Urban thermal influence on the background environment of convective precipitation

Hirofumi SUGAWARA

Earth and Ocean Sciences
National Defense Academy of Japan, Yokosuka, Japan

Ryoko ODA

Civil and Environmental Engineering,
Chiba Institute of Technology, Chiba, Japan

and

Naoko SEINO

Meteorological Research Institute, Tsukuba, Japan

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1) Corresponding author: Hirofumi Sugawara
Earth and Ocean Sciences, National Defense Academy of Japan
1-10-20 Hashirimizu Yokosuka Kanagawa 239-8686 JAPAN.
Email: hiros@nda.ac.jp
Tel: +81-46-841-3810 ext.3304
Fax: +81-46-844-5902
Abstract

Does the cities enhance precipitation? It is an unsettled question and the comprehensive answer has not been archived for it. This study focuses on the urban heat excess and evaluates its influence on atmospheric instability which is the background condition for the convective precipitation. A simple approach was developed that involved calculating the daytime evolution of the mixed layer over homogeneous ground surface. Calculations were based on the ensemble average of observations. The convective available potential energy (CAPE) was evaluated for both urban and rural land cover. Urban heat excess, which was 200 Wm$^{-2}$ higher in the urban than rural area, increased CAPE by 75% comparing to the rural CAPE of 513 J kg$^{-1}$. Results show that cities could cause favorable stratification of the atmosphere for convective precipitation.

Keywords urban heat island; convective available potential energy; convective precipitation
1. Introduction

Whether cities increase precipitation is a subject that has been debated for a long time. However, we do not have a satisfactory answer to date. Although the review by Shepherd (2005) summarized evidence of urban influence on precipitation, factors in addition to the urban environment alone have prevented the clear determination of urban influence on precipitation. For example, Shepherd (2002) focused on Atlanta, Georgia, USA, and examined the urban influence on precipitation using satellite data. Commenting on Shepherd et al. (2002), Diem et al. (2004) pointed out that precipitation in Atlanta should be influenced by mountains 110 km away, with a height of 150 m.a.s.l.

Some cities in Japan are located in areas of more complex terrain than Atlanta; and therefore, urban and topographical influences must be separated. Here, observations from Japan, particularly from the Tokyo region, were used to understand urban influence on precipitation. All studies reviewed below focused on convective precipitation in the summer. Inoue and Kimura (2004) analyzed satellite data for the wider Tokyo region and found a relatively high frequency of low-altitude clouds over cities. They also found the formation of line-type clouds along arterial roads (Inoue et al., 2004). In their study on the convective precipitation, Fujibe et al. (2002), found examples of radar echo being generated over regions of surface convergence in Tokyo. Kobayashi et al. (2009) found that the X-band radar echoes were generated at higher altitudes over the urban areas in Tokyo than over the surrounding rural area. Sato and Takahashi (2000) showed a positive trend between
heavy rain and surface convergence for Tokyo on a decadal time scale. Sato et al. (2006) showed a high frequency of radar echo over the city when precipitation systems generated in the rural mountainous areas passed through Tokyo.

In light of these previous results, the mechanisms of urban influence on the precipitation have been discussed; leading to four types of dominant mechanisms:

1) The activation of convection due to large surface sensible heat fluxes (Kusaka et al., 2014; Matheson and Ashie, 2008);
2) The evaporation of anthropogenic water vapor to the atmosphere (Moriwaki et al., 2008);
3) The modification of surface wind systems due to surface drag increases (Takahashi et al., 2011); and
4) The increase in condensation nuclei due to atmospheric pollutants (Rosenfeld and Lensky, 1998).

This study focuses on the thermal influence (1) of convective precipitation in the summer, because it seems to be the most influential of the mechanisms listed above. Senoo et al. (2004) concluded that the excess humidity from evaporation (2) is not influential on spatial distribution of vapor in urban air. The dynamic influence of surface wind (3) may have a more localized influence than the other factors; and an increase in atmospheric aerosols (4) can have both positive and negative influences on urban precipitation amounts (Rosenfeld and Lensky, 1998).

In order to simplify the discussion, this study considered a virtual flat homogeneous
surface with a single land cover. Two cases were considered: 1) where the land cover is urban; and 2) where the land cover is rural or country-side. This led to a spatial scale of a few tens of kilometers, which corresponds to the densely inhabited district of Tokyo. We focused on changes in atmospheric stratification, which supports initiation of precipitation events, in part due to different land covers. Land cover influences the triggering and development of precipitation events at a fine spatial scale; whereas convection is initiated at urban boundaries and in rural areas (Ohashi and Kida, 2002).

The thermal influence of cities, which are marked by a larger sensible heat flux than rural areas, appears to be the unstable stratification of the atmosphere. This study examines how the stability index changes between urban and rural land cover. Destabilization of stratification due to anthropogenic vapor is also tested. This simple type of analysis has not been conducted in previous studies. The urban influence on precipitation should be a quite complex problem which includes various physical processes. Most of studies reviewed before looked this complex problem as it is, however this study breaks down the problem into the elementary processes. Although our simplified analysis does not completely answer the question “Do cities increase precipitation?”, the simple discussion that follows is necessary to solve this complex problem.

2. Methodology

2.1 Outline
Assuming an idealized city and rural area whose differences are limited to the surface heat flux, convective available potential energy (CAPE) is evaluated for each land cover. CAPE indicates buoyant energy for the air parcel, and is an index used for assessing atmospheric stability. The approximate threshold is 2000 J kg\(^{-1}\) or more, which is a favorable condition for the generation of convective precipitation. CAPE is calculated as:

\[
\text{CAPE} = -R_d \int_{P_{LFC}}^{P_{LNB}} (T_v - \bar{T}_v) d(\ln p)
\]

where \(T_v\) and \(\bar{T}_v\) are the virtual temperature of the rising parcel and of its surrounding environment, respectively; \(p\) is air pressure; and \(R_d\) is the gas constant for dry air. The subscripts LNB and LFC indicate the ‘level of neutral buoyancy’ and the ‘level of free convection’, respectively. CAPE is calculated from the vertical profiles of air temperature and water vapor. In the calculation the virtual rising air parcel follows the dry-adiabatic and moist-lapse rate below and above the condensation level respectively. This study used a mixed layer model to determine the profiles, which reflect the surface sensible heat fluxes for both urban and rural areas. A schematic illustration is shown in Fig. 1. The model assumed a profile with constant potential temperature within the mixed layer. The increase in height and temperature within the mixed layer is the result of incoming heat from the surface.

\[
\int_0^{z_t} c_p \rho (T_i - T_{i-1}) dz = \int_{t_{i-1}}^{t_i} Q_H dt
\]

where \(c_p\) and \(\rho\) are the specific heat and density of air respectively; \(z_t\) is the depth of mixed layer; and subscript \(i\) denotes time. The model produces vertical air temperature profiles with the input of \(Q_H\). \(z_t\) at time \(i\) is determined from \(Q_H\) and temperature lapse rate above
The profile of vapor mixing ratio is also assumed to be constant in the mixed layer, and is calculated using the surface evaporation flux. The initial conditions at 06:00 LST (local sidereal time) were obtained from the observed results.

The calculated CAPE was compared with the measured CAPE in eight locations as shown in Fig. 2. The details of these CAPE measurements are summarized in Table 1.

2.2 Initial conditions

This study focuses on convective precipitation during the summer in Japan, and therefore the initial conditions of the mixed layer model were made from results observed in the summer. The upper part of the initial profile, above 2 km, was an average of 14 runs in the sonde observations taken in July and September 2013. The observations were made in Urawa, denoted as URW in Fig. 2. Observed profiles and initial condition are shown in Fig. 3. The lower part of the initial profile was acquired from observations made by the microwave radiometer at 06:00 LST. Different data sources were used for the upper and lower profiles due to an insufficient number of sonde runs made in the early morning, and the limited height range of the microwave radiometer. The two observation campaigns were conducted using a microwave radiometer: one over the rural site of Tsukuba (TKB in Fig. 2), and another over the urban site of Yoyogi (YYG). A microwave radiometer (KIPP & ZONEN, MTP-5H) measured radiant temperature at 60 GHz at several elevation angles, resulting in an air temperature profile from the surface to 600 m. Prior to these monitoring campaigns,
radiometer observations were validated using routine sonde observations made by the Japan Meteorological Agency over Tateno (near TKB). The vertical profile of root-mean-square-error (RMSE) of the radiometer to the sonde is shown in Fig. 4. The RMSE was less than 1.2 K throughout the height range, and larger RMSE in the morning hours likely reflects the residual nocturnal inversion layer.

Potential temperature profiles over Tsukuba and Yoyogi are shown in Fig. 5. Clear differences can be seen in the slopes of the profiles; steeper slopes occur at the rural site Tsukuba, due to the lower thermal inertia over the rural ground surface (Sugawara et al., 2001). The neutral profile at the lowest 200 m for Yoyogi is characteristic of cities, which experience stronger boundary layer mixing due to excess heat (buoyancy) and increased surface roughness compared with rural areas. Considering this urban–rural difference, we used two types of initial conditions for the lowest 2 km: one is urban whose potential temperature gradient is 3 K km$^{-1}$, referred to as ‘near neutral; in this study; and the rural gradient of 8 K km$^{-1}$, described as ‘stable’. As for the initial profile of water vapor, a common profile of relative humidity shown in Fig. 3 was applied for each cases.

2.3 Contrast in sensible heat flux

The surface sensible heat flux—the input for the mixed layer model—was acquired for three different land covers, listed in Table 2. At the rural site in Tsukuba, sensible heat flux was measured using a sonic anemometer mounted at 29.5 m above ground level on the
meteoretical tower. Within the footprint of the measured flux, dominant land cover was vegetation as well as some low storied residential houses. At the urban (Yoyogi) and suburban (Itabashi) sites, a scintillometer (Sintec, BLS-900) was used for flux measurements. The scintillometer transmits and receives light at 880 nm in wavelength and measures fluctuations in the refractive index. Sensible heat flux was calculated from fluctuations in refractive index using Monin-Obukhov (MO) similarity theory. The transmitter and receiver can be kilometers apart, and therefore, the footprint size can be larger than that of the eddy covariance method. This larger footprint is one of the advantages for urban heterogeneous land cover. The light path was 2.3 km long in Itabashi and 1.1 km in Yoyogi.

In solving the MO equations, this study used a mixed method (Largouarde et al., 2006), which is more rigid than other methods (e.g. free convection) and does not require the assumption of atmospheric stability. The mixed method requires two parameters: roughness length, and displacement height within the footprint. We evaluated these parameters using the morphometric method (Macdonald et al., 1998) with a modified canopy height as proposed in Tanaka et al. (2011). Diurnal variation in the sensible heat flux at all three sites is given in Fig. 6, which shows an ensemble average of fair-weather days with a solar duration exceeding 80% of the astronomically-possible solar duration. The anthropogenic heat flux, from the inventory database for Tokyo, produced by Ministry of the Environment Japan (2003), is also included in Fig. 6.
2.4 Calculation case

The mixed layer model produces a vertical profile every hour from the initial 06:00 LST to noon–time (12:00 LST). The CAPE was calculated for the profile up to 12:00 LST. We used eight cases for the simulation (Table 3). In the case 1 to 5 the initial profile was near-neutral (3 K km\(^{-1}\)) in the lowest 2 km, and stable (8 K km\(^{-1}\)) in the case 6 to 8. Three types of diurnal variation was used for surface sensible heat flux; rural (case 1 and 6), suburban (case 2 and 7) and urban (case 3 and 8). We also tested the anthropogenic heat (case 4) and water vapor (case 5). Diurnal variation of these anthropogenic component was referred from the database produced by Ministry of the Environment Japan (2003) and values at 1 km x 1 km area in Yoyogi was picked up from the database. The anthropogenic water vapor was 18 g m\(^{-2}\) (6h)\(^{-1}\) in the morning hours (6:00 to 12:00 LST), that correspond to the latent heat flux 2 Wm\(^{-2}\). The rural evaporation flux was determined from the measured sensible heat flux and the Bowen ratio (sensible heat/latent heat). We used a Bowen ratio of 1.87 based on Kuwagata et al. (1990).

3. Results

Calculations of CAPE at 12:00 LST are given in Fig. 7. As for the influence of urban-rural differences on the sensible heat flux, urban heat excess increased CAPE by 379 J kg\(^{-1}\) (74% of case 1) for the urban area (case 3 minus case 1); and by 36 J kg\(^{-1}\) (7% of case 1) for the suburban area (case 2 minus case 1). The anthropogenic heat flux increased CAPE by 44
J kg\(^{-1}\) (4%, case 3 minus case 4); and anthropogenic vapor caused an 8 J kg\(^{-1}\) (1%, case 3 minus case 5) increase in CAPE. As for differences in the initial profile, which reflects urban-rural differences in thermal inertia, CAPE was decreased by 735 J kg\(^{-1}\) in the stable profile (case 8) compared to the near-neutral profile (case 3)—corresponding to the five times the CAPE in case 8. The same is true in the other stable cases; CAPE in the stable case (6-8) were lower than the near-neutral case (1-3), respectively. The reason is the higher LCL (lifting condensation level) and LFC in the stable cases; e.g. LCL (LFC) was 1245 (1695) m and 1211 (1213) m in case 8 and 3 respectively. The higher LCL is mainly caused by the less water vapor, that is due to lower temperature, in the stable case. The high LFC causes very small CAPE in case 6 and 7. Note that even in the trial calculations for cases 6-8 where the relative humidity in the initial lower profile was switched to 99 % (80% in the original cases 6-8 shown in Fig. 3), CAPE was still lower than cases 1-3 respectively. CAPE in these trial calculations were 294 J kg\(^{-1}\) for rural, 425 J kg\(^{-1}\) for suburban and 753 J kg\(^{-1}\) for urban land cover. The lower CAPE in the stable cases could be partly due to the slower glowing speed of mixed layer. However, it would be a minor reason, because the stable layer near surface in cases 6-8 broke into the mixed layer at early morning roughly by 09 LST and did not have much influence on CAPE at 12 LST.

4. Discussion

Our results in Fig. 7 show that CAPE is higher in cities than in the rural countryside,
depending on surface heating. Here we discuss two points related to the universality of these results. One is the spatial representativeness of the input surface heat flux. Urban areas represent a complex mixture of various land covers including buildings, roads and parks. Therefore, the surface heat flux in urban areas varies across space (Schmid et al., 1991).

We used the observed diurnal variation in heat flux, whose maximum was 350 Wm\(^{-2}\) at noon, for the model input; however, some previous studies have shown different values. Moriwaki et al. (2004) found a diurnal variation of 300 Wm\(^{-2}\) at noon in their ensemble average for the summer season. Their measurements were made using the eddy covariance method across a 1 km residential area of Tokyo. Sugawara et al. (2015) found a 329 Wm\(^{-2}\) heat flux as the morning average across a few tens of kilometers in the center of Tokyo, although this case study relied on sonde observations during the summer.

The input heat flux for the model may be larger than that actually occurring in Tokyo. On the other hand, CAPE is positively correlated to the input heat flux shown in Fig. 7, and an evaluation of the urban influence on CAPE is also affected by the reference rural heat flux. Sugawara et al. (2015) showed that the heat flux over Tsukuba was 100 Wm\(^{-2}\) smaller than the heat flux over Tokyo, which is in quantitative agreement with the difference in inputs between suburban and rural areas used here (Fig. 6). Although Sugawara et al (2015) is a case study, their results help validate our model inputs and results.

The second point related to the universality of our results is the initial condition. CAPE depends on the initial temperature profile as well as the surface heating. We modeled
two cases with different profiles in the lower layer; however, the upper layer also influences CAPE. Here we check the actual variation in CAPE with sonde observation listed in Table 1. CAPE is shown as a function of surface air temperature in Fig. 8. CAPE has a positive correlation with air temperature greater than 20°C, although the scatter exceeds 1000 J kg⁻¹. This variation, which could not be explained by surface air temperature, is much larger than the urban influence shown in Fig. 7. Therefore, urban influence may be less important to CAPE than the daily and spatial variation of atmospheric stratification.

In terms of comparing the influence of topography and land cover, Lee and Kimura (2001) numerically demonstrated the difference between terrain-induced convection and convection triggered at the boundary of different surfaces. They found that thermal convection from a 50% difference in surface sensible heat flux would have a similar strength to the topographical convection induced by 350 m height difference. Considering the real situation in Tokyo, the urban heat flux approaches 2.3 times the rural heat flux at noon (Fig. 6). However, mountains with an elevation of 600 m are located 50 km west from Tokyo; and therefore the atmospheric convection induced by urban-rural differences in heating, may be canceled by topographical convection in the greater Tokyo area.

5. Conclusion

We evaluated the influence of urban heat excess on atmospheric stability leading to
convective precipitation in the greater Tokyo area of Japan. This study focused on
convective precipitation in the summer months. The methodology used is simple, and
assumed a flat homogeneous ground surface with a single type of land cover. CAPE was
calculated for different surface heat fluxes. Although a simple and idealized situation, the
ensemble average of observed values for the initial profile of temperature and heat flux were
used. Urban heat excess, which was 200 Wm\(^{-2}\) higher than for the rural area, increased
CAPE by 75%. The anthropogenic vapor flux also increased CAPE, but was near negligible
(1% in CAPE). The neutral stratification in the urban area in the morning is due to the large
thermal inertia in the urban canopy layer, which increased CAPE by five times its rural value.
These results show that cities could cause favorable stratification of the atmosphere for
convective precipitation, although urban influence should be less important than those from
topography or synoptic scale disturbance.

This study focused on the thermal difference between urban and rural areas. Other
possible factors influencing urban precipitation include the dynamic effects of high surface
roughness and the existence urban aerosols, which should be considered in future research.

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Figure 7. Calculated CAPE for the near-neutral initial profile (cases 1-5), stable (cases 6-8). The urban case without anthropogenic heat is case 4, and the urban case without anthropogenic water vapor is case 5. Note that suburban case with stable profile (case 7) has CAPE 4 J kg$^{-1}$ and in the rural case (case 6) a CAPE of 0 J kg$^{-1}$.

Figure 8. Relationship between the surface air temperature and CAPE. Location name refers to those in Fig. 1.

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<table>
<thead>
<tr>
<th>Location (Abbr.)</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Measurement period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choushi (CHS)</td>
<td>35°42'N</td>
<td>140°50'E</td>
<td>Aug. 2012</td>
</tr>
<tr>
<td>Koganei (KGN)</td>
<td>35°42'N</td>
<td>139°29'E</td>
<td>Oct. 2011</td>
</tr>
<tr>
<td>Tsukuba (TKB)</td>
<td>36°03'N</td>
<td>140°08'E</td>
<td>Aug. – Oct. 2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Jul. – Sep. 2013</td>
</tr>
<tr>
<td>Itabashi (ITB)</td>
<td>35°47'N</td>
<td>139°41'E</td>
<td>Aug. – Oct. 2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sep. 2013</td>
</tr>
<tr>
<td>Urawa (URW)</td>
<td>35°52'N</td>
<td>139°35'E</td>
<td>Jul. and Sep. 2013</td>
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<tr>
<td>Yokosuka (YKS)</td>
<td>35°15'N</td>
<td>139°43'E</td>
<td>Aug. – Oct. 2011</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Aug. 2012</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Jul. – Sep. 2013</td>
</tr>
<tr>
<td>Research vessel</td>
<td>34°20' -- 39°N</td>
<td>139°37 -- 49°E</td>
<td>Jul. 2013</td>
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<tr>
<td>Ryofu (RYF)</td>
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</table>
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<table>
<thead>
<tr>
<th>Location (Abbr.)</th>
<th>Land cover</th>
<th>Areal fraction of vegetation</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsukuba (TKB)</td>
<td>Rural, low height vegetation</td>
<td>74 %</td>
<td>Eddy correlation</td>
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<tr>
<td>Itabashi (ITB)</td>
<td>Suburban, low-storied residential houses</td>
<td>19 %</td>
<td>Scintillation</td>
</tr>
<tr>
<td>Yoyogi (YYG)</td>
<td>Urban, high-storied residential houses</td>
<td>2 %</td>
<td>Scintillation</td>
</tr>
</tbody>
</table>
### Table 3. Calculation cases.

<table>
<thead>
<tr>
<th>No.</th>
<th>Initial profile</th>
<th>Heat flux</th>
<th>Evaporation flux</th>
</tr>
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<tbody>
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<td>1</td>
<td>Near neutral</td>
<td>Rural observation</td>
<td>Rural value</td>
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<tr>
<td>2</td>
<td>Near neutral</td>
<td>Suburban observation</td>
<td>Rural value</td>
</tr>
<tr>
<td>3</td>
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<td>Urban observation</td>
<td>Rural value</td>
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<tr>
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<td>Near neutral</td>
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<tr>
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<td>anthropogenic comp. in Yoyogi</td>
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<td>5</td>
<td>Near neutral</td>
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<td>Rural value minus anthropogenic comp. in Yoyogi</td>
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<td>6</td>
<td>Stable</td>
<td>Rural observation</td>
<td>Rural value</td>
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<td>7</td>
<td>Stable</td>
<td>Suburban observation</td>
<td>Rural value</td>
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<tr>
<td>8</td>
<td>Stable</td>
<td>Urban observation</td>
<td>Rural</td>
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