DIURNAL VARIATION OF POTENTIAL TEMPERATURES IN A LARGE URBAN GREEN TRACT

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Abstract Relative humidity in a green tract reaches 60% or more on the average. It is considered that influence of water vapor cannot be ignored in such high humid conditions. In this paper, we led an equation of potential temperature that contained the effect of water vapor. From vertical profiles of air temperature that Hamada and Mikami observed, we calculated potential temperatures in moist air when the condensation did not occur. The ground inversion layer by radiative cooling was about 25 m at 0:00 J.S.T. on July 29, 1992 and about 60 m at 6:00 J.S.T. above the ground, respectively. However, it was clarified that there was an isothermal part in potential temperatures in the night, which existed between the ground inversion layer and another inversion layer above that. Temperature was rising in the upper part of an isothermal part in any case. The altitude of the ground inversion layer induced by radiative cooling is the highest in 4:00 J.S.T. Thickness of the mixed layer which is thought to have occurred by subsidence reached 95 m at that time. After 6:00 J.S.T., the ground inversion layer dissolved rapidly.

Key words: urban green tract, cooling effect, potential temperature, water vapor

1. Introduction

In a large city, urban heat island has been intensified due to the increase of anthropogenic energies, such as waste heat from factories and houses, and to the changes in heat balance of jammed buildings and multistory architectures. On the other hand, there exist a various type of parks and green tracts which form the low temperature area (cool island) inside the city of Tokyo (*e.g.* Mikami 1982). In recent years, the effect of green tracts mitigating the surrounding urban heat island intensity has been noticed.

According to the meteorological observation by Hamada and Mikami (1994), the low temperature air, oozed from the green tract, cooled peripheral built-up area. However, the research of evaluating climatic mitigation (cooling) effects of urban green tracts is still in the proof step. As a part of this step, Hamada and Mikami (1994) examined diurnal variations of vertical distribution of air temperature in a green tract, however we thought it necessary to examine the potential temperatures in order to clarify the nature of air parcel. So far, there are little studies which investigate the potential temperatures in relation to urban green tracts.

Generally, water vapor is ignored in calculation of potential temperatures in moist air. Namely, it is treated as dry air. As for the observation date (July 28-29, 1992) of Hamada and Mikami (1994), relative humidity in the night exceeds 90%, therefore we cannot ignore the effect of water vapor in such high humid conditions. In this paper, we led an equation of potential temperature that contained the effect of water vapor when the condensation did not occur. From this analysis, we elucidated atmospheric phenomenon in a large urban green tract from potential temperatures.

2. Data and Method

We used the data of the air temperature vertical profiles measured by a captive balloon in Meiji Shrine/Yoyogi Park from 21:00 on July 28, 1992 to 12:00 on July 29 which was observed by Hamada and Mikami (1994). The observation point is marked as ▲ in Fig. 1. Also, air temperature and relative humidity taken by the station of Tokyo Metropolitan Bureau of Environmental Protection (Shibuya), located in the south of 500 m of Yoyogi Park, were used for the analysis (■ in Fig. 1). The captive balloon was lifted up to 250 m from the ground every three hours.

Meiji Shrine/Yoyogi Park is a large urban park with the mixture of forest and grass, the area of which is 1,240,000 m^2 as shown in Fig. 1. Most part of Meiji Shrine/Yoyogi Park is covered with evergreen trees having broad leaves at the height of 15 to 20 m, whereas about one third of Yoyogi Park is covered with lawn and grass.

Potential temperature in moist air

Since conserved quantity in the adiabatic process of non-saturated moist air is potential temperature, it should be used to examine the nature of air parcel, because air temperature changes with the altitude. We do not understand the nature of air mass only by Fig. 8 of Hamada and Mikami (1994), therefore we should solve Eq. (1) in each altitude and clarify the vertical distribution of the potential temperature.

An equation of potential temperature is defined as

$$\theta = T\left(\frac{1000}{P}\right)^{R/C_P} , \qquad (1)$$

where θ(K) is temperature after adiabatic process, T (K) is temperature before adiabatic process, P (hPa) is atmospheric pressure before adiabatic process, R (J kg^{-1} K^{-1}) is gas constant and C_P (J kg^{-1} K^{-1}) is specific heat at constant pressure, respectively.

Here, we have data of the altitude Z of the balloon from the ground, air temperature T in each altitude, and air temperature and relative humidity taken by the station of Tokyo Metropolitan Bureau of Environmental Protection, and the surface pressure of Tokyo District Meteorological Observatory located in the east of 5.6 km of Yoyogi Park.

In Eq. (1), R and C_P must be values for moist air. Atmospheric pressure P of Eq. (1) changes with elevation, therefore it is estimated with the hypsometric formula in moist air (Eq. (10)). Air temperature T was observed value in each altitude.

Here, gas constant R of moist air is defined as

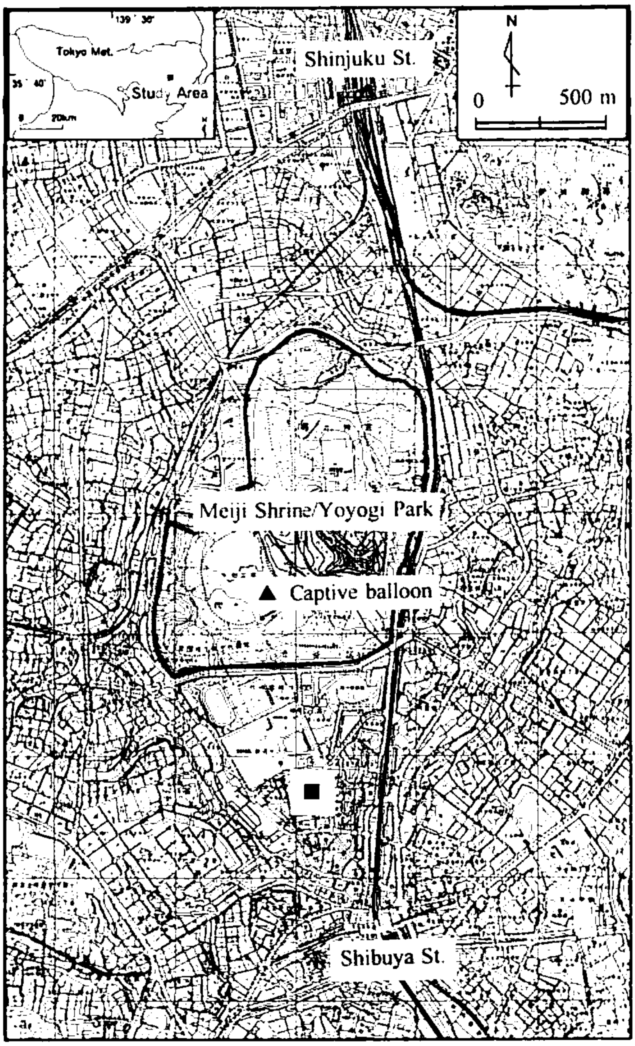

Fig. 1 The location of Meiji Shrine/Yoyogi Park and the observation point (▲)
■ is the station of Tokyo Metropolitan Bureau of Environmental Protection (Shibuya).

$$R=\frac{R^*}{m}\ , \tag{2}$$

where R^* (8.314 J mol^{-1} K^{-1}) is universal gas constant and m (kg mol^{-1}) is molecular weight of appearance of moist air.

From Eq. (2.7) of Kondo (1994), molecular weight m (kg mol^{-1}) of appearance of moist air is evaluated by

$$m=\frac{(P_S-e)\,m_d+em_W}{(P_S-e)+e} \quad , \tag{3}$$

where P_S (hPa) is the surface pressure, e (hPa) is the water vapor pressure on the ground, m_d (0.028964 kg mol^{-1}) is molecular weight of dry air and m_W (0.018015 kg mol^{-1}) is molecular weight of water vapor, respectively. We used the surface pressure data P_S of Tokyo District Meteorological Observatory.

We transformed from relative humidity H to water vapor pressure e using the equation of Teten (Eq. 2.14 of Kondo 1994). With this procedure, we obtain R of Eq. (2). It is clarified from the observation in the summer of 1997 (Kirihara *et al.* 1998) that relative humidity is constant up to the altitude of 250 m. From this result, Eq. (2) can be applied to each altitude in this study.

With the same manner of Eq. (3), specific heat C_P (J kg^{-1} K^{-1}) of moist air at constant pressure is written as

$$C_P=\frac{(P_S-e)\,C_{Pd}+eC_{PW}}{(P_S-e)+e} \quad , \tag{4}$$

where C_{Pd} (1005 J kg^{-1} K^{-1}) is specific heat of dry air at constant pressure, C_{PW} (1854 J kg^{-1} K^{-1}) is specific heat of water vapor at constant pressure, respectively. After all, R/C_P of Eq. (1) is evaluated as

$$\frac{R}{C_P}=\frac{8.314P_S{}^2}{29.109P_S{}^2+13.587P_S\cdot e-9.296e^2} \quad . \tag{5}$$

Relationship between atmospheric pressure and altitude in moist air

We sought for P of Eq. (1) as follows: First, substitution of state equation of moist air (Eq. 2.9 of Kondo 1994) into equation of statics (Eq. 2.20 of Kondo 1994) yields

$$\frac{1}{P}\,dP=-\frac{g}{R_dT_V} \quad . \tag{6}$$

where g (9.8066 m s^{-2}) is the gravitational acceleration on the ground, R_d (287.0 J kg^{-1} K^{-1}) is gas constant of dry air and T_V (K) is virtual temperature.

Integral form of Eq. (6) is written as

$$\int_{P_S}^{P}\frac{1}{P}\,dP=-\int_{0}^{Z}\frac{g}{R_dT_V}\,dZ \quad , \tag{7}$$

where Z (m) is the altitude. By solving Eq. (7), the equation is expressed as

$$P=P_S\exp\left(-\frac{Z\cdot g}{R_dT_V}\right) \quad . \tag{8}$$

In Eq. (8), T_V is written as

$$T_V=(1+0.608q)T \quad , \tag{9}$$

where q (kg kg^{-1}) is specific humidity, which is estimated from the water vapor pressure

e and the surface pressure P_S (Eq. 2.19 of Kondo 1994).

Generally, scale height of an isothermal atmosphere consists, therefore T_V did not depend on the altitude and took constant value. Subsequently, P of Eq. (1) is evaluated as

$$P = P_S \exp\left(-\frac{Z}{H_T}\right) \quad , \tag{10}$$

where H_T is scale height ($= R_d \cdot T_V / g$). In Eq. (10), we used the surface pressure data P_S, 1002.4 hPa, from July 28 to July 29, 1992 of Tokyo District Meteorological Observatory.

3. Results

Climatic condition of the observation day

Figures 2 and 3 show a diurnal variation of air temperature and relative humidity based on the data from July 28 to July 29, 1992 taken by the station of Tokyo Metropolitan Bureau of Environmental Protection. In Fig. 2, temperature was decreasing from 21:00 (29.7℃), and minimum temperature appeared at 6:00 (26.3℃). Namely, this day was in the torrid night. In the day time, temperature was increasing from 6:00 to 12:00. At noon, it reached 33.6℃. In Fig. 3, relative humidity, 72.0% at 21:00, increased progressively and reached 94.8% at 5:00. After sunrise, it was suddenly decreasing, and the lowest value, 56.3% was found at 11:00. Figure 4 is a diurnal variation of vertical air temperature profiles in Yoyogi Park shown by Hamada and Mikami (1994). The ground inversion layer existed from the night to the early morning, and strong stable layer was formed.

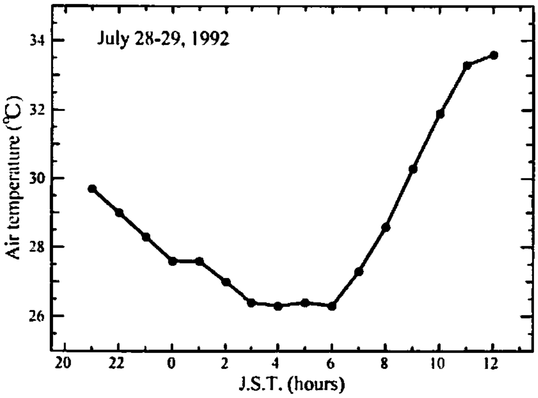

Fig. 2 A diurnal variation of air temperature taken by the station of Tokyo Metropolitan Bureau of Environmental Protection (Shibuya)

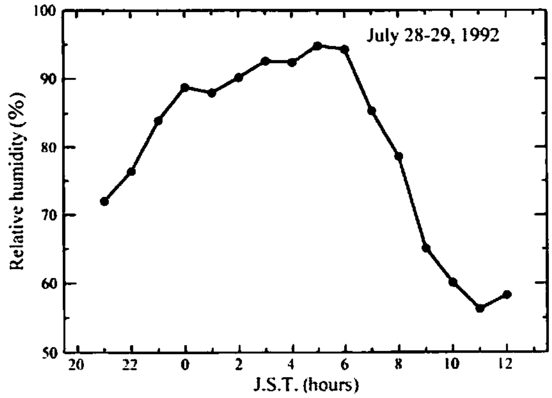

Fig. 3 Same as Fig. 2 but for relative humidity

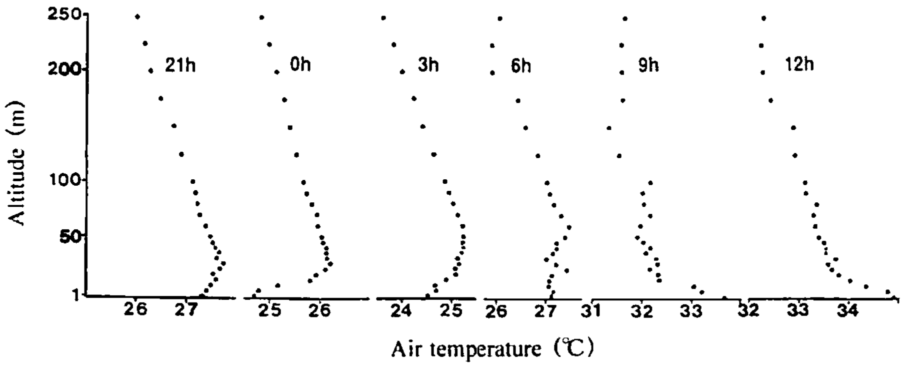

Fig. 4 A diurnal variation of vertical air temperature profiles in Yoyogi Park (with amendments of Fig. 8 of Hamada and Mikami 1994)

Calculation of potential temperatures in moist air

We calculated potential temperatures in moist air (Fig. 5) from Eq. (1). In Fig. 5, the ground inversion layer caused by radiative cooling appeared on about 25 m in 0:00 J.S.T. and on about 60 m in 6:00 J.S.T., respectively. It was clarified that there was an isothermal part in potential temperatures in the night, which existed between the ground inversion layer and another inversion layer above that. In any case, the temperature rising part existed above the isothermal part. Temperature rising occurred in the order of 0.1 degrees, which is almost equal to the accuracy of potential temperatures. Since the temperature rising part existed in any case, we thought that it was a signal not a noise.

Figure 6 shows the time evolution of the altitudes of the upper limit of the ground inversion layer in the night, that of the unstable layer which was induced by solar radiation in the day, lower and upper limits of an isothermal part and the altitude of the temperature rising part. In Fig. 6, the temporal interpolation was made with the spline function. Altitude of the ground inversion layer by radiative cooling is the highest in 4:00 J.S.T. (Fig. 6). Thickness of the mixed layer which is thought to have occurred by

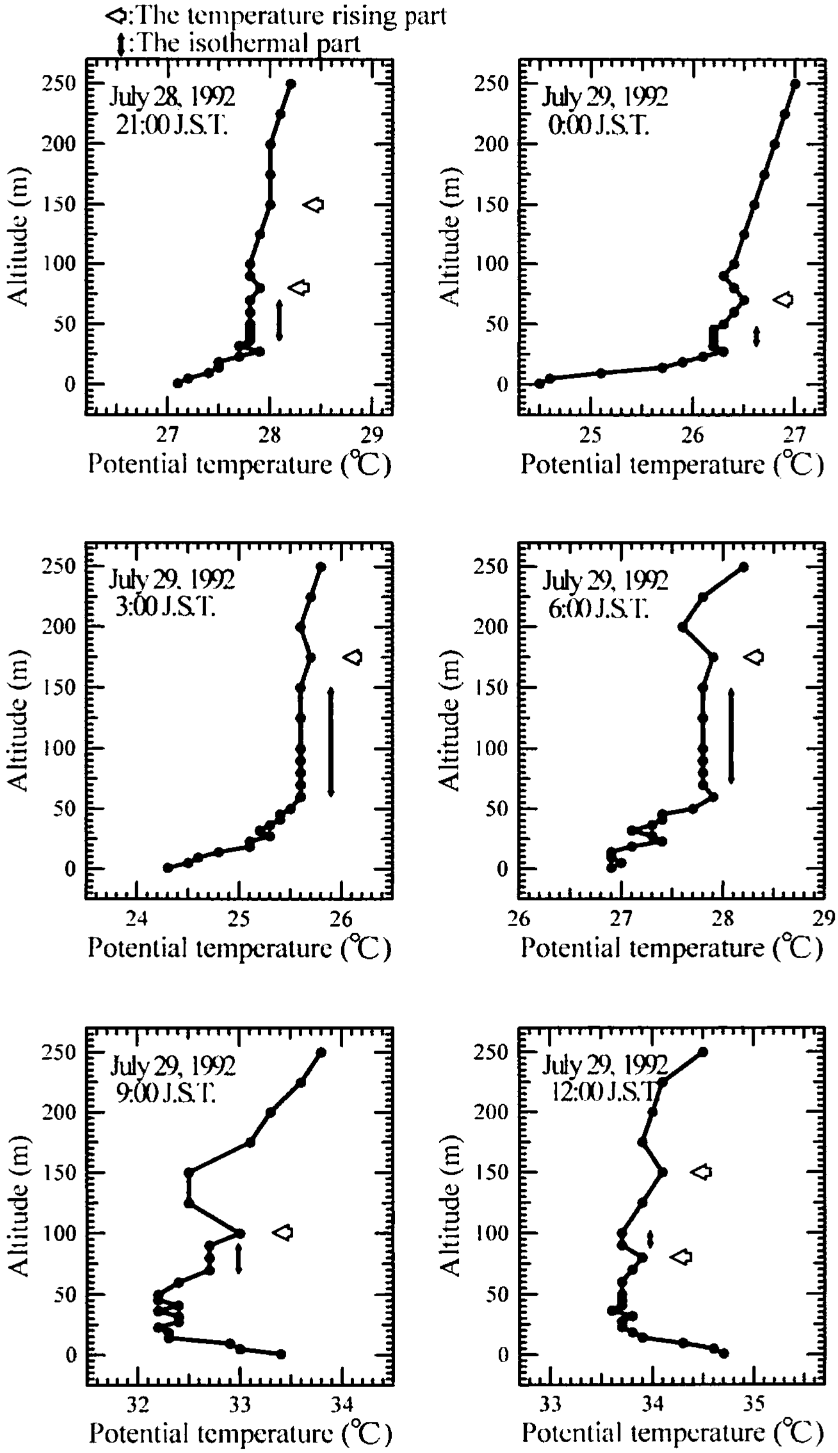

Fig. 5 Potential temperatures in moist air

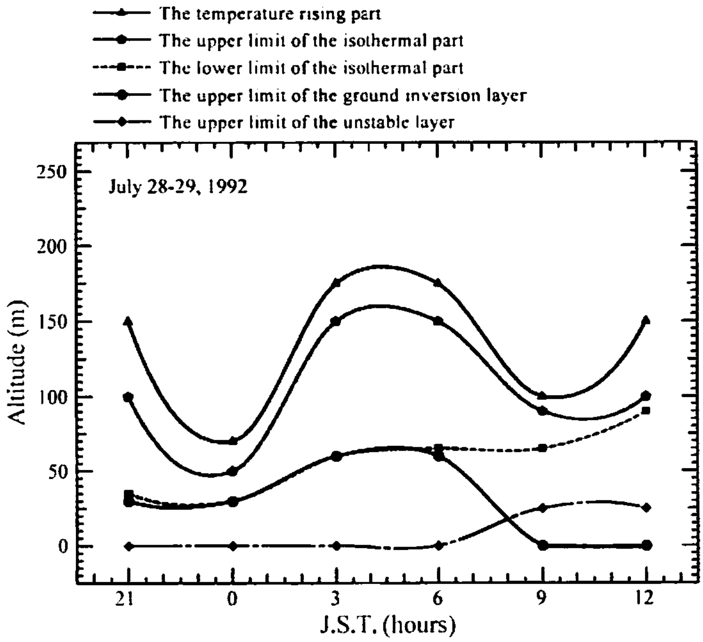

Fig. 6 Profiles of the altitudes of the upper limit of the ground inversion layer, the upper limit of the unstable layer which occurred by solar radiation, lower and upper limits of an isothermal part, and the temperature rising part

subsidence reaches 95 m thick at that time. After 6:00 J.S.T., the ground inversion layer dissolved rapidly. The temperature of forest floor is considered to have risen by solar radiation. Instead of the ground inversion layer, the unstable layer grow up to almost the same height of the forest crown. Thickness of the mixed layer which is considered to have occurred by subsidence becomes small in the day time. Progressively, the mixed layer which is caused by sensible heat flux grows up. This structure fairly resembles the illustration of potential temperatures observed in the central part of Aizu Basin by Kondo *et al.* (1989).

4. Discussion

In order to clarify the effect of water vapor, we show the result that we treated moist air as dry air (Fig. 7). In this case, R/C_P is 0.2856 ($e=0$ hPa in Eq. (5)) and T_V is equal to T. As a whole, the temperature rising part is not clear. Especially, the isothermal part is not clear in 3:00 J.S.T. and the inclination of the inversion layer over the altitude of 100 m is not smooth in 0:00 J.S.T. These are considered to be originated from the ignorance of the water vapor. Since the isothermal part does not exist in Fig. 7, it is apparent that

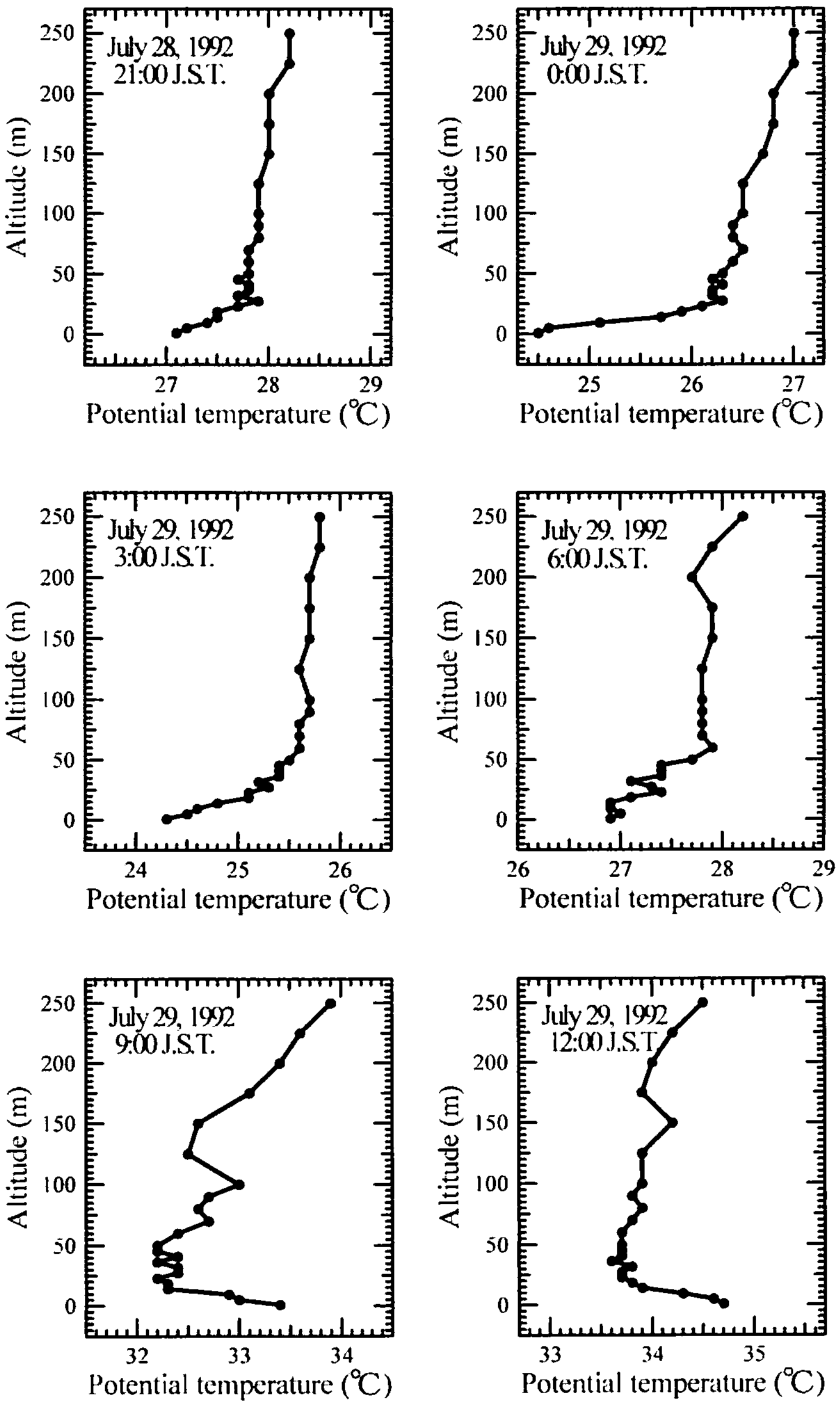

Fig. 7 Same as Fig. 5 but the moist air is treated as dry air

the isothermal part in Fig. 5 did not occur by advection in the night. Due to the existence of the ground inversion layer, energy supply from the ground is difficult to be considered for the existence of the isothermal part.

We can analogize this phenomenon with the subsidence inversion which exists in a core area of anticyclone if this temperature rising is caused by adiabatic compression (*e.g.* Wadachi 1984). Namely, we can expect existence of downward flow in the isothermal part. We considered that an isothermal part was the mixed layer which was caused by subsidence.

According to Hamada and Mikami (1994), difference of air temperature between a green tract and its peripheral built-up area became 4 degrees with maximum. We expect that pressure gradient is induced by this difference, and the relatively low temperature air, which is formed inside a green tract, flows out to built-up area. Divergent flow was observed on the roof of buildings's side of Meiji Shrine/Yoyogi Park (Kanda *et al.* 1997). If there was divergent flow, compensated subsidence should have existed as shown in Fig. 5.

From the north-south cross section of air temperatures observed in and around Meiji Shrine/Yoyogi Park in the night (Fig. 7 of Hamada and Mikami 1994), we can recognize that the relatively low temperature air, which is formed inside the green tract, oozes out to the leeward built-up area and that air temperature there is decreasing. Although the figure is a result of observations at the ground level, we can expect similar spatial structures.

5. Conclusions

Relative humidity in a green tract reached 60% or more on the average. Generally, water vapor is ignored in calculation of potential temperatures in moist air, and it is considered to be dry air. However we could not ignore the influence of water vapor in such high humid conditions. In this paper, we led an equation of potential temperature that contained effect of water vapor when the condensation did not occur.

It was clarified that there was an isothermal part in potential temperatures in the night, which existed between the ground inversion layer and another inversion layer above it. In any case, the temperature rising part existed above the isothermal part.

The altitude of the ground inversion layer induced by radiative cooling is the highest in 4:00 J.S.T. Thickness of the mixed layer which is thought to have occurred by subsidence reached 95 m at that time. After 6:00 J.S.T., the ground inversion layer dissolved rapidly.

Acknowledgments

We wish to express our gratitude to Dr. Hiroshi Matsuyama of Graduate School of Tokyo Metropolitan University. His helpful suggestions are very fruitful to this study.

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