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Thermal Environment in a Dense Housing Area in Summer - Field Observation and Numerical Analyses -

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1. Introduction

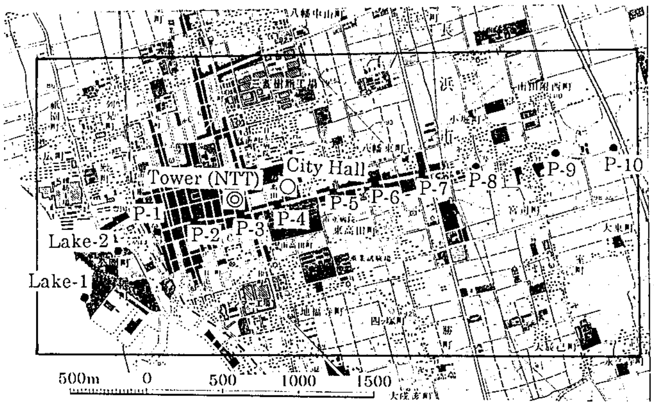
It is well-known that the development of cities has significantly changed the climate of the city areas. In the case of Tokyo, Japan, decades-long relentless removal of greeneries associated with rapid urbanization has resulted in severe deteioration of summer climate. As one example of local effect, the increase in the impervious portion of the ground surface in the urban area by pavements, road and buildings has significantly reduced the evaporation from the ground surface, and consequently increased the underground heat storage(e.g. Asaeda et al, 1996). On the other hand, to evaluate whole urban effect on the surroundings, various studies have been conducted on analyses by using numerical model(e.g. Fujino et al, 1996). However, most of them simplify a treatment of urban canopy layer. There have been few studies on the thermal environment for small district considering a treatment of urban canopy layer.

The purpose of this study is to give a detailed investigation on the effects of small residential district on the thermal climate through field observations, and to discuss the thermal structure of sub-urban area based on a modified numerical model which includes the effect of urban canopy.

2. Field Observation

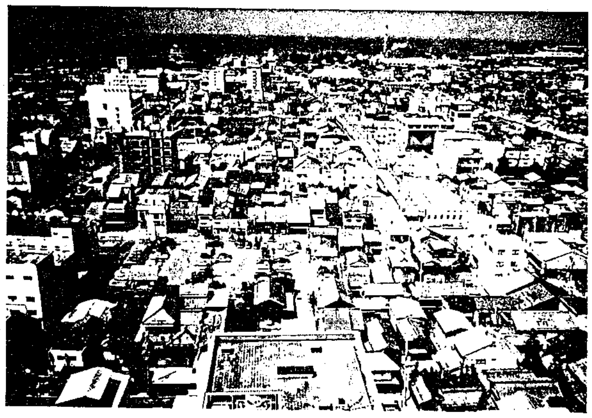
2.1 Observational Procedure

The field observation was conducted, in July 1996 and in August, 1997, at Nagahama City, on the coastline of Lake Biwa, the central part of Japan. The lake is more than 670 km^2 wide, the largest in Japan, Residential dwellings in Nagahama city spread along the coastline of the lake with approximately 3 km in width. Most of houses are wooden two stories high, about 7m until the top of the house, except for several dispatched concrete buildings. Across the center of the city from the lakeside towards inland, the main street, 12 m width extends, however, other pathways are as small as 7 m in width. Surrounding area is mainly covered with paddy field. Figures 1 and 2



Study Area and Temperature Observation Points

Figure 1



Photographic view from the tower facing the Lake

Figure 2

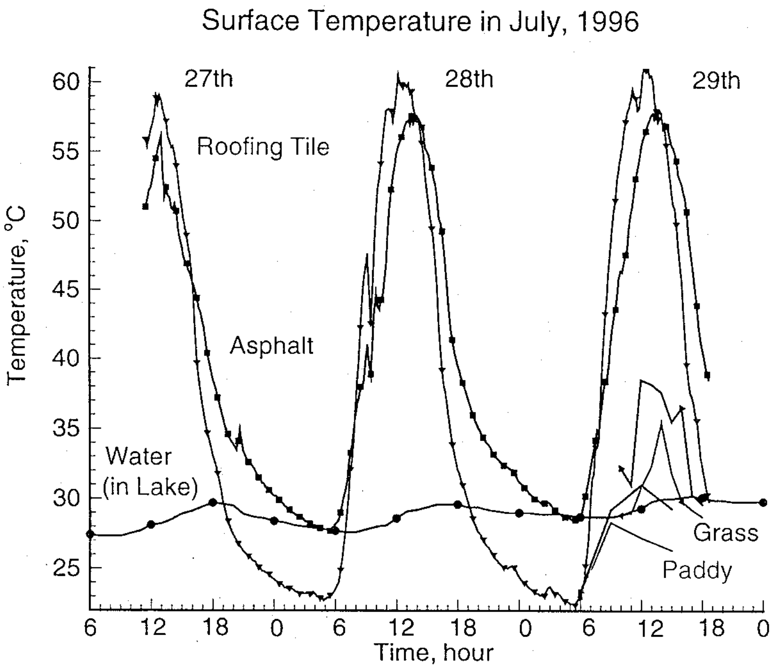


Figure 3

show the location of the site and photographic views of the lakeside and inland side.

Observations in 1996 were carried out over three days, along the main street. Twelve thermometers(ESPEC) were amounted at 1.5 m high on the side of the street, at about every 300 meters to obtain the horizontal pattern of temperature. Four anemometers were also installed at 3m and 5m away from the water, at 17m high on the roof top of the City hall located 1km inland, and at the top the NTT tower, 57 m high, near the City hall. Along the tower, another six thermometers were amounted at 13, 25, 38.5, 45, 51.5, and 58 m from the ground level.

Temperatures of street surface and residential roof and the infrared emissions from the paddy field were measured by the thermo-coupples(Chino) and radiation meter(Eko), respectively. All data were sampled at every 1 minute for wind velocity and 2 minutes for temperature.

2.2 Observational Results

The weather were clear during the entire period of the observation. Lake and land breezes were clearly observed all days. Figure 3 shows the observed diurnal temperature distribution of the ground surface. In daytime, temperatures of asphalt road and roofing tile reached more then 55 C at maximum, whereas, surface temperatures of grass and paddy field rose only at most 40 C. The temperature of the lake water at 50 cm deep near Nagahama bay, was kept at a nearly constant value, which was relatively high compared with that of the land surface except for streets. Figure 4 depicts the daily variation of wind vectors of each point on 27th in July, 1996. Lake breeze occurred during the daytime, from about 1000 to 1800 LST, which was turned to be land breeze during night.

Figure 5 depicts the corresponding air temperature at the ground level. In the horizontal distribution during daytime, air temperature always increased from the shoreline to inland, until the center of the city indicated by P-4, and then gradually decreased. In the time series of temperature at each points, temperature rises until about 1600-1800 LST in the afternoon, then, an abrupt drop was similarly seen when the wind pattern changed from the lake breeze to the land breeze. According to other observations in this district, highest temperature is normally recorded around 1400-1500 LST, thus, the continuous rise until the arrival of the land breeze front is abnormal. This will be discussed later. The sudden drop of temperature is due to the intrusion of land breeze front. Since the breeze is from the mountain range here, it is almost 13 degrees colder than the environment at 1700 LST. Since the temperature drop due to land breeze in this district is about 3 degrees, this large drop is

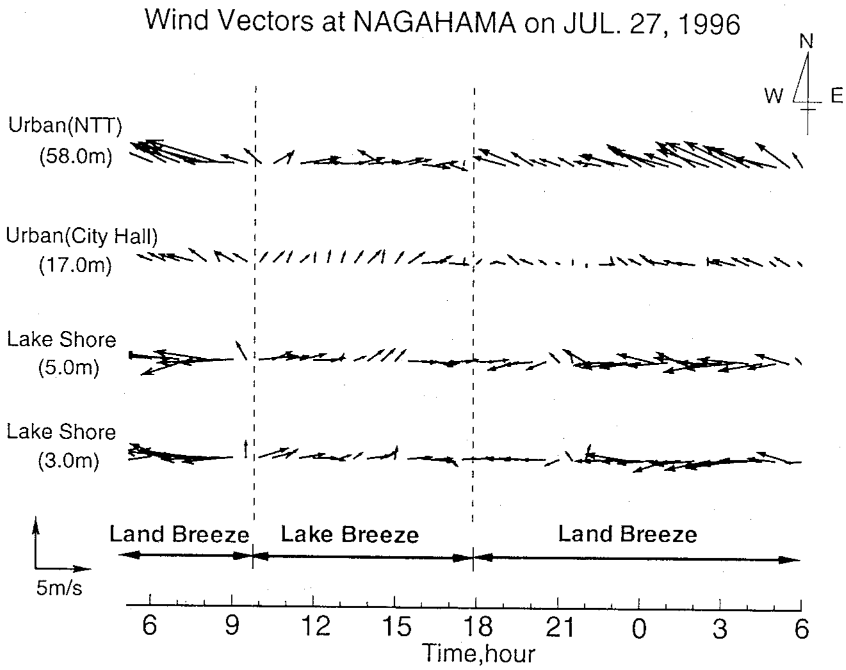


Figure 4

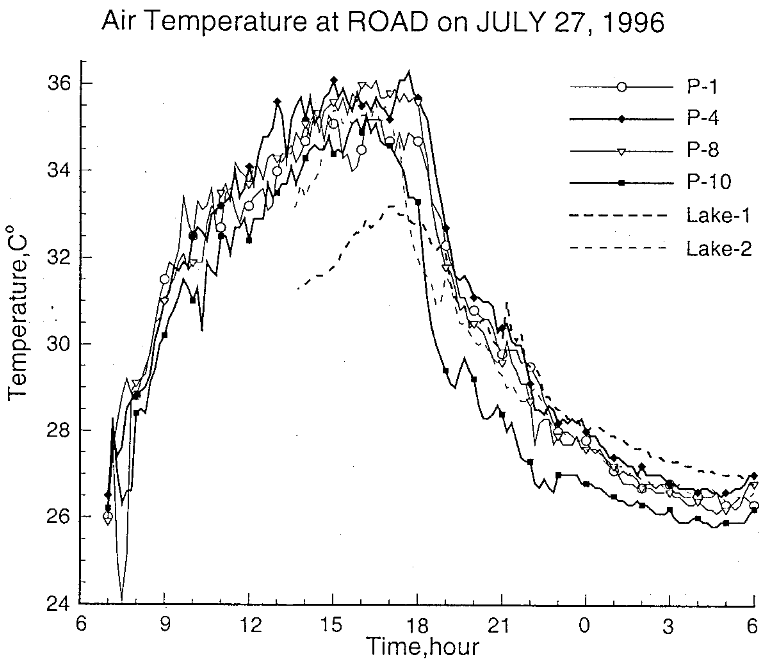


Figure 5

characteristic to the cities in this area, cities located in front of mountainous range. Temperature difference between P-4 and outskirts indicated P-10 was about 1 degree during lake breeze, while it became more than 2 degrees during lake breeze. The maximum difference reached to 4 degrees after sunset, 1800 to 2100 LST. It was found that heat island existed for 4 to 5 hours after sunset, 2200-2300 LST(James(1973), Oke(1981), Sakakibara(1994)). In this study, wind speed was low and sky was clear during night, however, upwind was cool air mass from mountains. It indicates that advection effect was more predominant for falling air temperature than the effects of the difference of radiate cooling for each city and outskirts. And it is possible that the maximum temperature differences appear just after turning land breeze, because advection effect to inner canopy from surrounding becomes week as it describe later.

Figure 6 shows vertical air temperature profiles at the center of city. The results illustrate that a thermal property of urban canopy remarkably appears; In daytime, higher temperature shows from the ground level up to the twice of canopy height. Nakamura and Oke(1983) pointed out that air temperature difference between the bottom of canyon and roof level, was 1 degrees at most, generally less than 0.5 degrees. This observation results recorded about 2 degrees. This is because the site is located only 1 km from lake-shore; relatively cool advection effect from lake was predominant over the canopy. This fact indicates that the warming of air temperature within the street canyon is developed much due to high building density.

3. Numerical Analyses

3.1 Outline of the Model

The mathematical model employed in the present study is referred to as a "second-moment turbulence closure model(Mellor and Yamada, 1982)". The model is basically a three dimensional time-dependent meso-scale atmospheric model. The model parameters are wind, potential temperatures, mixing ratio of water vapor, second moments of turbulence, turbulent energy. However, the effects of topography, ground surface conditions, as well as the presence of urban canopy, are also explicitly taken into consideration. The ground temperature distribution is computed by a local one-dimensional heat balance at the air-ground interface. The energy budget inside the urban canyon is computed by considering multiple reflection from building walls, aspect ratios between buildings, and the sky-view factors for the computation of net radiation, and the drag force for wind. Detailed derivations and discussions of the model are found in Asaeda et al.(1997).

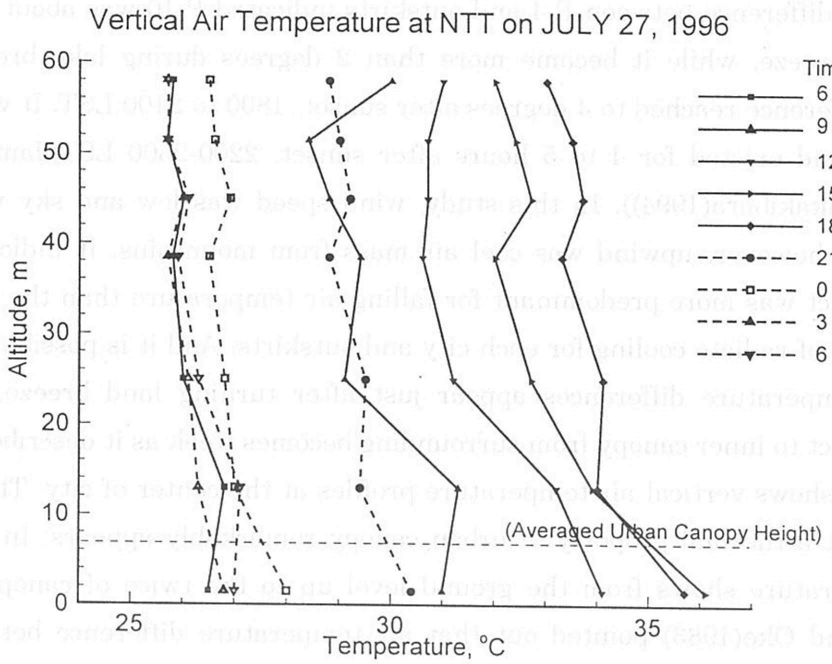


Figure 6

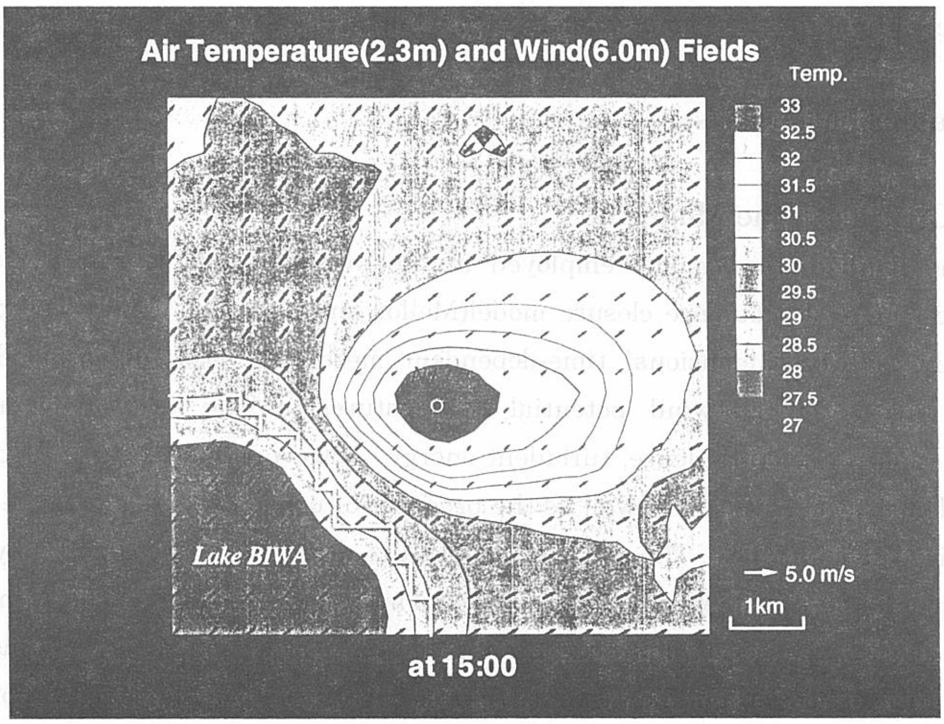


Figure 7

The governing equations together with the boundary and the initial conditions, as described above, are discretized in time and space using the second-order finite difference and are solved by ADI technique. The ground temperature distribution is computed by the one-dimensional finite volume method with implicit time-integration.

The computational domain of 10 by 10 km was discretized horizontally by 250 by 250 m mesh resolutions. The vertical domain was discretized into 50 meshes variably with height until an altitude of 1000 m. For the computation of subsurface temperature distribution, variable spacing mesh was also applied with 11 nodes extending to a depth of 1.5 m.

3.2 Computational Results

Figures 7 show the computed ground-level air temperature and wind fields at 1500 LST. Temperature contours represent values at 2.3 m above from the ground surface, while wind vectors indicate the magnitudes and directions of 6.0 m high. It is said that the computation could reproduce a local trend of the temperature distribution; air temperature over the water, 28.0 C at the upstream end of the computation, increases gradually until nearly 33.0 C at the center of city, then it decreases toward the inland. For the whole computational domain, however, absolute value of the computed temperature is about 3 degrees lower than that of the observation. This is explained as follows : This area is located at the basin surrounded by mountain range. Thus, the lake breeze observed here is not a uni-directional but a part of the divergent circulation which flows up along the slope of the surrounding mountain range. Flowing along the mountain surface and down to the central part of the lake, however, the air receives a large amount of heat fluxes from the original paper (Kondo et al. (1989), Lin (1983)), which then increases the potential temperature at the ground surface level. Therefore, the amplitudes of the diurnal temperature rise are larger at the bottom of a basin(Kimura and Kuwagata, 1995). Since the computation is limited only around the city and the surroundings, rather than the entire basin scale, then the diurnal temperature rise was underestimated.

For the evaluation of the urbanization effects on the thermal environment, vertical air temperature and wind profiles are compared for cases with and without the occupation of the present building canopy. Figures 8(a),(b) show the comparison between the present state and a fictitious case, in which land use was all paddy field, for 1500 LST at the center of city. The results is consistent with the observations. Figures 9(a) and (b) show the vertical air temperature and wind profiles at 1500 LST.

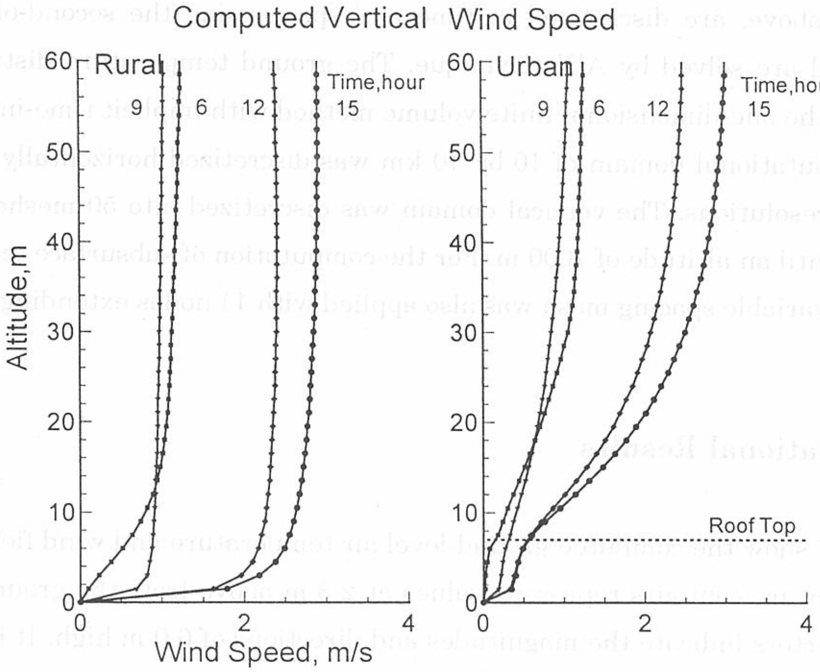


Figure 8 (a) fictitious case (b) present case

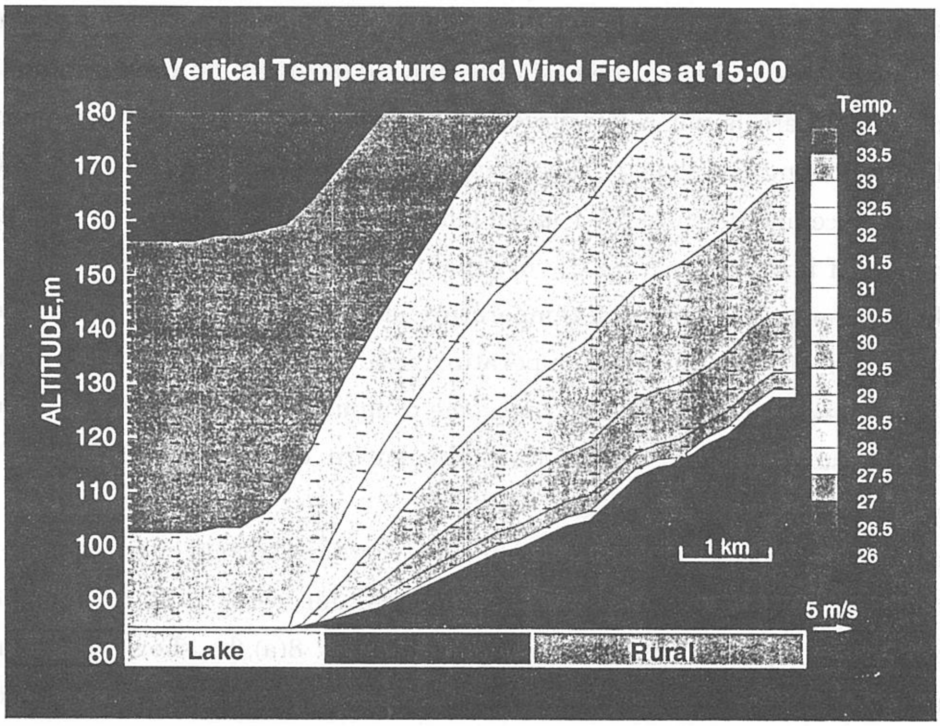


Figure 9(a) fictitious case

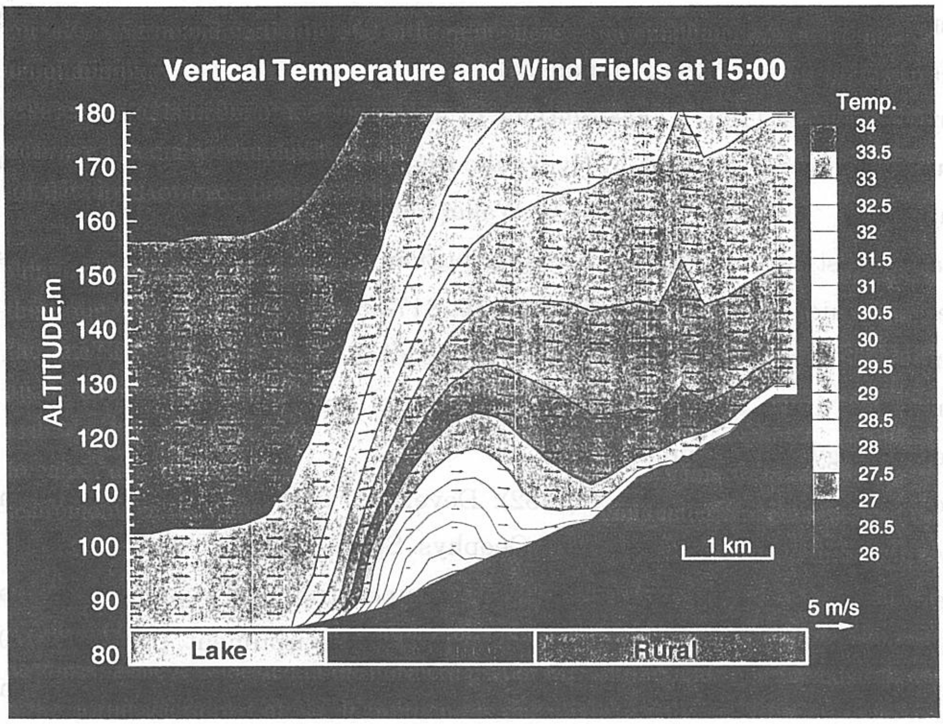


Figure 9(b) present case

high. The effect of this case's urbanization on developing a mixing layer is very small mainly due to the magnitude of city and a fetch problem.

4. Conclusions

Effect of urbanization on heat, based on the real condition along the lake Biwa, has been examined by observations and numerical analysis with explicit consideration of urban canopy layer. The results of study indicate that : 1) air temperature in this small residential area would be risen by about 1-2 degrees. 2) such low-storied small town as a few square km would be very effective in changing the thermal environment, specially within the urban canyon, even though the surroundings are exposed by lake-land breeze circulation. 3) effect of this case's urbanization on developing a mixing layer is very small due to a fecth problem.

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