Numerical Simulations and Trajectory Analyses of Local “Karakkaze” Wind: a Case that could have Contributed to an Aircraft Accident at Narita Airport on 23 March 2009

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Abstract

We conducted numerical simulations on a case of local “Karakkaze” wind on 23 March 2009. On this day, an aircraft crashed on landing at Narita Airport in the eastern Kanto Plain in Japan in the early morning when surface winds were significantly strengthened. Numerical simulations were used to elucidate the characteristics and mechanism of the strong wind over the Kanto Plain. This strong
wind was identified as the Karakkaze wind, which occurs in the lee of the convex
mountain range northwest of the Kanto Plain. The vertical shear associated with
the Karakkaze wind could cause strong turbulence near the surface. The results
of a sensitivity experiment suggest that the presence of the mountain convexity is
essential for the development of the Karakkaze wind. Backward trajectory analy-
ses reveal the area where the Karakkaze wind originated upstream of the mountain
range. The horizontal wind speed in this area is even weaker than in the northern
area. However, unlike in the northern area, the air with large momentum descends
from altitudes much higher than the height of the dividing streamline owing to the
mountain convexity, thereby driving strong surface winds in the leeward area.

1 Introduction

A cold air outbreak from the Eurasian continent occurs over Japan when a synoptic
low pressure is present to the east, which is a typical situation during the winter
monsoon around Japan (Fig. 1a). While the monsoon often causes heavy snow
in the area facing the Sea of Japan upstream of the central mountain range, little
precipitation occurs over the Kanto Plain, which is located downstream of the range.
Instead, strong surface winds, “Karakkaze” winds, prevail in the middle of the Kanto
The mountain range northwest of the Kanto Plain is curved, presenting a convex face to the northwest (Fig. 2). This feature is herein referred to as the “convex mountain range” following Nishi and Kusaka (2019c,d). This gives rise to a valley-type feature, herein termed the “semi-basin”, in the northwest of the Kanto Plain. The Karakkaze winds become significant starting from the semi-basin area just downstream of the convex mountain range. Recent studies have noted the importance of the mountain convexity in the formation of the Karakkaze wind in both realistic and idealized cases (Nishi and Kusaka 2019b,c,d).

Although Nishi and Kusaka (2019d) has investigated one of realistic cases of Karakkaze wind, previous studies (Kusaka and Fudeyasu 2017; Nishi and Kusaka 2019a) have also suggested a variety of types in the Karakkaze wind. Here, we address a case of the Karakkaze wind which peaked in the early morning and was stronger than the case of Nishi and Kusaka (2019d). This case could have impacts on aviation: an aircraft accident at Narita Airport occurred at 0649 Japan Standard Time (JST: +0900 UTC) on 23 March 2009. A cargo plane failed to land and burst into flames, causing the fatalities of two pilots. The official report of the accident (JTSB 2013) describes that the presence of a strong low-level wind shear could be one of the factors of the accident, although it does not mention the local Karakkaze
After the midnight on 23 March, the surface temperature over the Kanto Plain dropped significantly following the passage of a cold front (Figs. 1b, 1d, and S1a). At observatories of the Japan Meteorological Agency (JMA) on the Kanto Plain (AMeDAS at Haneda, Narita, and Kumagaya), wind directions changed to northwest, and the wind speed significantly increased in the early morning (Figs. 1c, 1e and S1b). Later than the other observatories, the wind speed at Narita increased remarkably after 0600 JST (Fig. 1c). The strong northwesterlies appeared to contribute to the aircraft accident that occurred at 0649 JST.

In the present study, we conduct numerical simulations on the case on 23 March 2009 when the strong Karakkaze wind occurred. Sensitivity experiments examine the mechanism of the Karakkaze wind and effect of small scale topography. Trajectory analyses, which have not been conducted for the Karakkaze wind, reveal upstream conditions and the pathway and strengthen confidence about the mechanism of the Karakkaze wind.

The rest of this paper is organized as follows. Section 2 describes the numerical simulations. Section 3 overviews results of the simulations. Section 4 elucidates the mechanism and factors affecting the strength. Section 5 gives conclusions.
2 Numerical simulations

We use a regional weather prediction model, JMA’s Non-Hydrostatic Model (NHM; Saito et al., 2007) in the present study. Table S1 summarizes the experimental design. The topography in each experiment is provided from GTOPO30 of the U.S. Geological Survey with a horizontal resolution of 30 arc seconds.

The experiment with the coarsest horizontal resolution $dx$ of 5 km (NHM5km) covers part of the Japanese islands and the Sea of Japan and the Pacific Ocean (Fig. 2). There are $201 \times 201$ horizontal grid points and 80 vertical levels. NHM5km employs the JMA’s 3-hourly meso-scale analysis for initial and boundary conditions and is run from 1500 JST on 22 March to 1800 JST on 23 March 2009. Note that horizontal resolution of the JMA’s meso-scale analysis for the date is 10 km.

Using the hourly outputs of NHM5km for initial and boundary conditions, a nested simulation with finer $dx = 2$ km (NHM2km) is started from 1800 JST. NHM2km has $376 \times 376$ horizontal grid points and 80 vertical levels. Sensitivity experiments in Section 4.2 are performed with the configuration of NHM2km.

The simulation with the finest horizontal resolution ($dx = 1$ km; NHM1km) is nested using hourly outputs from NHM2km for initial and boundary conditions. NHM1km has $501 \times 501$ horizontal grid points and 80 vertical levels and is started from 2100 JST. This is the smallest numerical domain. Nevertheless, it covers the
entire Kanto Plain, the convex mountain range, and semi-basin. The results of NHM1km are used for detail analyses.

3 Results

Northwesterlies prevailed in the lower atmosphere over the entire Kanto Plain when the aircraft accident occurred (Fig. 3a). An area with particularly strong northwesterlies (> 20 m s\(^{-1}\); hereafter referred to as the ST area) formed in the lee of the convex mountain range. The width of the ST area is ~ 50 km, and it lies below a height of ~ 1.5 km in the vertical section across Narita (Fig. 3b).

At Kumagaya, which is located close to the convex mountain range in the ST area, the results of NHM1km reproduce surface temperature and wind direction and speed reasonably well (Figs. S1a and S1b). The wind is also well reproduced in the upper levels, as seen in the comparison with a Wind Profiler at Kumagaya (Figs. S1c and S1d). As will be discussed in Section 4.1, the strong northwesterlies indeed correspond to the Karakkaze wind.

At Narita and Haneda, which are downstream of Kumagaya, the temporal evolution of temperature and wind direction in NHM1km are consistent with the surface observations (Figs. 1b–e). However, unlike the observations, the wind speed in
NHM1km at Narita is not significantly intensified in the morning (Fig. 1c), while that at Haneda is reasonably reproduced. Narita is near the boundary between the ST and WK areas in the simulated results (Figs. 3a and 3b), and the simulated ST area appears to be slightly shifted south of that in reality. Such a discrepancy of the ST area in the eastern Kanto Plain was also seen in the study of Nishi and Kusaka (2019d). The simulated Karakkaze winds may be more likely to differ from observations in downstream areas.

The observed surface wind speed at Narita notably increased after 0600 JST (Fig. 1c). Although NHM1km does not successfully reproduce the increase itself, we can infer this rapid increase might be caused by a shift of the ST area downstream rather than the onset of Karakkaze wind: the wind speeds had already intensified at Haneda and Kumagaya in both observations and NHM1km (Figs. 1e and S1b).

According to JTSB (2013), a pilot of another aircraft landed 8 minutes before the accident reported strong low-level wind shear below the altitude of 600 m. The turbulent kinetic energy (TKE) below the altitude of 300 m in the ST area is indeed intensified in NHM1km (Fig. 3c). The budget of the TKE (Fig. S2) suggests that the vertical shear production associated with northwesterlies (Fig. S2e) is dominant. The strong northwesterlies originating from the convex mountain range could have caused the strong low-level shear and affected the aircraft landing.
4 Discussion

4.1 Characteristics of northwesterlies as Karakkaze wind

The locally strong northwesterlies do indeed have the characteristics of the Karakkaze wind as reported by Nishi and Kusaka (2019c) and Nishi and Kusaka (2019d). The structures are almost stationary, since they are significant even after temporal averaging (Fig. 4). Horizontal divergence associated with downdrafts near the surface prevail in the ST area (Figs. 4a and 4b). At the semi-basin, the downdrafts along the slopes of the mountain accompany large momentum of the northwesterlies ($V_\perp$ in Fig. 4c). The air with larger momentum continuously descends from upper levels in the ST area along with the tilted isentropes (Fig. 4d). In fact, the air with larger momentum accompanies higher potential temperature near the surface (Fig. 3b). The formation of the area with weaker winds in the north has also been reported by Nishi and Kusaka (2019c).

Although many similarities with previous studies are found, the time series of the Karakkaze wind in the present case does not fit typical types suggested by Nishi and Kusaka (2019a). The wind speed becomes strong in the early morning (Figs. 1c and 1e) with decreasing the surface temperature (Figs. 1b and 1d) as similar to “type Bora” of Nishi and Kusaka (2019a). However, the wind speed remains strong
while the temperature increases as similar to “type Foehn” of Nishi and Kusaka (2019a).

4.2 Effects of mountain convexity and fine-scale topography

To confirm the effect of the mountain convexity on the Karakkaze wind, we performed a sensitivity experiment (NHM2kmMOD) that fills the semi-basin: the ground in the semi-basin was elevated up to an altitude of 1800 m while ensuring that slopes from the surrounding areas were not too steep. Figure 5 compares the time-averaged results of NHM2kmMOD with those of NHM2km.

If the mountain convexity is absent in NHM2kmMOD (i.e., the mountain range is nearly two-dimensional and linear; “Straight-SHF case” in Nishi and Kusaka, 2019c), the locally intensified northwesterlies originating from the convex mountain do not occur downstream (Figs. 5b and 5c), and none of the characteristics of the Karakkaze wind described above are seen (Figs. 5f and 5g). Therefore, the topography of the mountain convexity is critical to the development of the strong northwesterlies in the ST area, including even the region near Narita Airport, which is more than 100 km downstream of the convex mountain range. This result is consistent with Nishi and Kusaka (2019c) which has suggested the importance of mountain convexity.
The realistic topography considered in the present simulations includes numerous ridges and valleys whose horizontal scales are smaller than that of the mountain convexity (Fig. 2). In the ST area, significant fluctuations remain in the horizontal convergence even after the temporal averaging (Convergence regions in rows in Fig. 4a). These fluctuations are thought to be caused by the fine-scale variations in the topography. To examine the effect of the small-scale variations in topography, we conducted another sensitivity experiment (NHM2kmCOA) which is the same as the NHM2km but using the coarser topography generated for NHM5km. The two kinds of topography are compared in Figs. S3a–d.

Comparing the time-averaged wind speeds along the vertical section along A–B in Fig 3a, the wind speeds associated with the Karakkaze wind below 900 m are 2 to 5 m s\(^{-1}\) weaker in NHM2kmCOA (Fig. S3g). The potential temperature on the Kanto Plain is \(\sim 1\) K lower in NHM2kmCOA below \(z = 1\) km (Figs. S3e and S3f), suggesting that less volume of air descends from the upper levels: the small-scale variations in topography possibly promote vertical mixing that contributes to downward transport of the large momentum aloft and enhancement of the Karakkaze wind. In contrast, wind speeds at the upper levels (from 1.5 to 2 km) are larger in NHM2kmCOA (Fig. S3g). We speculate that the northwesterlies at the levels are less blocked at the mountain range: heights of peaks in the mountain range are
more reduced in the topography for NHM2kmCOA (Fig. S3d).

4.3 Backward trajectory analysis and upstream environment

To examine the environments upstream of the northwesterlies, backward trajectories were calculated based on 3-minute outputs from NHM1km. The air parcels to be tracked were initially allocated positions below $z = 5.31$ km with a horizontal spacing of about 1.2 km in the vertical cross-section along A–B in Fig. 3a. The backward tracking is performed from 0700 to 0100 JST on 23 March for each parcel. We compare two groups of backward trajectories whose tracking starts from the ST and WK areas near Narita Airport. Along the cross-section, the ST area is defined as between 139.6 and 140.5 °E below $z = 1.56$ km with $V_\perp \geq 25$ m s$^{-1}$. The WK area is defined as between 140.4 and 140.8 °E below $z = 1.56$ km with $V_\perp \leq 12.5$ m s$^{-1}$ (Fig. 6a). The backward trajectories of each group are shown in Fig. 6b.

The maximum attained altitudes for trajectories tracked from each position show that parcels in the ST area descend from altitudes higher than those in the WK area (Fig. 6a). The strong surface winds in the ST area appear to be caused by the downward momentum transport. Most of the trajectories tracked from the ST area pass over the convex mountain range (Fig. 6b). In contrast, those tracked from the WK area pass through an approximately two-dimensional mountain range in the
north. The hydraulic jump indeed occur in the lee of the northern mountain range as
similar to Nishi and Kusaka (2019c) (not shown). However, the tracked trajectories
of the parcels in the WK area near the surface did not follow the hydraulic jump
aloft: these trajectories appear to travel through the passes with low elevations in
the mountain range.

After backward tracking for 4 and 6 hours from the ST and WK areas, respec-
tively, most of the parcels have crossed the mountain range and reached areas over
the Sea of Japan. Figure 6b also shows rectangular areas bounded by one sigma
from the means of the horizontal distributions in the latitudinal and longitudinal
directions for parcels tracked from the ST and WK areas. These areas are referred
to as “UpST” and “UpWK”, respectively. The altitudes of parcels after tracking
differ significantly between UpST and UpWK (Fig. 7a): parcels in UpWK are likely
to be distributed at lower heights.

To characterize the difference, we investigate the horizontally averaged soundings
in each area (Figs. 7b and 7c). Since the convective mixed layers are formed, the
height of the dividing streamline $h_{\text{div}}$, above which air parcels have enough energy
to pass over a mountain range with height $H$, and the Froude number based on $h_{\text{div}}$
may be useful for characterizing flow over the mountains (Snyder et al. 1985; Heinze
et al. 2012; Ito and Niino 2016). The definition of $h_{\text{div}}$ is

$$\frac{1}{2}U^2(h_{\text{div}}) = \int_{h_{\text{div}}}^{H} N^2(z)(H - z)dz,$$

(1)

where $U$ is horizontal velocity, $N$ is the Brunt-Väisälä frequency, and $H$ is set as 2 km representing the mountain range as similar to Nishi and Kusaka (2019c). The present case should also consider uplift via diabatic heating, since the dry static energy is not conserved upstream of the mountains for both groups of trajectories, while the moist static energy is almost constant (Fig. S4). Therefore, we examine the height of the dividing streamline, $h_{\text{mdiv}}$ defined by the moist saturated Brunt-Väisälä frequency $N_m$ (Lalas and Einaudi 1974; Durran and Klemp 1982):

$$N_m^2 = \frac{g}{T}(\frac{dT}{dz} + \Gamma_m)(1 + \frac{Lq_s}{RT}) - \frac{g}{1 + q_w} \frac{dq_w}{dz},$$

(2)

where $g$ is gravitational acceleration, $T$ is temperature, $\Gamma_m$ is the moist adiabatic lapse rate, $L$ is the latent heat of vaporization, $q_s$ is the saturation mixing ratio, $R$ is the ideal gas constant, and $q_w$ is the total water mixing ratio. Then, $h_{\text{mdiv}}$ is obtained as

$$\frac{1}{2}U^2(h_{\text{mdiv}}) = \int_{h_{\text{mdiv}}}^{H} N_m^2(z)(H - z)dz.$$

(3)

Even parcels at $h_{\text{mdiv}}$ ($< h_{\text{div}}$) can pass over the mountain range if the air is saturated. In fact, $h_{\text{mdiv}}$ agrees better with the mean height of parcels in UpWK (Fig. 7a; ~0.9 km) than $h_{\text{div}}$. 


The Froude number based on $h_{\text{mdiv}}$, $Fr_{\text{mdiv}} = 1 - h_{\text{mdiv}}/H$, is 0.343 and 0.583 for the UpST and UpWK areas, respectively. We can expect occurrences of the Karakkaze wind or hydraulic jump with such low Froude numbers (Nishi and Kusaka 2019c).

The mountain convexity forces the air with the high potential temperature at upper levels to descend (cf. the comparison between NHM2km and NHM2kmMOD; Figs. 5e and 5g), contributing to form the Karakkaze wind. Comparing horizontal wind speeds at height $h_{\text{mdiv}}$ in the upstream soundings (Figs. 7b and 7c), the flow from the UpWK area is expected to give rise to stronger surface wind in the lee of the mountain range than that from the UpST area. However, because of the presence of the mountain convexity that effectively induces the downdrafts (Fig. 4c), the flow from the UpST area acquires large momentum from heights even above $z = 1.8$ km, which is the mean height of parcels in UpST (Fig. 7a). This height is significantly higher than $h_{\text{mdiv}} \sim 1.3$ km in UpST. The horizontal wind speeds are strongly accelerated below $z = 1$ km in both UpST and UpWK areas (Figs. 7b and 7c). This feature is seen between 21 JST on 22 March to 06 JST on 23 March and probably associated with the passage of the cold front (Fig. 1a).
5 Conclusions

A case study of the Karakkaze wind on 23 March 2009 employed numerical simulations and backward trajectory analysis. The main findings are summarized as follows.

1. Numerical simulations reasonably reproduce the Karakkaze wind in this case. Characteristics of the strong northwesterlies are consistent with previous studies of the Karakkaze wind (Nishi and Kusaka 2019c,d) except for the time series of surface temperature: the present case does not fit typical types suggested by Nishi and Kusaka (2019a).

2. When the aircraft accident occurred at Narita Airport in the early morning, turbulence was suggested to be strong near the surface due to the vertical shear associated with the Karakkaze wind. Recently, Yoshino (2019) and Ito et al. (2020) have suggested potential risks of convective turbulence in daytime southwesterlies for landing at the airport. The Karakkaze wind (northwesterlies) is another notable situation that may affect the landing.

3. In a sensitivity simulation with the semi-basin filled in, the Karakkaze wind did not develop. Therefore, the mountain convexity is critical for the formation of the wind as suggested by Nishi and Kusaka (2019c). Small-scale variations
in topography further enhance downward momentum transport and increase
the surface wind speed of the Karakkaze wind.

4. The altitudes of air parcels upstream of the flow that passed over the two-
dimensional mountain range to the north agreed with the height of the dividing
streamline based on the moist saturated Brunt-Väisälä frequency. In contrast,
for the flow that passed over the convex mountain range deemed to be the
strong Karakkaze wind, the air with large momentum descended from altitudes
significantly higher than the height of the dividing streamline.

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Table S1: Configuration of each experiment.

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**Figure S1:** Time series of (a) temperature and (b) wind speed (solid lines) and direction (dots) at Kumagaya observed by AMeDAS (black) and simulated results from NHM1km (red); time series of horizontal wind barbs and speed (colors) at Kumagaya observed by (c) JMA’s wind profiler and (d) simulated results from NHM1km. The long barbs represent 10 m s$^{-1}$, while the short barbs represent 5 m s$^{-1}$. 

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Figure S2: (a) Turbulent kinetic energy (TKE) and tendencies of TKE associated with (b) advection and diffusion, (c) buoyancy production, (d) horizontal shear production, (e) vertical shear production, and (f) dissipation in the vertical section along A–B in Fig. 3a, from NHM1km at 0648 JST on 23 March 2009. These tendency terms are calculated as follows:

\[
\frac{\partial E}{\partial t} = - \frac{\partial}{\partial x_j} \bar{u}_j E - \bar{u}_i \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} + \frac{g}{\theta_v} \frac{\partial}{\partial x_j} \theta_v - \frac{0.41 E^3}{l} + \frac{\partial}{\partial x_j} (K_e \frac{\partial E}{\partial x_j}),
\]

where \( E \) is TKE, \( \theta_v \) is the virtual potential temperature, \( l \) is the mixing length, and \( K_e \) is the subgrid-scale eddy coefficient for TKE. The Einstein summation convention is used, overbars denote the Reynolds average, and primes denote the deviations. The terms on the right-hand side represent, from left to right, advection, shear production, buoyancy
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production, dissipation, and diffusion.
Figure S3: Topography in (a) NHM2km and (b) NHM2kmCOA (the coarser topography generated for NHM5km is used), (c) difference between topographies for NHM2km and NHM2kmCOA, and (d) elevations along the line G–H shown in (c) in
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NHM2km (black) and NHM2kmCOA (red). Vertical section of potential temperature (contours) and horizontal velocity perpendicular to the transect, $V_{\perp}$ (shading), along the red line A–B in Fig. 3a in (e) NHM2km and (f) NHM2kmCOA. (g) Difference in $V_{\perp}$ between NHM2km and NHM2kmCOA. The results are temporally averaged between 0200 and 0700 JST on 23 March 2009.
Figure S4: Time series of averaged thermodynamic variables over backward trajectories tracked from the (a) ST and (b) WK areas. The red lines show $g z$, the gray lines show $c_p T$, the green lines show $L q$, the yellow lines show dry static energy $s$, and the blue lines show moist static energy $h$. All lines are shown as relative to the results at 0700 JST when the tracking was started.

Dry static energy and moist static energy can be written as

$$s = g z + c_p T,$$

$$h = g z + c_p T + L q,$$

where $c_p$ is the specific heat capacity, and $q$ is the water vapor mixing ratio in the air.