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TRENDS IN TEMPERATURE AND RAINFALL EXTREME CHANGES IN BANGKOK METROPOLITAN AREA

แนวโน้มการเปลี่ยนแปลงสภาวะความรุนแรงของอุณหภูมิและฝนในพื้นที่กรุงเทพมหานคร

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Abstract

Trends in temperature and rainfall extremes in the Bangkok Metropolitan area were analyzed on the basis of 3 high-quality series of daily data. A set of core climate extreme indices recommended by the WMO-CCL/CLIVAR Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) that measures many aspects of a changing climate including changes in intensity, frequency and duration of temperature and rainfall events was computed. Analysis of these indices provided clear evidence that different aspects of temperature and rainfall extremes in the Bangkok Metropolis exhibited significant changes during 1965-2006. The region has been clearly warming over the last few decades and extremes of temperature have changed accordingly. It was found that the frequency of warm days/nights has significantly increased while the frequency of cool days/nights has significantly decreased. In addition, there have been significant increases in the number of summer days and tropical nights, but the annual occurrence of cold spell duration has significantly decreased. Significant rainfall change was marked by a pronounced increase in total rainfall amount especially during summer monsoon period. In association with the change in mean state of rainfall amounts, there were coherent changes towards increases in both frequency and intensity of heavy rainfall events. Another noteworthy feature is that the Bangkok Metropolis has experienced more intense daily rainfall, as its index showed a significant increase in the recent decades. These findings suggest that the risk of disasters associated with temperature and rainfall extreme changes such as severe and flash floods in Bangkok Metropolitan area will increase and affect on millions of people, socio-economic and bio-physical environment. Impacts and consequences of such extreme rainfall and temperature events can substantially wipe out development gain and significantly reduce the standard of living as well as compound environmental degradation. Therefore, detailed study on vulnerability

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and risk assessment is urgently needed to provide valuable insights of adaptation strategy, disaster preparedness and management plan for Bangkok Metropolis, and to move forward as climate resilient sustainable development in a mega-city as well.

Keywords: Temperature and rainfall extreme, Trend, Bangkok Metropolis, Vulnerability

บทคัดย่อ

การศึกษานี้ ได้ทำการวิเคราะห์แนวโน้มการเปลี่ยนแปลงสภาวะความรุนแรงของอุณหภูมิและฝนจากข้อมูลรายวันคุณภาพสูงในพื้นที่กรุงเทพมหานคร ดัชนีหลักด้านสภาวะความรุนแรงของสภาพภูมิอากาศที่ถูกพัฒนาโดยทีมผู้เชี่ยวชาญด้านการติดตามตรวจสอบการเปลี่ยนแปลงสภาพภูมิอากาศขององค์การอุตุนิยมวิทยาโลก ถูกคำนวณเพื่อประเมินลักษณะต่าง ๆ ของสภาวะความรุนแรงของอุณหภูมิและฝนทั้งในแง่ความถี่ ความรุนแรง และระยะเวลาของเหตุการณ์นั้น ๆ ผลการวิเคราะห์ พบว่า สภาวะความรุนแรงของอุณหภูมิและฝนในพื้นที่กรุงเทพมหานคร ในช่วง ค.ศ. 1965-2006 มีการเปลี่ยนแปลงอย่างมีนัยสำคัญ โดยพื้นที่กรุงเทพมหานคร มีลักษณะที่ร้อนขึ้นอย่างชัดเจนในช่วง 2-3 ทศวรรษที่ผ่านมา และสภาวะความรุนแรงของอุณหภูมิมีการเปลี่ยนแปลงที่สอดคล้องกับการเพิ่มขึ้นของอุณหภูมิ ผลการศึกษา ยังพบว่า ความถี่ของวันและคืนที่อบอุ่นมีการเพิ่มขึ้นอย่างมีนัยสำคัญ ในทางกลับกัน ความถี่ของวันและคืนที่หนาว รวมทั้งช่วงระยะเวลาที่หนาว กลับลดลงอย่างมีนัยสำคัญเช่นกัน ยิ่งกว่านั้น จำนวนวันและคืนที่อุณหภูมิสูงกว่า 35 และ 20 °C เพิ่มขึ้นอย่างชัดเจน การเปลี่ยนแปลงอย่างมีนัยสำคัญของฝน ประกอบด้วยการเพิ่มขึ้นของปริมาณฝนรวมรายปี โดยเฉพาะอย่างยิ่งในช่วงมรสุมฤดูร้อน การเปลี่ยนแปลงสภาวะความรุนแรงของฝนที่สอดคล้องกับการเพิ่มขึ้นของปริมาณฝนรวมรายปี คือ การเพิ่มขึ้นของความถี่และความแรงของเหตุการณ์ฝนตกหนัก นอกจากนี้ ความแรงของฝนในพื้นที่กรุงเทพมหานครมีแนวโน้มเพิ่มขึ้นอย่างมีนัยสำคัญในช่วงที่ผ่านมา จากผลการศึกษานี้ แสดงให้เห็นว่า ความเสี่ยงของภัยพิบัติที่เกิดจากการเปลี่ยนแปลงสภาวะความรุนแรงของอุณหภูมิและฝนในพื้นที่กรุงเทพมหานครมีโอกาสเพิ่มขึ้นในอนาคตอันใกล้ ซึ่งจะส่งผลกระทบต่อสิ่งแวดล้อมด้านกายภาพ-ชีวภาพ เศรษฐกิจและสังคมรวมทั้งประชาชนจำนวนมาก โดยผลกระทบจากสภาวะความรุนแรงของสภาพภูมิอากาศนับเป็นปัจจัยเสี่ยงที่ส่งผลต่อการพัฒนาทางด้านเศรษฐกิจและคุณภาพชีวิตของประชาชน รวมทั้งเป็นปัจจัยเสริมที่ส่งผลให้ปัญหาสิ่งแวดล้อมที่กำลังประสบอยู่ในปัจจุบันมีความรุนแรงเพิ่มขึ้น ดังนั้น การประเมินความเสี่ยงและความล่อแหลม เป็นสิ่งจำเป็นต่อแนวทางการตั้งรับและปรับตัวต่อผลกระทบจากการเปลี่ยนแปลงสภาวะความรุนแรงของอุณหภูมิและฝน ทั้งนี้ ความรู้ความเข้าใจดังกล่าว มีความสำคัญต่อการพัฒนาอย่างยั่งยืนของชุมชนเมืองขนาดใหญ่ ตลอดจนการจัดการสิ่งแวดล้อมเมือง และการตั้งรับต่อภัยพิบัติทางภูมิอากาศอย่างมีประสิทธิภาพ

คำสำคัญ: สภาวะความรุนแรงของอุณหภูมิและฝน, แนวโน้มการเปลี่ยนแปลง, พื้นที่กรุงเทพมหานคร, ความล่อแหลม

Introduction

Climate change is the defining issue of our era. Hardly a day passes without a newspaper, a broadcast or a politician making at least one reference to the threats it poses and the urgency of taking action to limit the effects and to adapt to the change that is sure to come. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) advances our understanding on various aspects of climate change. New scientific evidence clearly shows increases in global temperature, widespread snow and ice melting and changes in wind patterns, precipitation and some aspects of extremes [(1)]. Many parts of the world are already experiencing its adverse impacts, and projections from IPCC suggesting that such impacts will become even more intense in the future [1]. The biggest threats are arguably the increasingly frequent and more intense extreme climate events such as tropical cyclones, floods and droughts.

The most adverse impacts of climate change are likely to be in urban areas with heavy concentrations of population and social-economic activities in fragile regions such as deltas and coastal zones. This is particularly true for the East Asia Region (EAR), where the epicenter of the current urbanization surge and home of more than 30 mega cities with population of more than 5 millions [2] are located. At present, 8 out of the 10 most populous cities in the world are located on the EAR coast, where 130 millions live in coastal low-lying cities [2, 3]. Climate change has then posed serious threats to social and economic figures of the EAR cities which account for high percentages of economic activities.

The concentration of people in cities increases their opportunities as well as their vulnerabilities to natural hazards and climate change impacts. There is evidence indicating that most of the coastal mega cities in the EAR are high risks of seismic and climatic natural disasters[1, 4, 5]. Since the beginning of the 20th century, they have experienced more than 500 floods affecting over 800 million people[6]. Moreover, the 2004 Indian Ocean Tsunami and the 2008 Cyclone Nagis that caused tremendous economic damages and large losses of life are recent examples of havoc on high-density population in the coastal low-lying zones [7, 8]. Consequences of climate change can therefore wipe out development gains and significantly reduce the standard of living as well as compound environmental degradation. Hence, climate change represents a critical challenge for coastal and low-lying cities.

Bangkok, the capital and also the largest city of Thailand, is one of the rapidly urbanized mega cities in the Southeast Asia. It is the world's 22nd largest city with current population approximately 8 million[3]. Bangkok has been the political, social and economic centers of not only Thailand but for much of the EAR, making it as the regional hub of a global city network. In 2005, it produced a GDP of about USD 220 billion, which accounts for more than 40% of the country's GDP [9, 10]. Its GDP per capita is well over USD 20,000, one of the highest in the Southeast Asia [11]. Bangkok is situated on a very low-lying flat plain of the Chao Phraya River Delta, where the ground-surface elevation is about 0-1.5 m above the mean sea level [12, 13]. The city is affected by flood in a regular basis. Urbanization is rapidly expanding on both sides of the river flood plain. Due to its geographic location at low-lying alluvial deposit in combination with rapid urbanization, land subsidence and increasingly degraded environment, Bangkok is increasingly recognized as a particularly vulnerable city from a wide range of climate-related disasters and other threats.

Through this study, trends in temperature and rainfall extremes in Bangkok Metropolitan area have been analyzed, aiming at evaluating whether the frequency and/or severity of temperature and rainfall extremes in the densely populated, low-lying mega city have changed in the recent decades. This knowledge will provide insight into the direction and significance of changes in climate extremes that are particularly essential for building sustainable, resilient coastal cities and effective disaster risk and coastal management.

Materials and Methods

Data sources

Series of daily temperature and rainfall data observed in Bangkok Metropolitan area provided the basis for this study. All series were obtained from archives of the Meteorological Department and the Irrigation Department of the Royal Thai Government. These data were parts of a large historical climate dataset complied and developed for climate change study in Thailand. Station series were selected on the basis of record length and data completeness. Overall, each of selected station records was at least 98% complete.

Data quality control and homogeneity checks

In addition to visual examination of any obvious outliers and discontinuities, all daily data were subjected to a multi-stage suite of objective quality control and homogeneity tests. The most widely used and accepted objective approaches which include tests of spatial and temporal outliers, data missing interpolation and homogeneity checks were applied to evaluate the quality of data[14-16]. Temporal checks for outliers were performed utilizing the sample distribution of each calendar month separately for each station. Extreme temperature values were flagged based on limits determined from $\pm$5*IQR (Inter-Quartile Range; 75th percentile minus 25th percentile)[14]. Because rainfall data are commonly positively skewed, a standard deviation as traditional quality control technique was applied instead[17]. Outliers were identified as those values trespassing a threshold of $\pm$15*SD. These thresholds were selected after having tried several other thresholds as a compromise to ensure that the severe errors were captured without including too many correct values in the output records. For spatial outlier checks, a nearby-station technique was employed. This method detects the outliers by comparing the candidate data with neighboring stations by mean of linear regression for each calendar month. Temperature and rainfall values were flagged as potential outliers if they felt outside $\pm$5*RMSE (root-mean-square-error) and $\pm$7*RMSE respectively of linear regression for all pairs of stations. Those data points that failed both of these tests were removed from data records. The outlier data screened by the two previous checks and missing data were estimated using the method described by two researchers[14, 18].

Data homogeneity was assessed using an R-based program, RH test, developed at the Climate Research Branch of Meteorological Service of Canada[16]. This program is capable of identifying multiple step changes based on a two-phase regression model with a linear trend for the entire base series [19]. Detailed discussion about this model can be found in the work of Wang [19]. Significant in-homogenous series were discarded for further analysis.

Based on extensive quality control and homogeneity checks, 3 series of daily temperature and rainfall data were prepared for temperature and rainfall extreme indicator calculation and trend analysis (Figure 1). Our thorough examination reviewed that daily temperature and rainfall data in the Bangkok Metropolis during 1965-2006 were relatively good, which no significant in-homogenous time series were detected.

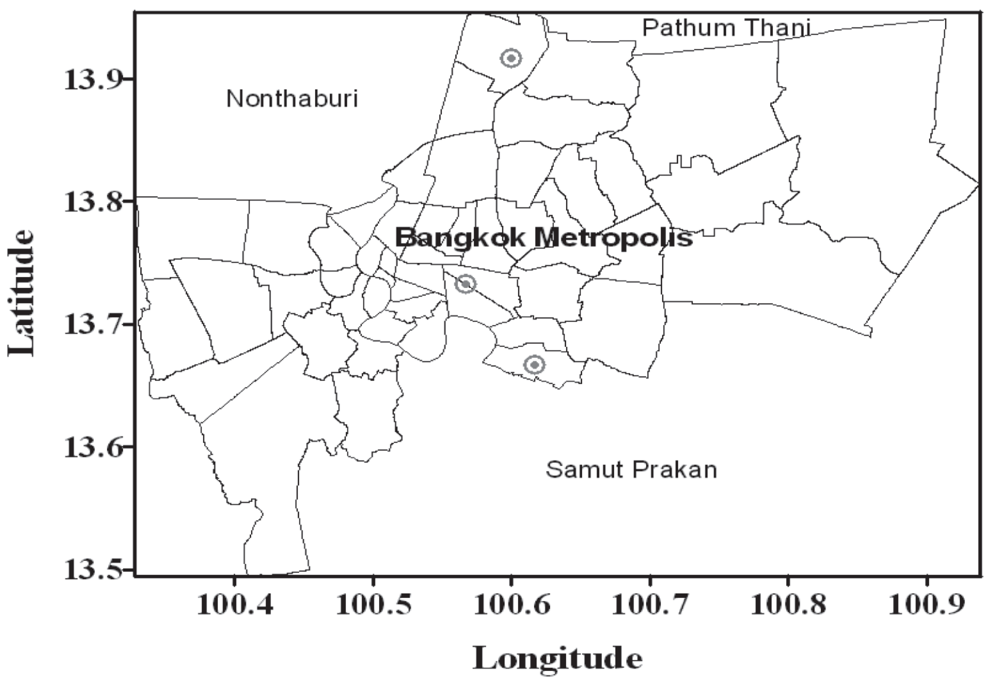

Figure 1 Locations of high-quality meteorological stations used in the temperature and rainfall extreme analysis.

The indices

Seventeen of the 27 core climate extreme indices recommended by WMO[20] were computed to assess changes in temperature and rainfall extremes [21, 22]. The indices were chosen primarily for assessment of many aspects of a changing climate, which include changes in intensity, frequency and duration of temperature and rainfall events. They represent events that occur several times per year, giving them more robust statistical properties than measures of extremes which are far enough into the tails of the distribution so as not to be observed during some years. A subset of 9 temperature and 7 rainfall indices were calculated for each of the stations that passed quality control and homogeneity testing. The indices can be divided into 5 different categories which are 1) percentile-based indices, 2) absolute indices, 3) threshold indices, 4) duration indices and 5) other indices [22]. For percentile indices (e.g. the number of days exceeding the 90th percentile of minimum temperature), the methodology uses bootstrapping for calculating the base period values so there is no discontinuity in the indices time series at the beginning or end of the base period [23]. Table 1 provides a description of these indices. Of the five extreme rainfall indices, four of them relate to 'wetness' [heavy rainfall days (R10), maximum 1 d rainfall total (R1d), simple daily intensity index (SDII) and very wet days (R95)] while one of them relates to 'dryness' [consecutive dry days (CDD)].

Table 1 Temperature and rainfall indices with their definitions and units.

Indices	Indicator name	Definitions	Units
SU35	Summer days	Annual count when TX (daily maximum) > 35^{o}C	d
TR20	Tropical nights	Annual count when TN (daily minimum) > 20^{o}C	d
TN10	Cold nights	Number of days when TN < 10th percentile	d
TN90	Warm nights	Number of days when TN > 90th percentile	d
TX10	Cold days	Number of days when TX < 10th percentile	d
TX90	Warm days	Number of days when TX > 90th percentile	d
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN > 10th percentile	d
AMAX	Tmax	Annual mean of TX	^{o}C
AMEAN	Tmean	Annual mean of mean temperature	^{o}C
AMIN	Tmin	Annual mean of TN	^{o}C
RX1day	Max. 1 day rainfall amount	Monthly maximum 1-day rainfall	mm

Table 1 Temperature and rainfall indices with their definitions and units. (con.)

Indices	Indicator name	Definitions	Units
SDII	Simple daily intensity index	Annual total rainfall divided by the number of rainy days (defined as the days when rainfall amounts > 1 mm)	mm
R10	Number of heavy rainfall days	Annual count of days when rainfall $\geq$ 10 mm	d
R95	Very wet days	Annual total rainfall when rainfall > 95th percentile	mm
CDD	Consecutive dry days	Maximium number of consecutive days with rainfall < 1 mm	d
RAINtot	Annual total rainy day rainfall	Annual total rainfall in rainy days (rainfall > 1 mm)	mm
WETtot	Annual total rainy days	Annual count of days when rainfall $\geq$ 1.0 mm	d

Trend calculation

A linear trend was computed from the index series using the ordinary least square (OLS) method, which is the most widely used and accepted non-parametric trend estimator in hydro-meteorological series (e.g. the work carried out in Canada [24], Northern Hemisphere oceans[25] and Northeast United States[26]). This estimator is resistant to the effect of outliers and robust to non-normal data distribution. Statistical significance was assessed following the non-parametric Kendall's Tau test [22]. For rainfall extreme indices, trend magnitudes were expressed as percentage change relative to the 1965-2006 means. To provide an overall picture of changes in the recent decades, empirical probability distribution functions (PDFs) for all stations before and after 1990 time periods were calculated by fitting two data intervals with gamma distribution function, which shape (α) and scale (β) parameters had been estimated by Maximum Likelihood method [27, 28]. To assess whether the probabilities of two periods for each extreme indicator were significantly different or not, a 2-tailed Kolmogorov-Smimov test was employed. This test has a null hypothesis that two PDFs for two time periods are identical [22, 26].

Results and Discussions

In this section, trend analyses for temperature indices are first presented and discussed, followed by the rainfall indices. At the end of this section, changes in the probability distribution of the indices are presented.

Trends in temperature indices

The analysis of annual mean of daily maximum, mean and minimum temperatures in the Bangkok Metropolitan area during 1965-2006 all indicated a significant warming. An annual averaged of daily mean temperature has increased, on an average, by 0.33 °C/decade (Table 2). Changes in temperature extremes were consistent with a general warming. All stations had statistically significant (at 95% significance level) decreases in the annual cold nights (TN10) and increases in the annual warm nights (TN90), reflecting the general warming in the region (Figure 2). As expected when a Gaussian shaped temperature distribution shifts towards higher temperatures [29], the trend in the count index for the warm tail TN90 (6.0 d/decade) is larger than the opposite trend in the count index for the cold tail TN10 (-2.4 d/decade) (Table 2). The daytime trends (TX10 and TX90) had the same sign as their nighttime counterparts (TN10 and TN90), but were markedly smaller (-2.2 d/decade for TX10 and 4.3 d/decade for TX90) (Figure 2 and Table 2). This result indicates that, over the Bangkok Metropolitan area, an increases in warn days and nights is a more than doubling of those changes associated with the cold tail of the distribution of daily minimum and maximum temperatures. A smaller warming of daytime versus nighttime extremes is consistent with the observed decrease in diurnal temperature range (DTR) in the Bangkok Metropolitan area[30]. It should be also noted that trends in four percentile-based temperature indices observed over the Bangkok Metropolitan area compare well with those detected in other parts of the world [31, 23, 22]. Additionally the annual occurrence of cold spell duration, which is defined as at least 6 d when daily minimum temperature less than 10th percentile (CSDI), significantly decreased at a rate -1.7 d/decade (Figure 3 and Table 2). For other temperature-based indices, they show trends that also correspond with the general warming. There are significant positive trends in the annual number of summer days and tropical nights, which have progressively increased by about 13 and 6 d/decade, respectively (Figure 3 and Table 2). Summary of trends estimated for each of extreme temperature indices by simply averaging from all three stations is shown in Table 2. All extreme temperature indices considered here exhibited significant increases and decreases, of which the SU35 represents the largest increase. It is obvious from these results that, during 1965-2006, Bangkok Metropolis has experienced the general warming and associated significant extreme temperature changes.

Table 2 Trends in averaged temperature and rainfall extreme indices. Trends in rainfall extreme indices expressed as percentage changes relative to the 1965-2006 means.

Extreme indices	Trends
SU35	13.0* (d/decade)
TR20	6.0* (d/decade)
TN10	-2.4* (d/decade)
TN90	6.0* (d/decade)
TX10	-2.2* (d/decade)
TX90	4.3* (d/decade)
CSDI	-1.7* (d/decade)
AMAX	0.30* (^{o}C/decade)
AMEAN	0.33* (^{o}C/decade)
AMIN	0.37* (^{o}C/decade)
RX1day	6.4* (% /decade)
SDII	4.2* (% /decade)
R10	4.0* (% /decade)
R95	14.9* (% /decade)
CDD	3.1 (% /decade)
RAINtot	5.9* (% /decade)
WETtot	0.4 (% /decade)

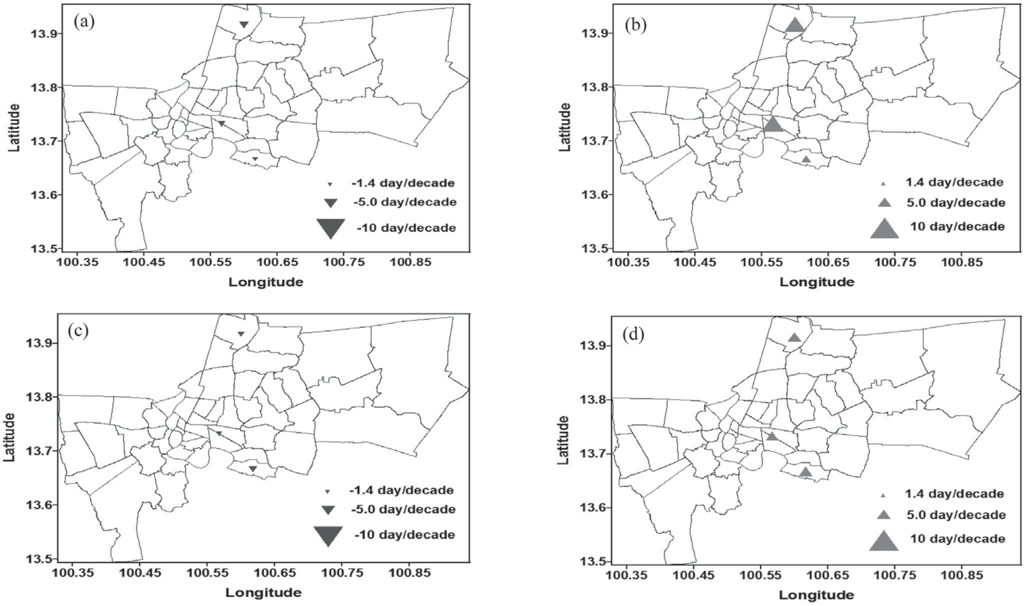

Figure 2 Trends in cool/warm nights (a and b) and cool/warm days (c and d). Filled triangles correspond to trends significant at the 5% level.

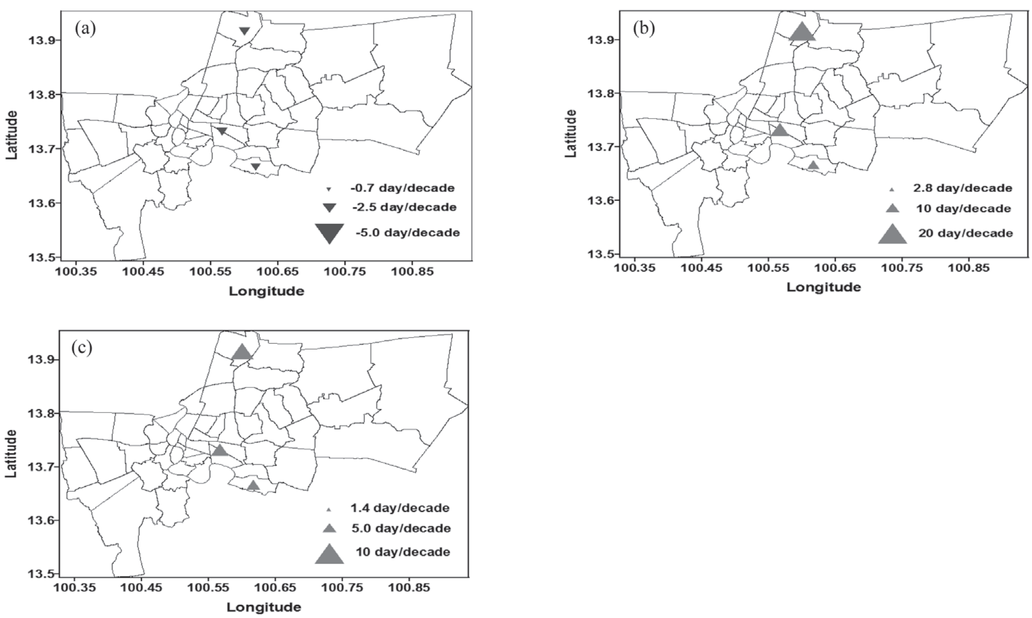

Figure 3 Trends in cold spell duration (a), summer days (b) and tropical nights (c). Filled triangles correspond to trends significant at the 5% level.

Trends in rainfall indices

In general, Bangkok Metropolis receives a relatively high average annual rainfall of about 1,400 mm and is influenced primarily by the Asian monsoon. The south-west monsoon, in which heavy rainfalls occur, begins from mid May and lasts until mid October. The north-east monsoon, which is comparatively dry and cool, occurs from mid October to mid February. Two monsoons are part of a seasonally reversing wind system associated with large-scale changes in atmospheric circulation over the whole of Asia and the Indo-Pacific sector [32]. The boundary zone between these two monsoonal flows called the Equatorial Through Zone (ETZ) passes back and forth over the central part of Thailand several times during the lulls and surges of the monsoons. Previous studies also indicated that strengthening and weakening of the seasonal monsoon over Thailand are linked to the phase reversals of the El Niño-Southern Oscillation (ENSO) and interact, to some extent, with the Indian Ocean Dipole (IOD) [33-35].

Based on our analysis, there is evidence of statistically significant rising trends in total annual rainfall amounts in the Bangkok Metropolis during 1965-2006 (Figure 4). All stations examined here showed on average 6.2%/decade increase relative to the 1965-2006 mean (Table 2). Further examination by analyzing separately the dry half-year period (Nov.-Apr.) and the wet half-year period (May-Oct.) revealed that only total rainfall amounts during the wet half-year period showed similar significant upward trends with comparative magnitudes (6.5 % /decade). This finding indicates that the Bangkok Metropolis has experienced increased annual rainfall amounts, resulting primarily from exceptionally enhanced rainfall amounts during the south-west monsoon. However, no significant changes were detected for the number of annual rainy days, which is defined as days with at least 1 mm of rain, during the same period (Figure 4). Trends in the number of rainy days both annual and seasonal time scales exhibited mixed patterns of change which their magnitude varied from -2.5 to 5.4 % /decade (Figure 4 and Table 2).

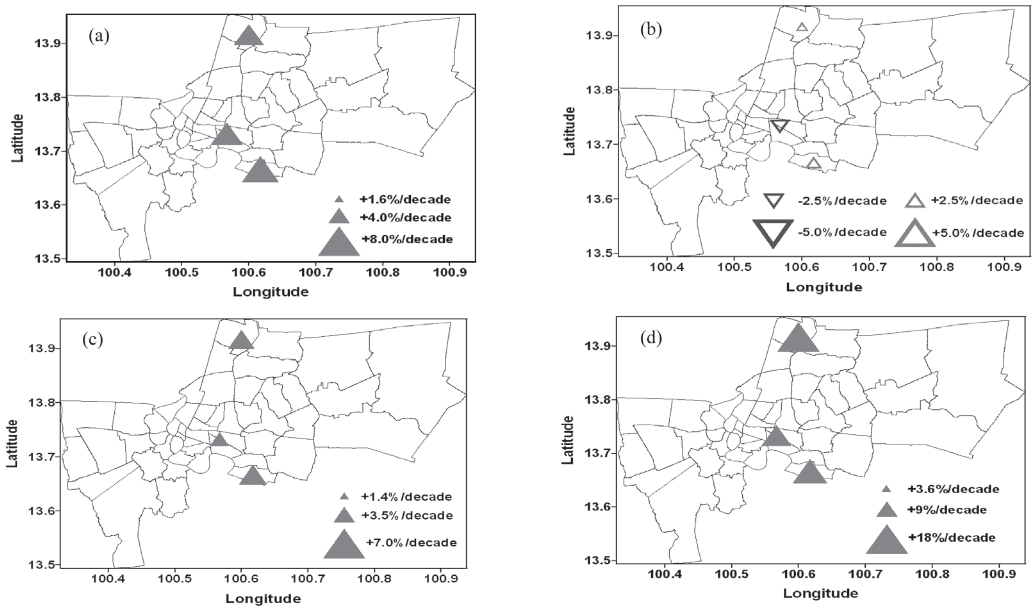

Figure 4 Trends in annual rainfall amounts (a), the number of rainy days (b), SDII (c) and R95 (d). correspond to trends significant at the 5% level.

Another noteworthy feature is a significant increase in the SDII, defined as total annual rainfall per the number of wet days in the year, in the Bangkok Metropolis during 1965-2006 periods (Figure 4). All stations showed significant increasing trends in the SDII at the 95% confidence level, which their magnitudes were in a range of 3.2-4.7% /decade (Table 2). It should be noted that there are consistent increases in the SDII in the Bangkok Metropolis and along the coast of the Gulf of Thailand [30]. By comparison with trends in total annual rainfall amounts and the number of rainy days, it is found that the increase in the SDII over the Bangkok Metropolis reflects an increase in rainfall amounts rather than the number of rainy days. Similar to changes in annual rainfall amounts, the significant increase in the SDII occurred only during the south-west monsoon (May-Oct.) with rates of increase ranging from 4.8 to 5.3%/decade. Consequently, a significant change during this period is mainly attributable to annual increase in the SDII.

Trends in heavy rainfall (R95) in the Bangkok Metropolis showed similar patterns as total annual rainfall amounts and the SDII. There were significant rising trends (at 0.05 significance level) in R95 at all stations, at rates of changes in a range of 12.8-17.9% /decade (Figure 4 and Table 2). This result is consistent with a recent study [34], illustrating significant rising trends in the frequency and the magnitude of extreme rain events over central India during the monsoon seasons between 1951 and 2000.

They further pointed out that the increasing trend in extreme rain events is related to a trend in large-scale moisture availability, which in turn is due to gradual warming of sea surface temperature. The rising trend in R95 was associated with a significant increase in the frequency of heavy rainfall days, R10 (Figure 5). For all stations in the Bangkok Metropolis, R10 index showed statistically significant upward trends, which increased in range of 3.8-6.8% /decade (Table 2). Similarly, another wetness indicator, R1d, exhibited a coherent change with R95 and R10. All stations revealed a tendency toward increased R1d, but only two stations have statistically significant increases at the 95% confidence level (Figure 5 and Table 2). For CDD, a dryness indictor, there is a mixture of stations exhibiting increasing and decreasing trends. However, no significant changes in CDD were found in the Bangkok Metropolis between 1965 and 2006 (Figure 5 and Table 2). Overall trends for each of extreme rainfall indices by simply averaging from all three stations (Table 2) indicate 5 out of 7 indices displaying significant increases, of which the R95 represents the largest increase. These findings suggest that there have been coherent and notable changes towards wetter conditions and increases in magnitude and frequency of more intense rainfall events in the Bangkok Metropolis in the recent decades.

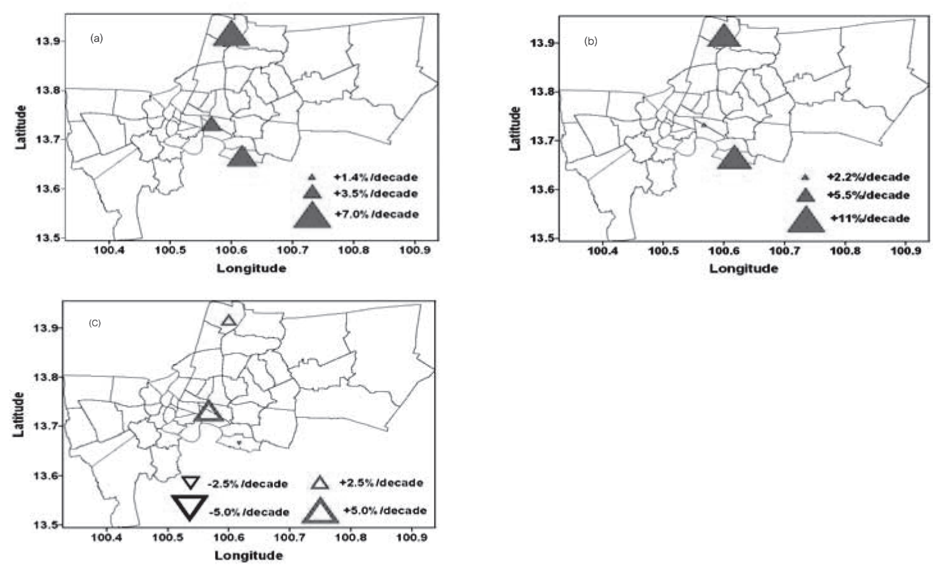

Figure 5 Trends in R10 (a), R1d (b) and CDD (c). Filled triangles correspond to trends significant at the 5% level.

PDFs of temperature and rainfall indices

Figures 6 and 7 show the PDFs of annual temperature and rainfall extreme indicators computed for 1965-1989 and 1990-2006 intervals using data from all three stations. From this analysis, there was evidence of a marked change in both temperature and rainfall extreme indices in the Bangkok Metropolis in the recent decades. The PDFs of 6 temperature extreme indices excepting CSDI in 1990-2006 intervals were significantly different from the previous interval. For rainfall extreme, there was a sharp increase in total annual rainfall amounts, accompanied by pronounced increases in SDII, R95, R10 and R1d indices in 1990-2006 periods comparing to 1965-1989 periods. The PDFs of these indices in 1990-2006 intervals were significantly different from the previous interval. These PDF patterns are consistent to the results in Table 2, indicating a shift in the distribution associated with the general warming, accompanied by wetter conditions towards notable increases in both severity and frequency of heavy rainfall events in the Bangkok Metropolis in the recent decades.

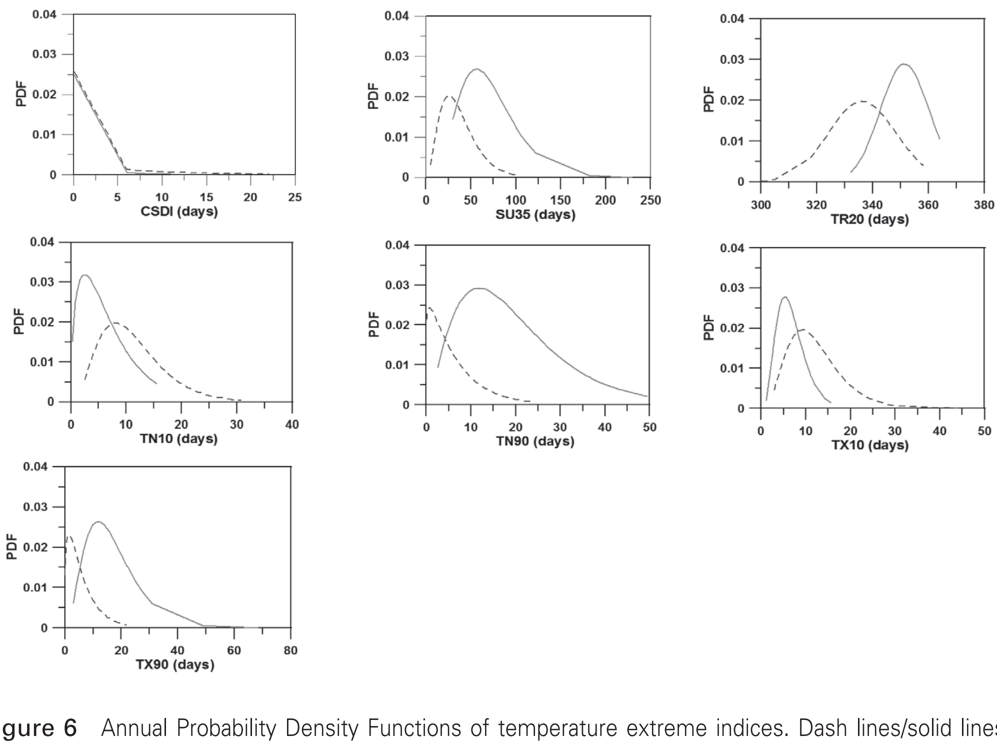

Figure 6 Annual Probability Density Functions of temperature extreme indices. Dash lines/solid lines are the data before and after 1990, respectively. All but CSDI are significantly different at 95% confidence level between two periods.

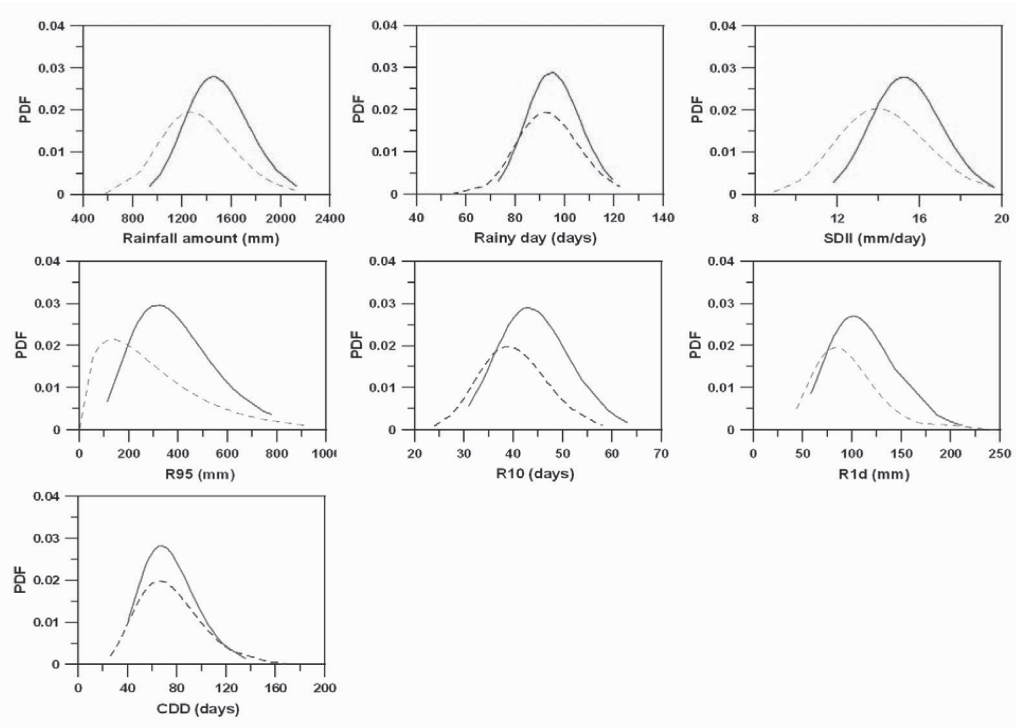

Figure 7 Annual probability distribution functions of rainfall extreme indices, estimated by gamma distribution. Dash lines/solid lines are the data before and after 1990, respectively. Two-tailed Kolmogorov-Smirnov test was used to assess different significance for the data of two periods. Rainfall amounts, SDII, R95, R10 and R1d are significantly different at 95% confident level.

Conclusions

Based on this study, there was clear evidence that different aspects of temperature and rainfall extremes in the Bangkok Metropolis exhibited significant changes during 1965-2006. The results shed more light on whether the distribution of temperature and rainfall extremes in mega-cities are changing and if so how that is one of very important questions posed by the climate community. The Bangkok Metropolitan area has been clearly warming over the last few decades and extremes of temperature have changed accordingly. It was found that the frequency of warm days and nights has significantly increased while the frequency of cool days and nights has significantly decreased. In addition, there have been significant increase in the number of summer days and tropical nights, but the annual occurrence of cold spell duration has significantly decreased.

Significant rainfall change was marked by a pronounced increase in total rainfall amount especially during wet season, when the summer monsoon originally from the Indian Ocean and the western North Pacific Ocean prevails over central Thailand. In association with the change in mean state of rainfall amounts, there were coherent changes towards increases in both frequency and intensity of heavy rainfall events, as indicated by significant increases in R95, R10 and R1d. Another noteworthy feature is that the Bangkok Metropolis has experienced more intense daily rainfall, as SDII showed a significant increase in the recent decades. These findings suggest that the risk of disasters associated with temperature and rainfall extreme changes such as severe and flash floods in Bangkok Metropolitan area will increase and affect on millions of people, socio-economic and bio-physical environment. Impacts and consequences of such extreme rainfall and temperature events can substantially wipe out development gain and significantly reduce the standard of living as well as compound environmental degradation. Therefore, detailed study on vulnerability and risk assessment is urgently needed to provide valuable insights of adaptation strategy, disaster preparedness and management plan for Bangkok Metropolis, and to move forward as climate resilient sustainable development in a mega-city as well.

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