Enhancement of Afternoon Thunderstorm Activity by Urbanization in a Valley: Taipei

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ABSTRACT

Located in northern Taiwan, Taipei is a metropolis surrounded by hills and mountains that form a basin in which two river valleys funnel the surface airflow of this basin to the open sea. Because of the southwest monsoon, summer is a dry season in northern Taiwan but is the season of maximum rainfall in the Taipei basin. This unusual summer rainfall maximum in Taipei is largely produced by afternoon/evening thunderstorms—in particular, on the downwind side and slopes of mountains south of the city. The population in the city of Taipei and the county in which this city is located has more than tripled during the past four decades while land use for building and surface construction increased by a factor of 3. This urbanization may contribute to an increase of 1.5°C in daily mean temperature, a decrease of 1°C in daily temperature range, an increase of more than 67% in the frequency of afternoon/evening thunderstorms, and an increase of 77% in rainfall generated by thunderstorms. These findings may explain the reduction in the water supply deficit to the Taipei metropolitan area and the ground subsidence of the Taipei basin caused by the excessive use of groundwater. Results of this study also provide important information for urban planning and pollution control and for management of the increasing traffic hazards caused by the enhanced thunderstorm activity and rainfall.

1. Introduction

Taipei, the capital of Taiwan, is located in a basin (referred to hereinafter as the Taipei basin) that is surrounded by low hills to its southwest and taller mountains in all other directions. Two river valleys carry surface airflow to the open sea: the Tanshui River in the northwest and the Keelung River in the northeast (Fig. 1). Such a geographic and orographic structure makes the urban region of the Taipei basin a unique environment among large cities around the globe. The eastern Asian climate/weather system is characterized by the winter northeast monsoon and the summer southwest monsoon. Because of the alternation of these two monsoons, the dry season of northern Taiwan occurs during summer. Despite this dry season, the maximum rainfall in the Taipei basin happens in summer. This unusually wet summer microclimate of the Taipei basin in northern Taiwan is primarily caused by afternoon/evening thunderstorm activity (shown later). Since the Vietnam War in the 1960s, Taipei was developed into one of the trade centers in eastern and Southeast Asia. Because of this modern development in the past several decades, the Taipei basin has been well urbanized; population has increased by a factor of 3.5, and land use has increased by a factor that is close to 3. Is the microclimate/weather in the Taipei basin affected by this urbanization through an increase in thunderstorm activity during summer?

The change of land use in urban areas leads to a change of surface characteristics. This change results in not only modifications of dynamic and physical processes in the atmospheric boundary layer, but also the alternation of the surface heat budget to form an urban heat island (UHI). It has been hypothesized that a UHI-induced mesoscale circulation enhances convection, leading to an increase in rainfall over or downwind of major urban areas. This hypothesis was extensively...
investigated and substantiated by the Metropolitan Meteorological Experiment (METROMEX) (Changnon et al. 1981; Huff 1986). As reviewed in depth recently by Shepherd (2005), the pre- and post-METROMEX research efforts of the UHI impact on the local weather/climate system—in particular, precipitation—were further expanded in two directions:

1) The UHI-induced mesoscale circulation was expanded to cover different urban environments with different terrains, surface roughnesses, and urban geometries (e.g., Changnon 1979; Diem and Brown 2003; Dixon and Mote 2003; Takahashi 2003; Fujibe 2003) and to simulate numerically the UHI effect on precipitation with different models (e.g., Baik et al. 2001; Craig and Bornstein 2002; Rozoff et al. 2003; Shepherd 2005). The spaceborne observations of rainfall by the Tropical Rainfall Measuring Mission (TRMM) were applied to explore the UHI impact on urban precipitation (e.g., Shepherd et al. 2002; Shepherd and Burian 2003; Jin and Shepherd 2005). The spaceborne observations of rainfall by the Tropical Rainfall Measuring Mission (TRMM) were applied to explore the UHI impact on urban precipitation (e.g., Shepherd et al. 2002; Shepherd and Burian 2003; Jin and Shepherd 2005).

2) Urbanization originates from an increase in population and human activity. Contributions of human-made aerosols also increase because of urbanization having significant impacts on precipitation processes, which may be suppressed or enhanced (e.g., Rosenfeld 1999, 2000; Ramanathan et al. 2001; Borys et al. 2000, 2003).

The spaceborne observations of precipitation currently available from TRMM only cover the period of 1997–2005, which is much shorter than the period of analysis performed in this study. The pollution monitoring system of the Taiwan Environmental Protection Administration (EPA) in Taipei was not established until 1994, but aerosol observations have not been conducted. On the other hand, the conventional surface observations inside the Taipei basin are available back to the 1960s. With these observations, it is possible for us to explore the impact of urbanization on the microclimate of precipitation in this basin. In addition, the complicated orography and geometry of the Taipei basin and its surrounding areas make the urbanization impact on the basin rainfall variability a unique case related to the first direction of the post-METROMEX research of the UHI effect.

The microclimate/weather of coastal cities is affected by the occurrence of afternoon/evening cumulus convection caused by boundaries that develop when moist air is transported from ocean to land by the sea breeze. If inland hills/mountains exist on the downwind side of the sea breeze, the orography creates upward flow and enhances convection and thunderstorms in the afternoon and evening. The downslope flow generated by the nocturnal cooling over these hills/mountains may intensify the land breeze in the early morning. The impact of the UHI–sea breeze–orography interaction on the local circulation was explored by Kitada et al. (1998). They noted that urbanization 100–200 km away from mountains has little effect on the diurnal airflow. In contrast, extensive urbanized coastal areas cause a shift of the highest temperature zone from the city center to inland suburbs. Later, examining the coastline
The curvature effect on sea-breeze-initiated precipitation with a coupled atmosphere–land surface model, Baker et al. (2001) found that timing and location of this precipitation are affected by coastline shape. Low-level convergence and subsequent heavy rainfall occur earlier with this convex curvature than a coastline with no curvature. Along the same line, Shepherd (2005) demonstrated the enhancement of precipitation downwind of a UHI by the interaction of the UHI convergence zone with the sea-breeze outflow boundaries with the regional fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5; e.g., Grell et al. 1995) coupled with various land surface and microphysics models.

Simulations of the urban circulation and precipitation by previous studies basically concerned urban areas near linear coastlines or open bays linked to open seas. In contrast, the Taipei basin is encircled by hills/mountains in all directions, except the two river valleys. The UHI–sea breeze–orography forcing within this almost closed basin may affect the rainfall pattern differently than in other major urbanized cities that have different orography. Sea breezes converge toward the southern part of the Taipei basin through two river valleys. These low-level flows interact not only with mountains south of this basin, but also with the Taipei UHI. The physical constraint of geographic and orographic structure in this basin compounded by the UHI effect causes the summer afternoon/evening thunderstorm activity and rainfall within the Taipei basin to develop a unique microclimate/weather system over a major urban city. In addition to the unique condition of this climate/weather system, the Taipei basin, with a spatial dimension of 60 km (NE–SW) \( \times \) 30 km (NW–SE), and its surrounding areas are covered by a well-developed mesonetwork of over 100 surface observation stations administered by several government agencies of Taiwan. This observation network offers an excellent opportunity to explore the possible impact of urbanization in this basin on its microclimate/weather.

To achieve the goal set in the previous paragraph, this study is outlined as follows. Surface observations and the analysis methods used in this study are described in section 2. A prerequisite to measure the impact of urbanization on the afternoon/evening thunderstorms and rainfall in the Taipei basin is to understand and measure diurnal variations of these two meteorological variables. This is done in section 3. Illustration of the possible influence of the sea breeze and UHI effect on the microclimate/weather system in the basin is shown in section 4. The impact of urbanization on the afternoon/evening rainfall in the Taipei basin through the UHI effect is presented in section 5. Some concluding remarks and implications of possible environmental impacts are given in section 6.

2. Data and analysis method
   a. Observational data

Observations of surface temperature \( T_s \), wind \( \mathbf{v}_s \), and precipitation \( P \) (\( P \) will be expressed in terms of rainfall rate hereinafter) over Taiwan were conducted by several agencies (as shown in Fig. 1): Weather Bureau of Taiwan [named in Taiwan as Central Weather Bureau (CWB)], EPA, and defense agencies of Taiwan. These stations are classified into two categories: (a) conventional surface stations, consisting of 25 CWB, 72 EPA, and several defense weather stations, and (b) over 300 Automatic Rainfall and Meteorological Telemetry System (ARMTS; Chen et al. 1999) stations established by CWB in 1993. An extremely dense surface observation network of more than 400 stations was developed over Taiwan with an area of approximately 36 000 km\(^2\). Hourly observations at these stations were used to analyze diurnal variations of \( T_s \), \( \mathbf{v}_s \), and \( P \) for the period of 1993–2005, and those from the conventional CWB surface stations were used to explore possible interdecadal variation over the period of 1961–2005. Radiosonde observations at Taipei [World Meteorological Organization (WMO) 46692] for the period of 1973–2005 were analyzed to verify the interdecadal variation at the surface and at upper levels.

The census record, land use, and groundwater level were provided by various Taiwan government agencies, and satellite images were employed to demonstrate the urbanization of the city of Taipei and its surrounding areas. Data provided by Taiwan were obtained from the following Internet sites of the aforementioned government agencies: census record (http://english.taipei.gov.tw/TCG/index.jsp), land use (http://www.land.moi.gov.tw/landdatabase/enhtml/index.asp), and groundwater level (http://www.subsidence.org.tw). Satellite images of Taipei and its vicinity in November of 1972 taken by Landsat-1 (United States) and in December of 2005 by the Satellite pour l’Observation de la Terre (SPOT) program (France) were used to verify the degree of urbanization in the Taipei basin. Both Landsat (http://www.sco.wisc.edu/aerial_sat/landsat.php) and SPOT (http://www.spotimage.fr) are resource satellites capable of distinguishing land surface characteristics (e.g., constructed land, vegetation, or water bodies). The Landsat image was obtained from Wang (1998) and was originally provided by the Center for Space and Remote Sensing Research (CSRSR) in Taiwan. The SPOT image was obtained from the Taiwan CSRSR (http://www.csrs.nchu.edu.tw/chin.ver/c5query/).
Orography of Taiwan was derived from the 800-m-resolution Digital Elevation Model of the U.S. Geological Survey (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html).

b. Selection of afternoon/evening thunderstorm cases

Afternoon/evening thunderstorms usually occur between 1200 and 1800 LST in the Taipei basin and contribute the most to the diurnal variation in rainfall (Chen et al. 1999). Because this diurnal variation is relatively regular, the following criterion was developed to select afternoon/evening thunderstorm cases for the 1961–2005 period: maximum rainfall in Taipei during 1200–1800 LST is larger than 0.5 mm h⁻¹ but during the rest of the day (excluding 1200–1800 LST) rainfall never exceeds 0.2 mm h⁻¹.

The summer mean daily rainfall including all weather systems in the Taipei basin is 0.35 mm h⁻¹, which is between the two limits of rainfall that have been specified in selecting a thunderstorm case. Based only on the selection criterion of afternoon/evening thunderstorms in this basin, it is difficult, if not impossible, for us to understand the synoptic conditions of individual cases. An example is presented in the appendix to illustrate the synoptic condition/development of a typical thunderstorm. To exclude rainfall produced by non–in situ weather phenomena, daily weather maps issued by the Japan Meteorological Agency (JMA) were checked and tropical cyclone tracks archived by the JMA and the Joint Typhoon Warning Center were traced. The tracking of tropical cyclones was already done as part of our recent study for the interannual variation of tropical cyclone activity in the western North Pacific Ocean (Chen et al. 2006). Rainfall was not included for any day on which a front appeared within 50 km of Taiwan or on which the 30-kt (~15 m s⁻¹) sustained wind radius from a tropical cyclone covered Taiwan. Under this provision, the selection of afternoon/evening thunderstorms is limited to cases in which the primary forcing mechanism is modulated by the diurnal cycle. In contrast, cases with rainfall produced by synoptic-scale perturbations or tropical cyclones are eliminated.

3. Summer rainfall climatological description within the basin and its surrounding areas

Because of the alternation of two separate (winter northeast and summer southwest) monsoons, rainfall in Taiwan exhibits two basic regimes: winter and summer (Chen et al. 1999; Yen and Chen 2000). The maximum rainfall during the summer monsoon occurs in southern Taiwan; that during the winter monsoon occurs in northern Taiwan. In other words, the dry season of northern Taiwan occurs in summer and that of southern Taiwan occurs in winter. Because Taipei is located in northern Taiwan, this city should be part of the dry summer regime of northern Taiwan. How is the summer rainfall maximum inside the Taipei basin established?

To answer the question posed above, the annual rainfall variations at three key locations (marked by three different symbols in Fig. 1) in the Taipei basin are displayed with rainfall histograms in Fig. 2: Taipei (circle symbol; inside the basin), Keelung (triangle symbol; the mouth of the Keelung River), and Tanshui (square symbol; the mouth of the Tanshui River). Summer season (June–August) is indicated by a yellow strip on the rainfall histograms in Fig. 2. Rainfall at Tanshui is much less than at the other two locations. In comparison with Taipei, Keelung rainfall exhibits a winter regime, with a minimum in summer. Because summer is the dry season in northern Taiwan, this minimum in summer rainfall at Keelung is expected. The distance between Taipei and Keelung is only about 30 km. Within this short distance, it is surprising that there is such a dramatic disparity in the rainfall regime between these two cities. It is important to disclose the mechanism that causes this rainfall regime change. The rainfall produced at the three locations by the afternoon/evening thunderstorms selected in section 2b for the 1993–2005 period is shown in the second column of Fig. 2. In comparison with the other two locations, much more warm-season rainfall at Taipei comes from these thunderstorms. After removing them, a winter regime emerges from all three locations shown in the third column of Fig. 2; the minimum rainfall occurs in summer, the dry season of northern Taiwan. As revealed from this comparison of annual rainfall variations, it is clear that the summer rainfall maximum inside the Taipei basin is primarily established by the afternoon/evening thunderstorm.

The discussion of the contrast between the winter and summer rainfall regimes is restricted only to three key stations shown in Fig. 2. It would be of interest to explore the distribution of these two rainfall regimes over the area of concern. In comparing rainfall histograms of all available rain gauge stations over the study area, we are able to divide it into two by the thick blue line on the map on the right side of Fig. 2: the northeast coastal zone (blue-dot area) belongs to the winter regime, and the rest of the area belongs to the summer regime. Areas where the amplitude of diurnal variation in summer mean hourly rainfall is larger than 0.5 mm h⁻¹ over the latter region are indicated by the area...
shaded with red dots, which covers the southern part of the basin and the northwestern slope of the mountains adjacent to the basin. The city of Taipei (red–black circle) is located at the northeast corner of this region. If the large amplitude of diurnal variation in daily rainfall is caused by afternoon/evening thunderstorms, what is the implication of Taipei’s location for thunderstorm activity? To explore this implication further, the summer rainfall in northern Taiwan is shown in Fig. 3a. As indicated by the blue area, the majority of the summer rainfall occurs in the southern part of the basin and the northwestern slope of the mountains. Rainfall is produced by afternoon/evening thunderstorms ($P_{TS}$ in Fig. 3b) over these regions, except for mountains taller than 500 m southeast of the region with $P_{TS} \geq 6$ mm day$^{-1}$. The ratio $P_{TS}/P$ is shown in Fig. 3c. Areas where this ratio is larger than 60% (70%) are shaded orange (red). The region with $P_{TS}/P \approx 65\%$ almost coincides with the region where the amplitude of diurnal rainfall variation is larger than 6 mm day$^{-1}$. The city of Taipei is located at the northeast corner of the red region ($P_{TS}/P > 70\%$ in Fig. 3c). It has been observed by numerous studies (e.g., Changnon 1979; Shepherd et al. 2002) that precipitation is enhanced downwind of pronounced urbanized areas. As will be shown later, afternoon/evening thunderstorms in the southern part of the basin and the northwestern mountain slope are located downstream of sea breezes along the Tanshui and Keelung River valleys. These thunderstorms can be enhanced by the interaction among the sea breeze, the Taipei UHI, and mountains adjacent to the southern basin.

4. Factors affecting the afternoon/evening thunderstorm activity

As shown in Fig. 3, the summer rainfall in the Taipei basin is primarily generated by afternoon/evening thunderstorms. What is the most important local factor affecting this thunderstorm activity? Some synoptic conditions are vital to storm genesis, but the downscale interaction of the synoptic system with the local orographic structure and thermodynamic conditions may be equally important. Based on our observations of the
Fig. 3. Distribution of (a) total summer rainfall $P$, (b) afternoon/evening thunderstorm rainfall $P_{TS}$, and (c) ratio $P_{TS}/P$. The contour interval of $P$ and $P_{TS}$ is 1 mm day$^{-1}$, and that of $P_{TS}/P$ is 5%. The orography scale is shown in the lower-left corner of (a)–(c), and the $P$, $P_{TS}$, and $P_{TS}/P$ scales are displayed in the lower-right corner of each corresponding panel.
genesis and development of numerous thunderstorms in the Taipei basin, the two crucial factors affecting the genesis of afternoon/evening thunderstorms in the Taipei basin are the sea-breeze circulation and the UHI effect.

a. Sea-breeze circulation

It was pointed out in section 1 that numerous studies dealing with UHI–sea-breeze–orography interactions focused on the linear/curved coastlines and open bays. The Tanshui and Keelung River valleys form two major openings of the Taipei basin. This geographic/orographic structure limits the interaction of surface airflows within the Taipei basin with the open sea only through these two river valleys.

Surface winds $\mathbf{V}_S$ at both Tanshui and Keelung are regulated by the alternation of the land–sea breeze. The climatological behavior of daily $\mathbf{V}_S$ time series at these two locations is shown in Fig. 4a. Land and sea breezes at these two locations occur during the time periods of 1700–0800 LST (dark blue vectors) and 0900–1600 LST (orange vectors). Daily variations of rainfall are also added onto these two $\mathbf{V}_S$ time series. Time series of $(\mathbf{V}_S, P)$ at Taipei are also displayed in Fig. 4a; $P$(Taipei) reaches its maximum at 1500 LST. As inferred from time series of $\mathbf{V}_S$ at these three locations, sea breezes transport cooler moist air into the Taipei basin through the Tanshui and Keelung River valleys. This sea air is then warmed by the urbanized Taipei basin and converges toward the mountains bordering the southeastern basin. Thus, afternoon/evening thunderstorm genesis is likely enhanced by the warm moist sea air downwind of the Taipei UHI. This inference derived from time series of $(\mathbf{V}_S, P)$ at three locations is supported by the horizontal map of $(\mathbf{V}_S, P)$ at 1500 LST (Fig. 4c) when $P$(Taipei) reaches its maximum.

b. Urban heat island effect

Penchiayu (Fig. 1), a small rural island located about 50 km northeast of Taipei, is uninhabited. The surface meteorological conditions of Penchiayu are not contaminated by urbanization. The Taipei UHI can be illustrated by contrasting surface temperature and precipitation between Penchiayu and Taipei in Fig. 4b. The difference between $T_S$(Taipei) (thick-solid blue line) and $T_S$(Penchiayu) (thin-dashed red line) is slightly larger than 1°C in the early morning and is about 4°C at 1200 LST, and the rainfall difference $P$(Taipei) (blue histogram) – $P$(Penchiayu) (red histogram) is over 1 mm h$^{-1}$ at 1500 LST (when afternoon rain reaches its maximum). The synoptic condition at upper levels may not be changed significantly 50 km away from Taipei.

The surface temperature difference of 4°C can make the lower troposphere adjacent to the surface more thermally unstable at Taipei than at Penchiayu. Thus, it is not surprising that Taipei has more rainfall than Penchiayu.

The horizontal map of $(\mathbf{V}_S, T_S)$ at 1200 LST is shown in Fig. 4d. In comparing the $T_S$(1200 LST) distribution with the orography of the Taipei basin (Fig. 1), we see that $T_S$ is larger at low elevations and along the two major river valleys. It is likely that this larger $T_S$ is at least in part caused by urbanization. The maximum $T_S$ indicated by the red color in Fig. 4d corresponds to the highly urbanized area of Taipei. Also seen by comparing Figs. 4c and 4d is the surface airflow converging toward the rainfall center located somewhat south of the $T_S$ center. Downslope flows that form once rainfall occurs over the sloped terrain and surface cooling begins likely contribute to this convergence into the basin. These downslope flows may merge with inbound sea breezes to strengthen the convergent center (Fig. 4c) south of the $T_S$ center.

In summary, the sea breezes are channeled toward the Taipei basin by the two major river valleys. A consequence of these sea breezes and downslope flows from the mountains along with the destabilizing effect that the Taipei UHI has on the atmosphere is that upward motion (as inferred from $P_{RS}$ shown in Fig. 3b) is strongest just downwind (southwest) of Taipei. Intensification of the UHI and sea-breeze circulation possibly affects the afternoon/evening thunderstorm activity and rainfall inside the Taipei basin.

5. Effects of urban heat island

The search for effects of the sea breeze and urban heat island on the afternoon/evening thunderstorm activity and summer rainfall in the Taipei basin in section 4 leads to the following two questions regarding possible mechanisms driving the summer thunderstorm activity in Taipei:

1) Is it possible for interdecadal changes of the western North Pacific (WNP) surface circulation to affect the afternoon/evening thunderstorm activity in this basin by affecting the strength of the sea-breeze circulation?

2) Does the increased urbanization of the Taipei basin in the past four decades have any effect on afternoon/evening thunderstorm activity in this basin?

a. Sea-breeze circulation

As indicated by surface wind vectors $\mathbf{V}_S$ at Tanshui and Keelung in Fig. 4, the sea-breeze intrusion along
the two river valleys reaches its maximum intensity at 1400 LST. To explore the impact of any possible interdecadal change in the WNP surface circulation on the basin sea breeze, $V_S$ from surface stations at three small islands surrounding Taiwan (Fig. 5c)—Penchiayu (labeled as $\text{\textasteriskcentered}$, northeast of Taiwan), Penhu (labeled as $\text{\textregistered}$, west of Taiwan), and Lanyu (labeled as $\text{\textcircled{z}}$, southeast of Taiwan)—are used as an indicator of this change. Time series of summer mean $V_S$(1400 LST) at these stations are shown in Fig. 5a, and departures from their climatological means $\Delta V_S$(1400 LST) are displayed in Fig. 5b. The surface airflow west of Taiwan (Penhu) is dictated by monsoon southwesterlies. In contrast, the surface airflow east of Taiwan (Lanyu) is characterized by
southwesterlies associated with the North Pacific anticyclone. These two surface airflows originating from different sources eventually merge to establish monsoon southerlies north of Taiwan. Regardless of their interannual/interdecadal variation, these characteristics of surface airflows around Taiwan are well reflected by $V_S$ at the five stations as shown in Fig. 5. Sea breezes at Tanshui and Keelung (characterized by northwesterlies and northeasterlies, respectively, in Fig. 4) converge toward the southern part of the Taipei basin.

Contrasts between time series of $\Delta V_S(1400\text{ LST})$ at the three open-sea stations do not exhibit systematically interdecadal trends. Although the WNP surface circulation undergoes a pronounced regional interdecadal variation in summer (e.g., Lau and Weng 1999), sea breezes along the Tanshui and Keelung valleys do not seem to be affected. Time series of $\Delta V_S(1400\text{ LST})$ at Tanshui and Keelung show the persistent convergence of surface airflow toward the southern basin of Taipei. However, these time series exhibit no coherent interdecadal trends with each other and with the three open-ocean stations. As inferred from this argument, the answer to question 1 is negative.

b. Urbanization

According to the census record of the Taiwan government (http://english.taipei.gov.tw/TCG/index.jsp), the population $N_{PO}$ of Taipei County (whose boundary is indicated by the orange dotted line in Fig. 1), including the city of Taipei, was 1.8 million in 1961 but was 6.4
million in 2005 (Fig. 6). The increasing trend of population in Taipei County is in phase to a great extent with that of daily mean \( T_S \) and land use shown in Figs. 6 and 7, respectively, the city of Taipei and its surrounding area have been urbanized in the past several decades.

The daily minimum temperature \( T_S(\text{Min}) \) is a good indicator of energy consumption by the population. The \( T_S(\text{Min}) \) at Taipei (Fig. 6) exhibits an increasing trend of more than 2°C in the past four decades. Note that, during 1992–97, the surface observation station at Taipei (46692) was moved to an open space on the campus of Taipei Teaching College because of construction of the Taiwan Weather Bureau's new building (http://www.cwb.gov.tw/v5/index.htm). A short-term cooling in daily mean \( T_S \) and \( T_s(\text{Min}) \) in this period may be caused by the location change of this station. Despite this short-term cooling, warming in \( T_s(\text{Min}) \) (Fig. 6) is still considerable.

To examine whether the increase of \( T_S \) in Taipei is part of an interdecadal variation in the WNP region, linear trends are superimposed with the time series of daily mean \( T_S \) and \( P \) at the three open-sea locations (Fig. 8). Trends in daily mean \( T_S \) suggest that warming in the past four decades is not deniable at the three open-sea stations, although their increases are less than 0.3°C. Recall that the daily mean \( T_S \) trend at Taipei in the past four decades is 1.5°C, which is much larger than the trends for the three open-sea stations. Contrasts of \( T_s(\text{Min}) \) and daily mean \( T_S \) between Taipei and the three open-sea stations lead us to conclude that the increasing trend of \( T_S \) in Taipei is likely a result of urbanization.

c. Impact

What could the meteorological impact of interdecadal change in \( T_S \) inside the Taipei basin be over the past four decades? Vertical profiles of temperature \( T \) at Taipei (WMO 46692) measured by radiosonde for 1973–88 and 1989–2005 (Fig. 9) show that temperature in the lowest part of the troposphere adjacent to the surface increased roughly 1.5°C from the first period to the second period, with the temperature increase becoming much less at the upper levels. It is inferred from this contrast in thermal structure at Taipei that the second period with the warmer lower troposphere is likely more unstable than the first period. Thus, convection might become more active and result in an increase of rainfall.

Rainfall histograms at the three open-sea stations are shown in Fig. 8b. Some interdecadal \( P \) trends are discernable, but they are not as coherent as those in the daily mean \( T_S \) of Taipei (Fig. 6). Interdecadal rainfall variations at the three open-sea stations are not coherent with their corresponding interdecadal \( T_S \) trend, ei-
ther. Just like daily mean $T_{S}(Taipei)$, $P(Taipei)$ exhibits a pronounced interdecadal trend in the past four decades (Fig. 10a). It is suggested by these two coherent trends that the interdecadal increasing trend of Taipei rainfall is linked to the urbanization inside the basin. Rainfall produced by afternoon/evening thunderstorms ($P_{TS}$) and thunderstorm occurrence frequency ($N_{TS}$) are shown in Fig. 10b. As estimated with interdecadal trends of $P_{TS}$ and $N_{TS}$, the former ($P_{TS}$) increased 77% and the latter ($N_{TS}$) increased 67% in the past four decades. However, the histogram of $\Delta P = P - P_{TS}$ (Fig. 10c), which is the rainfall produced by sources other than afternoon/evening thunderstorms, does not exhibit any systematic trend like that observed in $P_{TS}$. The contrast between $P_{TS}$ and $\Delta P$ once again supports our argument that interdecadal trends of daily mean $T_{S}$ and $T_{S}(Min)$, $P$, $P_{TS}$, and $N_{TS}$ at Taipei are results of the urbanization in the Taipei basin.

6. Summary and remarks

a. Summary and inference

A recent review by Shepherd (2005) indicates that numerous studies have observed an increase in precipitation downwind of an urban area. The city of Taipei and its suburbs are located within a basin surrounded by mountains with two major openings: the Tanshui and Keelung River valleys. The surface airflow of the Taipei basin interacts with that of the open sea through these two river valleys. Sea breezes along the NW–SE-oriented Tanshui River and the NE–SW-oriented Keelung River converge toward the southern part of the basin. The UHI effect of Taipei and the orographic forcing of mountains south of the city facilitate cumulus convection triggered by the convergence of sea breezes and maintain the precipitation over the southern part of the basin and slope of the mountains. The
daily mean surface temperature of the city has increased 1.5°C in the past four decades. This urban environment change may have contributed to a 70% increase in afternoon thunderstorm activity and rainfall linked to sea breezes.

The urbanization of Taipei is not only reflected by increases of population (by a factor of 3.5) and land use (by a factor of 3) in the past four decades, but also by increases in pollution and anthropogenic aerosols. Most changes of land use in the Taipei basin and its surrounding areas were caused by building construction and various urban surface developments. Because built-up area is concentrated on the northwest slopes of the mountains south of the basin, roughness increases over the area should slow down the inbound sea breezes [as inferred by Oke (1987)] through the Tanshui and Keelung River valleys. This speed reduction in surface airflow would likely result in the enhancement of low-level convergence downwind of major constructed lands and subsequent rainfall increase.

The pollution monitoring system in the Taipei basin was established in 1994, but measurements of aerosols have not been made. Therefore, an assessment of the possible impact of aerosol–microphysical forcing on urban precipitation variability in the Taipei basin is difficult. However, possible impacts may be inferred from relevant studies of pollution and aerosols. Analyzing atmospheric visibility trends in Tainan, a major city in southern Taiwan, Tsai (2005) found that the range of annual visibility was reduced from more than 20 km in

Fig. 8. (a) Time series of summer daily mean $T_s$ (dark-brown line) and (b) histograms of summer mean $P$ (blue bars) for three small islands (Penchiayu, labeled with 1; Penhu, labeled with 2; Lanyu, labeled with 3) surrounding Taiwan. The daily temperature range between $T_s$(Max) and $T_s$(Min) is shaded in pink. Linear trend lines of $T_s$ (red line) and $P$ (dark blue line) are superimposed.
the early 1960s to 6–7 km during 2002–03, and there is a negative correlation between visibility and the concentration of the pollutant known as particulate matter with diameter of less than 10 μm. Tainan, an academic-oriented city, has a population of two million. Population and built-up area have increased by 100% and 75%, respectively, in the past 25 years. The increases of both population and built-up area in Taipei were much more than in Tainan, and thus it is conceivable that pollution increases in Taipei are much larger than those in Tainan. Liu et al. (2002) observed a decreasing trend of sunshine duration in Taiwan (including Taipei) over the past century and suggested that this trend is most likely caused by an increase in clouds/cloud albedo as a result of increasing anthropogenic aerosols. Based on possible increases of pollution and aerosols, the contribution of aerosol–microphysical forcing to precipitation variability in the Taipei basin seems reasonable.

From a dynamic perspective, the UHI–sea breeze–orography interaction plays a significant role in the urban precipitation variability within the Taipei basin. The role of the aerosol–microphysical forcing should also be taken into account in establishing this precipitation variability. Because modifications/alternations of both dynamic and physical processes by urbanization in this basin are so complicated, it does not seem possible to quantify contributions of these two processes based on observations. An alternative approach to resolve this predicament is the numerical simulation of the change in rainfall pattern within the Taipei basin by.

![Fig. 10. Histograms of summer mean rainfall: (a) P (total rain), (b) P_{TS} (rainfall contributed by afternoon/evening thunderstorm), and (c) ΔP (=P - P_{TS}; rainfall produced by other sources). Frequency of afternoon/evening thunderstorms in the Taipei basin N_{TS} (red line) and the linear trend (straight red line) are added in (b). Trends of P, P_{TS}, and ΔP are also shown in (a)–(c).]
urbanization with an atmosphere–land surface model coupled with an aerosol-microphysical model.

b. Impact on the urban environment

Increases in rainfall and thunderstorm activity in the Taipei basin have a profound impact on many aspects of the basin, as shown below.

1) Water supply

Two lakes are located southwest and southeast of Taipei over the mountain slopes (Fig. 1), and dams built adjacent to these two lakes are the most important reservoirs supplying water for Taipei and its suburbs. Because the demand of water supply has increased following the urbanization in the Taipei basin, the rainfall increase that has resulted from more frequent afternoon/evening thunderstorms actually reduces the deficit of water supply.

2) Urban planning

Because space for expansion is limited by surrounding mountains, development has occurred on mountain slopes to meet housing demand, as seen from Landsat and SPOT images taken 30 yr apart (Fig. 7). The increasing trend in rainfall in the southern part of the basin and along the slopes of the mountains is useful information to develop a new construction code over these areas.

3) Ground subsidence

Increases in population and housing development in the Taipei basin were followed by an increasing demand for water supplies, which was partially met by groundwater. According to the Water Resources Agency, Ministry of Economic Affairs (http://www.subsidence.org.tw) in Taiwan, the consumption of groundwater in the Taipei basin has dramatically increased since the 1960s. Subsidence, which in some locations within the Taipei basin was 28 cm yr⁻¹ in the 1970s, was slowed down to 3 cm yr⁻¹ in 1991. The Water Resources Agency has suggested that this reduction may be due to water supply from the nearby dam. However, increasing water supply from the enhanced thunderstorm occurrence and the attendant rainfall resulting from the urbanization of the Taipei basin (section 4) should also be taken into account to explain the decrease in subsidence.

4) Pollution

The exchange of fresh air in the open sea and polluted air inside the Taipei basin can be accomplished by the land and sea breezes along the Tanshui and Keelung River valleys. On the other hand, pollutants in the air and ground can be washed into rivers by rainfall and transported by streamflow of the rivers from the basin into the open sea. In other words, the Taipei basin is “ventilated” by valleys of the two rivers. Rainfall produced by the afternoon/evening thunderstorms forms the ventilation mechanism of pollution of the Taipei basin.

5) Traffic hazard

The afternoon/evening thunderstorms and accompanying rainfall often create traffic hazards. Rainfall systems in the Taipei basin can lead to the formation of mesoscale cold fronts and gusty winds along these fronts similar to the mesoscale convective systems documented over the U.S. northern plains (e.g., Maddox 1981), according to preliminary results obtained from our small field experiment during the 2004 and 2005 summers. When a mesoscale cold front moves out of the southern basin, gusty winds accompanied with this front may make the landing or taking off of airplanes impossible. For example, the Songsun Domestic Airport in the Taipei basin was closed on 2 August 2004 by such a gust front. The airport has frequently been closed during the occurrence of thunderstorms in this basin. In addition, heavy rains from thunderstorms in the basin in the afternoon often cause flash flooding in the southern/southwestern basin and create traffic jams.

In summary, urbanization of the Taipei basin has created environmental hazards, such as heavy traffic and pollution, common to other large metropolitan areas. The increased rainfall and thunderstorm activity in the Taipei basin likely worsens traffic hazards but eases the stress of water supply, reduces ground subsidence, and cleans up pollution. Results of this study not only help to understand the impacts of urbanization on the local microclimate/weather system, but also provide important environmental information for future urban planning and environmental management.

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APPENDIX

Synoptic Condition/Development of a Summer Afternoon Thunderstorm (31 May 2004) in the Taipei Basin

The surface synoptic chart for East Asia issued by the JMA at 0600 UTC (1400 LST in Taiwan) 31 May 2004 is shown in Fig. A1a. The surface synoptic pattern is characterized by a front that is slowly propagating eastward along the northwest periphery of the North Pacific anticyclone (blue area in the western North Pacific). Because this front was located to the north, Taiwan experiences warm moist southwesterly flow. As revealed from the IR images of JMA Geostationary
Meteorological Satellite (GMS), a cloud band along this front extended from eastern Asia to the Japan Sea (Figs. A1b and A1c). The Taipei basin was clear at 0400 UTC (1200 LST in Taiwan), but well-developed deep cumulus formed at 0600 UTC (1400 LST in Taiwan). As shown in Figs. 4c and 4d, the climatological maximum intensity of sea breezes along the Tanshui and Keelung River valleys occurs at 1200 LST. Surface airflows of the sea breezes along the two river valleys on 31 May 2004 were well organized at 0400 UTC (1200 LST; Fig. A2). At this time, no rain was detected over the basin by surface rain gauges (Fig. A2a) and radar (Fig. A2b). However, 2 h later at 0600 UTC (1400 LST) rainfall generated by this afternoon thunderstorm is clearly seen from gauge reports (Fig. A2c) and radar reflectivity (Fig. A2d) mainly in the southern part of the basin and northwestern slopes of the mountains. Surface airflows around the rainfall center reversed direction to form the land breeze (Fig. A2c). Similar to the cold pools formed from mesoscale convective systems in the U.S. Great Plains (Maddox 1981), mesoscale cold fronts formed and moved out of the basin along the two river valleys. The surface synoptic pattern described here is typical of how afternoon/evening thunderstorms develop in the Taipei basin.

REFERENCES


