Contributions of Foehn and Urban Heat Island to the Extreme High-Temperature Event in Niigata City during the Night of 23–24 August 2018

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Abstract
We quantitatively evaluated the contributions of foehn winds and the urban heat island (UHI) effect to an extreme high-temperature nocturnal event at Niigata city on 23–24 August 2018. During this event, southeasterly winds blew continually across the Niigata Plain and temperatures on the plain were higher than those in the windward region of the mountain range. Back-trajectory analysis and numerical simulations with and without topography showed that the southeasterly winds were foehn winds that caused precipitation and latent heating on the windward slope of the mountain range. The foehn winds and UHI contributed about 2.8°C and 1.9°C, respectively, to the extreme high-temperature of 31.0°C at 2100 JST in Niigata city. The combined impact of the foehn winds and UHI at Niigata was about 4.0°C during the night. The contribution of the foehn winds was greater at around midnight, whereas that of the UHI was greater during the early night.

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1. Introduction
Nocturnal extreme high-temperature (EHT) events pose widespread public-health risks for senior citizens, such as heatstroke and sleep disturbance (e.g., Semenza et al. 1996) and can severely damage paddy rice growth (e.g., Wassmann et al. 2009). Public concern about the effects of both nocturnal and daytime EHT events has increased greatly in recent years. During a nocturnal EHT event on 23–24 August 2018 in the Niigata Plain, northeastern Japan, temperatures exceeded 40.0°C in several areas of Niigata Prefecture and temperatures above 30.0°C persisted until 0300 JST (all times hereafter are JST) in Niigata city. Background factors that may have contributed to this nocturnal EHT event include synoptic-scale summer pressure patterns and the presence of typhoon.

At mesoscale, a foehn-type downslope wind may have contributed to this event. Foehn winds can increase temperature by various mechanisms (Takane et al. 2015; Elvidge and Renfrew 2016; Miltenberger et al. 2016; Rotunno and Bryan 2018). In Japan, foehn winds caused the past two record-breaking EHT events on the Niigata Plain, on 16 August 2007 and 23 July 2018 (Takane and Kusaka 2011; Nishi and Kusaka 2019), and other EHT events have also been attributed to foehn winds (e.g., Takane et al. 2015). However, whether a foehn wind or warm advection from a tropical cyclone was the main cause of the nocturnal EHT event recorded at the Niigata Observatory on 23–24 August 2018 remains unclear.

Another possible cause of the 2018 nocturnal EHT event is the urban heat island (UHI) effect. Past studies have confirmed that even medium-sized cities can produce UHI effects on clear nights (e.g., Figuerola and Mazzeo 1998; Torres-Valcárcel et al. 2015). However, the degree to which the UHI contributed to the nocturnal EHT event at Niigata city has not been quantitatively evaluated.

The purpose of this study was to quantify and compare the effects of foehn winds and the UHI on the nocturnal EHT event of 23–24 August 2018. Most previous studies of foehn winds in Japan have focused on daytime high-temperature events in urban areas rather than on strong wind events in rural areas (e.g., Takane and Kusaka 2011; Takane et al. 2015; Nishi and Kusaka 2019). No previous studies have evaluated and compared the contributions of these two mesoscale phenomena to nocturnal temperature increases. Therefore, the results of this study will contribute not only to understanding the essential mechanism of the record-breaking EHT event in Niigata city on the night of 23–24 August 2018 but also to better understand the foehn winds on urban climate in Japan.

2. Data and numerical modeling
To characterize the nocturnal EHT event on the Niigata Plain, we used surface observational data from the automated meteorological data acquisition system (AMeDAS) and sounding data collected by the Japan Meteorological Agency at Wajima and Tateno observation stations (see Supplements, Fig. S1).

To investigate numerically the event, we ran high-resolution simulations using the Weather Research and Forecasting (WRF) model version 3.9.1 (Skamarock et al. 2008) with a single-layer urban canopy model. The WRF model configuration is explained in Supplement 1 and the urban canopy model configuration in Supplement 2.

To quantitatively estimate the effects of both foehn winds and the UHI on the nocturnal EHT event, we ran a control simulation and three simulations for sensitivity analyses. For the control simulation, we conducted a hindcast of the EHT event with real land-use and topographic data (CTRL simulation). In the first sensitivity analysis, we replaced the urban areas of Niigata city with paddies (NoURB simulation) (see Supplements, Fig. S2).

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3. Results and discussion
3.1 Observation data
At 0600 on 23 August 2018, two tropical cyclones in the Japan region (Fig. 1a) began to generate southeasterly winds that blew from the central Japanese mountains across the Niigata Plain (Fig. 1c). The southeasterly winds gradually strengthened as one of the typhoons approached the Japanese islands. The strongest southeasterly wind (11.0 m s⁻¹) was recorded at 0300 on 24 August, when the typhoon reached the Sea of Japan.
At Niigata observatory, the temperature at sunrise (at 0504) was 27.2°C (Fig. 1b). It began to rise at 0600, reaching 39.9°C at 1410; this was the highest temperature ever recorded at Niigata (Japan Meteorological Agency 2019a). Relative humidity at 1410 was about 30% despite it being the moist summer season in Japan (Figure is omitted). The temperature decreased after sunset (at 1740), but it remained above 30.0°C until 0300. These nighttime temperatures are comparable to the average of annual maximum temperature during 1981–2010 at Niigata (30.6°C). At around 0400, when precipitation commenced at Niigata observatory, the temperature decreased suddenly (Fig. 1b).

At 2100 on 23 August, southeasterly winds were blowing at 5–10 m s⁻¹ across the northern part of the Niigata Plain (around 38°N, 139°E, Fig. 2a) and the surface air temperature was above 31.0°C (Fig. 2b). On the windward side of the mountains (e.g., around the northern Kanto plain shown in Fig. 2b of Supplement), winds were weaker (< 1.0 m s⁻¹) and temperatures were below 28.0°C. Thus, at 2100 on 23 August the temperature at Niigata was about 3°C higher than it was on the windward side of the mountains. While the southeasterly winds were blowing across the Niigata Plain, precipitation was occurring on the windward slope of the mountains (Figure is omitted). These conditions of wind, temperature, and precipitation are characteristic of foehn events.

Here, we focus on nocturnal temperatures in the urban area of Niigata city, where the nighttime temperature (over 30.0°C) was higher than in the surrounding rural area (27.0–30.0°C). This temperature distribution suggests that the UHI effect was also active during the nocturnal EHT event of 23–24 August 2018.

### 3.2 Results of the control simulation

Comparison of CTRL simulation results with observation data showed that the WRF reproduced well the temporal changes of temperature and wind at Niigata city (Figs. 1b and 1c), although the simulation slightly underestimated daytime temperatures. The simulation could not capture the observed sudden temperature drop around 0400 on 23 August because the WRF model failed to reproduce precipitation in Niigata around 0400 on 23 August. The WRF model also reproduced well the spatial distributions of surface wind and temperature on the Niigata Plain (Fig. 1c).

Simulated potential temperature along cross-section A–B at 2100 on 23 August (Fig. 3) shows that potential temperature contours between 304 and 310 K rapidly descended the leeward slope of the mountain range (from 139.3°N to 139.2°N, Fig. 3), as did wind speeds exceeding 15 m s⁻¹. These phenomena together indicate the development of downslope winds. The simulated distribution of 12-h accumulated precipitation up to 2100 on 23 August (Fig. 4) suggests that the downslope winds are the foehn winds.

### 3.3 Back-trajectory analysis

Back-trajectory analysis can be used to determine whether or not downslope winds are foehn winds (e.g., Takane and Kusaka 2011; Takane et al. 2015; Miltenberger et al. 2016; Elvidge and Renfrew 2016; Ishizaki and Takayabu 2009). We conducted back-trajectory analysis around the Niigata city area by releasing 121 air parcels at 2100 on 23 August 2018 from the surface level of the model grid within an area of 484 km² around Niigata AMeDAS observatory. Those air parcels were then tracked backward every 3 min from the time of their release to 0900 on 23 August by using wind components of the CTRL simulation.

The back-trajectory analysis results indicated that the air parcels at the surface near Niigata city at 2100 on 23 August 2018 crossed around the Nasu mountain (see Supplements, Fig. S1b) from the northern Kanto Plain (Fig. 5a). Most of the air parcels (92%) were at heights of about 1.0 km above sea level (ASL) or lower when they were over the northern Kanto Plain (Fig. 5b). The average height of the air parcels passing over the most windward mountain crest was about 1.2 km ASL. These results suggest that the southeasterly winds observed at Niigata city during the nocturnal EHT event were “thermodynamic foehn (wet foehn)” winds, which characteristically ascend the windward slopes of mountain ranges accompanied by precipitation and latent heat release and then descend the leeward slopes accompanied by adiabatic heating (e.g., Seibert 1990; Miltenberger et al. 2016; Elvidge and Renfrew 2016).

We estimate the contribution of foehn winds to temperature change along each trajectory (ΔT_Foehn), referring Elvidge and Renfrew (2016) as follows:

\[
\Delta T_{Foehn} = \Delta T_{total} - \Delta T_{UHI} 
\]

\[
\Delta T_{total} = \Delta T_{ad} + \Delta T_{pr} + \Delta T_{other} 
\]

\[
\Delta T_{ad} = T_f(Z_a - Z) 
\]

\[
\Delta T_{pr} = (\theta_a - \theta_e) - (\theta_f - \theta_e) 
\]

\[
\Delta T_{other} = (\theta_f - \theta_e) 
\]

Here, \( T, Z, \theta, \) and \( \theta_e \) indicate the air temperature, altitude, potential temperature, and equivalent potential temperature of the air parcels, respectively. The variables with subscript “a” mean the values at the released position of the air parcels of backward trajectory around the Niigata city area (at 2100 on 23 August). On the other hand, the variables with subscript “f” mean the values at the position of each air parcel when each air parcel was located at the altitude of 36.0°N (around 1400 on 23 August). \( T_f \) is dry lapse rate (assumed to be \(-1.0 \times 10^{-2} \text{°C m}^{-1}\)).
ΔTUHI is the effect of UHI which is estimated in the next section. As a result, the averaged value of ΔT_{total} is 4.8°C. The averaged value of ΔTFoehn can be calculated if ΔTUHI is estimated.

3.4 Sensitivity analyses

Comparison of the CTRL (Fig. 2c) and NoURB (Fig. 6a) simulation results for the Niigata city area at 2100 on 23 August 2018 showed that temperatures estimated by the CTRL simulation were 1.0−2.0°C higher than those estimated by the NoURB simulation (Fig. 6b). That is, the simulated UHI effect in Niigata city was 1.0−2.0°C, which is consistent with the observed temperature difference between the central Niigata city area (the Niigata obser-
We conducted numerical simulations to quantitatively examine the contributions of foehn winds and urban heat island effects to the extreme high-temperature event at Niigata during the night of 23 August and early morning of 24 August 2018. Our main results are as follows:

- On 23 August 2018, two tropical cyclones were approaching the Japanese islands. Both observation data and numerical simulations indicated that nocturnal temperatures remained above...
30.0°C until 0300 on 24 August. Southwesterly winds blew continuously during this nocturnal EHT event.

- Observation data showed that nocturnal temperatures were higher on the Niigata Plain than on the windward side of the mountain range. Back-trajectory analysis and numerical simulations with and without topography (CTRL and NoTOPO) showed the southeasterly winds to be foehn winds that blew over the Niigata Plain throughout the nocturnal EHT event. While the foehn winds blew, there was rain on the windward side of the mountain range. These results suggest that the foehn phenomenon on the day of the nocturnal EHT event was the result of latent heating and precipitation. The contribution of the foehn winds to the EHT in Niigata city was about 2.8°C at 2100.

- Observation data indicated that a UHI effect occurred in Niigata city at 2100 JST. Numerical simulations, both CTRL and NoURB, showed that the UHI increased surface air temperatures in Niigata city by about 1.9°C at 2100 JST.

- The combined effect of the foehn winds and the UHI at Niigata was about 4.0°C during the night of 23–24 August 2018. The contribution of the foehn winds was greater around midnight, whereas the contribution of the UHI was greater early in the night.

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Supplements

Supplement 2 describes the configuration of the urban canopy model.

References


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SOLA: https://www.jstage.jst.go.jp/browse/sola/