Numerical Experiments on Fair-Weather Clouds Forming over the Urban Area in Northern Tokyo

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Abstract
On clear, calm summer days, cloud lines are often observed above the expanding urban area along the railroads from Tokyo. The cloud lines were simulated using a numerical model with a simplified urban surface parameterization. The horizontal distributions of the simulated clouds agree well with the observed clouds in satellite images. Some sensitivity tests indicate that the urban thermal effect enhances cloud formation but suppresses clouds in the adjacent rural area. The simulated clouds are consistent with the observations when the urban maximum sensible heat flux is substantially larger than the rural one. With a reduction of the thermal contrast, cloud suppression in the rural area is gradually weakened. The mechanisms of the cloud contrast are as follows: 1) Thermals form in the mixed layer above the land surface. 2) Because of the larger sensible heat flux, the mixed layer tends to be higher in the urban area; thus, thermals reach the lifting condensation level more easily than they do in the rural area. 3) The wide compensating downdrafts of the strong urban thermals cover the entire rural area and suppress thermals and clouds there.

1. Introduction
Although many studies have suggested that anthropogenic effects are likely to induce or reinforce precipitation around urban areas, the underlying mechanisms have remained unclear (Shepherd 2005). One of the major difficulties in investigating urban-induced precipitation is that convective rain may occur anywhere with a small trigger when unstable atmospheric conditions are prevalent (Fujibe 2004).

Shallow clouds form much more frequently than the deep convection over the land surface and may be more easily affected by anthropogenic surface conditions. In the last decade, some statistical studies have shown, using satellite data, that clouds tend to form in urban areas more than in surrounding areas (e.g., Rabin and Martin 1996). Inoue and Kimura (2004) showed that the frequency of shallow clouds is higher above long-shaped urban areas along the major railroads from Tokyo than that of those above the surrounding rural areas.

Baik et al. (2001) examined updraft cells induced by urban heat islands and how they initiate moist convection using a two-dimensional numerical model. Using a three-dimensional high-resolution numerical model, Kanda et al. (2001) recreated a small cloud line, which can sometimes be observed near Tokyo. Their numerical experiments indicated that a cloud line forms above the convergence line between two sea breezes. They also suggested that the sprawl of Tokyo may have changed the intensity and the position of the cloud line, implying that the observable cloud system may be the result of the urban effects.

Beside the urban effects, more general land surface effects on the fair-weather clouds have been well investigated. Using a two-dimensional high-resolution mesoscale model, Chen and Avisar (1994) showed that land surface moisture significantly affects the timing of the onset of clouds and the intensity of precipitation. Avisar and Liu (1996) also stated that clouds and precipitation are strongly affected by the landscape structure. When land surface moisture is heterogeneous, the land surface structure triggers the formation of mesoscale circulations, and clouds then concentrate in the dry part of the domain.

The purpose of this study is to clarify the mechanisms of cloud formation in the urban area along railroads and cloud suppression in the adjacent rural area north of Tokyo on clear, calm summer days.

2. Data and methods
2.1 Observed data
The simulated cloud distribution will be validated by comparison with satellite images observed by Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites. These are provided by Goddard Earth Sciences Data and Information Services Center, NASA. The resolution of the red channel is 250 m, while those of the blue and green ones are 500 m. We surveyed the MODIS images observed during the summers (late June to early September) in 2003 to 2005 and observed urban clouds in 29 images on 22 days.

To reveal the evolution of urban clouds, photographic observations were conducted on 54 selected days of summer in 2003 to 2005 at the point shown by an inverted triangle in Region A in Fig. 1. The camera was operated at two-minute intervals and focused on the clouds over the urban area indicated by “b” in Fig. 1 and the rural area west of it.

2.2 Numerical model design
The numerical model used in this study is a modified version of the Regional Atmospheric Modeling System (RAMS) (see Supplement 1). The horizontal grid interval is 1 km in the fine grid system (122 × 122 grid points), which is nested in the coarse grid system that covers central Japan with 5 km resolution. The domain is shown in Fig. 1.

Land use is classified into two categories, urban and rural, based on the land-cover data with 100-m resolution supplied by Ministry of Land, Infrastructure and Transport, Japan. The data surveyed in 1997 was classified into 11 land-use classifications, e.g., the paddy fields, other agricultural lands, the forests, the building sites, the water surface. Only the building sites are assumed to be urban areas and other classes over land are assumed to be rural areas. For the rural areas, the vegetation type is assumed to be uniform short grass, and the soil type is assumed to be silt-loam. The initial soil water content is assumed to be 0.5 at the layers up to 50 cm, which is defined by the ratio of the soil water
content and the saturated soil water content. In the urban area, the initial soil water content is assumed to be 65% of that of the rural area in the control run. We abbreviate the control run as “CTRL” here. The urban effect is expressed only by a drier soil surface to easily control the sensible heat flux (SH) in the urban area. Such a simple urban model tends to overestimate daytime heat flux compared with a sophisticated urban canopy model as suggested by Kusaka and Kimura (2004). However, we do not focus on the quantitative estimation of the urban heat flux but on the relation between the urban shallow clouds and the contrast of heat flux, so that we chose the simple urban expression, which allows to easily control sensible heat flux in the urban area. We are going to clarify the relation between cloud and heat flux by sensitivity experiments that cover the range of urban heat fluxes obtained by the past studies (Kusaka et al. 2001; Rotach et al. 2005). In the sensitivity experiments, the heat contrast between the urban and the rural areas is controlled by the soil moisture at the urban grid points, which is set to 75%, 85%, and 100% for Cases U75, U85, and N00, respectively. Case N00 does not assume any urban area.

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The fine grid system covers the Kanto Plain. The urban areas are indicated by shading in Fig. 1. We focus on Region A, which is enclosed by a rectangle with a thick solid line in the figure. Three long urban areas exist in the region. They are called “extending urban areas a, b, and c” and are abbreviated as “EUA-a, -b, and -c.” They are indicated by symbols “a,” “b,” and “c,” as shown in Fig. 1. They are surrounded by rural areas. The large and dense urban area, which is enclosed by thin solid lines and a thin broken line, is abbreviated as “LUA.” LUA almost corresponds to the 23 wards of Tokyo. The thin solid lines indicate the prefectural borders.

Vertical profiles of the potential temperature and relative humidity are assumed in the model as the initial conditions that are horizontally uniform. They are based on vertical profiles obtained by radiosonde at 09 LST (00 UTC) at Tateno station of the Japan Meteorological Agency on the 22 days when the urban clouds were observed by MODIS images (see Supplement 1). The initial horizontal winds are assumed to be a uniform southerly wind with a speed of 1 m s⁻¹, which is roughly consistent with the synoptic condition on clear, calm summer days. The simulation was started at 06 LST (21 UTC) and integrated twelve hours.

3. Results

3.1 Horizontal cloud distribution

Figure 2a shows the horizontal distribution of small cumulus clouds at 1030 LST simulated in CTRL. White areas indicate cloud cover. Small clouds systematically distribute above EUAs in Region A, forming cloud lines above each EUA. A cloud line is particularly prominent above EUA-b. On the other hand, no cloud cell can be found in the rural area between EUA-a and EUA-b. Few clouds are distributed above other rural areas near EUAs. Small clouds scatter inland over the LUA, while no clouds form above the coastal areas around the Tokyo Bay in the LUA, where sea breezes cover. Figure 2b indicates that of Case N00 (no urban) at 1030 LST in the sensitivity experiments, which are described in Section 3.6. A comparison between Figs. 2a and 2b demonstrates that the urban effects suppressed cloud formation in the surrounding rural areas.

Figure 3 is a satellite image observed by Terra/MODIS at 1035 LST on 4 August 2003. Dark-gray, green, and dark-blue indicate urban areas, the vegetated areas, and the water surface,
Percentage of the number of grid points covered by clouds in each of the urban and the rural areas. At around 0800 LST, the cloud fraction begins to increase in the urban area although that in the rural area remains close to zero. After that, the urban cloud fraction increases steadily until 1300 LST. The rural cloud fraction eventually begins to increase around 1100 LST, while it is much lower than that of the urban area until 1300 LST. After the sea breeze covers the entire Region A (1300 LST), the cloud fractions in both areas begin to decrease. Figure 4b indicates the evolutions of SH of both areas. In the urban area, the maximum SH is recorded at 1240 LST.

### 3.3 Vertical structures

The red and the blue lines shown in Fig. 4b indicate vertical velocity at the level of 439 m at the sampling points in urban and rural shown by the black and the white circles in Fig. 1, respectively. A strong ascending flow intermittently appears in the urban area, while a mild downward flow stationary prevails in the rural areas near the urban areas. The ascending flows are likely to be thermals in the mixed layer, although the horizontal sizes of the simulated ones are much larger than those in the real atmosphere. The small cumulus clouds form at the top of the ascending flows above the urban areas. The downward flows seem to be the compensating downward flows induced by the ascending flows over the urban areas.

The mixed heights were 1340 m and 1070 m at the urban and rural sampling points at 1030 LST, respectively. The mixed layer above the urban areas is higher than that above the rural areas and the ascending flow can easily reach the lifting condensation level (LCL). On the other hand, the downward flows suppress the height of the mixed layer in the rural areas; as a result, the relative humidity near the top of the mixed layer tends to be lower than that of the urban atmosphere.

### 3.4 Comparison with the ground-based photographic observation

The evolution of the small clouds in CTRL is consistent with that of the ground-based photographic observation. The urban clouds were observed on 12 out of 54 days when photographs were taken. The photographic observations on the 12 days are summarized as follows. In most cases, the onset time of the urban clouds was between 0800 LST and 1130 LST, and the dissipation time was between 1300 LST and 1700 LST, although the time evolution of clouds somewhat depended on the day. The duration of cloud forming ranged from 3 to 6 hours on most days. Those clouds were generally "active cumulus clouds," as defined by Stull (1985). The clouds developed gradually and became cumulus congestus in the early afternoon on some of those days. The evolution of the urban clouds on a typical day has been reported by Inoue et al. (2004) using color pictures of clouds.

### 3.5 Sensitivity experiments for thermal effect

The results of the sensitivity experiments are summarized in Table 1. Urban and rural SHs are defined as averages in the entire urban and rural areas of the domain, respectively. The index for the heat contrast can be defined as the ratio of the maximum SHs between the urban and the rural areas (hereafter, the index ratio). The index at 1000 m of CTRL is 6.9, while the maximum SHs are 297 W m⁻² at 1240 LST and 43 W m⁻² at 1110 LST in the urban and the rural areas, respectively. After the onset of urban clouds, the heat flux ratio exceeded 5.5 until cloud dissipation time. The table also shows the onset time of the clouds and the SH (130 W m⁻²) in the urban areas at the onset. The estimated SH seems to be reasonable by comparison with previous studies. Kusaka et al. (2001) made a comparison of SHs between a multi-layer urban model, a single-layer
model, and a slab model. Maximum SHs of the three models range from about 220 W m\(^{-2}\) to about 250 W m\(^{-2}\). Observation by Rotach et al. (2005) indicated that maximum SH were about 300 W m\(^{-2}\) to 400 W m\(^{-2}\) in midsummer at Basel, Switzerland.

The index ratio of Case U75 is 4.3. The evolution of urban clouds is almost the same as that in CTRL except for the 30-minute delayed onset. Clouds are almost suppressed in the rural areas before 1100 LST. The forcing of cloud suppression seems to be slightly weaker than that of CTRL.

The index ratio is 1.9 in Case U85, which is much lower than that in CTRL. The onset times of small clouds in the urban and the rural areas are almost the same, around 0900 LST. The cloud fraction in the rural area is only slightly lower than that in the urban area after 1030 LST. In this case, cloud suppression is very weak in the rural areas. These results suggest that the ratio of the maximum heat flux should be at least larger than 1.9 in order to form a clear contrast between the urban and the rural areas.

Small clouds are also generated in Case N00 (Fig. 2b), which assumes a uniform surface condition without urban areas (see Supplement 2). The maximum SH in Case N00 is 49 W m\(^{-2}\) at 1130 LST. The cloud distribution is unstructured except for that caused by sea breeze fronts and mountains. These clouds are not stationary, in contrast to those in the CTRL. The cloud fraction of the areas in Case N00, which correspond to the rural areas in CTRL, is larger than that in the rural of CTRL (see Fig. 4a); this suggests the cloud suppression in the urban areas of CTRL during the active phase of the urban clouds.

4. Conclusion

Small cumulus clouds that formed above urban areas along railroad lines were simulated by the numerical model, and their mechanism was elucidated. The distribution and the time evolution of those simulated clouds agreed well with those of the satellite images and the ground-based photographic observations on typical days. The model indicated that small clouds are not only enhanced in the urban areas but also suppressed in the surrounding rural areas. The distribution of small clouds is quite sensitive to the thermal contrast between the urban and the rural areas. When the ratio of the SH between them is about seven, cloud formation in the urban areas and cloud suppression in the rural areas are very clear. Small clouds are formed only in the urban areas but almost never in the rural areas because the urban effects on cloud suppression in the rural areas are predominant. The contrast of the cloud fraction is weakened but is still clear when the ratio of the SH is 4.3. When the ratio is 1.9, the cloud suppression in the rural areas disappears.

The mechanism of cloud contrast is as follows: 1) Thermoals reach the lifting condensation level more easily than they do in the rural area. 3) The wide compensating downdrafts of the strong urban thermals cover the entire rural area and suppress thermals and clouds there.

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Comments and supplements

1. Features of TERC-RAMS and initial condition of the model in Supplement 1.
2. Animation of the cloud distribution of (a) CTRL and (b) N00 in Supplement 2.
3. MODIS images of urban clouds on other typical days in Supplement 3.

References


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