Field Experiment on the Effects of a Nearby Asphalt Road on Temperature Measurement

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Abstract

A field experiment to clarify the characteristics of temperature distribution near an asphalt road was carried out at the Meteorological Instruments Center in Tsukuba, Japan. Fifteen thermometers equipped with artificially ventilated radiation shields were installed within a distance of 10 m from the road, and the results showed that the road's presence caused a significant positive bias at a height of 0.5 m on its leeward side. Thermometers nearer the road showed larger positive biases. The biases tended to be larger in summer than in winter, with greater temporal variations in cases of lower wind speed. At a height of 1.5 m above the ground, small positive biases were seen near the road. At a height of 2.5 m, smaller negative biases were seen with distance from the road. Biases showed diurnal variations with slightly negative values at around daybreak and positive values from late morning to midnight as well as an evening peak in summer. In winter, positive biases were observed throughout the night, while negative biases were seen during the day.

1. Introduction

Detection of climate changes based on observed temperature data can be affected by inhomogeneity arising from temporal variations in microscale environments around stations (Mahmood et al. 2006; Runnalls and Oke 2006; Pielke et al. 2007). As many observation stations in Japan are located in cities that have undergone rapid industrialization, more attention should be paid to evaluating the surroundings of such stations in terms of climate change monitoring. Fujibe (2009; 2011) described the possibility of microscale effects on observed temperature trends based on statistical analysis using data covering a period of 29 years from around 300 stations in Japan. A field experiment at the KNMI-terrain in De Bin (the Netherlands) showed that even minimal changes in site exposure may cause substantial differences in thermometer readings (Brandsma, 2004).

According to the siting classification for surface observation stations on land (hereafter referred to as WMO siting classification) in the CIMO Guide (WMO, 2010 a, 2010 b), the main factors adversely affecting temperature measurements are unnatural surfaces and shade. In 2011, the Japan Meteorological Agency (JMA) classified its 59 manned synoptic observation stations around the country in accordance with this classification. When only the conditions of neighboring artificial surfaces were taken into account, temperature measurement classification resulted in 37 out of 59 stations being categorized as Class 3, 18 as Class 4, 2 as Class 1, 1 as Class 2, and 1 as

Class 5. Thermometers are considered to be more than 10 m away from heat sources such as buildings and concrete surfaces at Class 3 stations. JMA plans to apply the same classification to its 93 unmanned synoptic observation stations in 2012. The results will be analyzed together with those for manned stations and presented later.

Meanwhile, JMA's own rules for siting environments are more relaxed than the WMO siting classification and flexible enough to be applied to the highly dense urban environments typical of many major Japanese cities. Firstly, a site should have open space of more than 600 m^2 with an area of more than 20 m in width and length covered with short grass. Secondly, buildings should be more than three times their height or more than 10 m away from the site edge. Thirdly, the mean elevation angle of surrounding obstacles observed from the center of the site at a height of 1.5 m should be less than 18 degrees. Comparing these requirements to the conditions of the WMO siting classification, it can be seen why most of JMA's stations fall into the Class 3 category.

Regardless of whether the WMO siting classification or JMA's approach is used, it is clear that such simple indicators are very useful both for data users and for observation staff in estimating factors related to site environments, even though they do not fully or truly describe the complicated environments of the variety of real observation stations in existence. However, as the methods of these classifications seem to rely more on experience and practice in operation than on concrete theories based on experiments and simulations, there may still be room for classification improvement. With today's advanced technology in terms of sensors, data transmission/processing and computer simulation, it should be possible to evaluate data observation biases caused by environmental conditions at observation stations more thoroughly and accurately. Using such modern instruments, Aoshima et al. (2010) conducted field experiments and succeeded in estimating the effects of various screens on thermometers. This is a good example of how well-designed field experiments can be very effective for determining how minor effects from site environmental factors influence meteorological observations. The present study focused on the effects of an asphalt road on temperature measurements and related quantitative evaluation via a field experiment. In the study, 15 thermometers with known levels of accuracy were set up at different distances from the road at various heights to enable observation of horizontal and vertical temperature distributions. The observations were conducted continuously for about a month in the summer of 2010 and in the winter of 2011 to include various patterns of advection in the vicinity of the road.

2. Data and study method

The experiment site was set up at JMA's Meteorological Instruments Center in Tsukuba, Japan (36° 3.4' N, 140° 7.5' E), which is one of the WMO RICs (Regional Instrument Centers) in RAII. The site is in a part of the city where several scientific research institutes are located, well away from residential areas and surrounded by a vast open space covered with vegetation. The nearest buildings stand a few hundred meters away. There are no artificial heat sources or objects projecting shade within 100 m. A 10-m-wide asphalt road crosses the site from east to west.

The layout of the instrumentation used is shown in Fig. 1 a. The thermometers were installed on one side of the asphalt road at four distances of 0.8, 3.2, 6.9 and 10.0 m from the road so that the road occupied 45, 30, 10 and 0%, respectively, of the area within a 10 m circle around each sampling point. These points were situated on the northern side of the road for the summer period and on the southern side for the winter period so that they were on the leeward side of the prevailing winds, which are southerly in summer and northerly in winter. At each point, three thermometers were mounted at heights of 0.5, 1.5 and 2.5 m from the ground. It should be noted that operational observation of surface air temperature is made at a height of 1.5 m. Reference temperatures were measured on the opposite side of the road at a distance of 10.0 m at each of the same three levels as those of the sample temperatures. All the thermometers were of the same model as those used in AMeDAS (JMA's operational Automatic Weather Station observation network), and were installed inside radiation shields with artificial ventilation. The sensors of the thermometers (Pt 100 Ω, 6 mm in diameter) were calibrated in a liquid bath-type measurement chamber before and after installation to allow adjustment of the observed values.

Several parameters other than temperature were also measured in the experiment. Two ultra-sonic anemometers and a pyranometer were installed to monitor in-situ wind speeds and weather conditions at the site. The anemometers were mounted at heights of 0.5 and 2.5 m near the reference point (Fig. 1 a). The surface temperatures of the road and the grass field were measured at 3 cm from the ground using thermocouple thermometers. The radiation balance (albedo) on the asphalt and grass surfaces was measured on a cloudless day during each experiment period in summer and winter (August 16, 2010, and January 6, 2011) using an albedometer. In addition, surface temperature distribution around the site was observed using a radiation thermometer (Thermo-Tracer TH7100) on August 16, September 3 and January 5.

The data sampling frequency for the thermometers, the thermocouple thermometers and the pyranometer was 1.0 second, and that for the anemometers was 0.25 seconds. In the data analysis, the values for the thermometers and the thermocouple thermometers were processed to give 1-minute moving averages of six 10-second periods of data as in operational temperature data processing. For the anemometers, 3-second moving averages of the 0.25-second sample data were used. The temperature departure from the reference point, δT, is defined as

$$\delta T = T - T_0$$

Here, T and T_0 are the temperatures at the sampling point and the reference point, respectively.

3. Results

Figure 2 presents the frequency distributions of all δT values at each height for each sampling point in summer and winter. In summer, the distributions were not influenced by the wind direction in the range from ESE to SSW, but differed significantly for other directions. Accordingly, data for southerly (ESE – SSW) and northerly (WNW – NNE) winds were composited separately as shown in Fig. 2. For southerly winds (ESE – SSW), the sampling points were located on the leeward side of the road, and for northerly winds (WNW – NNE) were located on the windward side. In each of the two composited groups, there was no particular distinction in the distributions depending on wind directions.

In the same manner, the winter cases were categorized into two groups of southerly winds (ESE – SW) and northerly winds (WNW – NE).

For the summer period, the frequency distributions of δT at a height of 0.5 m show positive biases for southerly winds (ESE – SSW) and a negative peak for northerly winds (WNW – NNE).

The bias for southerly winds reached 0.2 to 0.4°C, and tended to be larger with shorter distances from the road. At a height of 1.5 m above the ground, small biases were seen near the road, while significant negative biases were seen regardless of wind direction at a height of 2.5 m, especially at the farthest point (10 m from the road). Positive biases at a height of 0.5 m were also seen in winter with northerly winds, although these were smaller in magnitude than those observed in summer. Thus, positive temperature biases at 0.5 m were seen in both summer and winter for thermometers on the leeward side of the road. Figure 3 shows the frequency distributions of δT in relation to each wind speed range in summer for southerly wind cases in which the surface temperature difference between the road and the grass were greater than 10°C. The average magnitude of the bias and the range of its variation were larger at lower heights and for cases with lower wind speed. At a height of 1.5 m, δT ranged from 0.0°C to 0.2°C regardless of the distance from the road. These outcomes are also found in Kumamoto et al. (2012), and more detailed results and discussions appear in Hamagami et al. (2012), including those of winter cases.

The characteristics of time dependence in regard to δT were investigated in relation to surface temperatures and wind speeds. Figure 4 shows diurnal variations in δT, surface temperatures of the road and the grass field, and wind speeds for mid-summer (MS: July 17th – August 31st) and mid-winter (MW: December 6th – January 6th). During these periods, there was not much difference in wind direction between day and night. All values shown in Fig. 4 are 10-minute means averaged over the number of days in each period.

As shown in Fig. 4, the average δT at the point nearest the road (0.8 m distance) at a height of 0.5 m had the widest range of anomalies both in MS and MW. The bias was smaller with greater distance from the road. There were very slight variations at heights of 1.5 and 2.5 m at all sampling points, indicating a smaller influence from the road than that seen at a height of 0.5 m.

In MS, the surface temperature of the road rose to 55°C during the peak hours of 1200 – 1400 Japan Standard Time (JST) and remained high at around 30°C or more during the night, representing a difference of 8 – 14°C from that of the grass field throughout the whole day, while the wind intensified to speeds of over 1.5 ms^{-1} during the hours of 1200 – 1800 JST. The peak of the positive bias in δT appeared early in the evening at around 1900 JST with a maximum value of +0.47°C at 0.8 m from the road at a height of 0.5 m. In MW, positive biases in δT were conspicuous throughout the night, with a peak at around 1900 JST at a height of 0.5 m under a lower wind speed of about 1.0 ms^{-1} and larger temperature differences between the road and grass surfaces than in the daytime.

The albedo values for the asphalt surface and the grass field were measured using an albedometer (Table 1). The results corresponded to the generally accepted notion that asphalt absorbs more short-wave radiation with a lower albedo than grass does. The results of thermometer-based measurement confirmed that the surface temperature was almost uniformly distributed over each of the two surface types. The maximum surface temperature of the asphalt was around 55°C in summer and 20°C in winter, while that of the grass was around 40°C in summer and 18°C in winter according to the results of thermocouple thermometer measurement.

Finally, comparison with a 2D model simulation was conducted to clarify the mechanism at work when the asphalt road acts as a heat source. The simulation is designed to describe a real observed situation as a snapshot of a typical summer night (1920 JST, 3, September, 2010) when the effects of the asphalt road were considered significant. The model's domain was 70 m with a resolution of 1 m in the horizontal direction and 20 m with a resolution of 0.6 m in the vertical direction. The level-2 turbulent closure model of Mellor and Yamada (1974, 1982) was used. The upper boundary was set to a constant wind speed of 2.0 ms^{-1} and a constant temperature of 27°C based on observed values. The initial and inflow conditions of wind and temperature were estimated based on the Monin-Obukhov similarity theory up to 20 m. The road temperature was set to 37°C, and the surface temperature of the grass field was set to 28°C. Figure 5 shows the temperature distribution after a sufficient number of time integrations to establish an equilibrium state. The results show that the temperature difference (δT) was larger in the simulation than in the observation (Table 2). The model slightly underestimates wind speed compared to the observed values. However, the computed δT values correspond closely to the observed values overall.

4. Brief outline of ongoing experiment

To support reliable high-quality climate monitoring, it is necessary to consider how environmental changes around the site (such as installation of artificial structures and tree growth) influence observation data. Such surrounding objects may hinder wind, create shade or affect radiation balance around thermometers. To evaluate the extent to which trees around a site affect temperature observation data, actual field measurement is needed. This section details our ongoing examination in this area.

The examination is performed to allow quantitative evaluation for the effects of trees located at one side of the field on temperature and wind measurement data. For example, when wind is weakened by trees and air exchange around the site is reduced during the day, the temperature may rise more than that measured at an ideal site. The problem here lies in determining the extent of such temperature fluctuations depending on the distance from the trees.

An experiment is currently being performed at the surface observation field of the Aerological Observatory in Tsukuba (area: approx. 85 m east to west, approx. 75 m north to south; Fig. 1 b). Toward the eastern side of the field, eight thermometers and four anemometers are installed 4.5 H from the edge of the tree area (where 1 H is about 9 m, which is the average height of the trees). A reference thermometer is located at the 4.5 H point, which is the center of the observation field. The thermometer and anemometer height is 1.5 m except for one anemometer set up at a height of 5 m. The thermometers are the same type as those used in JMA's operational surface weather observation with artificially ventilated screens.

5. Summary and discussion

This section summarizes the results of the effects from the asphalt road. As the direction of wind over the road is southerly in summer and northerly in winter, the results indicate the direct influence of heated air transported by wind over the road. Significant negative biases were seen regardless of the wind direction at a height of 2.5 m in summer, suggesting the influence of factors other than the road.

In regard to height, the results showed that significant positive temperature biases were caused by the road at a height of 0.5 m from the ground, with the magnitude depending on the distance from the road and wind conditions. Small biases were seen at a height of 1.5 m near the road, while significant negative biases were observed 10.0 m from the road at a height of 2.5 m. A possible reason for these negative biases is the effect of vegetation located 100 – 200 m southwest of the site (Fig. 1 a), although further analysis will be needed.

As for diurnal variations, the temperature bias was found to be the largest at 1900 JST both in summer and in winter. In summer, the temperature difference between the road and grass surfaces was large in the early afternoon, but the temperature bias appears to have been reduced due to enhanced ventilation with relatively strong winds of 1.5 ms^{-1} or more. In winter, as the wind was weaker and the surface temperature of the asphalt was higher at night than during the day, positive temperature differences were seen all through the night.

In order to further clarify the mechanism by which nearby heat sources affect temperature measurement, it is necessary to consider other factors such as the presence of buildings and trees, terrain roughness, heat balance, soil moisture, and vapor from vegetation in the surrounding environment. This type of field experimentation and computer simulation is expected to enhance expertise on methods of evaluating the environmental conditions of observation stations.

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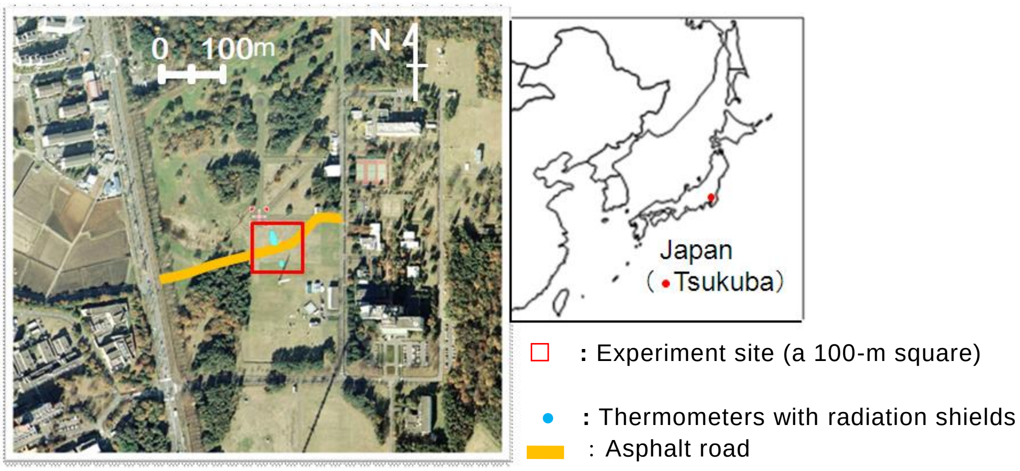

(Image: Google Maps)

Experiment site location

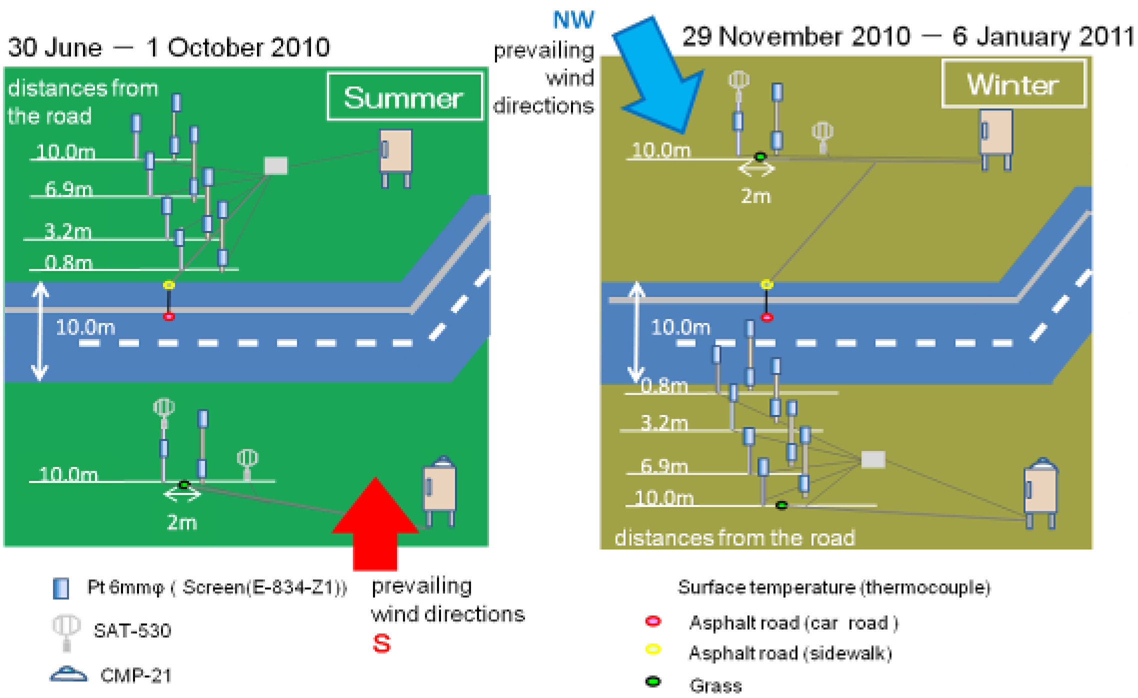

Fig. 1 a. Experiment site location (top) and instrumentation layout (bottom)

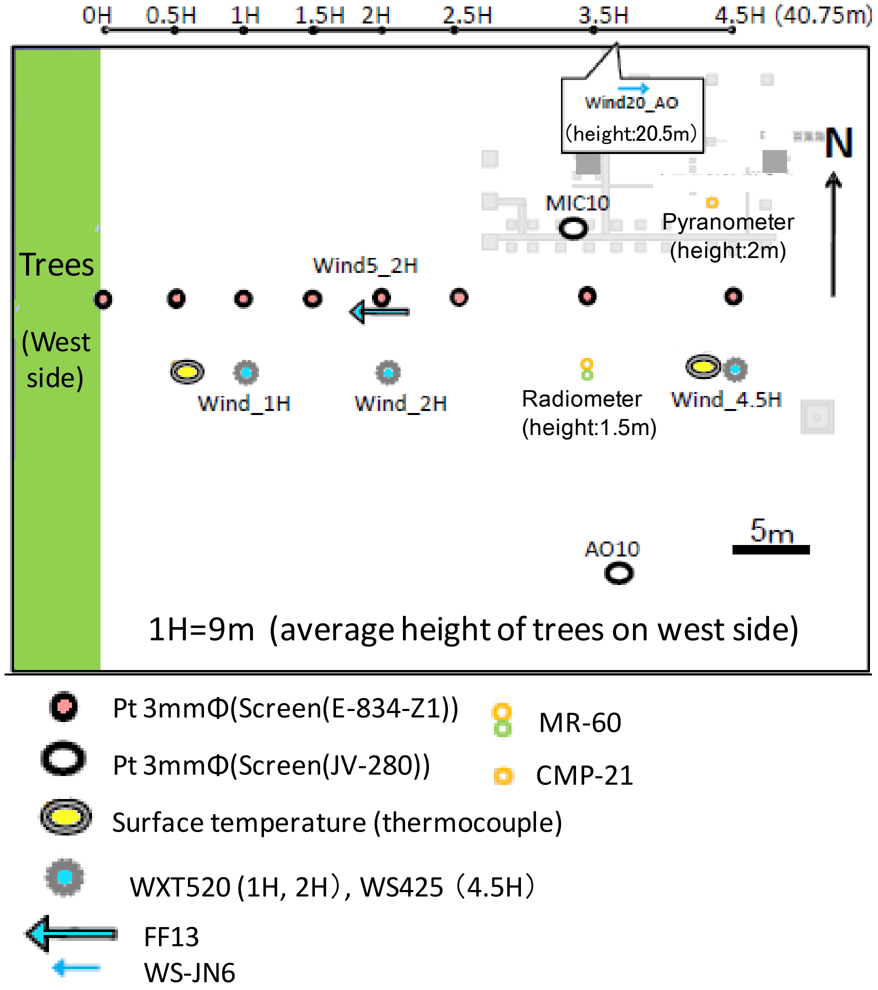

Fig. 1 b. Instrumentation layout for measurement of other experiment for the effect of trees around the observation site

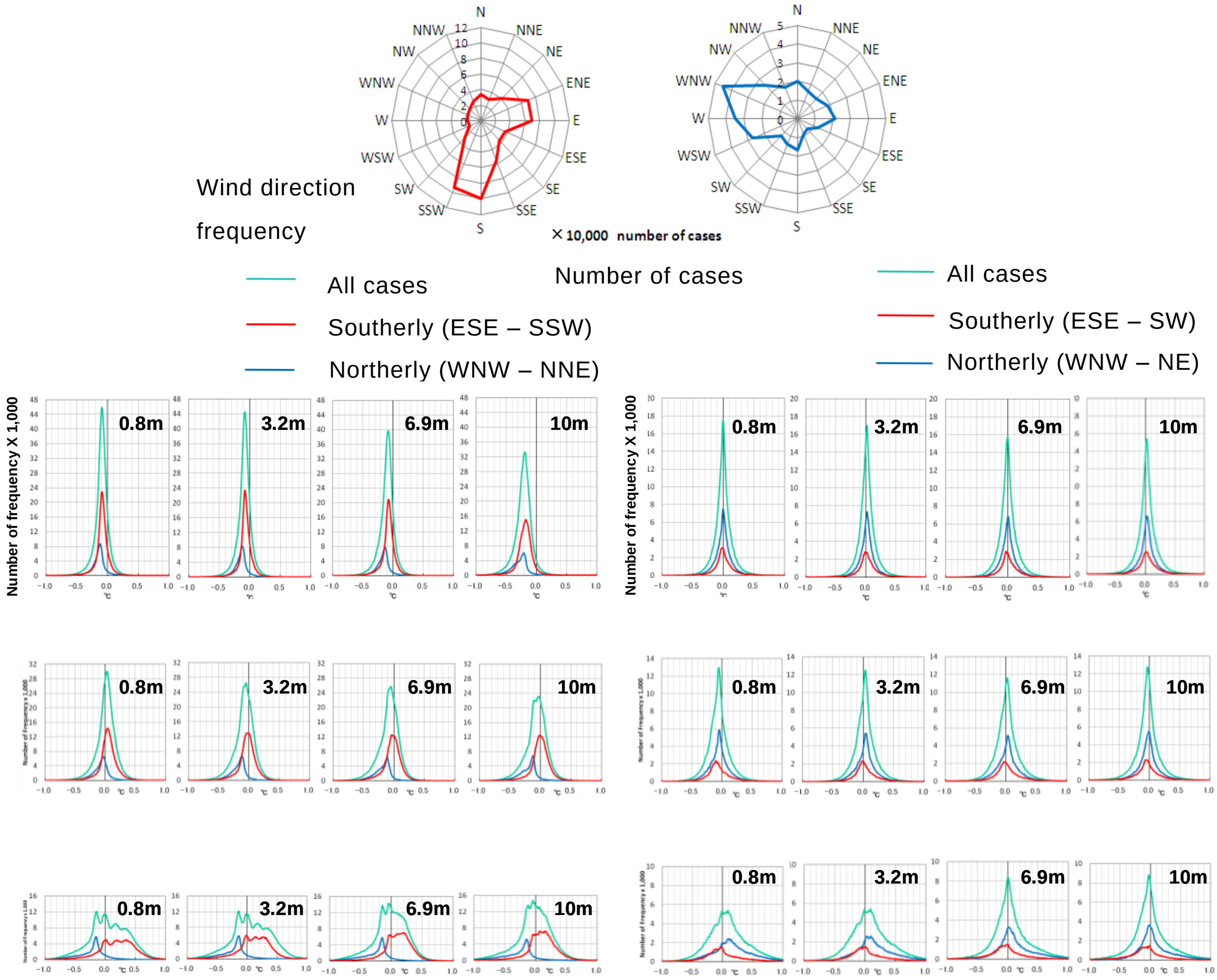

Fig. 2. Wind direction frequency and δTs distribution. The vertical axes indicate the number of cases with 1,000 as a unit. (a) δTs frequency from 30 June to 1 October at a height of 2.5 m, (b) at 1.5 m and (c) at 0.5 m, (d) δTs frequency from 29 November to 6 January at a height of 2.5 m, (e) at 1.5 m and (f) at 0.5 m. Figures (a) to (f) consist of four histograms for the four different sample points located at distances of 0.8, 3.2, 6.9 and 10.0 m from the road.

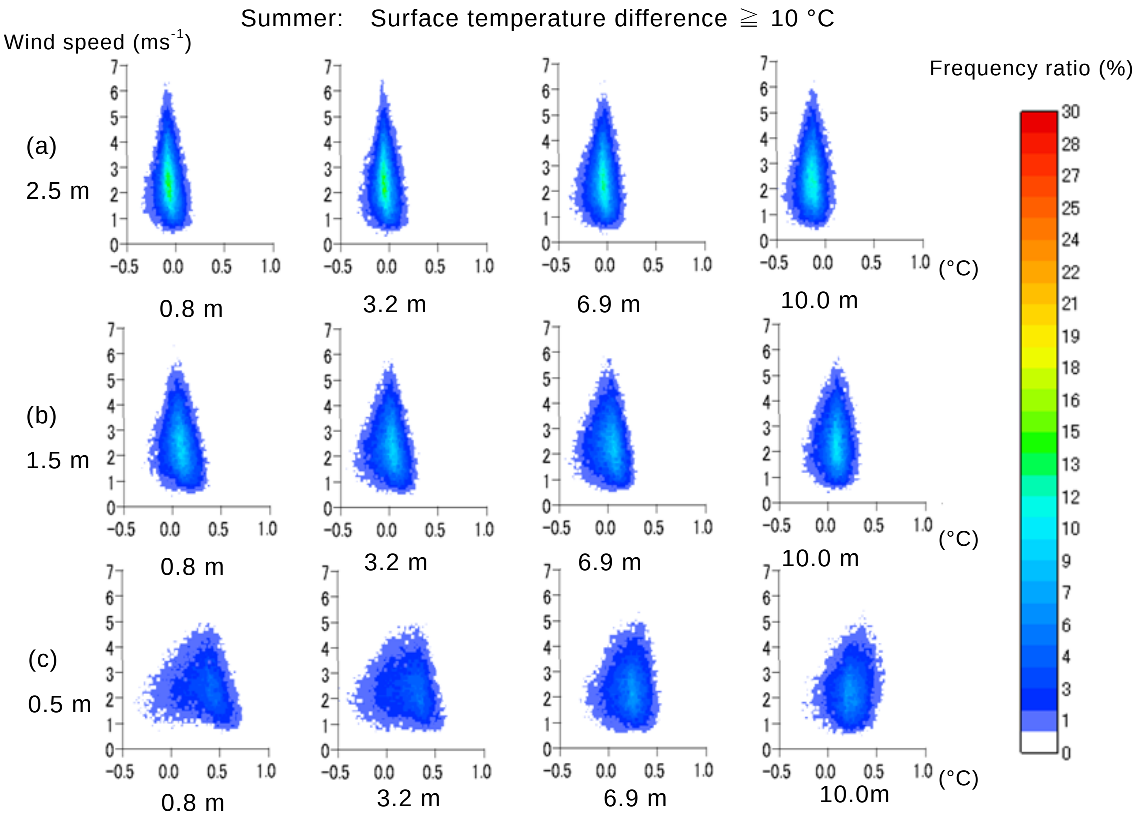

Fig. 3. δT frequency distributions by wind speed. Figures (a) to (c) represent the same positions and periods as those described in Fig. 2. The difference in surface temperature between the asphalt and the grass was greater than 10°C in summer.

Table 1. Albedo measured using an albedometer

Surface	Albedo	
	Summer (16 August 2010)	Winter (6 January 2011)
Asphalt road	0.098	0.142
Grass field	0.157 – 0.188	0.206 – 0.247
Bare ground	–	0.176

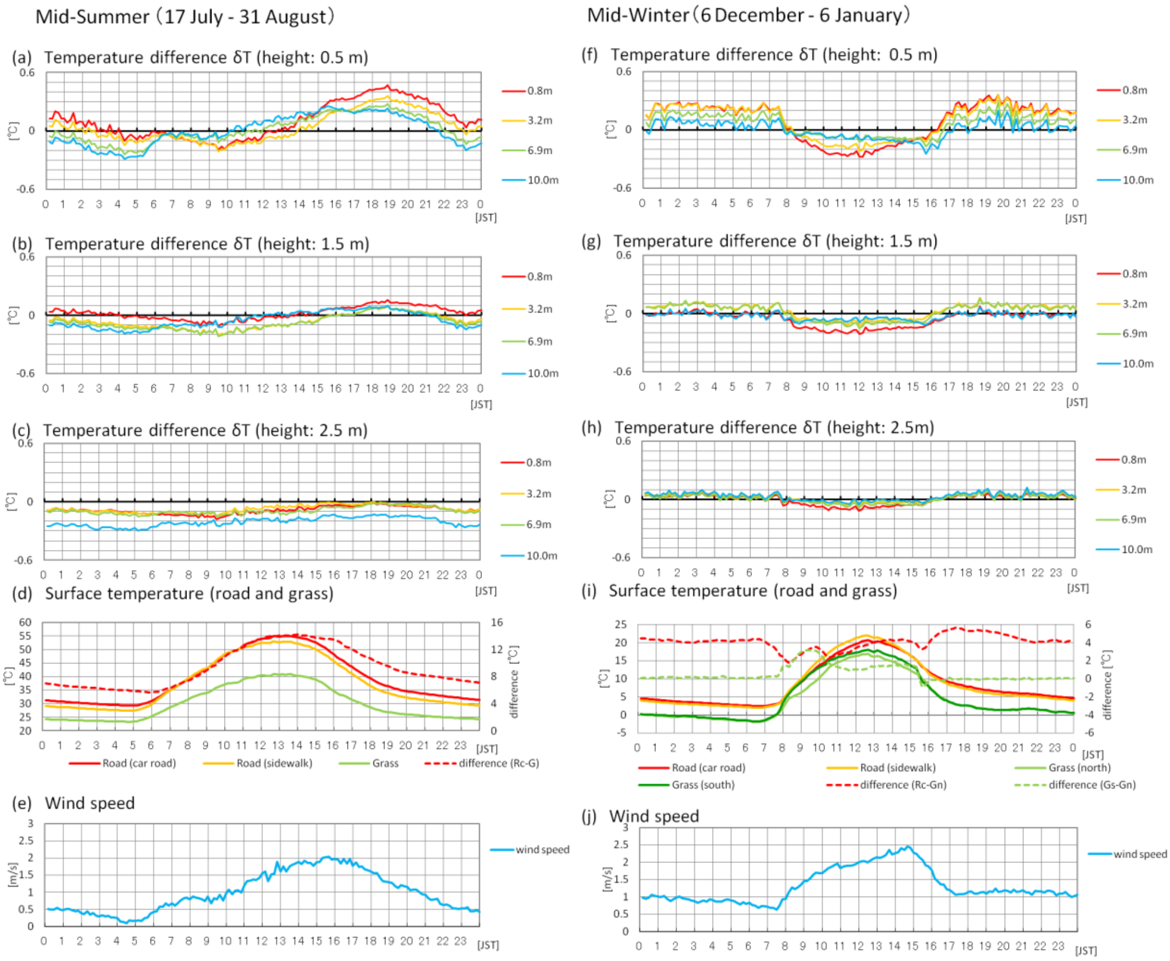

Fig. 4. Diurnal changes in δT, surface temperature and wind speed. (a) Diurnal changes in δT observed at each of the four sample points during the mid-summer period at a height of 0.5 m, (b) at 1.5 m, and (c) at 2.5 m, (d) diurnal changes in the surface temperature of the asphalt road and the grass field, and (e) wind speed. Figures (f) to (j) represent the same parameters for mid-winter as (a) to (e) for mid-summer.

Table 2. Comparison of computed δT values and wind speed data with observation values

Parameter	Simulation	Observation
δT (height: 2.5 m)	+0.1°C	- 0.1 ― - 0.2°C
δT (1.5 m)	+0.2°C	0.0°C
δT (0.5 m)	+0.6 ― +0.3°C	+ 0.3 ― + 0.1°C
Wind speed	1.7 ms^{-1} (height: 2.7 m)	2.3 ms^{-1} (height: 2.5 m)

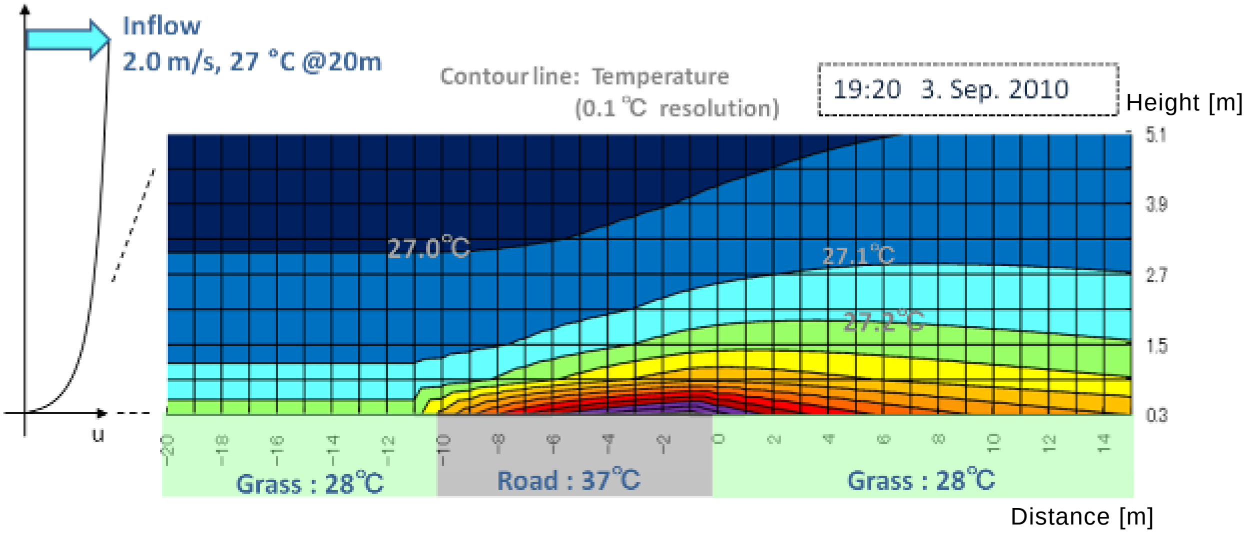

Fig. 5. Temperature distribution simulation using a 2D model