FAIR-WEATHER CUMULUS CLOUDS FORMING OVER URBAN AREAS AROUND TOKYO
Tadao Inoue*, Fujio Kimura**
* National Institute for Environmental Studies, Tsukuba, Japan; **University of Tsukuba, Tsukuba, Japan

Abstract

The analysis of 11-year satellite data shows that the cloud frequency is higher in urban areas than in rural areas around Tokyo in summer. The cloud lines along the urban areas were discovered in the ground-based photographic observation conducted in the area where the urban-rural contrast of cloud frequency is sharp. They are simulated by a numerical model with a simplified urban surface parameterization. Some sensitivity tests indicate that the urban thermal effect enhances cloud formation, but it also suppresses clouds in the adjacent rural areas. With reduction of the thermal contrast between urban and rural, the cloud suppression in the rural areas is gradually weakened. Furthermore, the ambient wind speed also affects the location of cloud formations.

Key words: Cumulus cloud, Observation, Numerical simulation

1. INTRODUCTION

Although many studies have suggested that anthropogenic effects are likely to induce or reinforce precipitation around urban areas, the underlying mechanisms are still unclear (Shepherd, 2005). One of the major difficulties in investigating urban-induced precipitation is that convective rain may occur anywhere with a small trigger under unstable atmospheric conditions (Fujibe, 2004). Shallow clouds form much more frequently than deep convective clouds over the land and may be more easily affected by anthropogenic surface conditions. In the last decade, some statistical studies have suggested that clouds tend to form in urban areas more than in surrounding areas (e.g., Rabin and Martin, 1996). 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 observed near Tokyo. Their numerical experiments indicated that a cloud line forms above the convergence line between two sea breezes and 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.

The purpose of this study is to clarify the urban effects on cloud formation and its mechanisms around Tokyo, Japan, on clear summer days. We summarize the series of our studies for cumulus clouds over urban areas around Tokyo here. First, we show the shallow clouds distribution around Tokyo with 11-year satellite data in summer. Second, the observational morphologic feature of clouds which generate over urban areas developed along railroads is displayed. Finally, we simulate those clouds with a numerical model and conduct some sensitivity experiments.

2. SUMMARY OF SATELLITE ANALYSIS FOR CLOUD DISTRIBUTION AROUND TOKYO IN SUMMER

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. In the study, the horizontal frequency distribution of shallow clouds is estimated around the Tokyo metropolitan area using NOAA satellite images obtained on summer days without regional-scale cloud cover from 1200 to 1500 LST (03-06 UTC) during an 11-year period. The urban area can be determined by the NDVI obtained by the same satellite. The frequency of shallow clouds is higher over the urban area than the rural areas in the early afternoon; in particular, cloud formation is reinforced over the radially extending urban areas (EUA; indicated as shaded areas of Region A in Figure 1) along the major highways or railroads from Tokyo. In contrast, cloud frequency is clearly low over the contiguous rural areas. The distributions of NDVI and the frequency of shallow clouds correlate well within a shift of only about 2 km in the west-east cross section through those EUAs. This implies that shallow clouds form at the top of the thermals in the mixed layer enhanced by a stronger sensible heat flux in the urban area. The frequency of the shallow clouds is low in the coastal urban zone due to the bay and sea breezes.

3. SUMMARY OF GROUND-BASED PHOTOGRAPIC OBSERVATION FOR URBAN CLOUDS

To investigate the features of the urban clouds, the ground-based photographic observation of the urban clouds was conducted around Saitama City, where the difference of cloud frequency between urban and nearby rural areas is the sharpest in the satellite analysis. We focused on EUA-b in Fig. 1 and its western rural area. The urban clouds were observed on 12 days in 54 days when photographs were taken. The horizontal cloud distribution was observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites and those clouds in the pictures were confirmed to form over the urban area.
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 variation of clouds somewhat depended on days. The duration of the cloud forming ranged between 3 to 6 hours in the most days. Those clouds were generally "active cumulus clouds" defined by Stull (1985). The clouds gradually developed, and then the tops of the clouds penetrated into LFC; they became Cumulus congestus in the early afternoon on some of those days.

4. NUMERICAL EXPERIMENTS ON CUMULUS CLOUD FORMATION IN NORTHERN TOKYO

Although the features of the urban clouds are comprehended by the observations, the mechanism of the cloud contrast between the urban and the rural areas is still unclear. We simulate the urban clouds with a three-dimensional numerical model and conduct some sensitivity experiments to investigate the mechanisms of those urban clouds. Most of this section was reported in Inoue and Kimura (2007).

4.1. Numerical model and experimental design

The numerical model used in this study is the Regional Atmospheric Modeling System (RAMS) originally developed at Colorado State University (Pielke et al., 1992) and modified at the Terrestrial Environment Research Center, University of Tsukuba. The horizontal grid interval is 1 km in the fine grid system (122x122 grids), which is nested in the coarse grid system that covers central Japan with 5 km resolution. The fine grid is centered at 35.8°N, 139.8°E and the domain is showed as figure 1. The vertical grid interval is 30 m in the lowest layer. It stretches up to 800 m in the upper layer and the height of the top of atmosphere is set 16 km. Land use is classified into two categories, urban and rural, based on the land-cover data supplied by Ministry of Land, Infrastructure and Transport, Japan. Only the building sites are assumed to be urban areas and others are assumed to be rural areas. For the rural areas, vegetation type is assumed to be uniform short grass, while soil type is assumed to be silt-loam. Initial soil water content is assumed to be 0.5 at the layers up to 50 cm, which is defined by the ratio of soil water content and the saturated soil water content. In the urban area, initial soil water content is assumed to be 65 % of that of rural in the control run. We abbreviate the control run as “CTRL” here. The urban effect is expressed only by drier soil surface. Sensitivity experiments are conducted to estimate the necessary minimum heat contrast between urban and rural areas. The thermal effect is controlled by the soil moisture at the urban grid points in the experiments. The soil moisture is kept to be the same value in the rural area. Thus, smaller moisture availability in the urban area leads to stronger thermal contrast. In experiments, the soil moisture in the urban grid points are set to 75%, 85% and 100% for Cases U75, U85, and N00, respectively. Case N00 does not assume any urban area. Additional sensitivity tests were conducted focusing on the ambient wind velocity. Each test assumes different initial and boundary conditions of wind velocity. Wind velocities below the level of 900 hPa were assumed to be 1 m/s (CTRL), 2 m/s (Case Uw2) and 3 m/s (Case Uw3) and all the experiments were set to southerly wind.

4.2. Results

4.2.1. Horizontal cloud distribution in the control run

Figure 2a shows the horizontal distribution of small cumulus clouds at 1030 LST simulated in CTRL. In the figure, light brown and dark green indicate urban areas and rural areas, respectively. White areas indicate cloud cover. We are going to discuss cloud distribution, but amount of cloud water here. Small clouds systematically distribute above EUAs in Region A, forming cloud lines above each EUAs. In particular, a cloud line is prominent above EUA-b. On the other hand, no cloud cell can be found in the rural area between EUA-a and -b. Few clouds are distributed not only above the other rural areas near EUAs, but also in the northern half of the entire domain except for mountains. Small clouds scatter over inland of the large urban area (LUA), in contrast, no cloud is formed above the coastal areas around the Tokyo Bay in LUA. Figure 2b displays a satellite image observed by Terra/MODIS at 1035 LST on a typical day. A numerous small clouds distribute above EUAs forming cloud lines similar to those of Fig. 2a, except for above EUA-a. The size of simulated cloud cell is larger than that of the observed cloud cells because of the coarse grid interval of the model. The simulated cloud distribution has good similarity to that in the satellite image, particularly in the following characteristics: (1) cloud lines form above EUAs, (2) the cloud lines consist of small cloud cells, (3) clouds are sparse in the rural areas near EUAs, (4) clouds are randomly distribute inland of LUA, (5) clouds are sparse in the coastal areas. The simulated cloud lines still consist of many cloud cells above EUAs at 1210 LST (not shown). The cloud fraction has increased in EUAs, but few clouds are formed in the rural areas. The clouds along the sea breeze front have shifted to near the northern boundary of LUA as the sea breeze penetrated inland.

4.2.2. Time evolution of small clouds in CTRL

Figure 3 shows the evolutions of the simulated cloud fractions above the urban and the rural areas in Region A. The cloud fraction (CF) is defined as the percentage of the number of grid points covered by to the number of total grid points in the estimating area. At around 0800 LST, the CF begins to increase in the urban area although
the rural CF stays almost zero. After that, the urban CF increases steeply until 1300 LST with some fluctuation. The rural CF eventually begins to increase at around 1100 LST, while it is much lower than that of the urban until 1300 LST. After the sea breeze covers the entire region from 1300 LST, the CFs in both areas begin to decrease narrowing down the difference in CF between the urban and the rural areas.

4.2.3. Vertical structures

In the urban areas, strong ascending flows are dominated in the mixed layer before noon. Figure 4 shows vertical velocity at the height of 439 m at the sampling points shown by the black and white circles in Fig. 1. A strong ascending flow intermittently appears in the urban point (solid line), while a mild downward flow prevails stationary in the rural point (dashed line). The downward flows seem to be the compensating downward flows induced by the ascending flows over the urban areas. The vertical cross section displayed by the dashed-dotted line in Fig. 1 indicates that absolute unstable condition in the simulated atmosphere is limited in the urban surface layer (figures are not shown); potential temperature and specific humidity are almost vertically uniform in the mixed layer, so that relative humidity becomes higher with altitude. The small cumulus clouds form at the top of the ascending flows above the urban areas. The ascending flows are likely to be thermals in the mixed layer. The mixed-layer heights at 1030 LST are 1340 m and 1070 m at each sampling point; thus the ascending flows can easily reach the lifting condensation level (LCL). In contrast, the downward flows suppress the rural mixed-layer height, hence relative humidity near the top of mixed layer tends to be lower than that of the urban atmosphere.

4.2.4. Sensitivity experiments in thermal effect

Sensible heat flux (SH) will decrease with soil moisture in the urban area. Urban and rural SHs are defined as averages in the entire urban and rural areas of the domain, respectively. An index for the heat contrast can be defined as the ratio of the maximum SHs between urban and rural areas. The index ratio 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 the urban clouds, the heat flux ratio exceeded 5.5 until cloud dissipation time. The index ratio of Case U75 is 4.3. The evolution of the urban clouds is the same as that in CTRL except for 30 minutes delayed onset. Although a few clouds appear in rural areas, clouds are almost suppressed in the rural areas before 1100 LST. The urban maximum SH is 199 W m$^{-2}$ in this case. In Case 85, the index ratio is 1.9 which is much lower than that in CTRL. The onset times of a small cloud in both areas are nearly the same. The evolution of clouds in the rural areas is synchronized with that in the urban areas during 0900 LST to 1030 LST. Even though rural CF is slightly lower than urban CF after 1030 LST, the cloud suppression in the rural areas is very weak. These results suggest that the ratio of the maximum SH should be at least larger than 1.9 in order to form a clear contrast in CF between the urban and the rural areas. In addition, mean levels of the urban cloud base at 1100 LST simulated in Case U75 and U85 are lower than 12% and 20% of that in CTRL, respectively. Small clouds also generate in Case N00 which assumes uniform surface condition without urban areas. Cloud distribution is unstructured except for clouds caused by sea breeze fronts, a wind convergence line extending from Miura Peninsula and orography. Small clouds form independently of the surface conditions in the areas farther inland of the sea breeze fronts. These clouds are not stationary in contrast with those in CTRL. The maximum SH in Case N00 is 49 W m$^{-2}$ at 1130 LST.

4.2.5. Sensitivity for wind field

Cloud formation is affected not only by SH but also by the ambient winds. In Cases Uw2 and Uw3, Small clouds tend to form in some rural areas located downwind of the urban areas especially in the morning. As a result of downwind clouds, the difference between CFs in the urban and the rural areas became smaller in Cases Uw2 and Uw3 than that in CTRL in spite of the same level of SHs. The time of the maximum CF in the urban areas becomes earlier than that in CTRL. Especially in Case Uw3, clouds completely dissipate after around 1400 LST, which is four hours earlier than CTRL.

5. CONCLUSIONS

The result of analysis of 11-year satellite data indicates that the cloud frequency is higher in urban areas than in rural areas around Tokyo, Japan, in clear calm summer days. The distributions of NDVI and the frequency of shallow clouds correlate spatially well within a shift of only about 2 km. The frequency of the shallow clouds is low in the coastal urban zone located within about 10 km from the coastline. To investigate the futures of those clouds, the ground-based photographic observation was conducted around Saitama City in northern Tokyo, where the urban-rural contrast of cloud frequency is sharp in the satellite analysis. The horizontal cloud distribution was observed by MODIS images. In the most case, the onset time of clouds over the urban area is before noon and the dissipation time is between early-afternoon to before sunset. Those clouds were generally active cumulus clouds, whose tops penetrated into the level of free convection. Those small cumulus clouds formed above the urban areas are simulated by the numerical model and elucidated its mechanisms. The distribution and the time evolution of those simulated clouds agree well with those of the
satellite images and the ground-based photographic observation on typical days. The model indicates that the small clouds are not only enhanced in the urban areas but also suppressed in surrounding rural areas. The distribution of small clouds is sensitive to the thermal contrast between urban and rural. When the ratio of maximum SH between urban and rural is about seven, the contrast between the cloud formation in the urban areas and the cloud suppression in the rural areas is very clear. The small clouds are formed only in the urban areas but very rare in rural areas, because urban effects on cloud suppression in rural areas are predominant. The contrast of cloud fraction between urban and rural gradually decreases with the reduction of the thermal contrast. The contrast of cloud fraction is weakened but is still clear when the ratio of maximum SH is 4.3. When the ratio is 1.9, the cloud suppression in the rural areas disappears.

The mechanism of the contrastive cloud formation between urban and rural is as follows: 1) Thermals form in the mixed layer above the land surface. 2) Because of the larger SH, 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.

References