Formation Mechanisms of the Extreme High Surface Air Temperature of 40.9°C Observed in the Tokyo Metropolitan Area: Considerations of Dynamic Foehn and Foehnlike Wind

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ABSTRACT

A record-breaking high surface air temperature in Japan of 40.9°C was observed on 16 August 2007 in Kumagaya, located 60 km northwest of central Tokyo. In this study, the formation mechanisms of this extreme high temperature event are statistically and numerically investigated using observational data and the Weather Research and Forecasting (WRF) model. The extreme event is caused by a combination of two particular factors: 1) Persistent sunshine and a lack of precipitation during the seven consecutive days preceding 16 August 2007 were seen in Kumagaya. This was the 12th-longest stretch of clear-sky days in July and August from 1998 up to 2008. Persistent clear-sky days allow the ground surface to dry out, which produces an increase in sensible heat flux from the ground surface. This contributes to the extreme event, and its mechanism is qualitatively supported by the results of sensitivity experiments of soil moisture on surface air temperature. 2) A foehnlike wind appears in the numerical simulation, which is caused by diabatic heating with subgrid-scale turbulent diffusion and sensible heat flux from the ground surface when this airflow passes in the mixed layer over the Chubu Mountains and the inland of the Tokyo metropolitan area. Backward trajectory analysis and Lagrangian energy budget analysis show that the foehnlike wind plays a more important role in the extreme event than the adiabatic dynamic foehn pointed out by previous studies.

1. Introduction

The northern part of the Tokyo metropolitan area in Japan is famous for the frequent occurrence of extreme high surface air temperatures of over 38°C, causing an increase in heat strokes there (Fujibe 1998, 2004). In this study, we define the events with a daily maximum surface air temperature of over 38°C as the extreme high temperature events, after the definition by Fujibe (1998). In the present region, the frequency of extreme high temperature events and the daily maximum temperature has been increasing over several decades (Fujibe 1995, 1998, 2004). These increases are often discussed in relation to global warming and urban heat island.

A 74-year-old record was broken on 16 August 2007, when a surface air temperature of 40.9°C was observed at 1442 Japan standard time (JST) in Kumagaya, located 60 km northwest of central Tokyo, which is surrounded by the Chubu Mountains and the Pacific Ocean (Fig. 1).

Several previous studies have tried to elucidate the formation mechanisms of the 16 August 2007 event. Sakurai et al. (2009) reported diurnal variations and horizontal distributions of surface air temperature and wind field on 16 August using the data from surface-observation and wind profiler networks operated by the Japan Meteorological Agency (JMA). Shinohara et al. (2009) conducted a numerical simulation and forward trajectory analysis with no-diffusion-process using the JMA nonhydrostatic model. Sakurai et al. (2009) and Shinohara et al. (2009) attributed the extreme high temperature event to the following factors: 1) adiabatic compression due to a large-scale descending current under the anti-cyclone, 2) high surface air temperature in the early morning on 16 August, 3) no penetration of sea breeze.
from Tokyo Bay, and 4) a dynamic foehn with northerly airflow from the Chubu Mountains. They insisted that the dynamic foehn was the most important factor in causing the extreme high temperature event. Watarai et al. (2009a,b) also agreed with their idea that the dynamic foehn is the most important factor from their simulation results. However, these conclusions are based on just a hypothesis and do not show clear and quantitative evidence of the role of the dynamic foehn. Hence, there are still many unknown aspects regarding the formation mechanisms of the extreme high temperature event.

Takahashi (1996) summarized three types of high temperature phenomena associated with airflow over a mountain (Fig. 2). Type 1 is a thermodynamic (wet) foehn wind caused by diabatic heating by water vapor condensation (Hann 1866, 1867; Barry 1992; Whiteman 2000). Type 2 is a dynamic (dry) foehn wind caused by adiabatic heating (von Ficker 1910; Scorer and Klieforth 1959; Arakawa 1969; Brinkmann 1973, 1974; Ikawa and Nagasawa 1989; Seibert 1990). Finally, type 3 is a phenomenon caused by airflow over a mountain and diabatic heating from the ground surface, which in turn has been heated by solar radiation (Kondo 1983; Kondo and Kuwagata 1984). In this study, we describe the type 3 as foehnlike wind.

Surface air temperature in the coastal area of Toyama Bay often reaches high figures, associated with airflow over the Chubu Mountains when cyclones pass over the Sea of Japan. Ishizaki and Takayabu (2009) reported that the above types 1, 2, and 3 caused some of these high temperature events. Consequently, all the three types should be considered as the possible causes in the extreme high temperature event on 16 August 2007, over the Kanto Plain, located on the south side of the Chubu Mountains.

The purpose of this study is to clarify quantitatively the formation mechanisms of the extreme high temperature event on 16 August 2007, specifically considering the contributions of the foehn and the foehnlike wind. These contributions will be quantitatively analyzed using backward trajectory analysis, Lagrangian energy budget analysis, Euler forward tracer analysis, and a sensitivity experiment of soil moisture on surface air temperature. The results will not only help to elucidate the formation mechanism of the extreme high surface air temperature events but will also be applicable to high temperature events that may occur in the regions with complex terrain.

2. Observed features of the extreme high surface air temperature event on 16 August 2007

The actual conditions of the extreme high temperature event are at first investigated using the following observational data: weather charts, rawinsonde data, wind profiler network and data acquisition system (WINDAS), and data from the Automated Meteorological Data Acquisition System (AMeDAS) network operated by the JMA.

Figure 3 shows the surface weather chart at 0900 JST 16 August 2007, showing a North Pacific anticyclone covered central Japan. Figure 4 shows the observed surface air temperature and wind fields at 1440 JST on the same day. High surface air temperature regions of over 38°C extend in and around Kumagaya and Saitama cities, which are north of the convergence zone between north-northerly winds and southerly sea breezes.

Figure 5a shows the daily precipitation from 1 to 16 August 2007 in Kumagaya. From 1 to 16 August,
precipitation occurred only on 5 August. Sunshine duration of more than 8 h was observed from 9 to 16 August (Fig. 5b). On 16 August, the sunshine duration was 10.8 h. The daily maximum surface air temperature progressively increased from 9 to 11 August (Fig. 5c). The temperature decreased on 12 August, but increased again after that.

Figure 6 shows the vertical profiles of potential temperature on 0900 JST from 13 to 16 August 2007, in Tsukuba, located 70 km east of Kumagaya. The potential temperature between 400- and 1500-m level gradually increased by the day—particularly seen from 14 to 15 August. On 15 August, an isentropic layer was seen around 1000 m. Above 2200 m, potential temperature decreased from 14 to 16 August. The opposite variation occurred in the layer between 400 and 1500 m.

Figure 7a shows the time–height cross section of wind during 0500–1900 JST 16 August 2007 at Kumagaya observed by the WINDAS. A north-northwesterly wind blew from 2000 to 4000 m during this period. On the other hand, northwest-westerly or weak winds were seen near the surface, from 0500 JST to around 1330 JST. After that, the wind direction changed from west-northwest to north-northwest, and the north-northwesterly wind flow continued until 1900 JST. Similar diurnal variations were observed at the surface (16.8-m height) at Kumagaya as well (Fig. 7b). The surface wind speed increased from 0500 JST (sunrise) to 1500 JST and the daily maximum wind speed appeared at 1500 JST.

Figure 8 shows the diurnal variation of surface air temperature observed at Kumagaya on 16 August. The daily minimum and the daily maximum temperatures were observed at 0519 JST (28.8°C) and at 1442 JST (40.9°C), respectively.

3. Numerical simulation

a. Description of numerical simulation

The numerical model used in this study is the Advanced Research Weather Research and Forecasting (WRF) model, version 3.0.1.1 (Skamarock et al. 2008). The WRF model is very versatile and has been applied to numerical studies of local wind and thermal environments in urban areas (e.g., Kusaka and Hayami 2006; Liu et al. 2006; Lo et al. 2007; Tsunematsu et al. 2009a,b; Chen et al. 2010; Grossman-Clarke et al. 2010; Kusaka et al. 2010). The specifications of the WRF model numerical experiments used in this study are summarized in Table 1. Table 2 shows the land-use categories from the Geospatial Information Authority of Japan (GSI) used in this study. The physics of the WRF model used in the present numerical experiment are shown in Table 3. Horizontal grid spacing is set at 2 km in the inner region. The model top is set to be 50 hPa, and 42 vertical sigma levels are used. Time integration was continuously conducted from 1 to 16 August 2007. The first day was considered as the...
model spinup. The initial and boundary conditions were created from the JMA–Mesoscale Objective Analysis Dataset (MANAL) data (atmosphere), National Centers for Environmental Prediction–Final (NCEP-FNL) data (land surface), and the NCEP–Real-Time Global Sea Surface Temperature Analysis (RTG-SST) data (sea surface). The land-use and terrain-height dataset created by the GSI was used in the present study. Note that the numerical simulations in this study do not consider the difference of urban parameters per grid point. Thus, the simulations cannot sufficiently represent the area around observation site on the microscale.

b. Results of the numerical simulation

Figures 7b and 8 indicate that the WRF model reproduces diurnal variations of observed surface wind and air temperature on 16 August in Kumagaya. The simulated wind direction and speed are in good agreement with those observed. Diurnal variation of surface air temperature is also reproduced well. However, the model underestimates the daily maximum temperature of 40.9°C by about 2°C; the simulated daily maximum temperature is about 39°C.

Figure 9 shows the performance of the WRF model in reproducing vertical profiles of wind and potential temperature in Tsukuba at 0900 JST 16 August 2007. The simulated wind direction above 1500 m is in good agreement with observed direction, although the model failed to reproduce observations between 500 and 1500 m.

For the wind speed, the model reproduces the observations well, except at around 2000 and 3300 m. The simulated potential temperature is roughly in agreement with the observed temperature, although the model overestimates the observations by about 1 K above 1200 m and 2 K below 500 m.

Figure 10 shows the horizontal distributions of simulated surface air temperature and wind field at 1440 JST. The high surface air temperature region of over 38°C is extended in and around Kumagaya and Saitama, and the north-northwesterly wind covers the northern part of the Tokyo metropolitan area. The high surface air temperature region is in close agreement with the north-northwesterly


FIG. 4. (a) Observed surface air temperature and (b) wind fields at 1440 JST 16 Aug 2007.
wind region. These results are similar to the observed results (Fig. 10 versus Fig. 4).

Figure 11 shows a time–height cross section of horizontal wind, the vertical component, and the potential temperature on 16 August in Kumagaya from the WRF model. Diurnal variation of the wind above 1200 m with a northwesterly wind component is roughly in agreement with the observations. Within the layer of 500–1000 m, the west wind changes to a northwesterly wind with time. Wind speed increases with time. The diurnal variation of the wind in this layer is roughly in agreement with the observed variation, except for the simulated westerly wind in the early morning.

The simulated potential temperature increases with time below 1700-m height associated with the northwest–westerly wind. An increase in the potential temperature is also seen from 1030 to 1230 JST below about 1000 m, and from 1330 JST to around 1500 JST at the surface. The increase in potential temperature results in the mixed layer developing to about 1400 m at around 1500 JST. Similar tendencies in the vertical profile of potential temperature are simulated in Saitama (figure omitted).

**c. Heat budget analysis in the column atmosphere**

To quantitatively evaluate the mechanism underlying the temperature change in the mixed layer, we conducted a heat budget analysis on the column atmosphere. The top of the column atmosphere is set to about 1400-m height based on the results of Fig. 11. The cumulative heat in the column atmosphere \((Q_C)\), the time-integrated sensible heat flux from the ground surface \((Q_H)\), and the cumulative heat flux convergence \((Q_{\text{CONV}})\) are defined as shown in the following equations:

\[
Q_C = \int Q_z dz \\
Q_H = \int Q_z dt \\
Q_{\text{CONV}} = \int Q_z dt
\]
column atmosphere from $Z_G$ to $Z_R$. The $H$ is the sensible heat flux from the ground surface, and $Q_H$ indicates the time-integrated $H$ from $t_0$ to $t_1$. The $Q_{\text{CONV}}$ represents the advection and diffusion of heat from the lateral and top of the column atmosphere and diabatic heating by water vapor condensation and radiation. However, condensation does not occur in the present simulation, and the temperature change by radiation is small. Thus, $Q_{\text{CONV}}$ can be assumed to be the cumulative heat flux convergence in the present study.

Figure 12 shows the results of the analysis: $Q_{\text{CONV}}$ is larger than $Q_H$ from 0500 to 1400 JST; $Q_{\text{CONV}}$ contributes at least 50% of the increase in $Q_C$ until 1500 JST. The results indicate that the temperature increase in the mixed layer is caused not only by $Q_H$ but also by $Q_{\text{CONV}}$, where $Q_{\text{CONV}}$ is seen as a very important factor of the temperature increase. The present result is different from that of Kusaka et al. (2000), who conducted

\[
Q_C = c_p \rho \int_{Z_G}^{Z_R} (\theta_1 - \theta_0) \, dz, \tag{1}
\]
\[
Q_H = \int_{t_0}^{t_1} H \, dt, \quad \text{and} \tag{2}
\]
\[
Q_{\text{CONV}} = Q_C - Q_H. \tag{3}
\]
a similar analysis in a flat area in the vicinity of Saitama, and obtained a negative $Q_{\text{CONV}}$ value. In contrast, the present results are similar to those of Ohashi and Kida (2002), who conducted a similar analysis in the Kyoto basin in western Japan. These results suggest that there is a relationship between $Q_{\text{CONV}}$ and mountainous areas. Sensible heat transfer from the top of the present column atmosphere by turbulent diffusion is small (figures omitted). Heat transfer from the top of the column atmosphere by advection is consistently seen and should be a factor to consider (Fig. 11). As described above, the northwest-westerly wind blows consistently from the surface to 2000-m height during the daytime. Based on these data, sensible heat advection with the northwest-westerly wind below 2000 m is significant in increasing $Q_{\text{CONV}}$.

4. Considerations of dynamic foehn and foehnlike wind

a. Backward trajectory analysis and Lagrangian energy budget analysis

A backward trajectory analysis is employed to quantitatively investigate the contributions of the foehn and

### Table 3. Physics of the WRF model used in the present numerical experiment.

<table>
<thead>
<tr>
<th>Physics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
<td>WRF single-moment 3-class (WSM3)</td>
</tr>
<tr>
<td>Radiation (longwave)</td>
<td>Rapid Radiative Transfer Model (RRTM)</td>
</tr>
<tr>
<td>Radiation (shortwave)</td>
<td>Dudhia</td>
</tr>
<tr>
<td>Boundary layer</td>
<td>Mellor–Yamada–Janjic (MYJ)</td>
</tr>
<tr>
<td>Surface layer</td>
<td>MYJ (based on similarity theory; Monin and Obukhow 1954)</td>
</tr>
<tr>
<td>Land surface (no urban area)</td>
<td>Noah land surface model (LSM)</td>
</tr>
<tr>
<td>Land surface (urban area)</td>
<td>Single-layer urban canopy model (UCM)</td>
</tr>
</tbody>
</table>

![0900 JST 16 August 2007 Tsukuba](https://example.com/image.png)

**Fig. 9.** Vertical profiles of (a) wind direction, wind speed, and (b) potential temperature at 0900 JST 16 Aug 2007 in Tsukuba. The circles represent the observed result and the solid line represents the simulated result.
foehnlike wind associated with the northwest-westerly wind on the extreme high temperature event. The trajectories of 100 air parcels were released from the lowest level of the model grid in a square area of 400 km² around Kumagaya at 1500 JST 16 August 2007. Air parcels on that day are tracked back every 10 min from 1500 to 0500 JST using wind components of \( u \), \( v \), and \( w \).

Figure 13a shows the trajectories of 100 air parcels. The results indicate that the air parcels take mainly two courses. The first main course consists of about 30% of all the trajectories and shows these air parcels are transported from the Sea of Japan to the vicinity of Kumagaya (Fig. 13b). Here, we define these 30 trajectories as course high lines. The second main course consists of about 57% of all the trajectories and shows these air parcels are transported from Toyama Bay to the vicinity of Kumagaya (Fig. 13c). We defined these 57 trajectories as course low lines.

Lagrangian energy budget analysis is performed by calculating dry static energy \( s \) (J kg\(^{-1}\)) to determine which kind of winds blow along each course:

\[
s = gZ + c_p T, \tag{4}
\]

where \( gZ \) is the geopotential energy and \( c_p T \) is the sensible heat energy. Generally, diabatic heating is produced by the following factors: water vapor condensation, radiation, subgrid-scale turbulent diffusion, and sensible heat flux from the ground surface. In the present analysis, water vapor condensation does not occur along either course. Thus, condensation does not contribute to the change in dry static energy \( s \). Direct heating by radiation is small. Therefore, in the present analysis diabatic heating is thought to be caused by subgrid-scale turbulent diffusion and sensible heat flux from the ground surface.

Figure 14a shows the Lagrangian mean energy budget along the trajectories for course high lines. Geopotential energy \( gZ \) shows that air parcels constantly pass through at about 2300-m height in the free atmosphere from 0500 to 1110 JST. The parcels then eventually descend from the free atmosphere to the mixed layer. The decrease in \( gZ \) causes \( c_p T \) to increase. During this time, air parcels approach near the ground surface. Dry static energy \( s \) is almost constant from 0500 to 1500 JST. However, it slightly decreases from 1110 to 1230 JST and increases from 1230 to 1340 JST. This increase could be supported by subgrid-scale turbulent diffusion and sensible heat flux from the ground surface (Fig. 14b). From these findings, the airflow along course high lines is under an adiabatic process and
corresponds to a dynamic foehn wind. It should be noted that the mean temperature in the air parcels at 1500 JST is about 36.1°C (Table 4), which is lower than the simulated surface air temperature at 1500 JST in Kumagaya.

Figure 15a shows the Lagrangian mean energy budget along the trajectories for course low lines. Geopotential energy $gZ$ shows that parcels pass through at the 900–1000-m height in the free atmosphere from 0500 to 0830 JST. After that, the air parcels penetrate from the free atmosphere into the mixed layer. At around 1100 JST, the parcels arrive near the mountain surface and eventually reach the vicinity of Kumagaya, with descending. The decrease in $gZ$ causes $c_pT$ to increase. Dry static energy $s$ is not constant from 0500 to 1500 JST. It is almost constant before 1000 JST and then begins to increase. As a result, dry static energy $s$ increases to about +5000 J kg$^{-1}$, which indicates that diabatic heating contributes to the increase in $s$. From these findings, we can conclude that the north-northwesterly airflow on 16 August corresponds to a combination of types 2 and 3 (hereinafter called type 4) shown in Fig. 16. It should be noted that the air parcels mean temperature at 1500 JST is about 38.1°C (Table 4). This temperature is higher than those of course high lines and close to the simulated surface air temperature in Kumagaya.

### b. Euler forward tracer analysis and measurement of the sensitivity of surface air temperature to soil moisture

Since the backward trajectory analysis does not calculate subgrid-scale turbulence diffusion every time step in the simulation, Euler forward tracer concentration analysis is performed to investigate the contribution of subgrid-scale turbulence diffusion for the course low lines. The release point of the tracers is a square area of
3600 km² around Toyama Bay from 1 to 8 of vertical model grid number (roughly equal below 1200-m height), which corresponds to the starting point of airflow along course low lines shown in Fig. 13b. The solid lines indicate $gZ$, dotted lines show $c_pT$, the white circles show $s$, and broken lines with dots show $z_i$ (all lines are based on anomalies at 1500 JST). Shades represent terrain height along the trajectories. (b) The time-integrated sensible heat flux from the ground surface $H$ (MJ m⁻²) along the trajectories.

Figure 17a shows the horizontal distribution of the simulated tracer concentration (m³ m⁻³) in the lowest level of the model grid at 1500 JST 16 August. The tracers are released at 0500 JST 16 August. The advection and diffusion of tracers are calculated every time step in the simulation.

Figure 17a shows the horizontal distribution of the simulated tracer concentration (m³ m⁻³) in the lowest level of the model grid at 1500 JST 16 August. The tracers cover not only the Chubu Mountains but also cover the inland part of the Tokyo metropolitan area, including Kumagaya. Figure 17b shows the vertical cross section of the tracers. The tracers reach 2600 m in height in some places. High-concentration areas of above 0.4 are seen only near the ground surface.

Second, the sensitivity of surface air temperature at Kumagaya to soil moisture in Chubu Mountain area is numerically examined to verify the effects of subgrid-scale turbulent diffusion and sensible heat flux from the mountain surface on the heating of airflow along the course low lines. The initial time of the sensitively experiments; case SMOIS_DRY and case SMOIS_WET are 000 JST 15 August. The soil moisture content at the initial time of the cases SMOIS_DRY and SMOIS_WET are defined as the following equations:

$$\Theta_D = \Theta - 0.15 \quad \text{and} \quad \Theta_W = \Theta + 0.15. \quad (6)$$

Here, $\Theta_D$ and $\Theta_W$ are soil moisture content at the initial time for cases SMOIS_DRY and SMOIS_WET, respectively. The $\Theta$ is soil moisture content at 000 JST 15 August for the control simulation (case CTRL). Note that the above modification is applied to all grid points higher than 200 m above sea level, which

<table>
<thead>
<tr>
<th></th>
<th>$s$ (J kg⁻¹)</th>
<th>$gZ$ (J kg⁻¹)</th>
<th>$c_pT$ (J kg⁻¹)</th>
<th>$H$ (MJ m⁻²)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High lines</td>
<td>310 455</td>
<td>20</td>
<td>310 435</td>
<td>2.5</td>
<td>36.1</td>
</tr>
<tr>
<td>Low lines</td>
<td>312 452</td>
<td>20</td>
<td>312 432</td>
<td>3.4</td>
<td>38.1</td>
</tr>
</tbody>
</table>

FIG. 14. (a) The mean energy variation (J kg⁻¹). The y axis indicates energy (J kg⁻¹), and the secondary y axis indicates the terrain height and mixed-layer height ($z_i$) along the trajectories for course high lines shown in Fig. 13b. The solid lines indicate $gZ$, dotted lines show $c_pT$, the white circles show $s$, and broken lines with dots show $z_i$ (all lines are based on anomalies at 1500 JST). Shades represent terrain height along the trajectories. (b) The time-integrated sensible heat flux from the ground surface $H$ (MJ m⁻²) along the trajectories.

FIG. 15. As in Fig. 14, but for course low lines shown in Fig. 13c.

FIG. 16. Schematic representation of type-4 foehn-like wind shown in the present study.
Fig. 17. (a) Horizontal distribution of simulated tracer concentration (m$^3$ m$^{-3}$) in the lowest level of the model grid at 1500 JST 16 Aug 2007. The red dashed line indicates the released area of the tracers. (b) Vertical cross section of the trace concentration at 1500 JST 16 Aug along line A–B shown in Fig. 1b.

roughly corresponds to the Chubu mountainous area (Fig. 1b).

Figure 18a shows the diurnal variation of surface air temperature for the cases SMOIS_DRY and SMOIS_WET in Kumagaya. A temperature difference of over +0.5°C appears after around 1330 JST. The horizontal distribution of the temperature difference between cases SMOIS_DRY and SMOIS_WET at 1500 JST is shown Fig. 18b. Areas with temperature differences of over +0.5°C are seen not only in the Chubu Mountains but also in the inland part of the Tokyo metropolitan area. This indicates that the temperature difference over the inland area is also caused by the difference in sensible heat flux from the ground surface in the Chubu Mountains. The horizontal distribution of the temperature difference inland is in good agreement with that of the tracer concentration (Fig. 18b versus Fig. 17a). This result suggests that the air masses are heated by subgrid-scale turbulent diffusion and sensible heat flux from the ground surface during the time when the air masses move over the Chubu Mountains. Those results support the theory of the type 4 foehnlike wind (Fig. 16).

5. Discussion

As described in section 2, the sunshine duration on 16 August 2007 in Kumagaya was 10.8 h. This is the 72nd-longest sunshine duration in July and August from 1998 to 2008 (Fig. 19a; Table 5). According to the numerical simulation in section 3, surface heat flux associated with sufficient solar radiation contributes to only 49% of the temperature rise in the mixed layer from 0500 to 1500 JST on the 16th. These results imply that the sunshine duration on 16 August 2007 is a necessary but not a sufficient condition to cause the extreme high surface air temperature event of 40.9°C.

Figure 19b shows a scatter diagram of the temperature around 1500-m height at 0900 JST in Tsukuba versus the
daily maximum surface air temperature in Kumagaya in July and August from 1998 to 2008. As the figure shows, the temperature around 1500-m height at 0900 JST on 16 August 2007 was 21.6°C, which is the 30th-highest temperature at that period (Table 5). This temperature is high; however, it is not a sufficient condition to cause the extreme high temperature event, although such a high temperature in the upper level would be a potential factor in the extreme event.

Figure 19c shows a scatter diagram of the number of previous consecutive clear-sky days versus the daily maximum surface air temperature in Kumagaya in July and August from 1998 to 2008. Here, a clear-sky day is defined as a day with sunshine duration of more than 6 h, and without precipitation on the previous day. There were seven consecutive clear-sky days preceding the 16th, which is the 12th longest in the study period (Table 5). There is a possibility that the ground surface in Kumagaya on 16 August 2007 was dry because of these persistent clear-sky days. Fujibe (1996) shows that the dryness of the ground surface was significant in causing the extreme events during the summer of 1994 in Japan. Thus, the persistent clear-sky days are thought to have contributed to the extreme high temperature event. This idea is qualitatively consistent with the results from the sensitivity experiments of cases SMOIS_DRY and SMOIS_WET, described in section 4.

The numerical simulation in section 4 shows that the dynamic foehn wind along the course high lines, and the foehnlike wind along the course low lines blew during...
the daytime on 16 August 2007. The backward trajectories of the air parcels along the course high lines occupy about 30% of the entire air parcel trajectories reached at Kumagaya at 1500 JST. On the other hand, the backward trajectories of the air parcels along the course low lines occupy about 57% of the total, almost double that along the course high lines. In other words, the air parcels reached at Kumagaya flew mainly along the course low lines. In addition, the mean temperature of the air parcels along the course low lines is about 38.1°C at 1500 JST, which is higher than that along the course high lines. One reason for this temperature difference is that the air parcels along the course low lines move in the mixed layer and have been heated by subgrid-scale turbulent diffusion and sensible heat flux from the ground surface for 5 h, whereas the air parcels move in the mixed layer for only 2.5 h in the course high lines. In other words, a fetch in the mixed layer of course low lines is longer than those of course high lines. From these findings, the foehnlike wind along the course low lines contributes substantially to the extreme high temperature event compared to the dynamic foehn wind along the course high lines.

6. Conclusions

A record-breaking high surface air temperature of 40.9°C was observed at 1442 JST 16 August 2007 in Kumagaya, located 60 km northwest of central Tokyo. Around this time, a high surface air temperature region of over 38°C extended over cities of Kumagaya and Saitama; Kumagaya is in the north of the convergence zone between north-northwesterly wind zone and southerly sea-breeze zone. In this study, we quantitatively investigated the formation mechanisms of the extreme high temperature event, considering the contribution of foehn and foehnlike winds associated with the north-northwesterly wind. Our findings are summarized as follows:

(i) A sunshine duration of 10.8 h was observed on 16 August in Kumagaya, which is the 72nd-longest duration for July and August from 1998 to 2008. According to the numerical simulation, surface sensible heat flux associated with sufficient solar radiation contributes to only 49% of the temperature rise in the mixed layer from 0500 to 1500 JST. Thus, this sunshine duration is a necessary but not a sufficient condition to cause the extreme high temperature event of 40.9°C.

(ii) A high temperature of 21.6°C around 1500-m height was observed at 0900 JST 16 August at the Tsukuba station, which is the 30th-highest temperature for that time in July and August from 1998 to 2008. This high temperature is not a sufficient condition to cause the extreme high temperature event, although such a high temperature in the upper level would be a potential factor in the extreme high temperature event.

(iii) A dynamic foehn wind was found in the numerical simulation. Backward trajectories of the air parcels along the course high lines account for about 30% of all the air parcel trajectories reached at Kumagaya at 1500 JST. At that time, the mean temperature of the air parcel was about 36.1°C. Consequently, the dynamic foehn wind is not a dominant factor in the extreme high temperature event. This idea differs from the conclusions of the previous studies.

(iv) The persistent sunshine and lack of precipitation during the seven consecutive days preceding 16 August in Kumagaya must be a significant factor. This was the 12th-longest duration of consecutive clear-sky days for July and August from 1998 to 2008. The persistent clear-sky days can dry out the ground surface, and this dryness can contribute to the extreme event. This is qualitatively supported by the sensitivity experiments of soil moisture on surface air temperature.

(v) A foehnlike wind with diabatic heating from the ground surface is an important factor. The trajectories of the air parcels along the course low lines occupy about 57% of all trajectories. This is almost double that of those backward trajectories of the dynamic foehn wind taking the course high lines. The mean temperature of the air parcels along the course low lines is about 38.1°C at 1500 JST, which is close to the simulated maximum surface air temperature of 39.0°C in Kumagaya. It can be concluded that the foehnlike wind along the course low lines contributed substantially to the extreme high temperature event compared to the dynamic foehn wind along the course high lines.

(vi) North-northwesterly winds blowing over the Chubu Mountains prevent the sea breeze from penetrating the cooler air mass, thus maintaining the high surface air temperature region in the northern part of the Tokyo metropolitan area.
We conclude that the combination of these factors caused the extreme high temperature event. Particularly, factors iv–vi played significant roles in the event. Consideration of factors iv and v, which the previous studies did not discuss, will help elucidate the formation mechanism of not only this extreme event but also other high temperature events in many regions with complex terrain.

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