modification of the land surface by urban development is the main cause of UHI. Materials commonly used in urban areas, such as concrete, asphalt have significantly different thermal conductivity, heat capacity and surface radiating properties from rural areas (Oke, 1982). Building materials in urban areas have high heat capacity and high heat conductivity (Bornstein, 1968). These cause a change in the energy balance and lead the air temperature in an urban area higher than surrounding. These can be explained that during the day, the urban surfaces absorb heat more readily and then become a radiating source after sunset and cause higher temperature at during the night (Komonveeraket, 1998). The high heat was collected in urban building structures because the ability of heat release by long wave radiation is low due to decreased sky view (Rizwan *et al.,* 2008). In addition, the albedo which referred to the reflected light in comparison to the incident light, is also very low in an urban due to typical street canyon configurations, and is one of the main reasons of high temperature (Giridharan *et al*., 2004).

2.1.2.2 Anthropogenic heat source

Hung *et al*. (2006) have studied UHI in twelve Asian mega cities and reported that the magnitude and extent of UHI was positively correlated with city population. About 50% of the world's population and approximately 7.6 % in more developed countries live in urban areas (Omer, 2008). Oke (1973) stated that even a city of 1,000 people could have an UHI effect and the magnitudes of UHI effects were correlated with the city size (defined by population density). The population could have effects on heat generation, the effect was that more people means more anthropogenic heat source (Rizwan *et al*., 2008). Anthropogenic heat which referred to the heat generated from the human activities such as heating and cooling the building, cooking, manufacturing lighting, transportation, etc. is released to the atmosphere and can contribute UHI. Ichinose *et al*. (1999) found that the UHI is the most intense in winter because the influence of anthropogenic heat is relatively greater in winter than in other season. Kim and Baik (2005) showed that the UHI in Seoul is stronger on weekdays than weekends due to high commercial activities on weekdays. The change of population, the changes of land use and production and dispersal of anthropogenic emissions and pollutants interact with regional climate as well as the frequency and intensity of specific weather events (Roth *et al.,* 1989; Sailor, 1994; Taha, 1997; Saaroni *et al,* 2000). However, Rizwan *et al.* (2008) suggested that other variable such as sky view factor, building design etc. play in increasing heat contents that means these factors are not population dependent and may or may not favor in increasing heat content with increased population.

2.1.2.3 The reduction of evaporating surfaces

The urban areas have less vegetation due to the change of land use and land cover (Rizwan *et al*., 2008). The reduction of evaporating surfaces in the city gives more energy into sensible heat and less into latent heat (Oke *et al*, 1991). The low evaporative heat flux in cities is the significant factor in development of UHI (Sailor, 1994).

2.1.2.4 The local topography and weather

The formation and evolution of weather in an urban area were modified by the local topography. Therefore many studied showed that there was significant relationship among the weather condition, local topography, and UHI. It was especially evident on days of strong stability, weak barometric gradient, calm wind, and no cloud (Jaurigui. 1997; Klysik and Fortuniak, 1999; Montavez *et al.,* 2000; Morris *et al*, 2001; Kim and Baik, 2002). Kim and Baik (2005) studied the UHI intensity in the large cities of Korea and they found that the UHI intensity of the coastal cities was lower than the UHI intensity of the inland cities due to the influence of sea breeze.

2.1.2.5 Air pollution and greenhouse effect

Air pollution is caused by the emission of particulates and carbon monoxide from industrial, domestic, and automobile combustion process. These atmospheric 'pollutant' can retain more heat (Hidore and Oliver, 1993; Kubo, 1996). This means that high levels of pollution in urban areas can increase the absorption of radiation in the boundary layer and develop UHI (Oke, 1982). The process is some incoming solar radiation is reflected back to space by gaseous particles, at the same time, these particles can absorb energy and re-emission to the atmosphere, which effectively warm the ambient air (Hidore and Oliver, 1993).

2.1.3 The effects of UHI

Elevated temperature from UHI can affect a community's environment and quality of life. The effects of UHI can be included as follow:

2.1.3.1 Health effects

Urban warming have the potential directly influence the health and welfare of urban resident. Warmer days and nights can contribute to general discomfort, respiratory difficulties, heat stroke, and heat related mortality (Changnon *et al.*,1996).

2.1.3.2 Increase energy consumption

UHI can impact the energy consumption (Shahmohamadi *et al.,* 2010). Higher urban temperatures increase the energy demand for cooling and this can increase the production of carbon monoxide and other pollutants. Konopacki and Akbari (2002) noted that by mitigating UHI effects in Houston it was possible to achieve savings of USD 82 million with reduction of 790 MW peak power, together with an annual decrease of 170,000 t of carbon emission.

2.1.3.3 Elevated emission of air pollutants and greenhouse gas

Urban warming increase the demand of energy generally results in greater emission of air pollutant and greenhouse gas emissions from power plants include sulfur dioxide, carbon monoxide, nitrous oxide, and suspended particulates, as well as carbon dioxide, a greenhouse gas known to contribute to global warming (SOS, 1995). In addition, nitrous oxides and volatile organic compound combine photo chemically to produce ground level ozone (Rosenfeld *et al.*, 1998). Rosenfeld *et al.* (1998) assumed that ozone level could exceed 120 ppbv at 22°C and could reach 240 ppbv at 32°C.

2.1.4 UHI intensity

The magnitude of UHI can be studied in term of UHI intensity. UHI intensity is determined as the spatially averaged temperature difference between an urban and its surrounding rural area (Magee *et al.*, 1999; Kim and Baik, 2005). The comparison time period can be a time of day, a month, a season, a year, or some cases using few selected period of the time or days (Velazquez-Lozada *et al.*, 2006). UHI intensity is an important indicator of evaluating the severity of the urbanization and civilization in an area (Rizwan *et al.*, 2008). Rizwan *et al.* (2008) reviewed that the UHI intensity has also been reported as the temperature change over time. Mochida *et al.*, (1997) reported UHI intensity in Tokyo as the temperature change from 1930 to 1990. In another approach the average present time temperature was subtracted from the average past time temperature for both urban and rural areas and the difference of the changed temperature is then reported as UHI intensity (Magee *et al.*, 1999). Hung *et al.* (2006) summarized that UHI studies are generally conducted in one of two ways: (1) measuring the UHI intensity by using the data from automobile transects and weather station and (2) measuring the UHI intensity through the use of airborne or satellite remote sensing.

Many researchers reviewed and summarized the strengths and the weakness of these techniques as follow:

Landgrebe (2003) concluded that remote sensing technique can provide a satellite thermal images which can be used to describe the distribution of temperature and UHI. Liu *et al.* (2007) summarized that surface temperature is frequently affected by the weather and air condition over time, so this method cannot explicitly characterize the surface air temperature. They suggested that this method can describe the distribution of UHI at a given moment, but it cannot investigate the UHI intensity quantitatively.

Henry *et al*. (1989) reviewed that the automobile transects method has facilitated the understanding of the spatial variability of UHI. However, the problem is it may take several hours if the traverses cover many parts of the city. They noted that sometimes researchers require time-standardization when they want to apply the data from this method.

Terjung (1976) and Oke (1982), cited in Henry *et al.* (1989) pointed out the advantages of computer simulation modeling technique that allows the prediction of the space-time variations of the morphological components of the atmosphere, interfaces, and substrates. However, one problem encountered in most modeling simulations is parameterizations which are used for approximations of actual conditions. These are usually required because of computer limitations and/or lack of data in regard to certain aspects of the modeling process.

The observation of the data from the weather stations is the most popular method the to analyze the UHI effect. Available weather station data can help us to obtain an average variation of the UHI over long period. This technique can provide the UHI intensity. The weakness was the problem of choosing stations which are representatives of the general urban and rural conditions (Henry *et al*. 1989).

Many UHI studies have appeared in the following literature.

Oke (1973) used the meteorological data gathered by automobile traverses in 10 settlements on the St. Lawrence Lowland, whose populations range from 1,000 to 2 million inhabitants to study the relationship existing between the size of city (as measured by its population), and the magnitude of UHI. The locations of these settlements effectively eliminate all non-urban climatic influences. The results showed that the UHI intensity under cloudless to be related to the inverse of the regional wind speed, and the logarithm of population.

Komonveeraket (1998) used surface radiant temperature, transformed vegetation index (TVI), and land use type derived from Landsat TM to study UHI throughout Bangkok Metropolis.

The results revealed an inverse relationship between TVI and surface temperature and the variation of these values on difference land surface properties. The study showed that the presence of vegetation could cool down the surface temperature in such land cover type. The decreasing of vegetation and the extension of built-up area can raise surface temperature. It was found that the values of TVI in urban area were lower than rural area for 2.15 % and 1.18 % in 1988 and 1997, respectively, whereas the surface radiant temperature in urban area were higher than those in rural area by 1.71°C and 1.53°C in 1988 and 1997.

Bunyawatt *et al.*, (2000) used the weather data that derived from mobile surveys. The result showed the UHI intensity of 5°C in Bangkok Metropolis on February nights. This study found that the temperature in urban areas was significantly higher than that in suburban areas in the night time.

Alonso *et al.* (2003) used the weather station data to study the characteristics of UHI in the city of Salamanca, Spain. The results showed that the greatest mean nocturnal intensities of UHI were recorded in autumn and winter. The intensity of the UHI depends on the atmospheric situation. Under conditions of atmospheric stability, the UHI was more intense than under conditions of instability.

Kim and Baik (2002) used the weather data to study the UHI in Seoul. This study found that the average maximum air temperature difference between urban and suburban areas was 3.4°C. The results indicated that the UHI intensity was high during nighttime or early morning and low during daytime. In addition, they related UHI intensity to meteorological elements such as the maximum UHI for the previous day, wind speed, cloudiness, and relative humidity. The results showed that the previous-day maximum UHI intensity was positively correlated with the maximum UHI intensity, and the wind speed, cloudiness, and relative humidity are negatively correlated with the maximum UHI intensity.

Liu *et al.* (2007) studied the inter-annual trend, the seasonal variation, and hourly variation of UHI in Beijing, China by using data from the weather station. The results indicated that the UHI intensity had the greatest increasing trend for minimum temperature, while the UHI intensity of maximum temperature showed a slow decrease over time. UHI intensity had a strong positive correlation with the increase in urban population and the expansion of the yearly construction area. Seasonal analyses showed the UHI intensity was strongest in winter and seasonal variation tended to be negatively correlated with seasonal variation of relative humidity and vapor pressure.

Hung *et al*. (2006) used the weather station data to study urban microclimate in four types of ground cover, namely urban bare concrete cover, urban wood, urban water areas and urban lawn, and the urban heat island was also analyzed using air temperature data measured at fixed observation in Nanjing, China, during hot season. The result showed that the microclimate of these four types of land cover had significant differences among different observation sites. The air temperature of these four types of land cover complied with the order during daytime: bare concrete >lawn>water areas >woods. The average UHI intensity was 0.5°C-3.5°C. However, there were also significant day-to-day variations. A strong UHI effect occurred around midnight, while about 2-3 hours after sunrise the UHI effect began to decrease.

Chow and Roth (2006) studied the temporal variability of UHI intensity in Singapore by using data from observations for the 1-yr period. The results indicated that the strongest UHI intensity occurred 3-4 h after sunset. Higher UHI intensity occurred during drier month associated with the southwest monsoon season (May-August) and lowest UHI intensity occurred during the wet northeast monsoon season (December-January).

Zhang *et al.* (2009) studied characteristics of UHI intensity in Shanghai, China using meteorological data. The results indicated that the UHI intensity was strongest in autumn and the weakest in summer, as a consequence of the prevailing weather conditions. The UHI intensity was stronger in the nighttime than in the daytime. Analysis of the association of UHI and urbanization indicated that the UHI intensity increased with the expansion of population and rapid increase of gross domestic product. The continuous increase of power consumption and area of paved road and decrease of area of cropland caused the growth of UHI intensity.

Green land had a positive effect on mitigation of heat island based on an inversed U-shaped curve with UHI intensity.

2.2 Fundamentals of atmospheric structure

2.2.1 Planetary Boundary Layer

The atmosphere is characterized by its constituent gas, particulate substances, the physical forces and phenomena that act upon and within it (Stull, 1988). These include solar radiation, thermal energy, gravity, air density and associated pressure, and the movement of individual air molecules and the atmosphere itself (Godish, 2004). The Planetary boundary layer (PBL) is defined as the lowest part of the troposphere where the air is influenced by the earth's surface and responds to surface facings such as frictional drag, evapotranspiration, heat transfer, and pollutant emission (Stull, 1988; Cooper and Eichinger, 1994). Within the PBL, several identifiable layers can exist which depend on the state of atmosphere and local conditions. As shown in Figure 2.3, these layers are the surface layer, mixing layer (ML), entrainment zone (EZ), stable layer, residual layer, and capping inversion. Above the PBL is the free atmosphere where the effects of friction from the earth's surface are negligible and the motion of air can be treated as an ideal fluid (Glickman, 2000). The surface layer is the layer of the atmosphere in contact with the earth's surface and is where the generation of mechanical turbulence by strong winds (Glickman, 2000). During daytime the ground is heated by the sun and a convectively driven, vertically ML grows (Stull, 1988). ML is above the surface layer and is characterized by turbulence created from forced or free convection that actively mixes such quantities as aerosols, potential temperature, and wind speed (Stull, 1988). At the top of the ML there exists a stable layer called the entrainment zone that is not well-mixed, and within which turbulence intensity decrease upwards (Seibert *et al.*, 2000). This layer is often called an inversion layer because there is a temperature increase with height (Smith, 2005). Above EZ, in the free atmosphere, the temperature usually decreases with height and the atmosphere becomes less stable (Stull, 1988). Above the nocturnal stable boundary layer is the residual layer, a left-over convective mixed/unstable layer. After sunrise, surface thermals rise easily to the top of the residual layer resulting in a rapid growth of the ML. During daytime the ML starts to slow down after sunset due to decay of turbulence and the presence of a capping inversion (Smith, 2005). During the night, the bottom portion of the residual layer starts to contact with the cool ground and is transformed into a stable boundary layer (Stull 1988).

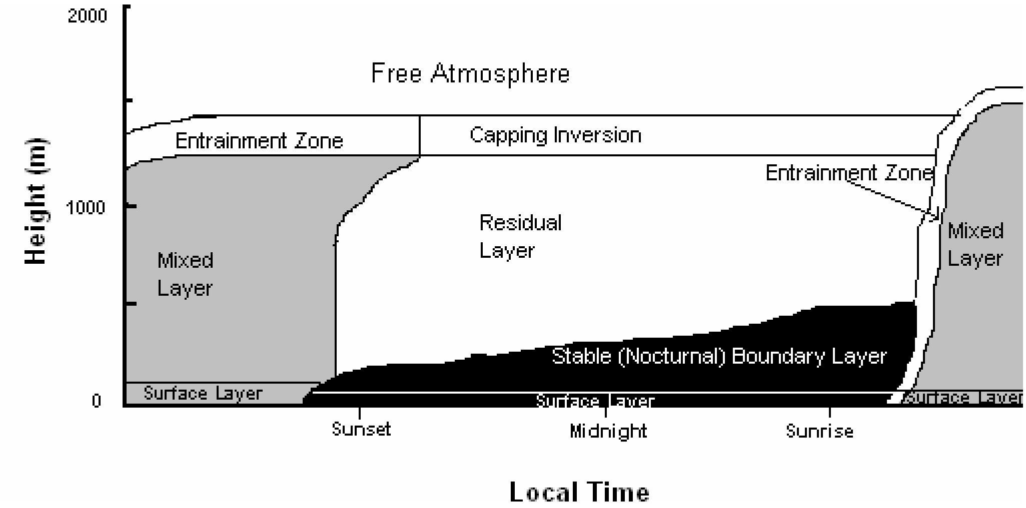

Figure 2.3 The diurnal evolution of PBL (Available from: Smith, 2005)

2.2.2 Adiabatic cooling process

As shown in Figure 2.4, adiabatic cooling process is the process in which the temperature of a system is reduced without any heat being exchanged between the system and its surroundings. The change in temperature of a mass of air as it moves upwards is defined as the adiabatic lapse rate (Glickman, 2000). There are two adiabatic lapse rates as follow.

2.2.2.1 Dry adiabatic lapse rate

The dry adiabatic lapse rate is the rate of temperature decrease with height for a parcel of dry air rising under adiabatic conditions (Glickman, 2000). Under this condition the air parcel expands due to the pressure decrease at higher altitudes. the air parcel pushes on the air around it, doing work when it expand. Since the air parcel does work by gaining no heat, it loses internal energy so that its temperature decreases at the rate 9.8°C per 1,000 m. But this process will not happen in the nature because in the nature the air is saturated with water vapor (Glickman, 2000).

2.2.2.2 Wet adiabatic lapse rate

The wet adiabatic lapse rate is applied when the air is saturated with water vapor. The lapse rate is around 5°C per 1,000 m for wet adiabatic cooling process. The reason for the difference between the dry and wet lapse rate is that latent heat is released when water condenses, thus decreasing the rate of temperature drop and make the wet lapse rate is lower than the dry lapse rate (Glickman, 2000).

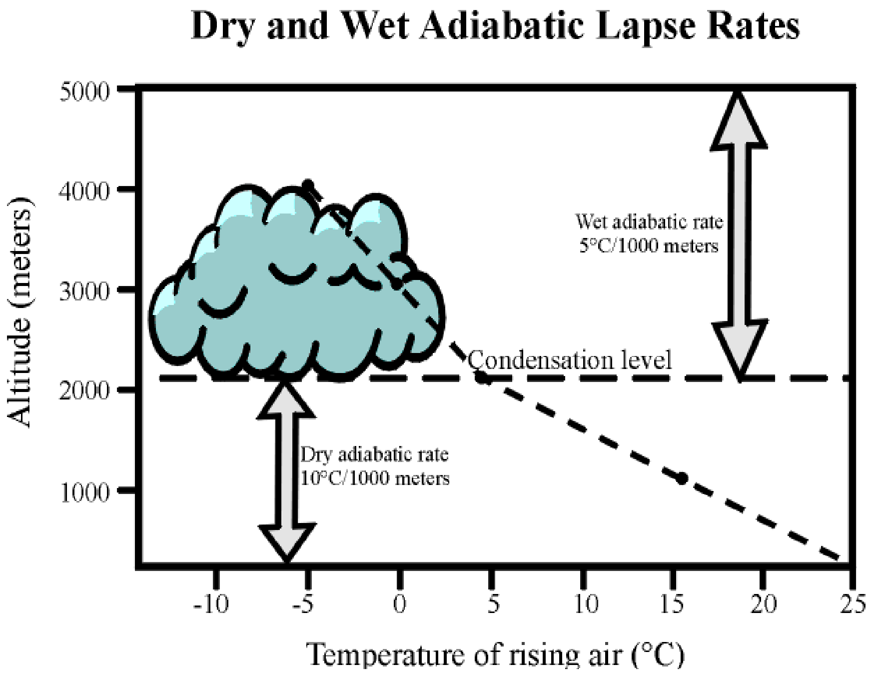

Figure 2.4 Adiabatic cooling process (Available from: http://www. geology. csupomona. edu)

2.2.3 Potential temperature

Many meteorologists determined the height of the boundary layer by using the concept of potential temperature. The scientists have defined the potential temperature as the temperature in a parcel of dry air could have if it was expanded or compressed adiabatically to a pressure of 1,000 mb. Potential temperature is going to be an important term when the scientists discuss the vertical stability of the atmosphere. Comparing the potential temperature of a parcel to its surroundings can tell us whether a region of air is stable or subject to lifting or sinking (Smith, 2005).

The equation which is used to describe the relationship between the temperature and pressure of the atmosphere during adiabatic expansion and compression referred to Poission's equation (Huschke,1959) and it is written as

$$\theta = T\left(\frac{1000}{P}\right)^{0.286}$$

Where θ is the potential temperature in Kevin (K)

T is current absolute temperature in Kevin (K)

P is the pressure in millibars (mb)

Potential temperature is a more dynamically important quantity than the actual temperature because it is not affected by the physical lifting or sinking associated with large scale atmospheric turbulence (Smith, 2005)

2.2.4 Mixing height

The mixing height is defined by the American Meteorological Society as the location of a capping temperature inversion or statically stable layer of air and often associated with, or measured by, a sharp increase of potential temperature with height, a sharp decrease of water-vapor mixing ratio, a sharp decrease in turbulence intensity, a sharp decrease in pollution concentration (Glickman, 2000). The mixing height is a key parameter in air pollution models determining the volume available for pollutants to dispersion (Seibert *et al.,* 2000). The mixing height concept is based upon the principle that heat transferred to the atmosphere at the earth's surface results in convection, vigorous vertical mixing and establishment of a dry adiabatic lapse rate. The development, temporal evolution, and spatial distribution of the mixing height depends on many factors including variations in surface albedo, surface moisture, synoptic condition, local circulation pattern, cloud cover, horizontal advection, land use, land cover and the urban heat island effect (Seibert *et al*., 2000; Smith, 2005). Many previous researches pointed that the UHI affected mixing layer by create mixing height (Duckworth and Sandberg, 1954; DeMarrais, 1961; Summers, 1967). Ludwig and Dabberdt (1973) found that nighttime mixing heights in urban area are higher than the rural area because of UHI effect. The depth through which such mixing extends depends primarily upon the initial vertical temperature structure and the heat input at the surface (Holzworth, 1972). A definable mixing height is assumed to occur under unstable and neutral conditions and it cannot be defined when the air mass above the surface is stable (Godish, 2004). In stable conditions, the height is not necessarily present because turbulence tends to be weaker and sporadic leading mixing to condition that range from well-mixed layer to little mixed layer (Seibert *et al*., 2000). They noted that the turbulent properties of PBL will rule whether pollutants are dispersed and diluted or whether they build up and led to pollution episodes. Thus the mixing height will determine the pollutant dispersion and depends on basic parameters, surface turbulent fluxes and physiographic parameters, and follows a diurnal cycle. Mixing height cannot be observed directly by standard measurements, so that it must be indirectly estimated from profile measurements or simulation (Piringer *et al.,* 2007). Smith (2005) summarized the techniques used to determine the mixing height that included the use of rawinsonde, radiosonde, wind profiler, lidar, sodar, and measurements of aerosol concentrations. The most common methods for determining the mixing height are utilization of radio-soundings by using a profile-intersection technique firstly proposed by Holzworth (1967).

The Holzworth (1967) noted that his method provides twice-per-day (morning and afternoon) mixing height based on calculations using upper-air-data. The Holzworth method was used to estimate mixing heights at times when radiosonde soundings were not available (usually in the afternoon), and was based on the concept that heating of the surface during the daytime results in vertical mixing that allows the development of a dry adiabatic lapse rate. The morning mixing height is calculated as the height above ground at which the dry adiabatic extension of the morning minimum surface temperature plus $5^{\circ}C$ intersects the vertical temperature profile. The minimum temperature is determined from the regular hourly airways reports from 0200 through 0600 LST (Local standard time). The “plus $5^{\circ}C$” was intended to allow for the effects of the nocturnal and early morning UHI. Holzworth (1967) realized that an overall average value of $5^{\circ}C$ might be excessive, even for large cities. Urban-rural temperature differences appear to depend on many factors such as city size, topography, state of ground, ect. (Holzworth, 1967). The afternoon mixing height can be calculated in the same way except that the maximum surface temperature observed from 1200 through 1600 LST is used and the temperature differences between an urban and rural are assumed negligible.

Previous studies of vertical atmospheric structure have appeared in the following literature.

Holzworth (1967) studied mixing height and wind speed through the mixing layers of the areas in United States. The results showed that monthly mean values of mixing heights and average wind speeds were shown to vary more or less from place to place, from month to month, and from morning to afternoon. The mixing heights and wind speeds were greater in the afternoons than in the mornings. The frequency of occurrence of various combinations of mixing height and wind speed were used in an urban diffusion model to calculate values of relative pollutant concentration. The results showed that the highest relative pollutant concentration occurred in the morning and lowest in the afternoon.

Bornstein (1968) studied differences in the temperature fields through lowest 700 m of the atmosphere in and around New York City during the hours near sunrise by using data from an instrumented helicopter. The results showed that urban surface inversions were less intense, and less frequent than those in the surrounding non-urban areas due to UHI effect.

May and Wilczak (1993) studied diurnal and seasonal variations of boundary-layer structure by using wind profiler at Denver in the latter half of 1989. The results showed the diurnal and seasonal variations of the boundary layer. The results reflected the effects of surface heating and local topography.

Revathy *et al.* (2001) studied the temperature profile at the tropical station Gadanki by using the radar technique. The results indicated that the diurnal variation of the temperature revealed a prominent diurnal variation with the peak in the afternoon hours increasingly delayed in altitude. The observed diurnal cycle appears to be driven by surface heating caused by solar insolation.

Emeis (2001) studied the mean wind speed profile at different sites in Germany by using the data from a mini-sodar. The results showed that the wind speed increased with height, and the general level of wind speed is higher than during the day in all heights.

Wang *et al.* (2008) studied seasonal variation of temperature profile and its characteristics within urban roughness sublayer in Beijing. The study results showed that the effect of urban building on the UBL thermal state had seasonal difference. That indicated the building rooftop played the role of heating or cooling the urban roughness sublayer, in winter or summer respectively.

Aikawa and Hiraki (2009) studied the seasonality of the vertical temperature profile in urban areas of Japan in the vicinity of the coast. They found that the vertical temperature profile showed the characteristic seasonality. The results showed that the elevated temperature inversion layer at noon was observed in summer.

2.3 Study areas description

Bangkok, Chiang Mai, Ubon Ratchathani, Songkhla and Phuket were chosen to be study areas. These cities have the difference size (defined by population density), local weather condition, and topography. The UHI intensity was analyzed by using data measured at two meteorological observatories (an urban site and a rural site) in each study area from the period 2004 to 2008. The criteria for selecting the urban/rural weather stations was that the urban station must lie in an area that is representative of the typical characteristics of the city such as high population density and high building density, while the rural station must lie outside the area of urban influence (Alonso *et al.,* 2003). The descriptions of study areas are described as following and the locations of study areas are shown in Figure 2.5.

Bangkok Metropolis

Bangkok Metropolis is the capital, largest urban area of Thailand. The Chao Phraya river flows through the Bangkok Metropolis area from the north to the Gulf of Thailand. It covers an area 1,568 km^2 (Department of Provincial Administration (DOPA), 2012). The elevation is about 2 m above the sea level. Bangkok has a tropical monsoon climate with three seasons namely summer (February-April), rainy season (May-October) and winter (November-January) (TMD, 2012). The urban weather station for this study was Bangkok Metropolis station (station code 455201). It is located in Khlong Toei District which the population density was 8,822 person/km^2(DOPA, 2012). The rural weather station was Bang Na agricultural station (station code 455301) which is located approximately 30 km from downtown Bangkok Metropolis in Bang Na District. The population density of Bang Na District was 5,298 person/km^2(DOPA, 2012).

Chiang Mai

Chiang Mai is the largest city in Northern Thailand. It is located 700 km north of Bangkok among the high mountains in the city. It covers an area 20,107 km^2 (DOPA, 2012). The elevation is about 310 m above the sea level. Chiang Mai has a tropical monsoon climate with three seasons namely summer (March-April), rainy season (May-October) and winter (November-February) (TMD, 2012). The urban weather station for this study is Chiang Mai meteorological station (station code 327501). It is located in Mueang Chiang Mai District which the population density was 1,545 person/km^2(DOPA, 2012). The rural weather station is Mae Jo agricultural station (station code 327301) that is located approximately 25 km from Mueang Chiang Mai in Sansai District. The population density of Sansai district was 398 person/km^2(DOPA, 2012).

Songkhla

Songkhla is one of the southern cities of Thailand. It is located on the coast of the Gulf of Thailand. The elevation is about 4 m above the sea level. There are two seasons, a dry season (February-July) and rainy season (August-January)(TMD, 2012). It covers an area 7,393 km^2 (DOPA, 2012). The urban weather station for this study was Songkhla meteorological station (station code 568501). It is located in Mueng Songkhla District which the population density was 946 person/km^2(DOPA, 2012). The rural weather station was Sadao meteorological station (station code 568401) that is located approximately 60 km from Mueng Songkhla District in Sadao District. The population density of Sadao District was 116 person/km^2(DOPA, 2012).

Phuket

Phuket is an island off the south-west coast of Thailand. Phuket has a fairly typical tropical weather pattern. There are two seasons, a dry season (December-April) and wet season (May-November)(TMD, 2012). It covers an area 3,634 km^2 (DOPA, 2012). The urban weather station for this study was Phuket meteorological station (station code 564201). It is located in Mueng Phuket District which the population density was 931 person/km^2(DOPA, 2012. The rural weather station was Phuket airport meteorological station (station code 564202) that is located approximately 20 km from Mueng Phuket District in Thalang District. The population density of Thalang District was 398 person/km^2(DOPA, 2012).

Ubon Ratchathani

Ubon Ratchathani is one of the north-eastern cities of Thailand. Ubon Ratchathani has a tropical monsoon climate with three seasons namely summer (February-April), rainy season (May-October) and winter (November-January)(TMD, 2012). It covers an area 16,112 km^2. The elevation is about 130 m above the sea level. The urban weather station for this study was Ubon Ratchathani meteorological station (station code 407501). It is located in Mueang Ubon Ratchathani District which the population density was 533 person/km^2(DOPA, 2012). The rural weather station was Ubon agricultural meteorological station (station code 407301) that is located approximately 20 km from Mueang Ubon Ratchathani District in Sawang Wirawong District. The population density of Sawang Wirawong District was 187 person/km^2(DOPA, 2012).

Figure 2.5 The location of the study areas.

(Adapted from: http://upload.wikimedia.org/wikipedia/Thailand_Bangkok_locator_map.svg)

Urban and rural weather stations' location and description are shown in Table 2.1

Table 2.1 Urban and rural weather stations' location and description

Station	Urban station	Rural station
Bangkok	Chaloemprakiet station (Bangkok Metropolis station)	Bang Na station
Altitude (m)	2	3
Longitude	100.30°E	100.36°E
Latitude	13.44°N	13.40 °N
Location	Khlong Toei District	Bang Na District
Chaing Mai	Chiang Mai station	Mae Jo station
Altitude (m)	312	317
Longitude	98.59° E	99.0°E
Latitude	18.47°N	18.55° N
Location	Mueang Chiang Mai District	Sansai District
Songkhla	Songkhla station	Sadao station
Altitude (m)	4	24
Longitude	100.37°E	100.25°E
Latitude	7.11°N	6.38°N
Location	Mueang Songkhla District	Sadao District
Phuket	Phuket station	Phuket airport station
Altitude (m)	9	2
Longitude	95.19°E	98.24°E
Latitude	8.8°N	7.53 °N
Location	Mueang Phuket District	Thalang District
Ubon Ratchathani	Ubon Ratchathani station	Ubon Agricutural station
Altitude (m)	122	130
Longitude	104.53°E	105.02°E
Latitude	15.15°N	15.14°N
Location	Mueang Ubon. District	Sawang Wirawong District

CHAPTER III

METHODOLOGY

3.1 Data collection

The data of the study areas were collected for this study as follows.

3.1.1 Meteorological data

The hourly meteorological data for the 5-yr period from 2004 to 2008 were obtained from an urban weather station and a rural weather station in study areas which were operated by TMD.

3.1.2 Upper meteorological data

The upper meteorological data were obtained from 2 sources;

3.1.2.1 The upper meteorological data from TMD

The upper meteorological data for the 1-yr period during 2008 were obtained from TMD. The upper meteorological data are usually investigated by using radiosonde technique at 0700 LST in the weather stations. The five weather stations which have conducted the radiosonde data are shown in Table 3.1 as the following.

Table 3.1 Location of weather stations which have the upper meteorological data collection

Station	Latitude	Longitude	Station code
Bangkok Metropolis station	113.44°N	100.3°E	455201
Chiang Mai station	18.47°N	98.59°E	327501
Songkhla station	7.11°N	100.37°E	568501
Phuket airport station	8.8°N	95.18°E	564202
Ubon Ratchathani station	15.15°N	104.5°E	407501

3.1.2.2 The upper meteorological data from CAPE project

The upper meteorological data were obtained from CAPE project during February 2008. The extra radiosonde data which followed CAPE project were conducted more than one time per day at the weather stations. This study selected Bangkok Metropolis station and Chiang Mai station to be the case studies. At Bangkok Metropolis station, the balloons were conducted six times per day (0000, 0300, 0600, 0900, 1200, 1800 LST) on 19-21 February 2008. At Chiang Mai station, the balloons were conducted four times per day (0000, 0600, 1200, 1800 LST) on 25-28 February 2008.

3.2 Methodology

This study proceeded through the following step. Work flow diagram is shown in Figure 3.1

3.2.1 Magnitude and characteristics of urban heat island analysis

The magnitude of UHI was studied in term of UHI intensity. UHI intensity is determined as the spatially averaged temperature difference between an urban and its surrounding rural area (Magee *et al.*, 1999; Kim and Baik, 2005). This study focused on maximum UHI intensity which referred to the maximum temperature difference between an urban and a rural area (Kim and Baik, 2005). The maximum UHI intensity stands for the highest warming of an urban area under most favorable weather conditions, such as few or no clouds and calm wind (Wienert and Kuttler, 2005).

The surface air temperature data was used to study the UHI intensity of the study areas by using the equation as below;

$$\Delta T = T_U - T_R$$

Where ΔT is the UHI intensity

T_U is the urban air temperature

T_R is the rural air temperature

3.2.1.1 Diurnal variation of UHI intensity analysis

In order to study diurnal variation of UHI intensity, the hourly surface air temperature data were proceeded through the following step.

1. The hourly surface air temperature data from the urban/rural weather station in study areas were calculated the UHI intensity for each individual hour (0100, 0200, 0300, 0400,…, 2400 LST) of the diurnal cycle for the period 2004-2008.
2. The highest value of UHI intensity in each hour of the study years was taken as the maximum UHI intensity.
3. The maximum UHI intensity data for each individual hour from the 5-yr period were averaged and were taken as the average maximum UHI intensity for each individual hour of the diurnal cycle.

3.2.1.2 *Seasonal variation of UHI intensity analysis*

In order to study seasonal variations of UHI intensity, the hourly surface air temperature data were proceeded in the following step.

1. The hourly surface air temperature data from urban/rural weather station in study areas were averaged for daily values.
2. The daily values of the surface air temperature from the urban/rural weather station in study areas were calculated the UHI intensity for each day.
3. The highest value of the UHI intensity in each month of the study years was taken as the maximum UHI intensity.
4. The maximum UHI intensity data for each individual month from the 5-yr period were averaged and were taken as the average maximum UHI intensity.

3.2.2 Analysis of the relationship between the meteorological elements and UHI

In order to study the relationship between the three meteorological elements (wind speed, cloud cover, relative humidity) and UHI intensity, the data of surface air temperature, wind speed, cloud cover, and relative humidity for the 5-yr period from 2004 to 2008 which were derived from weather stations were proceeded in the following step.

1. The hourly surface air temperature data from the urban/rural weather stations in study areas were averaged for daily values.
2. The daily values of the surface air temperature from the urban/rural weather station in study areas were calculated the UHI intensity for each day.
3. The hourly data of wind speed, cloud cover, and relative humidity from the urban weather station in study areas were averaged for daily values.
4. The further investigation of possible influence of environmental variables on urban heating was explored by carrying out regression analysis. In the regression analysis, the independent variables were the meteorological elements namely cloudiness, wind speed and relative humidity and the dependent variable is the UHI intensity.
5. The coefficients of determination (R^2) were summarized.

3.2.3 The vertical atmospheric structure analysis

In order to study the vertical atmospheric structure during the UHI events the upper meteorological data in study areas derived from CAPE project were used to study the variations of vertical atmospheric structure. The extra radiosonde data which followed CAPE project were conducted more than one times per day at the weather stations. This study selected Bangkok Metropolis station and Chiang Mai station to be the case studies. At Bangkok Metropolis station, the balloons were conducted six times per day (0000, 0300, 0600, 0900, 1200, 1800 LST) on 19-21 February 2008. At Chiang Mai station, the balloons were conducted four times per day (0000, 0600, 1200, 1800 LST) on 25-28 February 2008. Radiosonde technique provided the temperature data, wind speed data at standard pressure levels (1,000, 850, 700, 500 mb etc.). In this study the standard pressure levels were converted to altitude.

3.2.3.1 Vertical atmospheric profiles analysis

In order to study the vertical profile of temperature, potential temperature and wind speed during the UHI events, the radiosonde data for temperature, wind speed were proceeded in the following step.

1. The upper air temperature data from CAPE project were examined vertical temperature profile at 0000, 0300, 0600, 0900, 1200, 1800 LST for Bangkok and 0000, 0600, 1200, 1800 LST for Chiang Mai.
2. The upper air temperature data from CAPE project were analyzed potential temperature by using Poisson’s equation as below;

$$\theta = T\left(\frac{1000}{P}\right)^{0.286}$$

Where θ is the potential temperature in Kevin (K)

T is current absolute temperature in Kevin (K)

P is the pressure in millibars (mb)

3. The upper wind speed data from CAPE project were examined the vertical wind speed profile at 0000, 0300, 0600, 0900, 1200, 1800 LST for Bangkok and 0000, 0600, 1200, 1800 LST for Chiang Mai.

3.2.3.2 Mixing Height analysis

The surface temperature data from TMD and the upper air temperature data from CAPE project were used to examine mixing height in the case study area (Bangkok Metropolis station and Chiang Mai station) by using Holzworth method. As follow Holzworth method, the data were proceeded in the following step.

1. The upper temperature data were used to plot the vertical temperature profile.
2. The minimum surface temperature from 0200 through 0600 LST plus 5°C was used to plot dry the adiabatic lapse rate line.
3. The morning mixing height was determined as the height above ground at which the dry adiabatic lapse rate line intersected the vertical temperature profile.
4. The afternoon mixing height were calculated in the same way except that the maximum surface temperature observed from 1200 through 1600 LST was used to plot the dry adiabatic lapse rate line.

3.2.4 Analysis of the relationship between UHI effect and vertical atmospheric structure

3.2.4.1 The relationship between UHI and vertical atmospheric structure

In order to study the relationship between UHI effect and vertical atmospheric structure in ML, the surface temperature data, the upper meteorological data for 1-yr period (2008) at 0700 LST, the upper meteorological data from CAPE project were preceeded through the following step.

1. The surface temperature data from urban/rural weather station in study areas for 1-yr period (2008) at 0700 LST were calculate the UHI intensity.

2. The surface temperature data and the upper temperature data for 1-yr period (2008) at 0700 LST were used to study the difference of temperature between the surface temperature and the upper temperature (ΔT) at the levels 110m, 1,353m and 2,563 m.

3. The surface wind speed data and the upper wind speed data for 1-yr period (2008) at 0700 LST were used to study the difference of temperature between the surface wind speed and the upper wind speed (ΔW) at the levels 110m, 1,353m and 2,563 m.

4. In order to study the relationship between UHI and the vertical atmospheric structure in each altitude, regression analysis was carried out. The coefficient of determinations (R^2) indicated the strength of the association of the two variables.

5. The surface temperature data and the upper meteorological data from CAPE project which were conducted at 0000, 0300, 0600, 0900, 1200,1800 LST in Bangkok Metropolis on 19-21 February 2008 and were conducted at Chiang Mai station at 0000, 0600, 1200 and 1800 LST on 25-28 February 2008 were preceeded through the step 1-4 as shown in the beginning.

3.2.4.2 <u>The relationship between UHI and mixing height</u>

In order to study the relationship between UHI effect and mixing height the surface air temperature data and the upper air temperature data from CAPE project in the case study areas (Bangkok Metropolis and Chiang Mai) were preceeded through the following step.

1. The surface temperature data from urban/rural weather station in the case study areas during the study period which followed CAPE project were examine the UHI intensity in study areas.

2. The upper air temperature data from CAPE project were used to examine the mixing height by Holzworth Method.

3. In order to study the effects of UHI on mixing height, regression analysis were carried out. In regression analysis, independent variable was the UHI intensity and dependent variable was the mixing height. The coefficient of determination (R^2) indicated the strength of the association of the two variables.

3.2.4.3 Sensitivity analysis for estimating morning mixing height by Holzworth method

In order to analyze the sensitivity of estimation for mixing height by Holzworth method, surface air temperature from TMD and the upper air temperature data from CAPE project in the case study areas (Bangkok Metropolis and Chiang Mai) were preceeded through the following step.

1. The upper air temperature data from CAPE project were used to estimate the morning mixing height by using Holzworth Method.
2. To analyze the sensitivity for estimation mixing height by Holzworth method, the "plus 5°C" which was established to allow for urban-rural difference in morning surface air temperature would be change to 4°C, 3°C, 2°C and 1°C. These constant values were used to add the minimum surface temperature followed Holzworth method and were conducted the scenarios for estimating mixing height.
3. The mixing height from each scenario would be compare with the mixing height which was observed by using temperature profile.

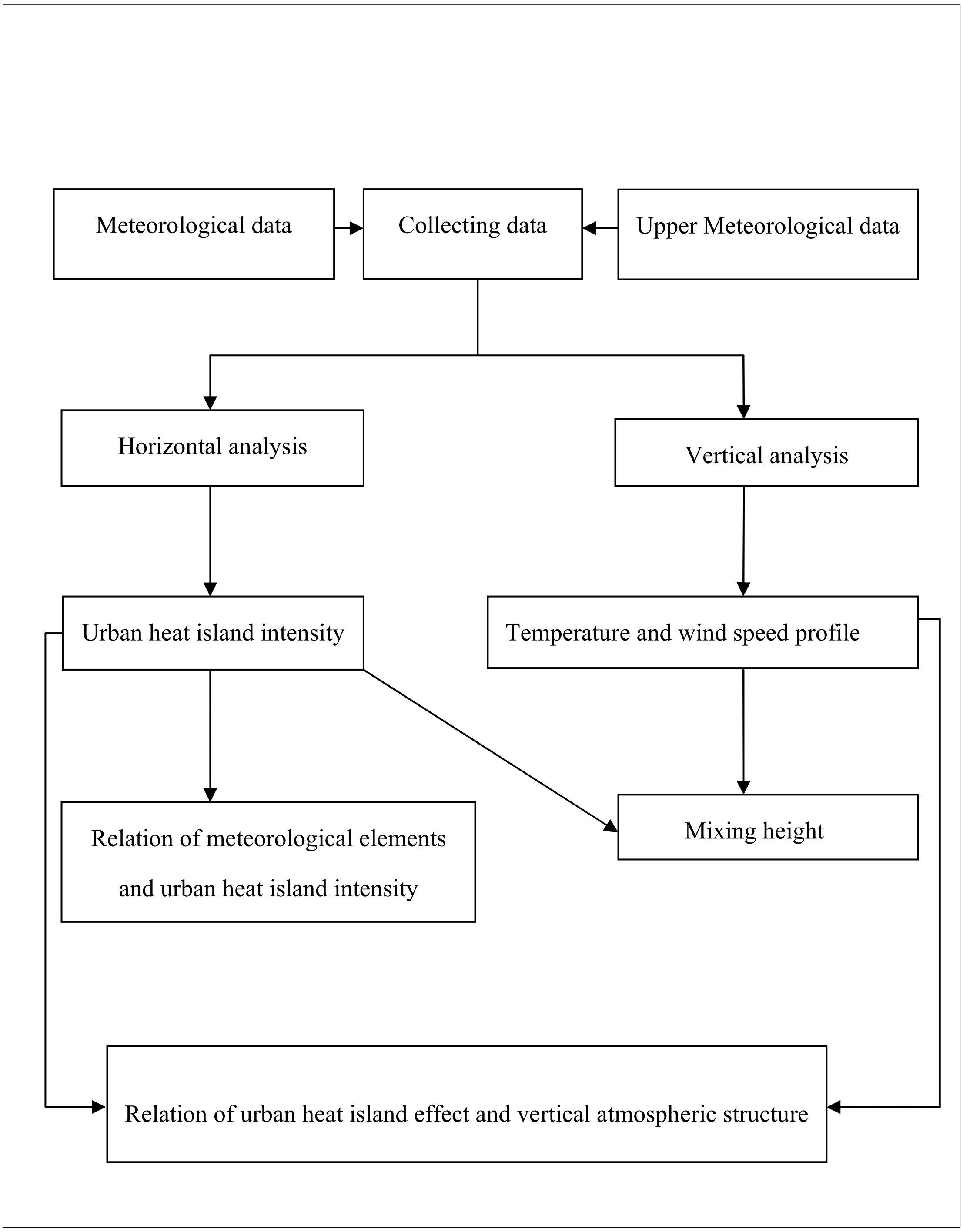

Figure 3.1 Work flow diagram

CHAPTER IV

RESULTS AND DISCUSSIONS

This present study could be divided into 3 parts; the magnitude and characteristics of UHI, the vertical atmospheric structure during the UHI events, and the effects of UHI on vertical atmospheric structure.

4.1 Magnitude and characteristics of UHI

The magnitude and characteristics of UHI were investigated by analyzing the difference of surface air temperature between an urban and a rural area. This study focused on the maximum UHI intensity which referred to the maximum temperature difference between an urban and a rural area. The magnitude and characteristics of UHI were examined for diurnal cycle and seasonal cycle.

4.1.1 The diurnal variation of UHI intensity

In order to study the diurnal variation of maximum UHI intensity, the average maximum UHI intensity was examined for each individual hour of the diurnal cycle for the 5-yr period from 2004 to 2008. The results of the diurnal variations of average maximum UHI intensity at all study areas were showed in Figure 4.1. The frequency of UHI events were examined by analyzing UHI intensity which was more than 1 °C maintained more than 1 hour from the period 2004-2008 (Jauregui, 1997; Kim and Baik, , 2005). The results of frequency (%) of UHI events were showed in Figure 4.2. The study results from this data set are described in the following.

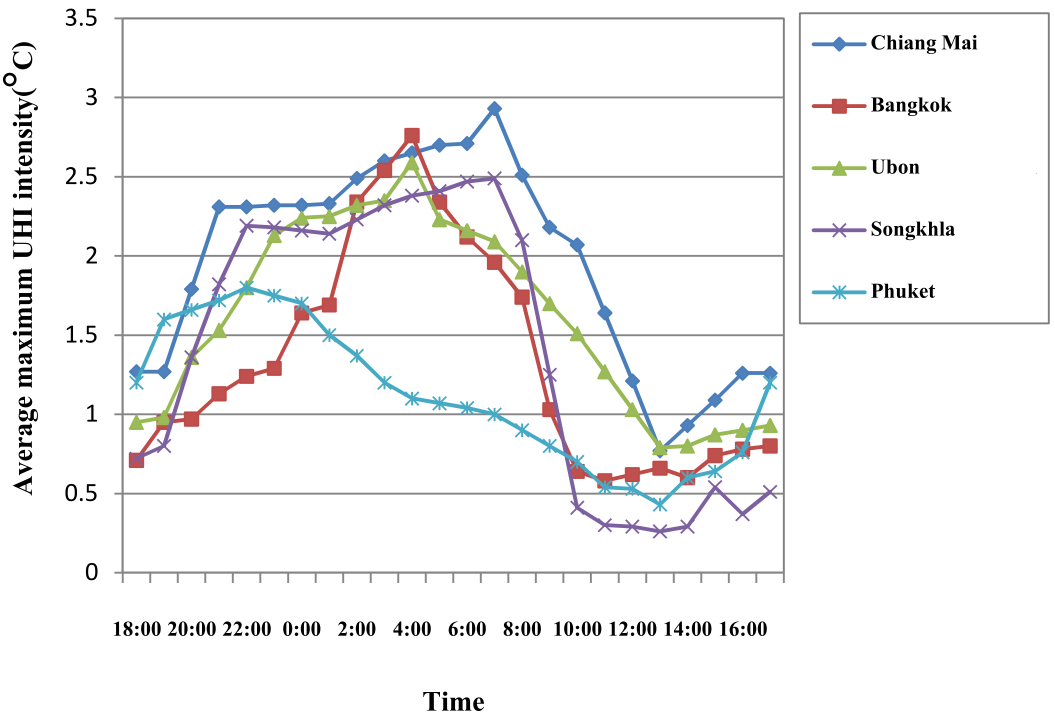

Figure 4.1 The diurnal variation of the average maximum UHI intensity at the study areas for the period 2004-2008

According to Figure 4.1, the study results showed the difference of the average maximum UHI intensity among the cities. Concerning the magnitude of intensity for diurnal cycle, the average value of the maximum UHI intensity was the highest in Chiang Mai (1.96°C), followed by Ubon Ratchathani (1.61°C), Songkhla (1.42°C), Bangkok (1.33°C) and Phuket (1.13°C). The average value of maximum UHI intensity for diurnal cycle was 1.96°C in Chiang Mai city with a population density of 1,768 person/km^2, while the average value of maximum UHI intensity for diurnal cycle was 1.33°C in Bangkok city with a population density of 8,822.61 person/km^2. These results showed that the city size (defined by a population density) did not clearly relate to UHI intensity because the maximum of UHI did not appear as expect. Many previous studies were agreeable with this finding. Rizwan *et al.* (2008) reviewed the UHI from other researches and suggested that the city size could, but not necessarily affect on the UHI intensity. Kim and Baik (2005) studied UHI in Seoul of Korea and the study results did not showed the UHI intensity related with population. On the other hand, Tran *et al.* (2006) studied UHI in twelve Asian mega cities and reported that the magnitude of UHI was positively correlated with city population. Zhang *et al.* (2009) found a positive correlation between UHI intensity and total registered population in Shanghai, China. Rizwan *et al.* (2008) reviewed that the heat content will likely be increased with the increasing population due to the population density could have effects on heat generation, a direct effect as more people means more anthropogenic heat and indirect effect as a number of buildings, vehicles, factories etc. However, they reviewed that other variables such as sky view factor, building design and building material etc. do play an important part in increasing heat content. This present study showed that UHI intensity tended to be depended on the city topography and local weather conditions. The average maximum UHI intensity was weaker in coastal cities (e.g. Bangkok, Songkhla and Phuket) than in inland cities (e.g. Chiang Mai and Ubon Ratchathani). This finding was similar to previous study in Korea. Kim and Baik (2005) showed that the UHI intensity in the large cities of Korea tended to be lower in coastal cities than in inland cities due to the influence of sea breeze. Therefore, the UHI intensity was different among the cities because many factors influence the UHI intensity including city size, and its geographical location, urban morphology, local and synoptic weather, season and time of day, (Kim and Baik, 2005; Rizwan *et al.*, 2008).

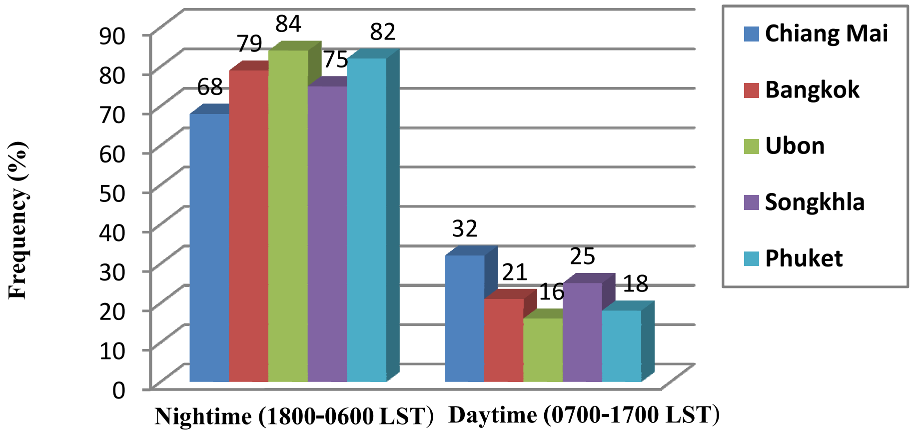

Figure 4.2 Frequency (%) of UHI events which the UHI intensity was more than 1°C and maintained more than 1 hour during two periods of the day for the period 2004 -2008.

According to the Figure 4.1, the results from all study sites showed diurnal variations of the average maximum UHI intensity. The highest values was 2.93°C at 0700 LST for Chiang Mai, 2.76°C at 0400 LST for Bangkok, 2.59°C at 0500 LST for Ubon Ratchathani, 2.49°C at 0700 LST for Songkhla and 1.80°C at 2200 LST for Phuket. While the lowest values was 0.77 °C at 1300 LST for Chiang Mai, 0.58°C at 1100 LST for Bangkok, 0.79°C at 1300 LST for Ubon Ratchathani, 0.26°C at 1300 LST for Songkhla and 0.43°C at 1300 LST for Phuket. These results indicated that the highest value of the maximum UHI intensity was found during the nighttime or the early morning, while the lowest value of maximum UHI intensity was found during daytime. In addition, as shown in Figure 4.2, the frequency which thermal contrast between urban and rural area were more than 1°C maintained more than 1 hour occurred during 1800-0600 LST with 68 % for Chiang Mai, 79 % for Bangkok, 84 % for Ubon Ratchathani, 75 % for Songkhla, and 82 % for Phuket, while occurred during 0700-1700 LST with 32 % for Chiang Mai, 21 % for Bangkok, 16 % for Ubon Ratchathani, 25 % for Songkhla and 18 % for Phuket. The results showed that the UHI events which were determine by this criteria was observed during the nighttime more than the daytime. These results were similar to the previous studies in other cities such as Seoul (Kim and Baik, 2005), Singapore (Chow and Roth, 2006), Beijing (Liu *et al*, 2007), and Mexico City (Jauregui *et al,* 1997). The main cause of these results was the differences in heating rate after the sunrise and cooling rates after the sunset between urban and rural areas. The cooling rates are influenced by surface geometry and surface thermal properties (Oke *et al.*, 1991). During the day, urban surfaces trap more incoming solar radiation by the building, road and other constructions than surfaces in rural areas. During the night, stored heat is released slowly from the urban surface, while in rural surface the stored heat can release rapidly (Shahmohamadi *et al*., 2010). The ability of heat release by long-wave radiation in urban areas is low due to decreased sky view which results in heat storage in building structures (Rizwan *et al.,* 2008). While the open spaces of the rural areas enhances radiative cooling because the areas cannot confine air which has been heated during the day (Liu et al., 2007). Furthermore, the urban areas release heat at night from human activities (e.g. light, traffic, cooling or heating the building etc. which play a significant role in increase the UHI events at nighttime.

On the other hand, the study results showed that thermal contrasts between an urban and a rural area were negative values in some of the days. This means the temperatures in an urban area were lower than a rural area. The data showed that the air temperature of an urban area was 1-2°C lower than its surrounding rural area during the daytime (1000 LST- 1600 LST). The frequency of these events were approximately 5 % for Bangkok, 14 % for Chiang Mai, 11 for Songkhla, 13 % for Phuket and 10 % for Ubon Ratchathani and could be found every season. The negative UHI intensity or lower temperature in urban area is conventionally referred to urban cool island (UCI) or urban cool valley (UCV) (Jauregui, 1997; Montavez *et al*., 2000; Kim and Baik, 2005). This finding was similar to previous study in other countries. Alonso *et al*. (2003) found that the UHI intensity in the cities of Spain displayed negative values, such that the highest temperatures were found at the lowest density of buildings and the lowest daytime temperatures were seen in areas where the density and height of the buildings were greater because the building, which afford shade, prevent the arrival of direct solar radiation. Tran *et al*. (2006) studied the UHI intensity in mega cities and they found that the UCI intensity increased during the solar peak hours (from 0900 to 1800 LST), while solar radiations have decreased during the same time. Shigeta *et al*. (2009) studied the cool island intensity of Okayama City and the results indicated that the UCI intensity was larger from 0800 to 1800 JST and was smaller from 2100 to 0600. Especially, a cool island clearly appears about 1-2° C for 1000-1200 JST. Many studies pointed that attenuation of solar radiation is the main reason of urban cool island (Lee *et al*., 2009).

4.1.2 Seasonal variation of UHI intensity

In order to investigate seasonal variation of UHI intensity, the average surface air temperature data from urban and rural weather station in study areas were examine the UHI intensity. The highest value of the UHI intensity in each month was taken as the maximum UHI intensity. The average of maximum UHI intensity from 5-yr studied period would be presented. The study results from this data set are described in the following.

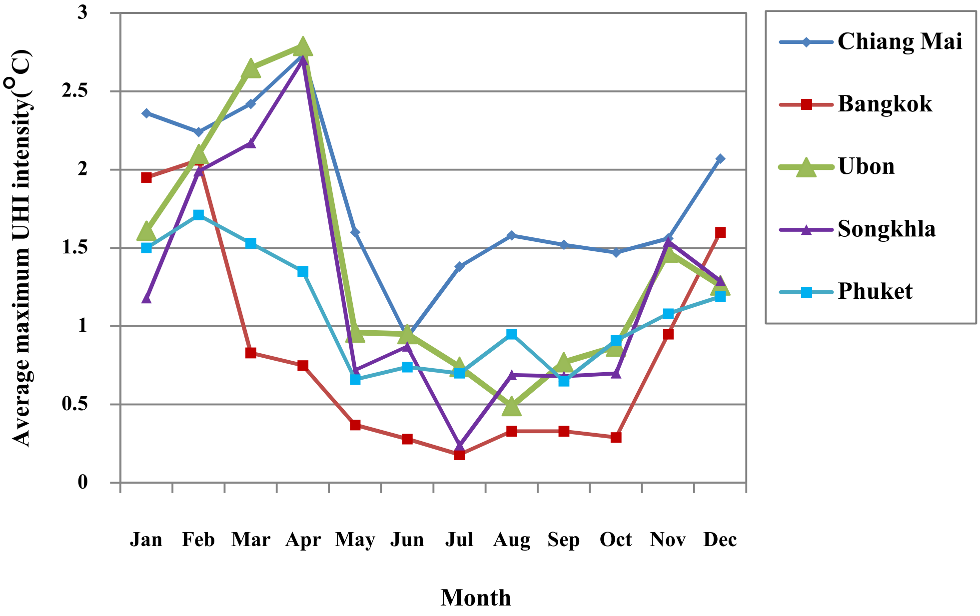

Figure 4.3 The seasonal variation of the maximum UHI intensity at the study areas for the period 2004-2008

As showed in Figure 4.3, the study results showed the seasonal variation of maximum UHI intensity for all study areas. The highest value of the average UHI intensity was 2.73^{O}C in April for Chiang Mai, 2.06^{O}C in February for Bangkok, 2.79^{O}C in April for Ubon Ratchathani, 2.70^{O}C in April for Songkhla, and 1.71^{O}C in February for Phuket. While the lowest value was 0.90^{O}C in August for Chiang Mai, 0.18^{O}C in July for Bangkok, 0.49^{O}C in August for Ubon Ratchathani, 0.24^{O}C in July for Songkhla, 0.42^{O}C in September for Phuket. The results from the cities in northern Thailand (e.g. Chiang Mai, Bangkok, Ubon Ratchathani) showed that the average maximum UHI intensity was highest in dry season (from November to May) and the lowest value was observed in wet season (July-October). In northern Thailand between November and May the weather is mostly dry and the wind speed, cloud cover and relative humidity were less than in the wet season (from May to November). During the wet season the weather is dominated by the southwest monsoon, so this period the rainfall is at its heaviest. In the southern Thailand, on the east coast, the southwest monsoon brings rain and storm between September and December, while on the west coast the rainfall between April and October. Similar to the cities in the northern Thailand, the results from Songkhla and Phuket which located in the southern Thailand showed that the average maximum UHI intensity was the lowest in wet seasons, while the highest value was found in dry season. Therefore the maximum UHI intensity tended to have the negative correlation with the wind speed, cloud cover, and relative humidity. Many previous studies have indicated that the seasonal variations of UHI intensity related to local meteorological conditions such as wind speed, cloud cover and relative humidity (Oke, 1982; Montavez *et al*., 2000; Unger *et al.*, 2001; Kim and Baik, 2002; Zhang *et al*., 2009). Liu et al. (2007) reported that in summer, when relative humidity was high, the UHI intensity was low. Chow and Roth (2006) reported that the seasonal variability in the UHI intensity related to the variability of moisture content, which was largely influenced by the seasonal variation of precipitation. Zhang *et al*. (2009) reported that the wind speed and cloudiness had the smallest values in autumn, so at that time the UHI intensity was the strongest and the highest wind speed and cloudiness caused the UHI intensity was the weakest in summer.

In addition, many previous studies pointed that the UHI intensity related to the seasonal variations of energy demand. Liu *et al. (*2007) found that intensity in Beijing was greatest in winter and in spring and they gave the reason that because energy demands in winter were higher than other seasons. Kim and Baik (2005) also found the mean maximum UHI intensity was weakest in summer and was strong in autumn and winter due to energy demands in winter for cooling building are much higher than other seasons. Therefore, an increasing of energy consumption to heat or cool buildings can generate UHI in an urban area (Shahmohamadi *et al*., 2010). On the other hand, Oke (1982) suggested that the fact that UHI is best displayed in summer, whereas peak heating requirements are in winter, may indicate that anthropogenic heat is not a primary cause.

4.1.3 The relationship between the meteorological elements and UHI

The linear regression analysis was carried out for investigation the impact of environmental variables on UHI effect. The average UHI intensity, wind speed, cloud cover and relative humidity were used to carry out regression analysis. The study results from this data set are described in the following.

4.1.3.1 <u>Wind speed and UHI</u>

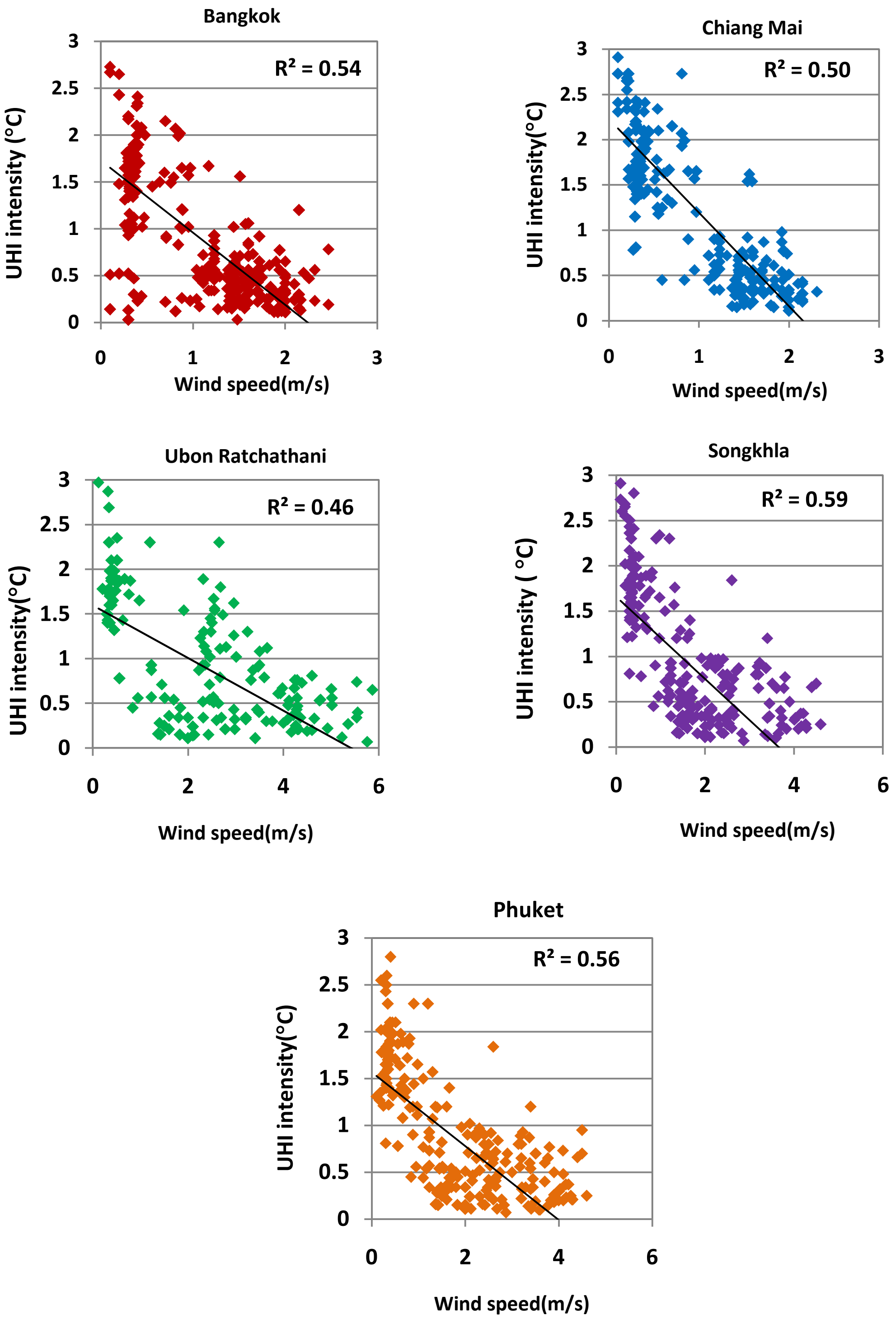

Figure 4.4 The relationship between of the UHI intensity and wind speed for Bangkok, Chiang Mai, Ubon Ratchathani, Songkhla, and Phuket.

As shown in Figure 4.4, the results for all study areas indicated that the average UHI intensity and wind speed had the negative correlation. This means is the UHI intensity will increase as the wind speed decrease. The coefficient of determinations (R^2) was 0.54 for Bangkok, 0.50 for Chiang Mai, 0.59 for Songkhla, 0.56 for Phuket and 0.46 for Ubon Ratchathani. The study results were similar to the previous studies. Sundborg (1950) was the first to relate UHI intensity to meteorological elements such as cloudiness, wind speed, temperature, and absolute humidity using a multiple linear regression method, the results showed that the cloudiness and wind speed parameters are negative correlated with the UHI intensity in Uppsala, Sweden. Kim and Baik (2002) examined the relationship between the maximum UHI intensity and meteorological elements by carrying out regression analysis, the results showed the negative correlation between maximum UHI intensity and wind speed. Many previous studies indicated that the mean UHI intensity was strong during the calm wind. Morris *et al*. (2001) found that for Melbourne, Australia, low wind speeds and litter or no cloud resulted in the largest UHI development. Kim and Baik (2002) reported the maximum UHI intensity in Seoul that a decrease in maximum UHI intensity could be visible with wind speed greater than 0.8 m/s while with the critical wind speed of 7.0 m/s maximum UHI intensity of 0.3°C or less could vanish. Chow and Roth (2006) reported that the highest maximum UHI intensity (7.07°C) in Singapore was observed under conditions of light wind (0.9 m/s). These can be explained that when the wind speed increased, enhanced air advection and turbulent activity then caused thermal contrast between urban and rural area reduced (Kim and Baik, 2002). However, although event with complete cloud cover and wind speeds in excess of 5 m/s the UHI was still present (Morris *et al.,* 2001).

The results showed the wind speed affected the UHI intensity. On the other hand, the UHI can affect the wind speed of an urban area. Collier (2006) pointed that UHI affects the air flowing over the city by modifying local pressure field, increasing turbulence, and the stability. Hand (2005) noted that the frequency of showers in light wind conditions in summer revealed the impact of the London heat island effect to the south and east of the city.

4.1.3.2 *Cloud cover and UHI*

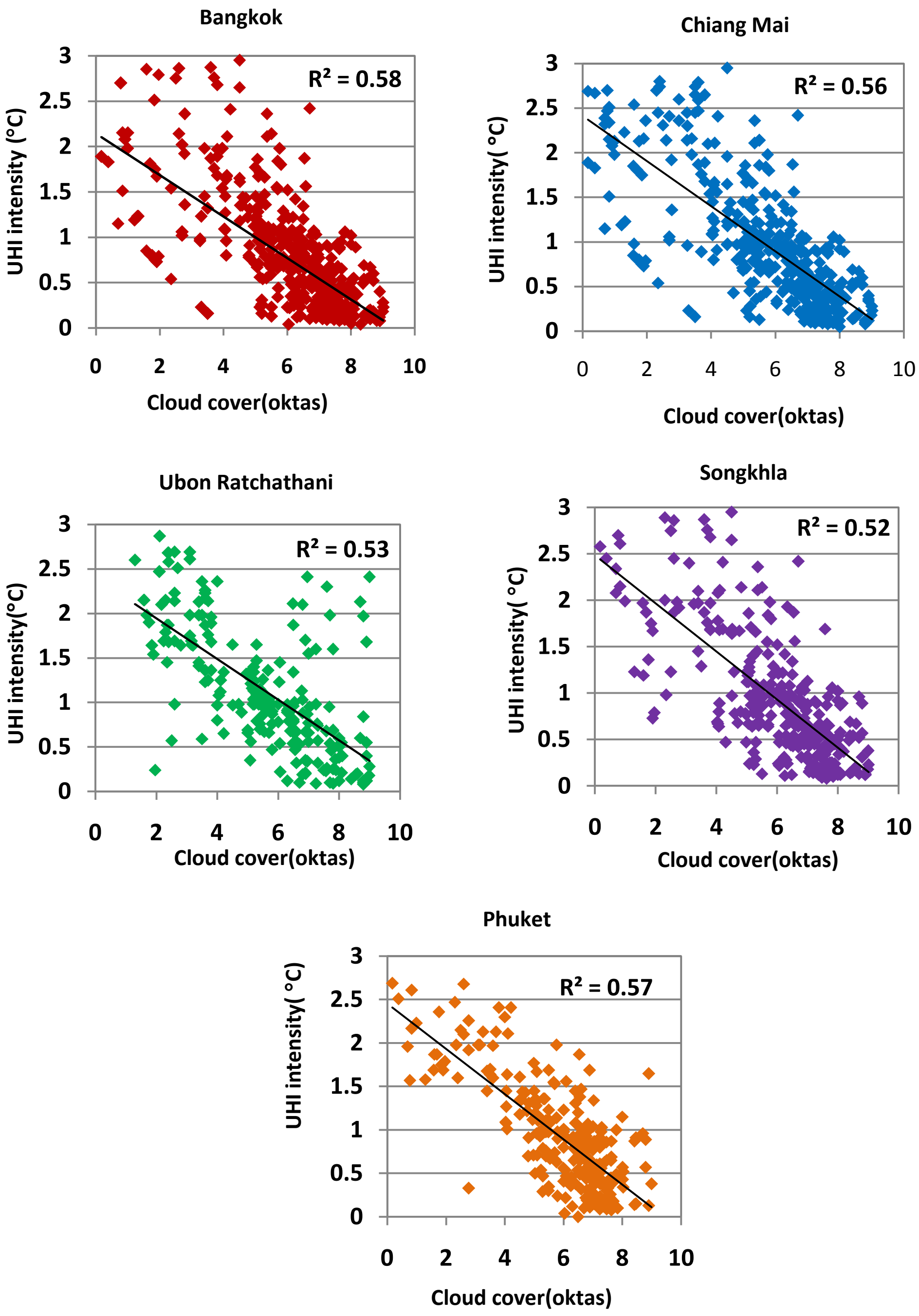

Figure 4.5 The relationship between of the UHI intensity and cloud cover for Bangkok, Chiang Mai, Ubon Ratchathani Songkhla, and Phuket.

As shown in Figure 4.5, the correlation between the average UHI intensity and cloud cover demonstrated negative correlation for all study areas. The coefficient of determinations (R^2) was 0.58 for Bangkok, 0.56 for Chiang Mai, 0.52 for Songkhla, 0.57 for Phuket and 0.53 for Ubon Ratchathani. These indicted that the UHI would decrease when the sky was cloudy. The study results were similar to the previous studies. Morris and Simmonds (2001) studies the influences of wind and cloud on the nocturnal UHI of the large cities of Melbourne and the results indicated that low wind speeds and little or no cloud were typically associated largest UHI development. Kim and Baik (2002) found that the maximum UHI intensity in Seoul had a peak at 4.5°C when the cloudiness is 0, while the maximum UHI intensity was 1.7°C when the cloudiness is 10. They pointed that UHI phenomena can be observed even when the sky is completely covered by clouds or precipitation or fog exists, but the maximum UHI intensities are usually much weaker than those where there are no cloud. A negative correlation between the UHI intensity and cloud cover can be explained that when the sky is cloudy, clouds absorb long wave radiation from the sun and the surface, so the diurnal variations of temperature in urban area is reduced (Oke, 1987). These cause the thermal contrast between an urban and a rural area reduce.

4.1.3.3 Relative humidity and UHI

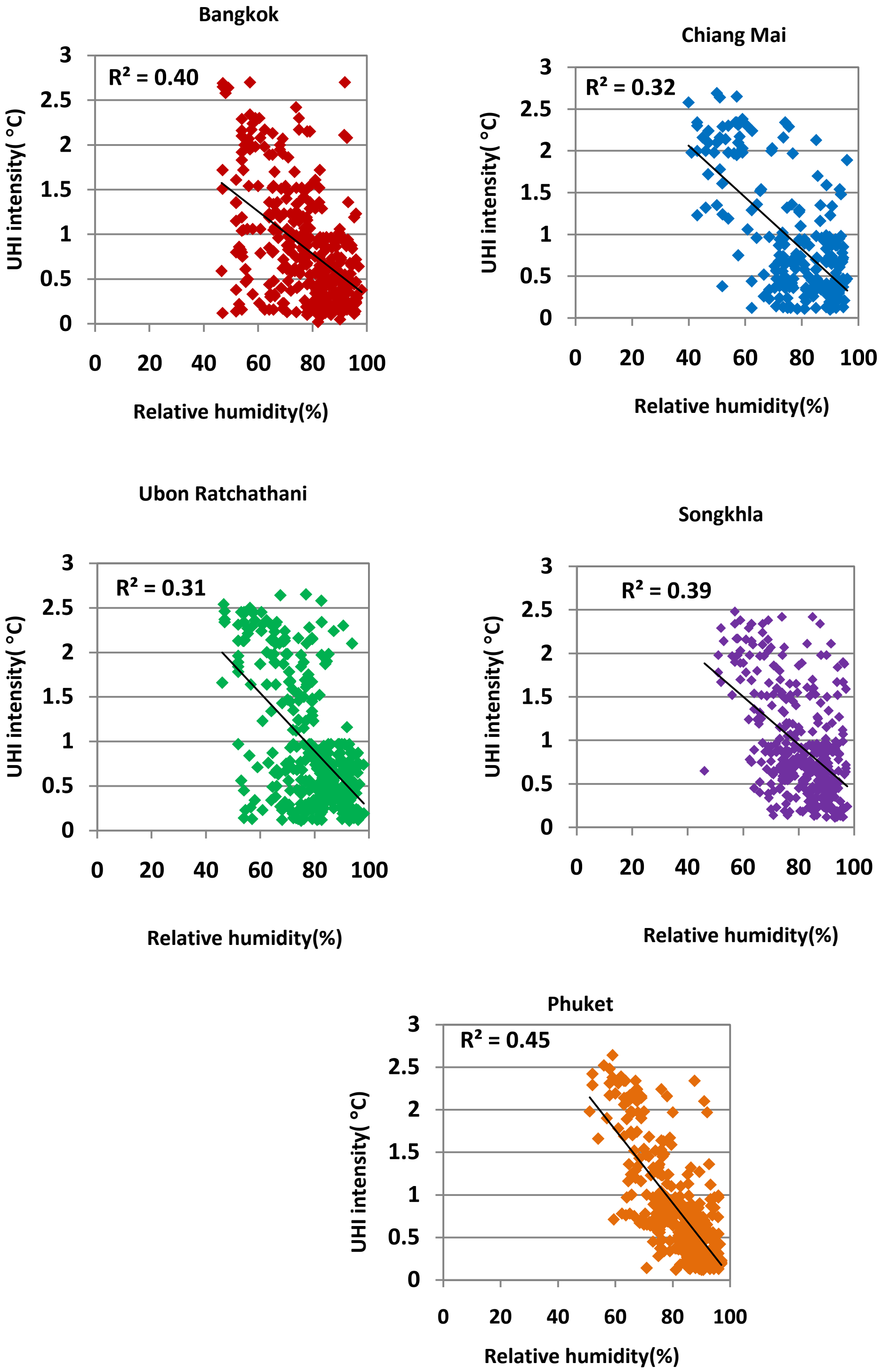

Figure 4.6 The relationship between of the UHI intensity and relative humidity for Bangkok, Chiang Mai, Ubon Ratchathani Songkhla, and Phuket

As shown in Figure 4.6, the correlation between the mean UHI intensity and relative humidity demonstrated negative correlation for all study areas. The coefficient of determinations (R^2) was 0.40 for Bangkok, 0.32 for Chiang Mai, 0.39 for Songkhla, 0.45 for Phuket and 0.31 for Ubon Ratchathani. This mean the UHI would increase when the relative humidity decrease. These results were agreeable with the previous research. Lie *et al.* (2007) studied the UHI in Beijing and the results showed that seasonal variation of UHI tended to be negatively correlated with seasonal variation of relative humidity and vapor pressure. Kim and Baik (2002) investigated the relationship between maximum UHI intensity and relative humidity in Seoul and the results showed the negative correlation between them. Based on this result, they explain the mechanism for this relationship that when evaporation from the surface takes place, the surface air temperature decreases because of evaporative cooling and relative humidity increases due to an increase in water vapor pressure and a decrease in saturation water vapor pressure. So, the UHI intensity tends to decrease as relative humidity and water vapor pressure increase. Liu *et al.* (2007) compared the relative humidity and water vapor pressure between urban and rural areas in Beijing and they found that relative humidity in urban areas is always less than the relative humidity in rural areas due to lack of vegetation and natural soil.

From these results, it can be summarized that the meteorological conditions from day to day or from season to season influence on the magnitude of UHI intensity apart from magnitude of surface temperature and surface properties.

4.2 Vertical atmospheric structure during the UHI events

In order to examine vertical atmospheric profiles of temperature, potential temperature, wind speed during the period of UHI events, the upper meteorological data derived from investigation by using radiosonde technique which followed the project of characteristics of atmospheric profile and its effects on variation of air pollutants in Thailand (CAPE) were used. The extra radiosonde observations were performed for Bang Na station on 19-21 February 2008at 0000 LST, 0300 LST, 0600 LST, 0900 LST, 1200 LST, and 1800 LST and for Chiang Mai station on 26-28 February 2008 at 0000 LST, 0600 LST, 1200 LST, and 1800 LST. The study results from this data set are described in the following.

4.2.1 The variation of temperature profile during the period of UHI events

Bangkok Metropolis

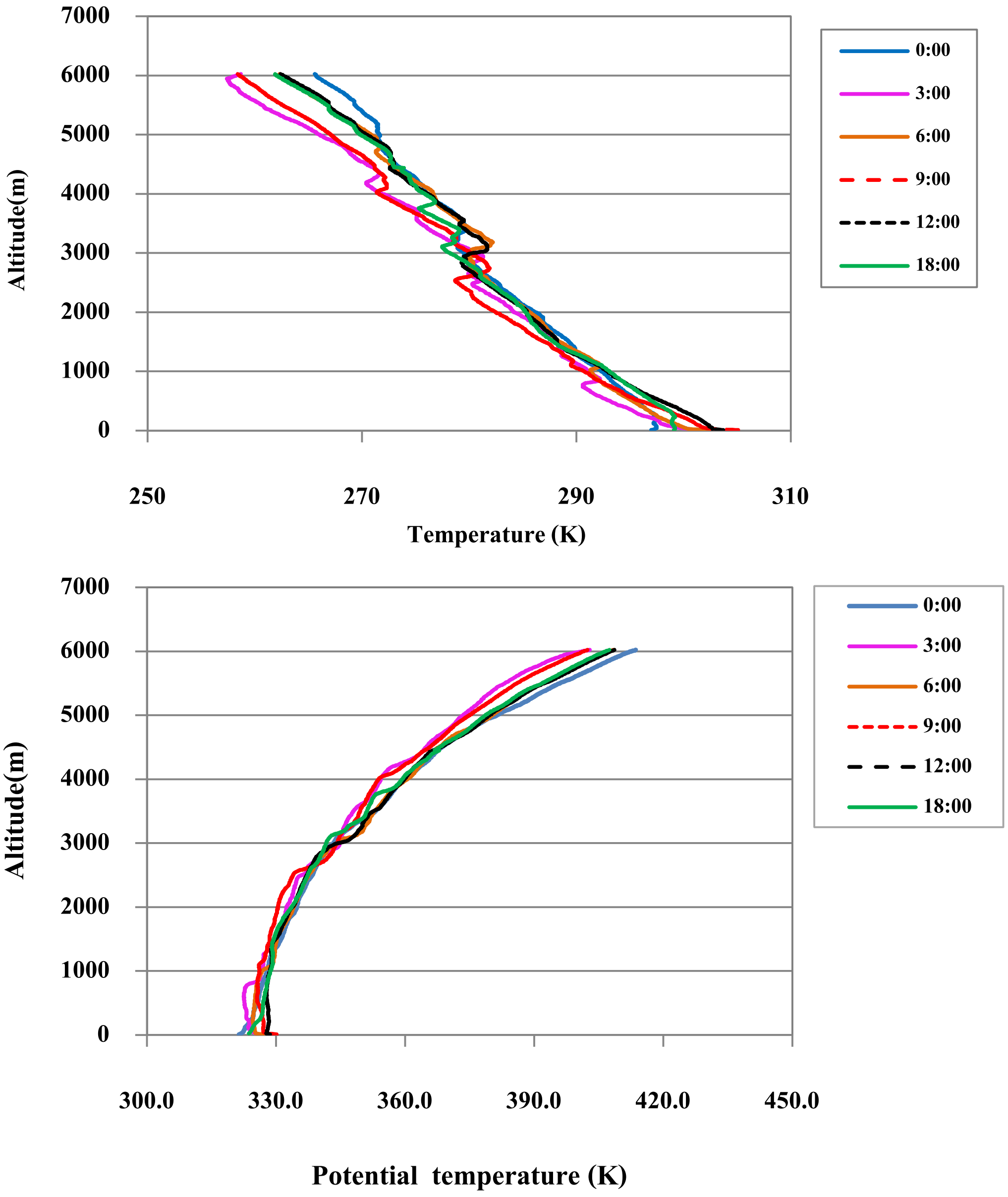

Figure 4.7: Diurnal variation of average temperature profile and average potential temperature profile for Bangkok on 19-21 February 2008

The Figure 4.7 showed average vertical temperature profile and average potential temperature profile for Bangkok on 19-21 February 2008. Both vertical temperature profile and potential temperature profile had the diurnal variation. The average temperature gradient for study period was 1.6-17.3 K per 1,000 m.

Table 4.1 The average UHI intensity, temperature gradient and the height of the inversion at Bangkok Metropolis on 19-21 February 2008

Time (LST)	Average UHI intensity(°C)	Average temperature gradient (K)	The height of the inversion (m)
0000	1.3	1.6	2,961
0300	2.3	13.4	935, 2660
0600	2.1	17.3	1,054
0900	1.2	15.6	1,600, 2,653
1200	2.3	8.3	3,000
1800	1.3	2.3	200

As shown in Table 4.1, considering the UHI intensity and the average temperature gradient, the urban heat island intensity was not significantly correlated with the temperature gradient. However, it was found that the height of the inversion tended to have positive correlation with the UHI intensity. The inversion in this study was characterized by a marked rate of increase of temperature with height from temperature profile. This result showed that the height of the inversion tended to be associated to the formation of the UHI intensity. The relationship between the UHI intensity and the height of the inversion would be further investigated.

Chiang Mai

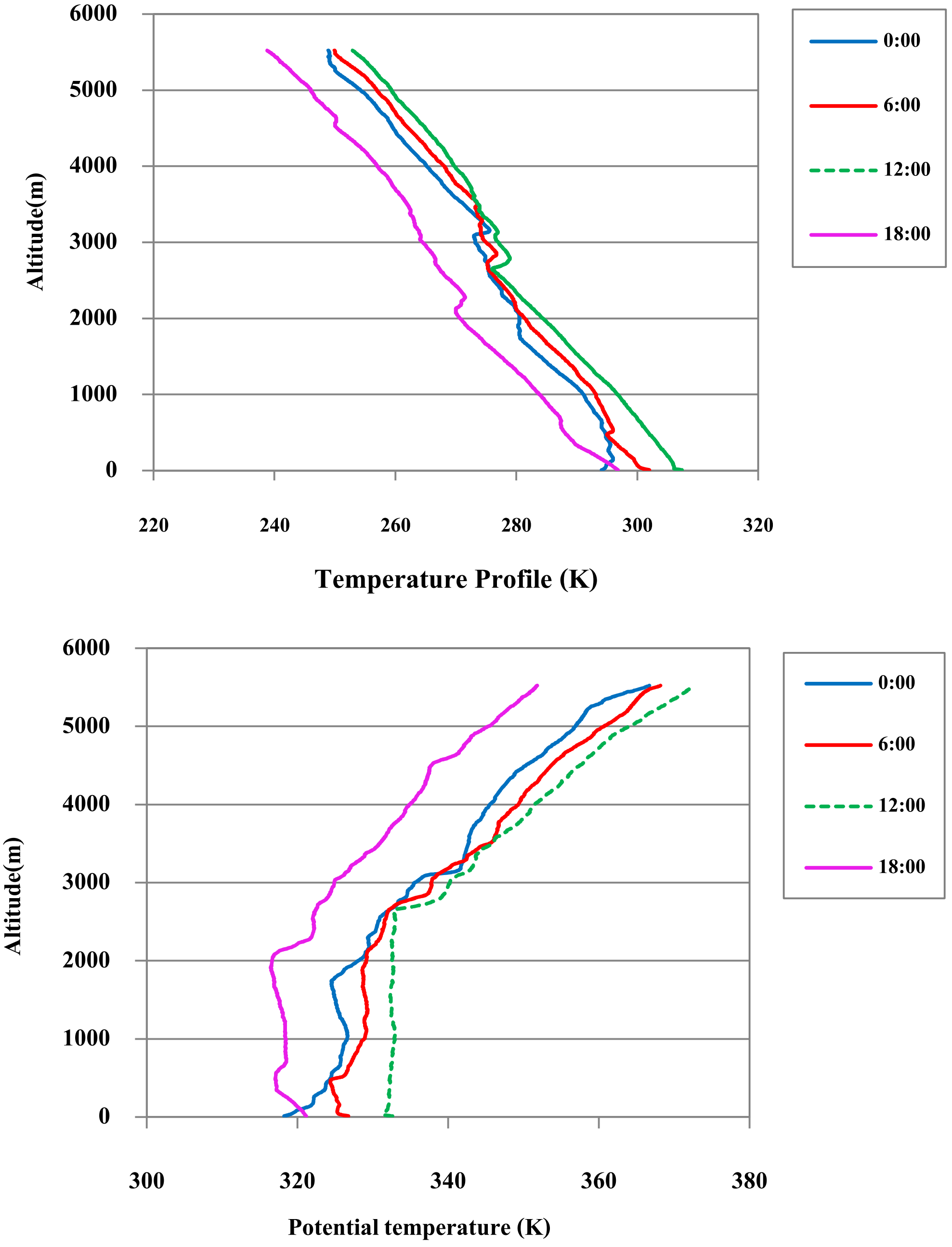

Figure 4.8 Diurnal variation of temperature profile and potential temperature profile for Chiang Mai on 25-28 February 2008

The Figure 4.8 showed average vertical temperature profile and average potential temperature profile for Chiang Mai during 25-28 February 2008. The study results showed that temperature and potential temperature profile had the diurnal variation. The average temperature gradient was 6.5-17.8 K per 1,000 m.

Table 4.2: The average UHI intensity, temperature gradient and the height of the inversion atChiang Mai on 25-28 February 2008

Time (LST)	Average UHI intensity (°C)	Average temperature gradient (K)	The height of the inversion (m)
0000	2.17	12.7	2,786
0600	2.6	19.8	2,800
1200	2.31	15.3	2,676
1800	1.95	16.9	2,137

As shown in Table 4.2, considering the UHI intensity and the average temperature gradient, similar to the results from Bangkok, the urban heat island intensity was not significantly correlated with the temperature gradient. Similar to the results from Bangkok, it was also found that the height of the inversion tended to have positive correlation with the UHI intensity. This result showed that the height of the inversion which was characterized by a marked rate of increase of temperature with height from temperature profile tended to be associated to the formation of the UHI intensity. The relationship between the UHI intensity and the height of the inversion would be further investigated.

The results from Bangkok and Chiang Mai were similar. The vertical profiles of temperature and potential temperature had the diurnal variation. The diurnal cycle of vertical temperature profile appear to respond directly to surface heating caused by solar insulation (Revathy *et al.,* 2001). The UHI intensity was not significantly correlated with the rate of change of temperature with height. However, the UHI intensity tended to relate with the height of inversion. These results were similar to the previous studies. Jauregui(1997) studied urban heat island intensity in Mexico city and the results showed that there was a highly inverse relationship of the heat island intensity with the inversion thickness and he noted that in the case of Mexico City the heat island intensity was not significantly correlated with the temperature gradient.

4.2.2 The variation of wind speed profile during the period of UHI events

Bangkok Metropolis

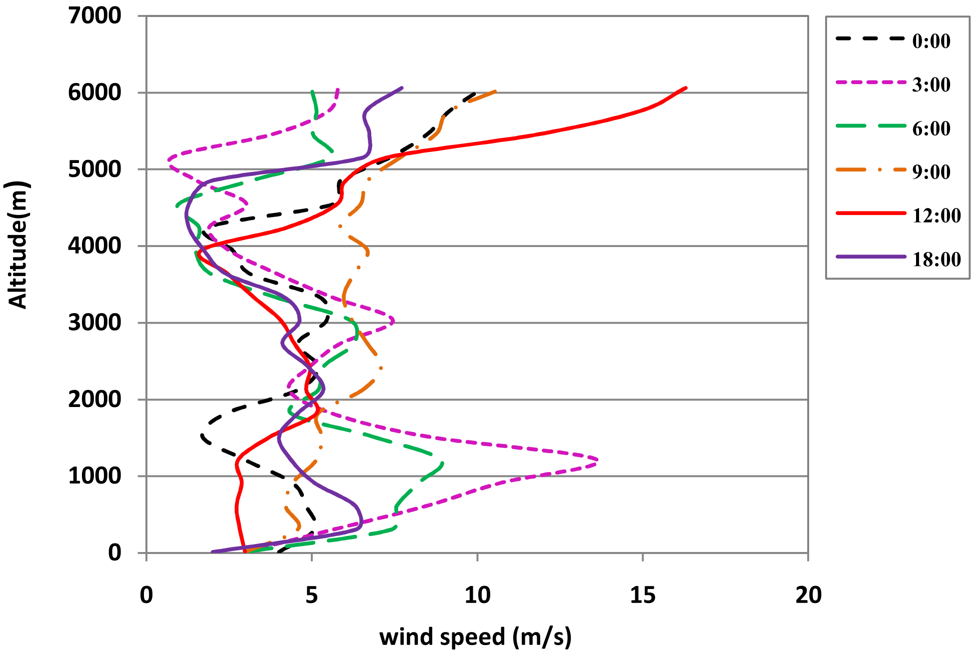

Figure 4.9: Diurnal variation of wind speed profiles for Bangkok on 19 -21 February 2008

As shown in Fig. 4.9 and Table 4.1, considering the height that the wind speed changed from increasing with height to decreasing with height and the height of inversion, the inversion occurred at 935 m and 2,660 m, while the vertical wind speed change from increasing with height to decreasing with height at 1,000 m and 2200 m at 0300 LST and the inversion occurred at 1,054 m, while the vertical wind speed change at 1,000 m. The study results showed that the vertical wind speed tended to have the correlation with the height of inversion. From the results in the beginning the inversion related to the UHI effect. Therefore, the UHI effect tended to related to the vertical wind speed.

Chiang Mai

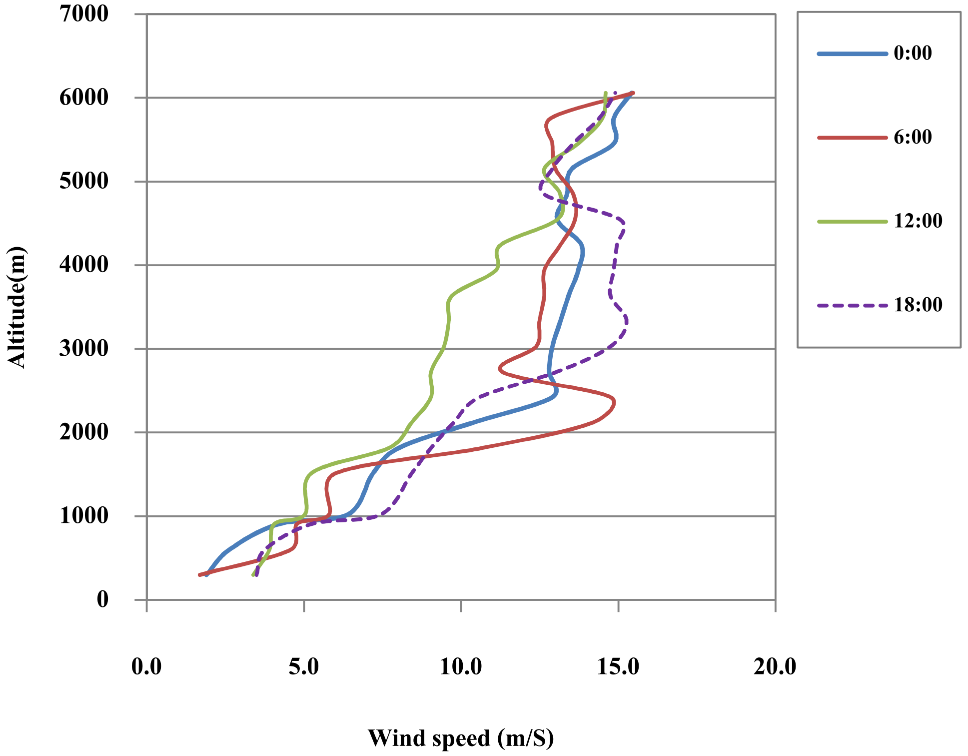

Figure 4.10 Diurnal variations of wind speed profile for Chiang Mai on 25-28 February 2008

As shown in Figure 4.10 and Table 4.2, considering the height that the wind speed changed from increasing with height to decreasing with height and the height of inversion at 0600 LST, the height of the inversion was 2,800 m, while the wind speed changed to decreasing with height at 2,600 m. The study results showed that the vertical wind speed tended to have the correlation with the height of inversion. From the results in the beginning the inversion related to the UHI effect. Therefore, the UHI effect tended to related to the vertical wind speed.

. **4.2.3 Diurnal variation of mixing height**

The mixing heights in study areas were examined by using the radiosonde data derived from CAPE project during the study period time. This present study selected two stations in study areas to be case studies. The study results are described in the following.

Bangkok Metropolis

The extra radiosonde observations were performed for Bang Na Station on 19-21 February 2008 at 0000 LST, 0300 LST, 0600 LST, 0900 LST, 1200 LST and 1800 LST. The data were used to determine mixing height by Holzworth method. The results of this data set are show in the following.

Table 4.3 Diurnal variation of mixing height in Bangkok Metropolis on 19-21 February 2008

Date	**Mixing height (m)**					
	0000 LST	**0300LST**	**0600LST**	**0900LST**	**1200LST**	**1800 LST**
19 Feb. 2008	*	974	1,059	1,790	2,073	*
20 Feb. 2008	*	501	1,282	1,672	1,689	*
21 Feb. 2008	24	389	1,459	1,715	1,783	*

* The dry adiabatic extension of the morning minimum surface temperature plus 5°C did not intersect the vertical temperature profile

As shown in Table 4.3, the study results for Bangkok showed the mixing height increased gradually in the early morning (0300 LST) and reached the maximum height with 2,073 m on 19 February 2008, 1,689 m on 20 February 2008 and 1,783 m on 21 February 2008 in the early afternoon (1200 LST).

Chiang Mai

The extra radiosonde observations were performed for Chiang Mai Station on 26-28 February 2008 at 0000 LST, 0600 LST, 1200 LST and 1800 LST. The data were used to determine mixing heights by Holzworth method. The results of this data set are show in the following.

Table 4.4 Diurnal variation of mixing height in Chiang Mai on 25-28 February 2008

Date	**Mixing height (m)**			
	0000 LST	**0600 LST**	**1200 LST**	**1800 LST**
25 Feb.2008	**	**	**	705
26 Feb.2008	490	1,028	2,168	600
27 Feb.2008	439	1,022	1,742	300
28 Feb.2008	*	1,443	2,130	*

* The dry adiabatic extension of the morning minimum surface temperature plus 5°C did not intersect the vertical temperature profile

** The radiosonde was not conducted.

As shown in Table 4.4, mixing height increased gradually in the early morning (0000 LST) and reached the maximum height with 2,168 m on 26 February 2008, 1,742 m on 27 February 2008 and 2,130 m on 28 February in the early afternoon (1200LST).

The results from all the study sites showed that the mixing heights had diurnal variation. The mixing heights were greater in the afternoon than in the morning. These results were similar to the previous studies. Holzworth (1967) found the mean monthly mixing heights in the cities of United States from the period 1960-1964 were greater in the afternoon than in the morning. Berman *et al* (1995) found that mixing depth estimated from rawinsonde profiles showed large temporal and variability during daytime convective period, while it showed little spatial variability at nighttime. The mixing height concept is based upon the principle that heat transferred to the atmosphere at the surface results in convection, vigorous vertical mixing (Holzworth, 1967). It evolved in a parabolic manner after sunrise and a rise in the inversion top after sunrise is due to low level convergence which caused the entire inversion layer to be lifted (Godowitch *et al.,* 1987).

4.3 The effects of UHI on vertical atmospheric structure

4.3. 1 UHI and vertical temperature profile

4.3.1.1 The relationship between the UHI and vertical temperature profile at 0700 LST

In order to study the effects of urban heat island on vertical temperature profile, the radiosonde data for 1-yr period from Janurary 2008 to December 2008 at 0700 LST was used. Regression analysis was carried out to examine the relationship between the UHI and the difference temperature between the surface and the upper level (ΔT) at the three levels 110 m, 1,353 m and 2,563 m. The study results from this data set are described in the following.

Bangkok Metropolis

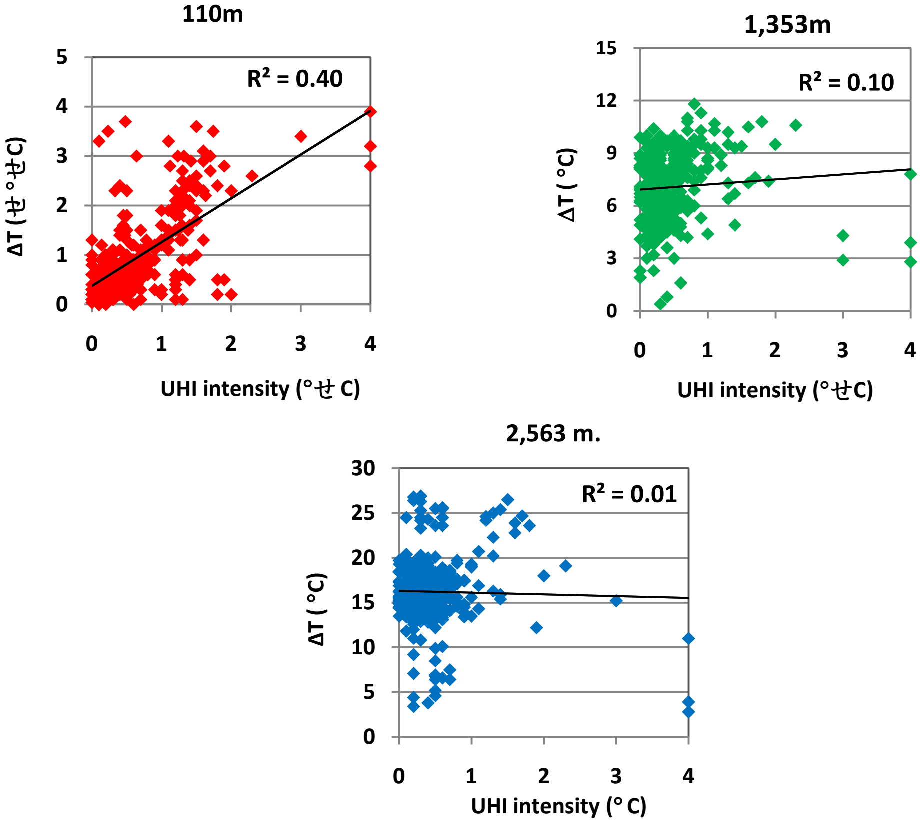

Figure 4.11 The relationship between the UHI intensity and ΔT for Bangkok at 0700 LST

Figure 4.11 showed the results of scatterplot for the UHI intensity and ΔT at levels 110m, 1,353m and 2,563m for Bangkok at 0700 LST. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.40, 0.10, and 0.01 respectively. The results showed that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

Chiang Mai

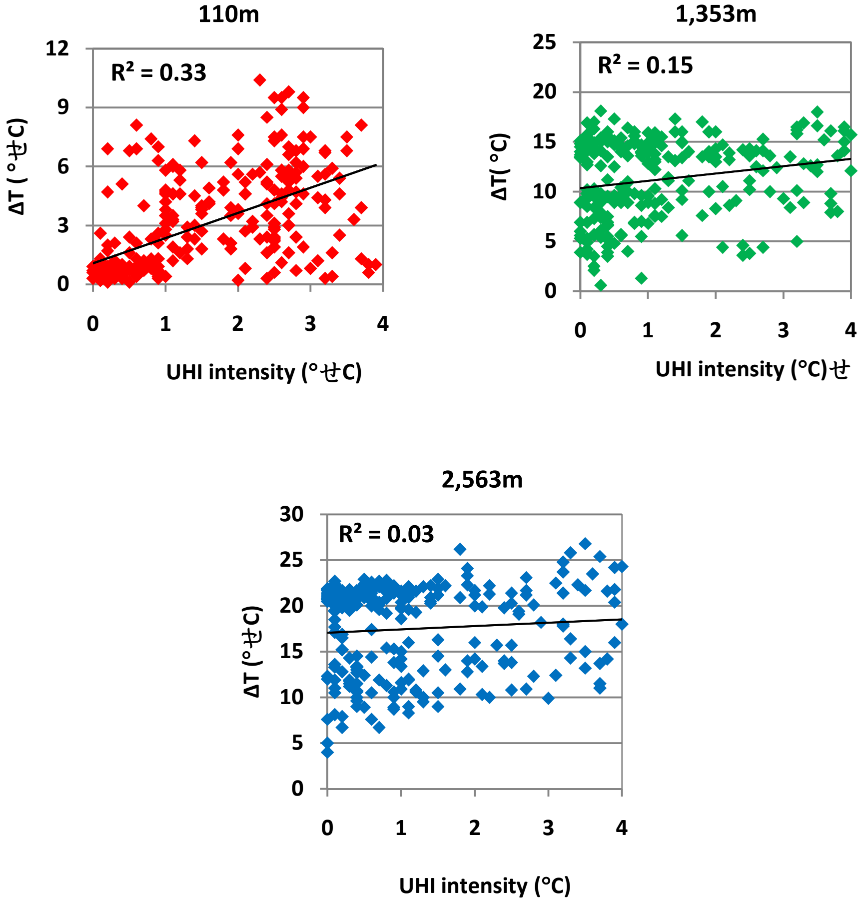

Figure 4.12 The relationship between the UHI intensity and ΔT for Chiang Mai at 0700 LST

Figure 4.12 showed the results of scatterplot for the UHI intensity and ΔT at levels 110m, 1,353m and 2,563m for Chiang Mai at 0700 LST. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.33, 0.15, and 0.03 respectively. The results indicated that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

Ubon Ratchathani

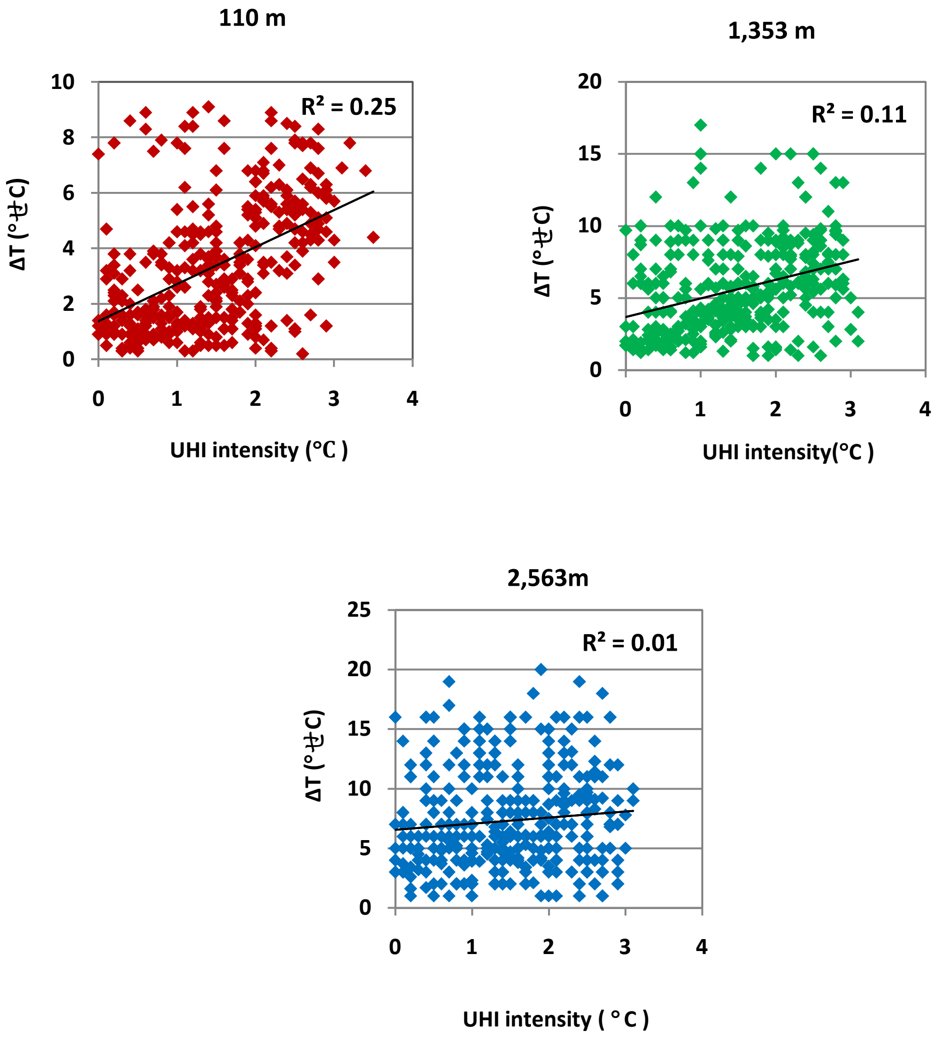

Figure 4.13 The relationship between the UHI intensity and ΔT for Ubon Ratchathani at 0700 LST

Figure 4.13 showed the results of scatterplot for the UHI intensity and ΔT at levels 110m, 1,353m and 2,563m for Ubon Ratchathani at 0700 LST. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.25, 0.11, and 0.01 respectively. The results indicated that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

Songkhla

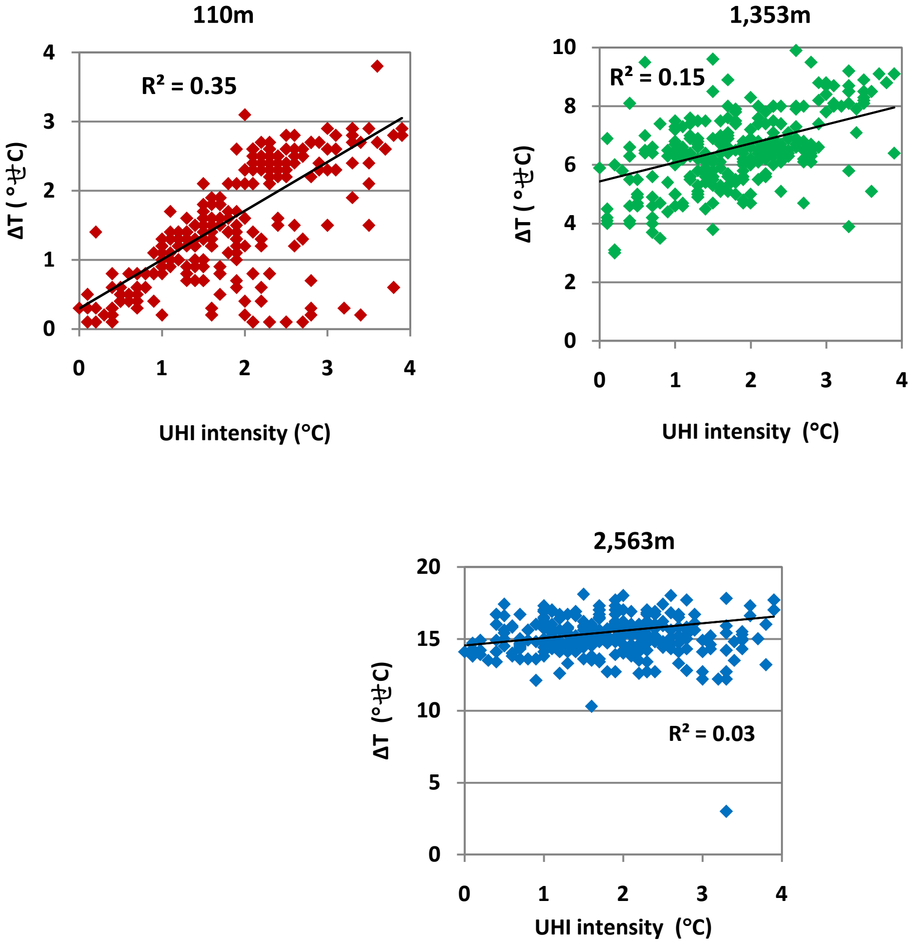

Figure 4.14 The relationship between the UHI intensity and ΔT for Songkhla at 0700 LST

Figure 4.14 showed the results of scatterplot for the UHI intensity and ΔT at levels 110m, 1,353m and 2,563m for Songkhla at 0700 LST. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.35, 0.15, and 0.03 respectively. The results indicated that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

Phuket

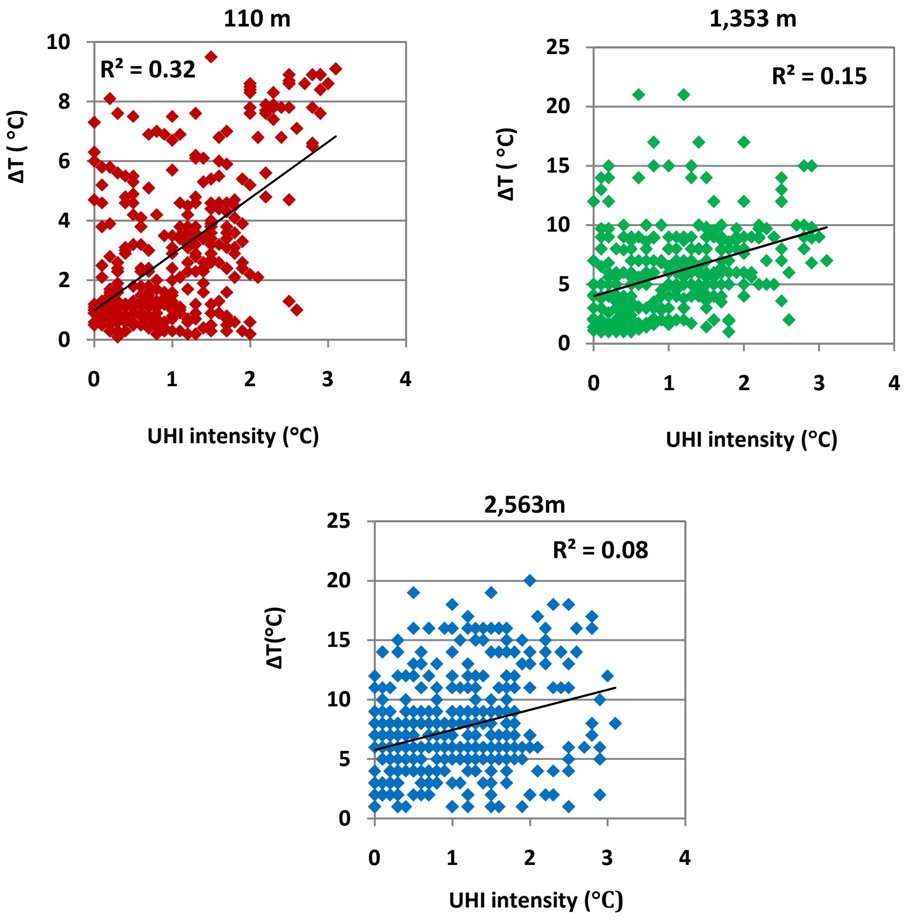

Figure 4.15 The relationship between the UHI intensity and ΔT for Phuket at 0700 LST

Figure 4.15 showed the results of scatterplot for the UHI intensity and ΔT at levels 110m, 1,353m and 2,563m for Phuket. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.32, 0.15, and 0.08 respectively. The results indicated that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

The results for all the study areas were similar that the correlation between the UHI intensity and ΔT appear at 110 m. However, the correlation of determinations from all study areas were not significantly to indicate the correlation between these two variables. In addition, the correlation between these two variables were very weak at the higher level for all study areas. These correlations were observed at 0700 LST, while both of the UHI study results and vertical temperature showed the diurnal variation of UHI intensity. This may be the reason to explain that why the UHI intensity did not show the relationship with ΔT. For further investigation to find the relationship between these two variables, the data should be from the diurnal cycle.

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4.3.1.2 The relationship between the UHI and vertical temperature profile for diurnal cycle

In order to study the effect of urban heat island on temperature profile for diurnal cycle, the extra radiosonde data from CAPE project were used to study this relationship. The radiosonde data were conducted at Bang Na station for six times per day on 19-21 February 2008 (0000, 0300, 0600, 0900, 1200, 1800 LST), while the radiosonde data were conducted at Chiang Mai station four times per day on 25-28 February 2008 (0000, 0600, 1200, 1800 LST). Regression analysis was carried out to examine the relationship between the UHI and the difference temperature between the surface and the upper level (ΔT) at the three levels namely 110 m, 1,353 m and 2,563 m. The study results from this data set are described in the following.

Bangkok Metropolis

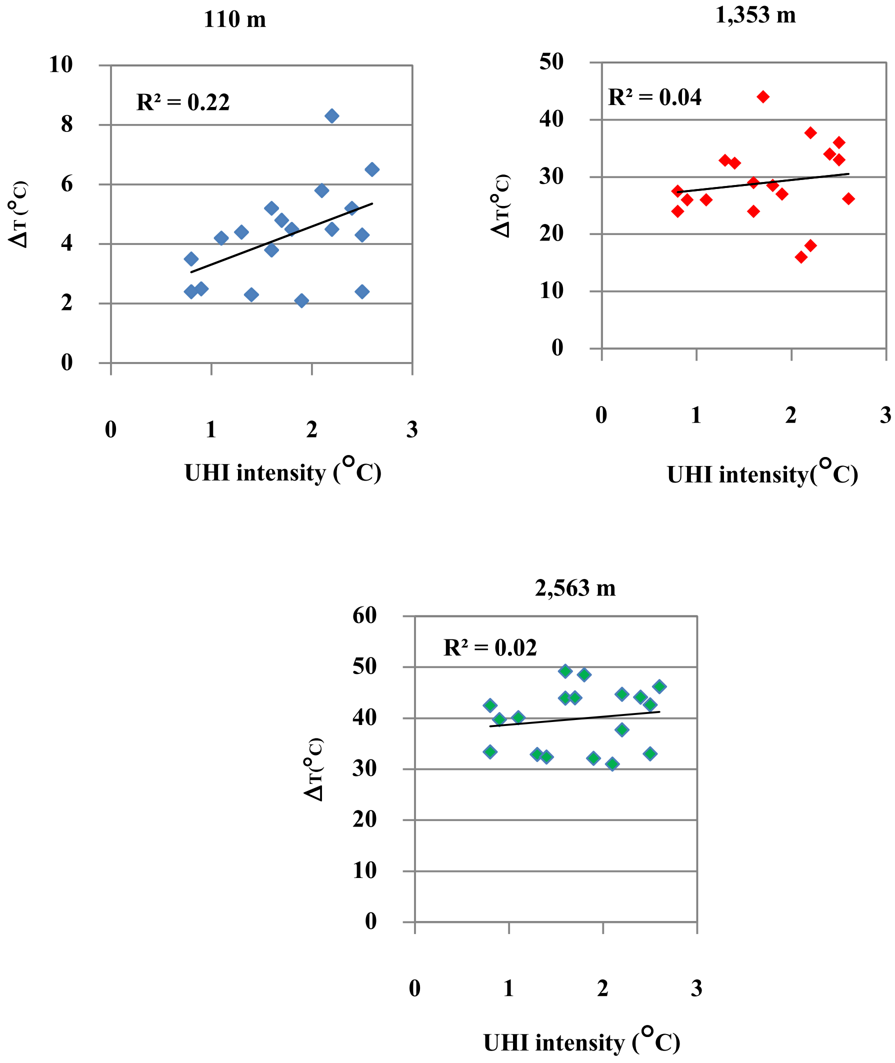

Figure 4.16 The relationship between the UHI intensity and ΔT of diurnal cycle for Bangkok

Figure 4.16 showed the results of scatterplot for the UHI intensity and ΔT at levels 110m, 1,353m and 2,563m for Bangkok. The study results showed that the UHI intensity was not significantly correlated with ΔT for every height. The coefficient of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.22, 0.04, and 0.02 respectively.

Chiang Mai

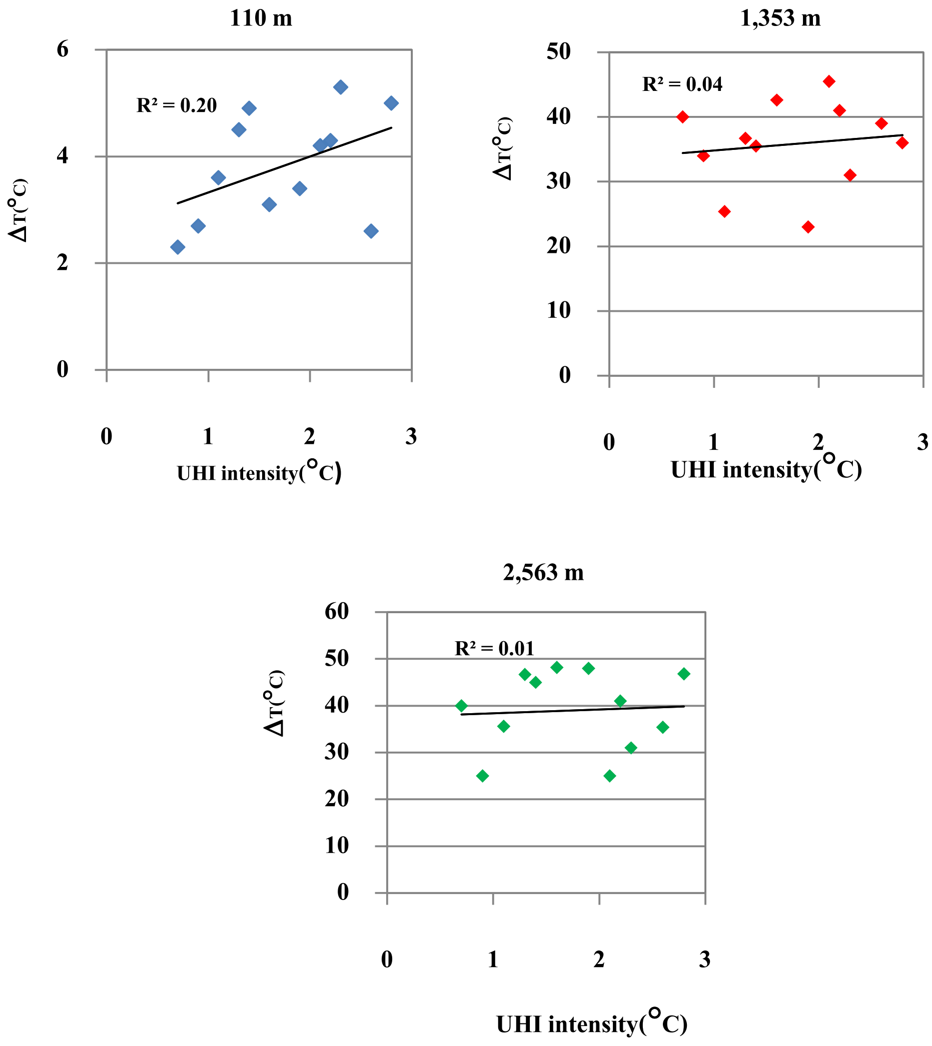

Figure 4.17 The relationship between the UHI intensity and ΔT of diurnal cycle for Chiang Mai

Figure 4.17 showed the results of scatterplot for the UHI intensity and ΔT at levels 110m, 1,353m and 2,563m for Chiang Mai. The results indicated that two variables did not significantly correlate. The coefficient of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.20, 0.04, and 0.01 respectively.

The results from all study areas showed that the UHI intensity was not significantly correlated with the thermal contrasts between the surface and the higher level. However, the atmospheric state in a city is a response to exchanges of the energy between the surface and the atmosphere (Oke, 1982). In the case study areas (Bangkok and Chiang Mai), they were found that the height of the inversion tended to be associated to the formation of UHI intensity. Therefore, the UHI affected the vertical temperature profile by modification surface temperature and increasing the turbulent from the surface. These study results were similar to the previous research of Jauregui (1997) in Mexico City that was the UHI intensity not significantly correlated with the thermal contrast between the surface and the top of the surface inversion layer. However, there was the positive correlation between the UHI intensity and the surface inversion thickness.

4.3.2 UHI and vertical wind speed profile

4.3.2.1 The relationship between the UHI and vertical wind speed profile at 0700 LST

In order to study the effects of urban heat island on wind profile, the radiosonde data for 1-yr period from January 2008 to December 2008 at 0700 LST was used. Regression analysis was carried out to examine the relationship between the UHI and the difference wind speed between the surface and the upper level (ΔW) at the three levels namely 110 m, 1,353 m and 2,563 m. The study results from this data set are described in the following.

Bangkok Metropolis

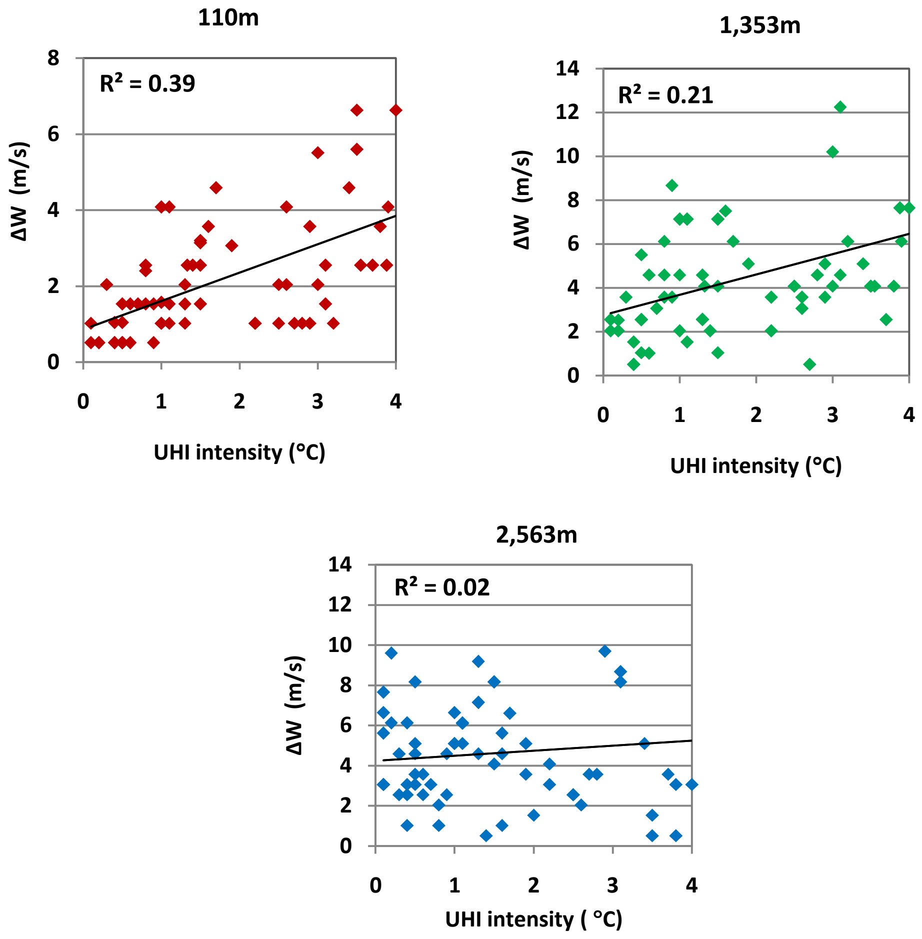

Figure 4.18 The relationship between the UHI intensity and ΔW for Bangkok at 0700 LST

Figure 4.18 showed the results of scatterplot for the UHI intensity and ΔW at levels 110m, 1,353m and 2,563m for Bangkok. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.39, 0.21, and 0.02 respectively. The results indicated that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

Chiang Mai

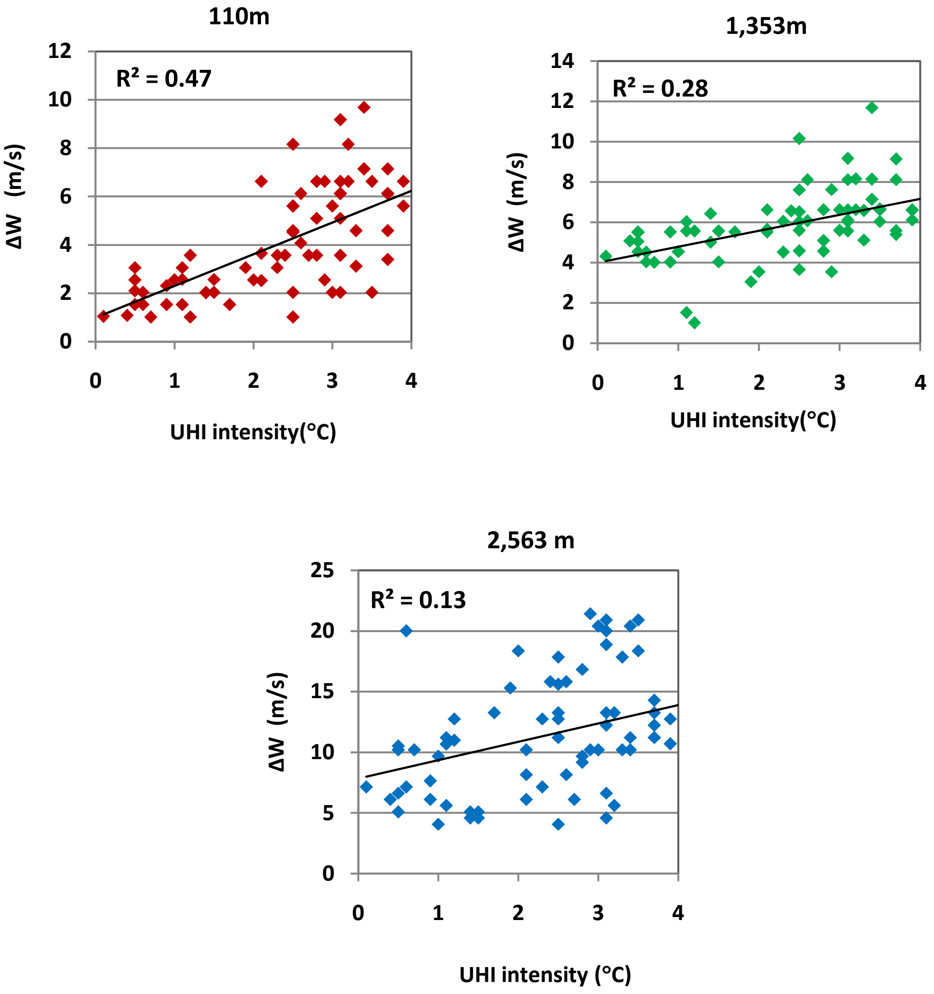

Figure 4.19 The relationship between the UHI intensity and ΔW for Chiang Mai at 0700 LST

Figure 4.19 showed the results of scatterplot for the UHI intensity and ΔW at levels 110m, 1,353m, and 2,563m for Chiang Mai. The results indicated that two variables had the positive correlation. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.47, 0.28, and 0.13 respectively. The results indicated that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

Ubon Ratchathani

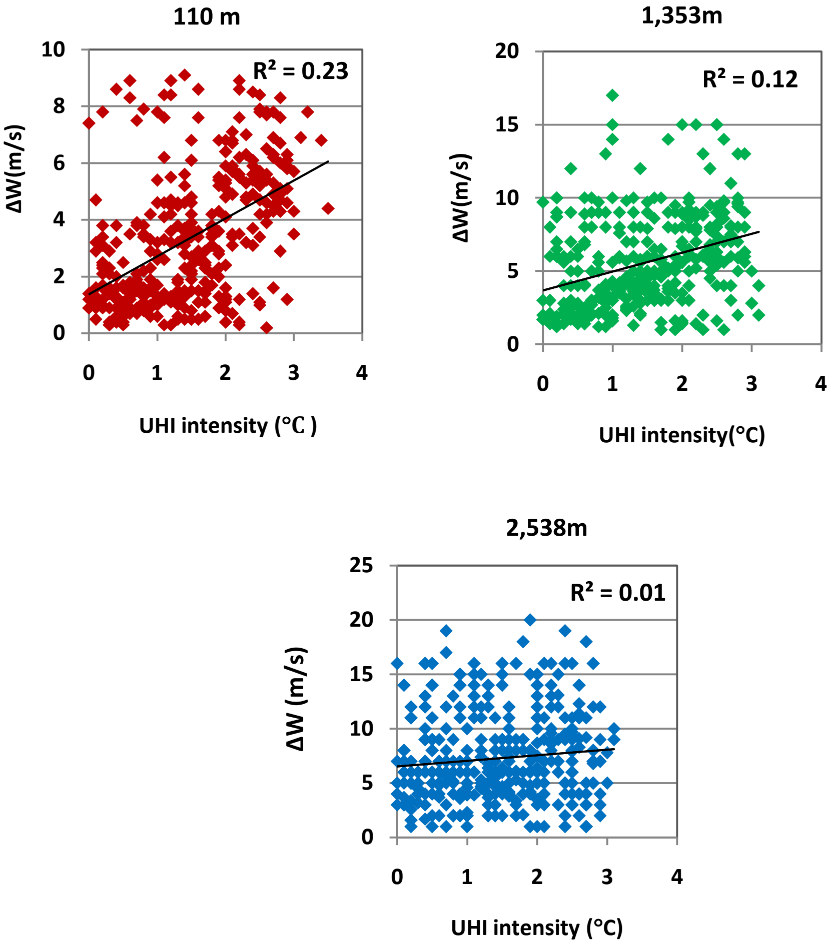

Figure 4.20 The relationship between the UHI intensity and ΔW for Ubon Ratchathani at 0700 LST

Figure 4.20 showed the results of scatterplot for the UHI intensity and ΔW at levels 110m, 1,353m and 2,563m for Ubon Ratchathani. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.23, 0.12, and 0.01 respectively. The results indicated that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

Songkhla

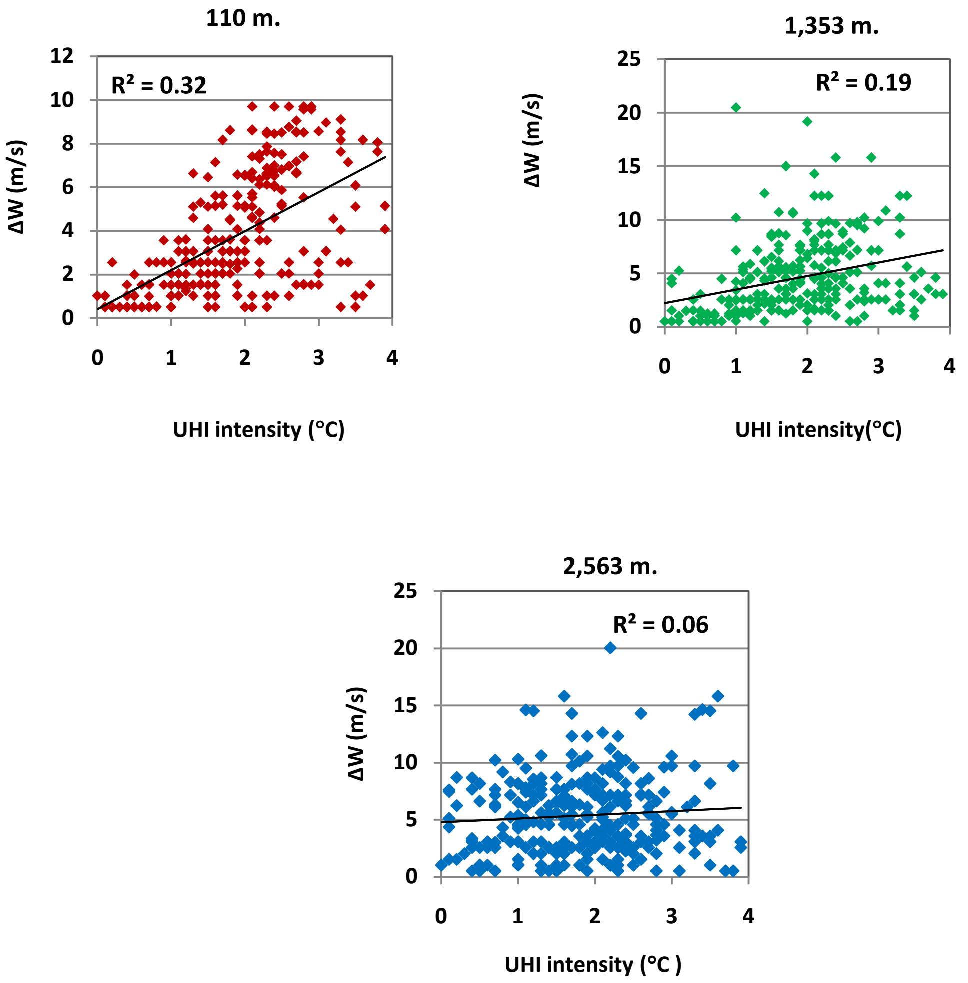

Figure 4.21 The relationship between the UHI intensity and ΔW for Songkhla at 0700LST

Figure 4.21 showed the results of scatterplot for the UHI intensity and ΔW at levels 110m, 1,353m and 2,563m for Songkhla. The respective coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.32, 0.19, and 0.06 respectively. The results indicated that two variable had the strongest positive correlation at 110 m, while the correlation at the levels 1,353 m and 2,563 m appeared very weak.

Phuket

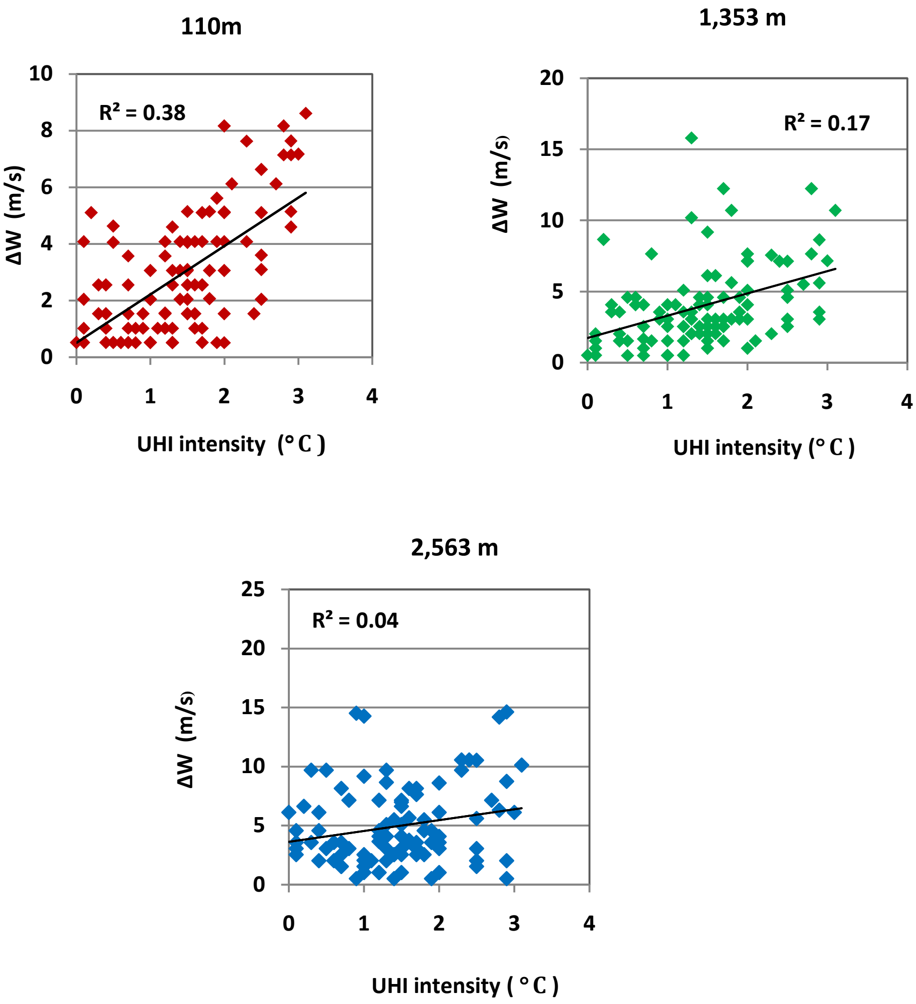

Figure 4.22 The relationship between the UHI intensity and ΔW for Phuket at 0700 LST

Figure 4.22 showed the results of scatterplots for the UHI intensity and ΔW at levels 110m, 1,353m and 2,563m The results indicated that two variables had strongest positive correlation at 110m with the coefficients of determination (R^2) 0.38. The correlation derived between UHI intensity and ΔW at the levels 1,353m and 2,563 m appeared very weak (R^2 approximately 0.17 and 0.04).

The results for all study sites were similar that was the correlation between UHI intensity and ΔW was strong at the near surface (110 m), while appeared very weak at the higher level. Considering the coefficient of determination (R^2), the UHI intensity was not significantly correlated with ΔW. However, the UHI thermal anomaly presented by a city affects existing airflow by altering the local pressure field, changing the balance of forces, and modifying the stability and thermal turbulence which affect the vertical motion (Oke, 1987). In addition, Oke (1987) pointed out that the magnitude of such influence depends upon the strength of the gradient flow and UHI intensity. This study did not find the relationship between these two variables because the UHI intensity had the diurnal variation but the correlation was observed at 0700 LST. Therefore, the further investigation should be the diurnal cycle.

4.3.2.2 The relationship between the UHI and vertical wind speed profile for diurnal cycle

In order to study the effects of urban heat island on wind speed profile for diurnal cycle, the extra radiosonde data from CAPE project were used to study this relationship. The radiosonde data were conducted at Bang Na station for six times per day on 19-21 February 2008 (0000, 0300, 0600, 0900, 1200, 1800 LST), while the radiosonde data were conducted at Chiang Mai station four times per day on 25-28 February 2008 (0000, 0600, 1200, 1800 LST). Regression analysis was carried out to examine the relationship between the UHI and the difference wind peed between the surface and the upper level (ΔW) at the three levels namely 110 m, 1,353 m and 2,563 m. The study results from this data set are described in the following.

Bangkok Metropolis

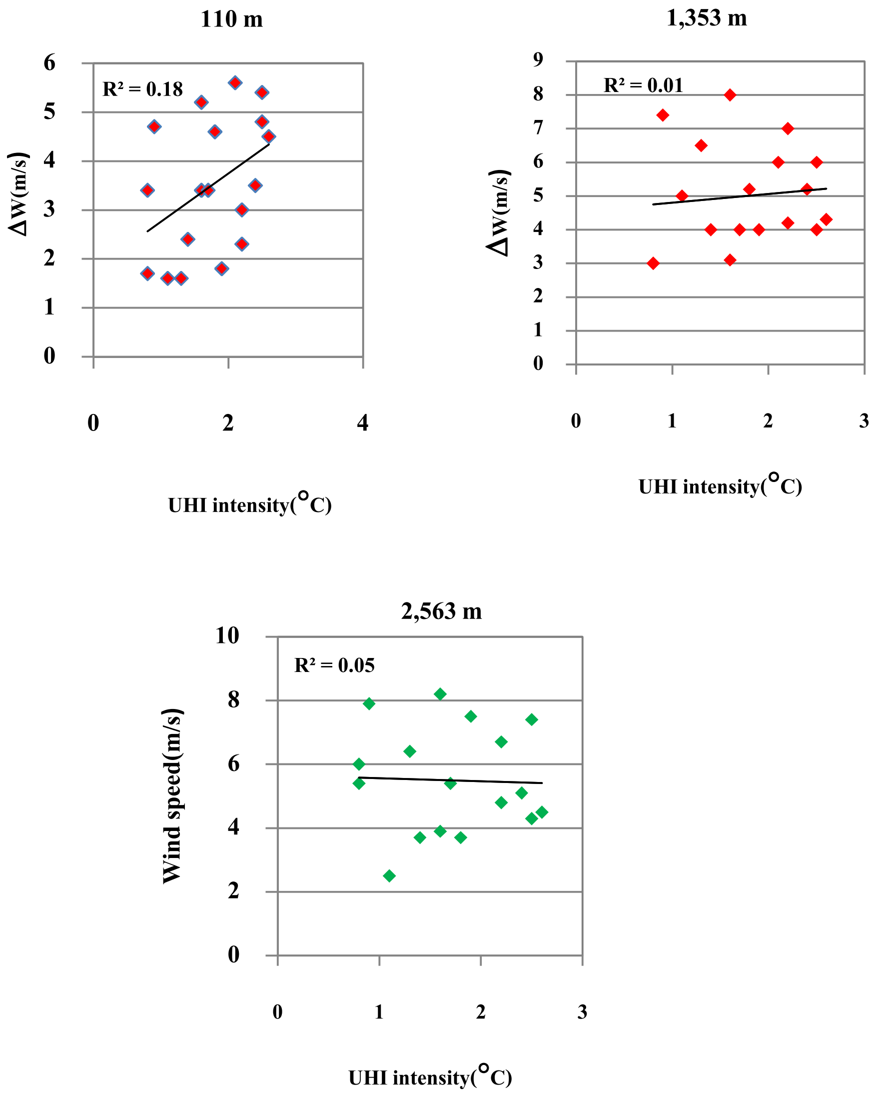

Figure 4.23 The relationship between the UHI intensity and ΔW of the diurnal cycle for Bangkok during on 19-21 February 2008

Figure 4.23 showed the results of scatterplot for the UHI intensity and ΔW at levels 110m, 1,353m and 2,563m for Chiang Mai. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.18, 0.01, and 0.05 respectively. The results indicated that the UHI was not significantly correlated with ΔW.

Chiang Mai

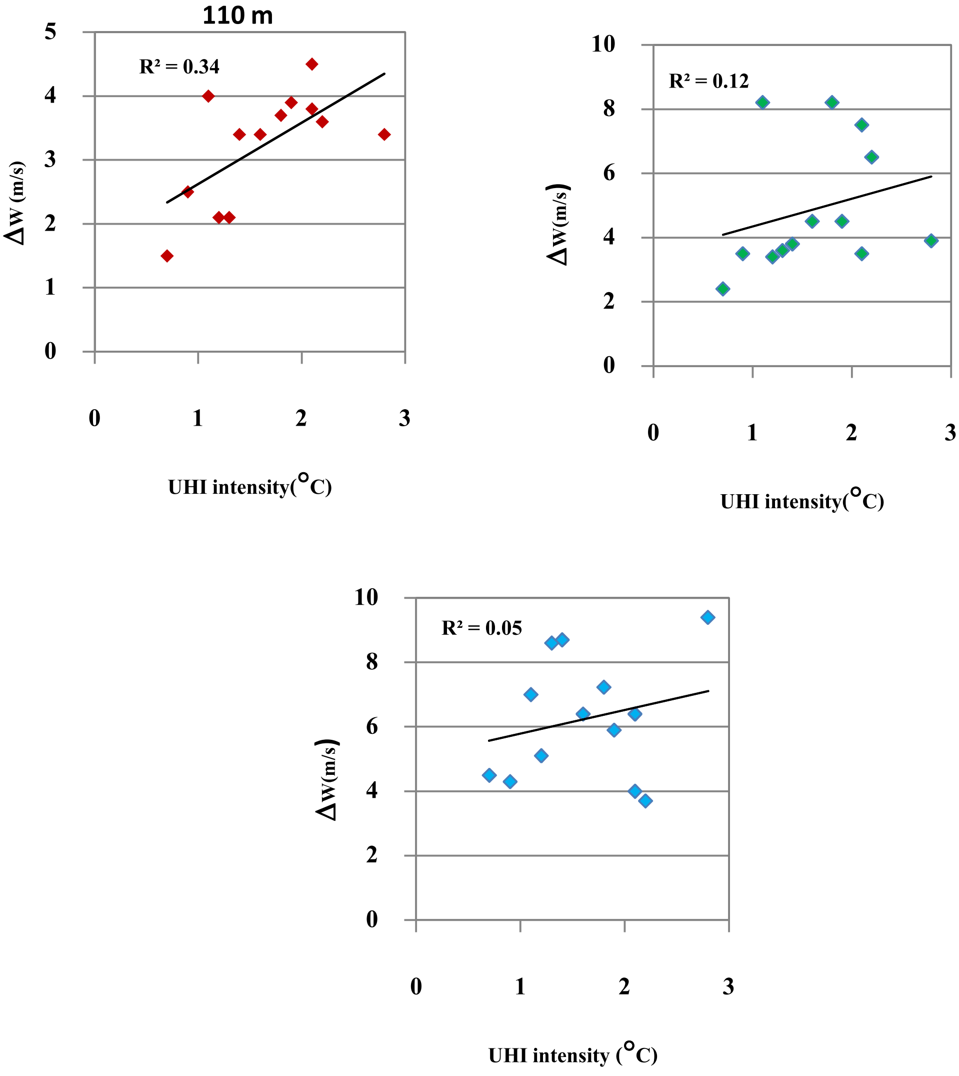

Figure 4.24 The relationship between the UHI intensity and ΔW of the diurnal cycle for Chiang Mai during 25-28 February 2008

Figure 4.24 showed the results of scatterplot for the UHI intensity and ΔW at levels 110m, 1,353m and 2,563m for Chiang Mai. The coefficients of determinations (R^2) for 110 m, 1,353 m, and 2,563 m were 0.34, 0.12, and 0.05 respectively. The results indicated that the UHI was not significantly correlated with ΔW.

The results for the case study areas namely Bangkok and Chiang Mai were similar that was the correlations between UHI intensity and ΔW were found to be the strongest at the near surface (110 m), while they appeared very weak at the higher level. Considering the coefficients of determination (R^2), the UHI intensity were not significantly correlated with ΔW. The results did not show the relationship as expect due to the shortness of the period which was examined. However, the UHI effect can modify the stability and thermal turbulence which affect the vertical motion and can associate vertical wind speed.

4.3.3 UHI and mixing height

In order to study the relationship between UHI and mixing height, the surface temperature data from TMD and radiosonde data from CAPE project at the same period hours were used. The surface temperature data from the urban/rural weather stations in study areas were used to calculate UHI intensity at 0000, 0300, 0600, 0900, 1200, 1800 LST on 19-21 February 2008 for Bangkok, and at 0000, 0600, 1200, 1800 LST on 26-28 February 2008 for Chiang Mai. The radiosonde data at the same period were used to examine mixing height by Holzworth method. The regression analysis was carried out to examine significant association between these two variables. In regression analysis, independent variable was UHI intensity and dependent variable was the mixing height. The study results from this data set are shown in Figure 4.25

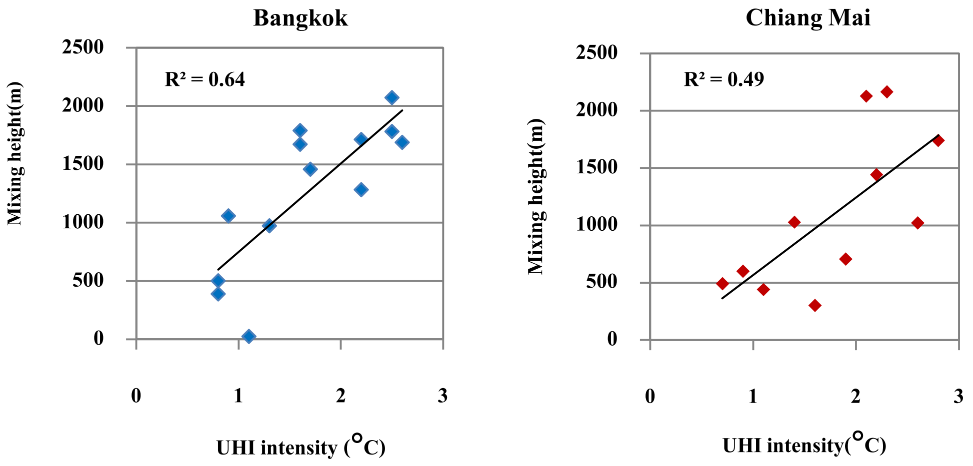

Figure 4.25 The relationship between the UHI intensity and mixing height for Bangkok and Chiang Mai

As showed in Figure 4.25, the results showed that two variables had positive correlation with the respective coefficient of determination (R^2) 0.64 for Bangkok and 0.49 for Chiang Mai. These results indicated that the UHI effect could raise the mixing height. This mean when the UHI occurred, the mixing height would increase at that time. These results were agreeable with the previous researches. Ludwig and Dabberdt (1973) found that nocturnal urban mixing heights are greater than the rural values because of UHI effect. The effect of nocturnal urban heat island is to create a mixing layer (Duckworth and Sandberg, 1954; DeMarrais, 1961; Summers, 1967). The depth through which such mixing extends depends primarily upon the initial vertical temperature structure and the heat input at the surface (Holzworth, 1967). Berman *et al.* (1995) noted mixing height depends strongly on surface temperature, which is determined by a variety of factors ranging in scale from synoptic scale to the micro scale (Berman *et al.*, 1995). Therefore when the UHI occurred, the heat from the surface will be transfer to the atmosphere and create the mixing height.

4.3.4 Sensitivity analysis for estimating mixing height by Holzworth method

The Holzworth method provides twice per day (morning and afternoon) mixing height based on calculations using upper air data. Holzworth (1967) described his method that the morning mixing height is calculated as the height above the ground at which the dry adiabatic extension of the morning minimum surface temperature plus 5°C intersects the vertical temperature profile observed at 0700 LST. The minimum temperature is determined from the regular hourly reports from 0000 through 0600 LST. The afternoon mixing height is calculated in the same way except that the maximum surface temperature observed from 1200 through 18000 LST is used. Holzworth (1967) assumed a constant 5°C to be urban-rural differences and realized that this value was too high and could applied for specific case. The "plus 5" factor was established to allow for urban-rural differences in morning surface temperature. TMD also have used this value to estimate mixing height by Holzworth method. In order to study the suitable constant value of urban-rural temperature difference used in estimating morning mixing heights in Thailand, the sensitivity analysis was applied and conducted. The constant value of urban-rural difference which was used to add the minimum temperature difference would be changed to 4°C, 3°C, 2°C, and 1°C and were used to estimate morning mixing height by Holzworth method. The estimated mixing heights would be compared with the observed data which was determined by using temperature profile.

Bangkok Metropolis

In order to find the suitable constant value of urban-rural temperature difference used in estimating morning mixing height for Bangkok, the surface minimum temperature would be added with the different constant values. The scenarios of Tmin + 5°C, Tmin + 4°C, Tmin + 3°C, Tmin + 2°C and Tmin + 1°C were conducted for estimating mixing height by Holzworth method. The upper meteorological data which were derived from CAPE project on 19-21 February 2008 at 0600 LST and 0900 LST were used. The estimated data and the observed data would be analyzed the different values. The study results are shown in Table 4.3 as the following.

Table 4.5 The morning mixing height in Bangkok Metropolis from the different scenarios estimated by Holzworth method on 19-21 February 2008

Scenarios	Mixing height (m)					
	The estimated data	The observed data	The different value	The estimated data	The observed data	The different value
19 Feb 2008	**0060 LST**			**0900 LST**		
$T_{min} + 5^{o}C$	1,059	1,028	31	1,790	1,378	412
$T_{min} + 4^{o}C$	999	1,028	29	1,597	1,378	219
$T_{min} + 3^{o}C$	979	1,028	49	1,390	1,378	12
$T_{min} + 2^{o}C$	*	1,028	-	959	1,378	419
20 Feb 2008	**0060 LST**			**0900 LST**		
$T_{min} + 5^{o}C$	1,282	988	294	1,672	1,547	125
$T_{min} + 4^{o}C$	1,078	988	90	1,582	1,547	35
$T_{min} + 3^{o}C$	963	988	25	1,506	1,547	41
$T_{min} + 2^{o}C$	*	988	-	1,208	1,547	339
$T_{min} +1^{o}C$	*	988	-	*	1,547	-
21 Feb 2008	**0060 LST**			**0900 LST**		
$T_{min} + 5^{o}C$	1,459	1,439	20	1,715	1,638	77
$T_{min} + 4^{o}C$	1,428	1,439	9	1,625	1,638	13
$T_{min} + 3^{o}C$	845	1,439	594	1,605	1,638	33
$T_{min} + 2^{o}C$	*	1,439	-	1,031	1,638	607
$T_{min} +1^{o}C$	*	1,439	-	*	1,638	-

* The dry adiabatic extension of the morning minimum surface temperature plus constant value of urban-rural difference did not intersect the vertical temperature profile

As shown in Table 4.3, the morning mixing heights for Bangkok estimated by Holzworth method showed the different values in the different scenarios which were conducted by changing the constant value of urban-rural temperature difference. Concerning the frequency of the events which the estimated mixing height was closest to the observed data, the highest frequency of the total data was 67 % for the scenario which was Tmin + 4 °C, and 33 % of total data for the scenario which was Tmin + 3°C. The other scenarios did not show the frequency of this event. The study results also showed that the mixing heights estimated by using the constant value of 5°C followed by Holzworth method were higher than the observed data. Considering the UHI intensity of Bangkok Metropolis from this research, the maximum UHI intensity for the diurnal cycle of Bangkok Metropolis was 1-4°C. So, the recommendation for a constant value of urban-rural temperature difference which is suitable for estimating morning mixing height in Bangkok Metropolis should be 3°C or 4°C.

Chiang Mai

In order to find the suitable constant value of urban-rural temperature difference used for estimating morning mixing height, the surface minimum temperature would be added with the different constant values. The scenarios namely Tmin + 5°C, Tmin + 4°C, Tmin + 3°C, Tmin + 2°C, Tmin + 1°C were conducted for estimating mixing height by Holzworth method. The upper air which were derived from CAPE project on 26-28 February 2008 at 0000 LST and 0600 LST were used. The estimated data and the observed data would be analyzed the different values. The study results are shown in Table 4.3 as the following.

Table 4.6 The mixing height in Chiang Mai from different scenario estimated by Holzworth method on 26-28 February 2008

Scenarios	Mixing height (m)					
	The estimated data	The observed data	The different value	The estimated data	The observed data	The different value
26 Feb 2008	**0000 LST**			**0600 LST**		
$T_{min} + 5^{\circ}C$	490	425	108	1,028	939	89
$T_{min} + 4^{\circ}C$	450	425	25	946	939	7
$T_{min} + 3^{\circ}C$	388	425	37	916	939	23
$T_{min} + 2^{\circ}C$	365	425	50	*	939	-
$T_{min} +1^{\circ}C$	*	425	-	*	939	-
27 Feb 2008	**0000 LST**			**0600 LST**		
$T_{min} + 5^{\circ}C$	439	399	40	1,022	651	371
$T_{min} + 4^{\circ}C$	413	399	14	709	651	58
$T_{min} + 3^{\circ}C$	368	399	31	431	651	220
$T_{min} + 2^{\circ}C$	343	399	56	*	651	-
$T_{min} +1^{\circ}C$	314	399	85	*	651	-
28 Feb 2008	**0000 LST**			**0600 LST**		
$T_{min} + 5^{\circ}C$	430	327	103	1,443	1,345	98
$T_{min} + 4^{\circ}C$	314	327	13	1,364	1,345	19
$T_{min} + 3^{\circ}C$	327	327	100	1,213	1,345	132
$T_{min} + 2^{\circ}C$	*	327	-	*	1,345	-
$T_{min} +1^{\circ}C$	*	327	-	*	1,345	-

* The dry adiabatic extension of the morning minimum surface temperature plus constant value of urban-rural difference did not intersect the vertical temperature profile

As shown in Table 4.3, the morning mixing heights for Bangkok estimated by Holzworth method showed the different values in the different scenarios which were conducted by changing the constant value of urban-rural temperature difference. Concerning the frequency of the events which the estimated mixing height were nearest to the observed data, the frequency of the total data was 100 % for the scenario which was Tmin + 4 ^{O}C, while the other scenarios did not show the frequency of this event. The study results also showed that the mixing heights estimated by using the constant value of 5^{O}C followed by Holzworth method were higher than the observed data. Considering the UHI intensity of Chiang Mai from this research, the maximum UHI intensity for the diurnal cycle of Chiang Mai was 1-4 ^{O}C. So, the recommendation for a constant value of urban-rural temperature difference which is suitable for estimating morning mixing height in Chiang Mai should be 4^{O}C.

DeMarrais (1975) studied the nocturnal heat island intensities in United States and relevance to estimate of mixing height. He noted that the results from his study indicated that the constant urban-rural temperature difference in estimating mixing height by Holzworth method was questionable because “plus 5^{O}C” was too high. Holzworth (1967) suggested that urban-rural temperature differences should vary and should depend on city size, topography, weather conditions, etc. In addition, He commented that the constant value of 5^{O}C was too high even for large cities and should be used only in specific cases. Gross(1970) referred to The National Weather Service in its air pollution weather forecast program have make use of the technique for estimating morning urban mixing heights and assumes that the UHI intensity is a constant 3^{O}C or 5^{O}C, depending on the location of the upper meteorological station. They have used 5^{O}C when the station is in a rural area, other wise 3^{O}C. So, the recommendation for a constant value of urban-rural temperature difference which is suitable for estimating morning mixing height in Thailand should be 3^{O} or 4^{O}C depend on the location of the upper meteorological station.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS

5.1 Conclusions

This present study could be divided into 3 parts; magnitude and characteristics of UHI effect, vertical atmospheric structure during the UHI events and the effects of UHI on vertical atmospheric structure.

5.1.1 Magnitude and characteristics of UHI effect

The magnitude and characteristics of the UHI effect in five urban areas of Thailand namely Bangkok, Chiang Mai, Ubon Ratchathani, Songkhla, and Phuket were examined by using data measured at two meteorological stations (an urban station and a rural station) in study areas for the 5-yr period from 2004 to 2008. This present study focused on the maximum UHI intensity. The study results could be concluded as follows:

1) The average maximum UHI intensity for diurnal cycle was the highest in Chiang Mai (1.96°C), followed by Ubon Ratchathani (1.61°C), Songkhla (1.42°C), Bangkok (1.33°C) and Phuket (1.13°C). The maximum UHI intensity was found to be different for the cities because the influence of local and synoptic weather and its geographical location. The study results did not showed the relationship between the maximum UHI intensity and city size as expect. However, it showed the maximum UHI intensity of the coastal cities (e.g. Bangkok, Songkhla and Phuket) tended to be lower than the maximum UHI intensity of inland cities (e.g. Chiang Mai and Ubon Ratchathani).

2) The average maximum UHI intensity showed the diurnal variations. The highest value of the average maximum UHI intensity was 2.93°C for Chiang Mai at 0700 LST, 2.76°C for Bangkok at 0400 LST, 2.59°C for Ubon Ratchathani at 0500 LST, 2.49°C for Songkhla at

0700 LST, and 1.80°C for Phuket at 2200 LST, while the lowest value was 0.77°C for Chiang Mai at 1300, o.58°C for Bangkok at 1100 LST, 0.79°C for Ubon Ratchathani at 1300 LST, 0.26°C for Songkhla at 1300 LST, and 0.43°C for Phuket at 1300 LST. The highest average maximum UHI intensity in each study area was observed during the nighttime or the early morning, while the lowest maximum UHI intensity was observed during daytime.

3) The frequently of the UHI events which the UHI intensity more than 1°C maintained more than 1 hour were observed during nighttime 79 % for Bangkok, 68 % for Chiang Mai, 84 % for Ubon Ratchathani, 75 % for Songkhla, and 82 % for Phuket. These UHI events were observed during the nighttime (1800-0600 LST) more than during the daytime (0700-1700 LST) due to the difference in heating and cooling rate between the urban and rural areas.

4) The average maximum UHI intensity showed the seasonal variations. The highest value of the average maximum UHI intensity was 2.73°C in April for Chiang Mai, 2.79°C in April for Ubon Ratchathani, 2.70°C in April for Songkhla, 2.06°C in February for Bangkok and 1.71°C in February for Phuket. The lowest value was 0.90 in August for Chiang Mai, 0.18°C in July for Bangkok, 0.24°C in July for Songkhla, 0.49°C in August for Ubon Ratchathani and 0.42°C in September for Phuket. This study results indicated that the higher maximum UHI intensity was observed during dry season (November-May), while the lower maximum UHI intensity were observed during rainy season (June-October). The main cause of seasonal variation was the local weather conditions which were related with cloud cover, wind speed and relative humidity.

5) The UHI effect related to meteorological elements (wind speed, cloud cover, and relative humidity).

- The UHI intensity had a negative correlation with wind speed. The respective coefficient of determination (R^2) was 0.59 for Songkhla, 0.56 for Phuket, 0.54 for Bangkok, 0.50 for Chiang Mai, and 0.46 for Ubon Ratchathani.

- The UHI intensity had a negative correlation with cloud cover. The respective coefficient of determination (R^2) was 0.58 for Bangkok, 0.57 for Phuket, 0.56 for Chiang Mai, 0.53 for Ubon Ratchathani and 0.52 for Songkhla.

- The UHI intensity had a negative correlation with relative humidity. The respective coefficient of determination (R^2) was 0.45 for Phuket, 0.40 for Bangkok, 0.39 for Songkhla, 0.32 for Chiang Mai and 0.31 for Ubon Ratchathani.

However, the study result showed that the UHI intensity from all study areas was the negative value in sometimes. The results showed the temperature in a rural area was 1-2°C higher than an urban area and was found during daytime (1000-1600 LST) for all study sites. This phenomenon was referred to urban cool island (UCL) .

5.1.2 Vertical atmospheric structure during the UHI events

Vertical atmospheric profiles of temperature, potential temperature, wind speed, relative humidity were examined by using radiosonde data which were obtained from the CAPE project. This present study examined these profiles during the UHI events. The study results could be concluded as follows:

1) The UHI intensity was not significantly correlated with the gradient of temperature.
2) The UHI intensity tended to have the relationship with the height of inversion.
3) Mixing heights were greater in the afternoon than in the morning.

5.1.3 The effects of UHI on vertical atmospheric structure

The effects of UHI on the vertical atmospheric structure were examined by determining the relationship between the UHI intensity and the difference of the surface meteorological data and upper meteorological data at the three standard levels (110 m, 1,563 m and 2,563 m). The study results from all study areas could be concluded as follows:

1) The UHI intensity and the difference of temperature between the surface and the

three higher levels (ΔT) at 0700 LST had the positive relationship. The strongest coefficient of determinations (R^2) for this correlation was found at 110 m with 0.40 for Bangkok, 0.35 for Songkhla, 0.33 for Chiang Mai, 0.32 for Phuket, and 0.25 for Ubon Ratchathani. The correlation between the UHI intensity and ΔT for all study areas was weaker at the higher levels (1,563 m and 2,563 m).

2) The UHI intensity and the difference of wind speed between the surface and the higher levels (ΔW) at 0700 LST had the positive relationship. The strongest coefficient of determinations (R^2) for this correlation was found at 110 m with 0.47 for Chiang Mai, 0.39 for Bangkok, 0.38 for Phuket, 0.32 for Songkhla, and 0.23 for Ubon Ratchathani. The correlation between the UHI intensity and ΔW from all study areas was weaker at the higher levels (1,563 m and 2,563 m).

3) For Bangkok and Chiang Mai which the extra radiosonde were conducted more than one time per day at the upper meteorological weather stations, the UHI intensity and the difference of temperature/wind speed between the surface and the higher levels would be examine during the study period followed CAPE project (19-21 February 2008 for Bangkok and 26-28 February 2008 for Chiang Mai).

- The UHI intensity and ΔT in Bangkok had the positive correlation. The strongest coefficient of determinations (R^2) for this correlation was found at 110 m with 0.40. While, the correlation between the UHI intensity and ΔT was weaker at the level 1,563 m and 2,563 m with R^2 0.21 and 0.04 respectively.
- The UHI intensity and ΔT in Chiang Mai had the positive correlation. The strongest coefficient of determinations (R^2) for this correlation was found at 110 m with 0.40. The correlation between the UHI intensity and ΔT was weaker at the levels 1,563 m and 2,563 m with R^2 0.29 and 0.08 respectively.
- The UHI intensity and ΔW in Bangkok had the positive correlation. The strongest coefficient of determinations (R^2) for this correlation was found at 110 m with 0.40. The correlation between the UHI intensity and ΔW was weaker at the levels 1,563 m and 2,563 m with R^2 0.17 and 0.05 respectively.

- The UHI intensity and ΔW in Chiang Mai had the positive correlation. The strongest coefficient of determinations (R^2) for this correlation was found at 110 m with 0.40. The correlation between the UHI intensity and Δw were found to be weaker at the levels 1,563 m and 2,563 m with R^2 0.12 and 0.05 respectively.

The results showed that the UHI intensity did not have the significant correlation with the difference of temperature or wind speed between the surface and the higher levels.

4) The UHI and mixing height had a positive correlation. The coefficient of determination (R^2) for this correlation was **0**.64 for Bangkok and 0.49 for Chiang Mai

5.2 Suggestions

This present study is the first research which established the maximum UHI intensity for the different cities from all parts of Thailand by using surface temperature data measured at two meteorological stations (an urban station and a rural station). Available data from weather stations can help us to obtain magnitude and characteristics of UHI effect. Therefore, this research is different from the previous UHI researches in Thailand. Komonveeraket (1998) used remote sensing technique to study the UHI through Bangkok Metropolis. This technique can provide the distribution of surface temperature in difference land surface properties and can use surface temperature to investigate the UHI intensity at a given moment, but it cannot investigate the UHI quantitatively. Bunyawatt *et al.*, (2000) used the mobile surveys technique to study the UHI intensity in Bangkok Metropolis. This technique can provide the spatial variability of the UHI. However, it must take several hours if the researchers need to study the UHI in many part of the city. In addition, the UHI intensity from this technique is established at a given moment and the researcher need the standard time to determine the data.

However, this research had the problem of choosing the stations which are representatives of the urban and rural conditions due to the limit of weather station in study areas. The average maximum UHI intensity for the diurnal cycle of Bangkok Metropolis was 1.33°C and the highest average value was 2.76°C which these values were less than the average maximum UHI intensity of Chiang Mai. This result pointed that Bang Na station may not be the representatives of the real rural area.

This research provided the maximum UHI intensity which could be considered a replacement for the constant value of temperature difference between an urban and a rural area used for estimating morning mixing height in Thailand by Holzworth method. The recommendation for a constant value of urban-rural temperature difference which is suitable for estimating morning mixing height in Thailand should be 3°C - 4°C depend on the location of the upper meteorological station.

APPENDIX

Table A-1 The diurnal variation of the maximum UHI intensity for Chiang Mai during 2004- 2008

Time(LST)	The maximum urban heat island intensity (°C)					**Average**
	2004	2005	2006	2007	2008	
18:00	1.07	1.08	1.3	1.24	1.41	1.27
19:00	1.07	1.12	1.28	1.34	1.37	1.27
20:00	1.35	1.45	1.75	1.7	1.69	1.79
21:00	2.1	2.13	2.21	2.14	2.24	2.31
22:00	2.13	2.22	2.07	2.27	2.39	2.31
23:00	2.32	2.13	2.22	2.31	2.09	2.32
0:00	2.17	2.19	2.17	2.36	2.39	2.32
1:00	2.24	2.13	2.01	2.31	2.45	2.33
2:00	2.1	2.34	2.46	2.31	2.37	2.49
3:00	2.31	2.4	2.55	2.53	2.67	2.6
4:00	2.25	2.34	2.48	2.67	2.73	2.65
5:00	2.48	2.53	2.64	2.74	2.9	2.7
6:00	2.58	2.64	2.76	2.68	2.93	2.71
7:00	2.58	2.61	2.63	3.01	4	2.93
8:00	2.04	2.17	2.31	2.47	3.01	2.51
9:00	2.07	2.01	2.02	2.58	2.74	2.18
10:00	1.93	1.87	1.87	1.96	2.24	2.07
11:00	1.64	1.6	1.53	1.6	1.9	1.64
12:00	1.04	1.12	1.09	1.03	1.34	1.21
13:00	0.57	0.67	0.93	0.87	1.01	0.77
14:00	0.78	0.94	0.78	0.94	1.1	0.93
15:00	0.98	0.78	1.02	1	1.21	1.09
16:00	1.02	1.12	1.23	1.41	1.3	1.26
17:00	1.04	1.23	1.14	1.33	1.54	1.26

TableA- 2 The diurnal variation of the maximum UHI intensity for Bangkok during 2004-2008

Time(LST)	The maximum urban heat island intensity (°C)					**Average**
	2004	2005	2006	2007	2008	
18:00	0.68	0.64	0.71	0.68	0.84	0.71
19:00	0.57	0.69	0.76	0.87	1.02	0.95
20:00	0.67	0.57	0.64	0.97	1.12	0.97
21:00	0.96	1	0.98	1.04	1.13	1.13
22:00	1	1.12	1.2	1.35	1.02	1.24
23:00	1.02	1.13	1.29	1.31	1.34	1.29
0:00	1.5	1.53	1.68	1.74	1.87	1.64
1:00	1.45	1.45	1.47	1.68	2.13	1.69
2:00	2.09	2.21	2.13	2.34	2.59	2.34
3:00	2.4	2.51	2.45	2.75	2.87	2.54
4:00	2.55	2.65	2.6	2.79	3.25	2.76
5:00	2.50	2.56	2.64	2.78	2.97	2.34
6:00	2.06	2.13	2.01	2.12	2.34	2.12
7:00	0.98	1.02	1.48	3.14	4	1.96
8:00	1.24	1.36	1.97	1.98	2.47	1.74
9:00	0.64	0.87	1.24	1.23	2.01	1.03
10:00	0.34	0.48	0.51	0.49	1.05	0.64
11:00	0.3	0.5	0.61	0.74	0.97	0.58
12:00	0.42	0.59	0.63	0.57	0.75	0.62
13:00	0.47	0.49	0.53	0.67	0.7	0.66
14:00	0.47	0.64	0.59	0.7	0.74	0.6
15:00	0.64	0.68	0.68	0.7	0.84	0.74
16:00	0.59	0.7	0.74	0.81	0.91	0.78
17:00	0.64	0.65	0.7	0.86	0.92	0.8

TableA- 3 The diurnal variation of the maximum UHI intensity for Ubon Ratchathani during 2004-2008

Time(LST)	The maximum urban heat island intensity (°C)					Average
	2004	2005	2006	2007	2008	
18:00	0.6	0.61	0.7	0.94	1.12	0.95
19:00	0.74	0.75	0.75	0.98	1.28	0.98
20:00	1.24	1.25	1.45	1.39	1.65	1.36
21:00	1.42	1.45	1.46	1.5	1.93	1.53
22:00	1.46	1.5	1.5	1.56	1.97	1.8
23:00	2.12	2.2	2.25	2.25	2.37	2.13
0:00	2.15	2.2	2.25	2.35	2.48	2.24
1:00	2.35	2.4	2.41	2.78	2.93	2.25
2:00	2.12	2.09	2.1	2.34	3.04	2.32
3:00	2	2	2.25	2.35	3	2.35
4:00	2.4	2.49	2.63	2.53	3.02	2.59
5:00	1.98	2.01	2.04	2.41	2.85	2.23
6:00	2.09	2.21	2.13	2.34	2.59	2.16
7:00	1.56	1.6	2.01	2.12	3.9	2.09
8:00	1.56	1.02	1.48	2.14	2	1.9
9:00	1.6	1.64	1.65	1.8	1.9	1.7
10:00	1.24	1.36	1.97	1.98	1.8	1.51
11:00	1	1.12	1.2	1.35	1.6	1.27
12:00	0.64	0.87	1.24	1.23	1.54	1.03
13:00	0.68	0.64	0.71	0.68	1.2	0.79
14:00	0.64	0.65	0.7	0.86	1	0.8
15:00	0.64	0.65	0.7	0.94	1.21	0.87
16:00	0.57	0.59	0.76	0.87	1.31	0.9
17:00	0.78	0.75	1.12	1.24	1.2	0.93

TableA- 4 The diurnal variation of the maximum UHI intensity for Songkhla during 2004-2008

Time(LST)	The maximum urban heat island intensity (°C)					**Average**
	2004	2005	2006	2007	2008	
18:00	0.6	0.61	0.7	0.94	1	0.72
19:00	0.64	0.65	0.78	0.86	0.98	0.8
20:00	1	1.12	1.2	1.35	1.87	1.36
21:00	0.78	0.9	1.25	3	3.85	1.82
22:00	2.35	2.4	2.41	2.78	2.93	2.19
23:00	2.35	2.35	2.39	2.78	2.95	2.18
0:00	2.3	2.45	2.41	2.78	2.9	2.16
1:00	2.09	2.21	2.13	2.34	2.59	2.14
2:00	2.05	2.4	2.41	2.78	2.8	2.23
3:00	2.12	2.09	2.1	2.34	3.04	2.32
4:00	2.25	2.3	2.3	2.35	2.9	2.38
5:00	2.1	2.34	2.46	2.31	2.57	2.41
6:00	2.29	2.3	2.45	2.58	2.69	2.47
7:00	1.97	2.05	2.1	2.7	3.8	2.49
8:00	2.12	2.2	2.25	2.25	2.37	2.1
9:00	1	1.05	1	1.25	1.8	1.25
10:00	0.5	0.4	0.5	0.75	0.97	0.41
11:00	0.15	0.2	0.1	0.5	0.8	0.3
12:00	0.1	0.25	0.2	0.4	0.8	0.29
13:00	0.1	0.1	0.1	0.3	0.6	0.26
14:00	0.2	0.2	0.23	0.2	0.5	0.29
15:00	0.5	0.5	0.51	0.55	0.6	0.54
16:00	0.3	0.4	0.4	0.5	0.5	0.37
17:00	0.4	0.45	0.5	0.57	0.6	0.51

TableA- 5 The diurnal variation of the maximum UHI intensity for Phuket during 2004- 2008

	The maximum urban heat island intensity (°C)					
Time(LST)	2004	2005	2006	2007	2008	**Average**
18:00	1	1.05	1.2	1.2	1.4	1.2
19:00	1.2	1.25	1.3	1.5	1.85	1.6
20:00	1.3	1.5	1.5	1.87	2.1	1.66
21:00	1.5	1.64	2	2	2.5	1.72
22:00	1.55	1.54	1.65	1.7	2.4	1.8
23:00	1.4	1.45	1.6	1.6	2.9	1.75
0:00	1.4	1.45	1.6	1.6	2.7	1.7
1:00	1.25	1.3	1.6	1.6	2.5	1.5
2:00	1.25	1.3	1.6	1.6	1.97	1.37
3:00	1.25	1.2	1.5	1.5	1.6	1.2
4:00	1.05	1.1	1.3	1.5	1.6	1.1
5:00	1	1.1	1	1.15	1.2	1.07
6:00	1	1.1	1	1.1	1.3	1.04
7:00	0.4	0.5	0.6	2.1	3.1	1
8:00	0.64	0.65	0.78	0.86	1	0.9
9:00	0.64	0.65	0.78	0.86	0.98	0.8
10:00	0.6	0.6	0.75	0.8	0.95	0.7
11:00	0.5	0.5	0.51	0.55	0.6	0.54
12:00	0.5	0.5	0.51	0.53	0.6	0.53
13:00	0.3	0.4	0.4	0.6	0.65	0.43
14:00	0.5	0.45	0.75	0.7	0.7	0.6
15:00	0.5	0.45	0.75	0.7	0.78	0.64
16:00	0.6	0.61	0.7	0.87	0.95	0.76
17:00	1	1.05	1.2	1.25	1.35	1.2

TableA- 6 The seasonal variation of the maximum UHI intensity for Chiang Mai during 2004-2008

Month	The maximum urban heat island intensity (°C)					**Average**
	2004	2005	2006	2007	2008	
Jan	2	2.1	2.2	2.54	2.68	2.36
Feb	2	2	2.1	2.21	2.54	2.19
Mar	2.2	2.3	2.35	2.5	2.6	2.42
Apr	2.5	2.4	2.8	2.86	3.1	2.73
May	0.65	0.8	0.9	1.1	1.6	0.93
Jun	1.34	1.5	1.6	1.7	1.9	1.6
Jul	1.45	1.58	1.64	1.6	1.78	1.63
Aug	0.74	0.75	0.8	1	1	0.9
Sep	1.36	1.32	1.42	1.56	1.65	1.52
Oct	0.68	0.8	1.1	1.2	1.23	1.03
Nov	1.25	1.36	1.6	1.45	1.52	1.31
Dec	1.9	1.88	1.87	2.21	2.57	2.07

Table A-7 The seasonal variation of the maximum UHI intensity for Bangkok during 2004-2008

Month	The maximum urban heat island intensity (°C)					**Average**
	2004	2005	2006	2007	2008	
Jan	1.34	1.5	1.4	1.6	2.94	1.95
Feb	1.64	1.75	1.87	2.1	2.85	2.06
Mar	0.56	0.69	0.71	0.8	1.01	0.83
Apr	0.65	0.58	0.6	0.75	0.86	0.75
May	0.2	0.25	0.4	0.45	0.5	0.37
Jun	0.15	0.2	0.2	0.3	0.35	0.28
Jul	0.14	0.16	0.15	0.15	0.21	0.18
Aug	0.23	0.21	0.35	0.4	0.45	0.33
Sep	0.15	0.28	0.3	0.35	0.5	0.33
Oct	0.18	0.2	0.24	0.35	0.36	0.29
Nov	0.5	0.57	0.7	0.69	1.2	0.95
Dec	1.34	1.21	1.23	2.01	2.54	1.6

TableA- 8 The seasonal variation of the maximum UHI intensity for Ubon Ratchathani during 2004-2008

Month	The maximum urban heat island intensity (°C)					**Average**
	2004	2005	2006	2007	2008	
Jan	1.4	1.5	1.56	1.8	1.9	1.61
Feb	1.95	1.98	2	2.34	2.3	2.1
Mar	2.54	2.56	2.68	2.7	2.79	2.65
Apr	2.69	2.73	2.7	2.75	2.86	2.79
May	0.7	0.78	0.8	1	1.02	0.96
Jun	0.7	0.78	0.8	1	1.02	0.78
Jul	0.65	0.58	0.6	0.75	0.86	0.74
Aug	0.3	0.32	0.45	0.55	0.56	0.49
Sep	0.58	0.65	0.7	0.85	0.97	0.77
Oct	0.65	0.75	0.97	0.68	1.02	0.87
Nov	1.25	1.35	1.45	1.56	1.96	1.47
Dec	1.2	1.12	1.15	1.04	1.56	1.26

TableA- 9 The seasonal variation of the maximum UHI intensity for Songkhla during 2004-2008

	The maximum urban heat island intensity (°C)					
Month	2004	2005	2006	2007	2008	**Average**
Jan	1	1.05	1	1.24	1.25	1.18
Feb	1.5	1.65	1.7	1.65	2.95	1.99
Mar	2	2.04	2.08	2.32	2.68	2.17
Apr	2.34	2.5	2.97	3	3.01	2.70
May	0.55	0.65	0.75	0.85	0.97	0.72
Jun	0.53	0.65	0.7	0.87	1.02	0.87
Jul	0.14	0.18	0.15	0.35	0.35	0.24
Aug	0.5	0.55	0.6	0.76	0.87	0.69
Sep	0.5	0.5	0.6	0.65	0.9	0.68
Oct	0.5	0.55	0.58	0.6	0.85	0.7
Nov	1.2	1.45	1.65	1.35	2.34	1.54
Dec	1.1	1.2	1.23	1.42	1.55	1.29

TableA-10 The seasonal variation of the maximum UHI intensity for Phuket during 2004-2008

Month	The maximum urban heat island intensity ($^{\circ}$C)					**Average**
	2004	2005	2006	2007	2008	
Jan	1.2	1.3	1.35	1.41	2.6	1.5
Feb	1.23	1.2	1.4	1.74	2.75	1.71
Mar	1.35	1.42	1.45	1.65	1.71	1.53
Apr	1.2	1.32	1.24	1.29	1.42	1.35
May	0.5	0.51	0.56	0.61	0.74	0.65
Jun	0.6	0.64	0.62	0.74	0.81	0.74
Jul	0.5	0.54	0.55	0.64	0.84	0.7
Aug	0.87	0.88	0.8	0.97	1.02	0.95
Sep	0.5	0.51	0.56	0.61	0.74	0.66
Oct	0.68	0.67	0.57	0.98	1.12	0.91
Nov	1	0.97	0.95	1.21	1.23	1.08
Dec	1	1	0.95	0.98	1.32	1.19

BIOGRAHPY

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