A Climatological Study of the Local "Karakkaze" Wind, with a Focus on Temperature Change

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Abstract

This study revealed that the Karakkaze events accompanied by rising temperature are more frequent than those accompanied by dropping temperature. This finding contrasted with the general belief for many years that the Karakkaze is a bora-type local wind. By focusing on the temporal evolution of temperature and wind, we were able to characterize three types of Karakkazes as follows: the surface wind speed and temperature both increase in the morning and then decrease in the afternoon (type Foehn-D); during the night, the temperature increases or stops decreasing, and the surface wind speed increases (type Foehn-N); and in the morning, the temperature decreases or stops increasing, and the surface wind speed increases (type Bora). As a result, we found that among the 238 Karakkazes that we identified, 103 were type Foehn-D events, 56 were type Foehn-N events, and 79 were type Bora events.

(**Citation**: Nishi, A., and H. Kusaka, 2019: A climatological study of the local "Karakkaze" wind, with a focus on temperature change. *SOLA*, **15**, 149−153, doi:10.2151/sola.2019-027.)

1. Introduction

The Japanese islands have complex terrain, and Japan is located in one of the world's prominent storm tracks. The islands are thus in an environment that favors the development of strong winds caused by terrain, and many local winds occur in Japan (Yoshino 1975; Kusaka and Fudeyasu 2017). Well-known examples of such local winds include the Karakkaze (Yoshino 1975, 1978; Kusaka et al. 2011), Matsubori-kaze (Yoshino 1975; Kurose et al. 2002), Hirodo-kaze (Yoshino 1975; Fudeyasu et al. 2008), Yamaji-kaze (Saito and Ikawa 1991; Saito 1993), and Kiyokawa-dashi (Yoshino 1975; Ishii et al. 2007; Sasaki et al. 2010).

Local winds often change temperatures in the lee of mountains. Downslope windstorms have historically been classified in terms of warm or cold advective flow (e.g., Yoshino 1992; Serafin et al. 2017). Yoshino (1992) classified local winds into foehn-type winds with warm advective flow and bora-type winds with cold advective flow. Yoshino (1992) has characterized the Chinook and south foehns in the Alps as foehn-type winds that occur in the warm season in low- and mid-latitude regions, in contrast to bora-type winds that occur in the cold season in high- and mid-latitude regions. Although classifying local winds based on the temperature change in the lee of mountains would seem to be a significant achievement, it is questionable whether a specific local wind can be identified as a foehn or bora, because the mechanisms of foehn phenomenon can be inherent in the flows of air over a mountain range, even if the approaching flows advect cold air, as a bora does (Yoshino 1992).

The Karakkaze ("a dry wind" in Japanese) is one of the most famous local winds in Japan because it blows in the Kanto Plain, which includes Japan's largest metropolitan area, the Tokyo metropolitan area. The Karakkaze is a dry, strong northwesterly wind. Yoshino (1975) has noted that the daily maximum temperature on a Karakkaze day is lower than the temperature on the previous day, and thus they indicated that the Karakkaze is a bora-type local wind. Since then, this wind has been regarded as a bora-type local wind (e.g., Yoshino 1975; Urushibara 1985; Fujibe 1998; Iwasaki 2018).

Recent studies, however, have found diurnal cycles of the wind and temperatures on Karakkaze days (e.g., Yamagishi 2002; Yomogida and Rikiishi 2004; Kusaka et al. 2011). In particular, wind speed and air temperature generally increase in the morning and decrease at night. Based on the diurnal cycles, Yamagishi (2002) has hypothesized that the Karakkaze is an ordinary boundary-layer wind that becomes stronger due to collapse of the surface inversion layer after sunrise.

In addition, "foehn" winds are liable to occur in the northwestern part of the Kanto plain in winter depending on a pressure pattern (Watarai et al. 2015). Foehn winds are downslope winds which are warm and dry (e.g., Brinkmann 1971; WMO 1992).

The present study focused on temporal changes of the wind and temperature on Karakkaze days and investigated whether the climatological characteristics of this local wind were similar to those of a bora, a foehn, an ordinary boundary-layer wind, or some other winds.

2. Data and methods

The present study defined the Karakkaze as a dry and strong northwesterly wind from the mountain range during the cold half-year, from October to March. We also determined the frequency of Karakkaze from December to February (DJF) based on surface 10-minute observation datasets maintained by the Automated Meteorological Data Acquisition System (AMeDAS) at Maebashi (the star in Fig. 1b) from 2000 to 2016. The present study specifically defined the formation of Karakkaze based on the following four criteria derived from previous studies (e.g., Yoshino 1975; Kusaka et al. 2011): (1) wind speed at a height of 10 m at Maebashi must be more than 8 m s^{-1}, (2) the most frequent wind direction at 10 m at Maebashi must be between 270° and 360° while a strong wind is blowing, (3) relative humidity at 2 m at Maebashi must be < 40% when the most strong wind blows on the event, and (4) there must be no precipitation at Maebashi while the strong wind is blowing. We defined a Karakkaze event as a period that satisfied the above criteria and during which the wind speed was 4 m s^{-1} or more.

3. Results

3.1 Classification of Karakkaze events using temporal changes of temperature

Based on the four criteria in the previous section, we identified 238 Karakkaze events from 2000 to 2016.

We examined the diurnal variations of temperature and wind for all Karakkaze events. The results revealed that at the beginning of a Karakkaze during the day, there were events during which the temperature rose and other events during which the temperature dropped. Furthermore, there was an event when the temperature rise was concurrent with the start of a Karakkaze at night.

In accordance with this analysis, we defined three types of Karakkazes based on the temporal evolution of temperature and

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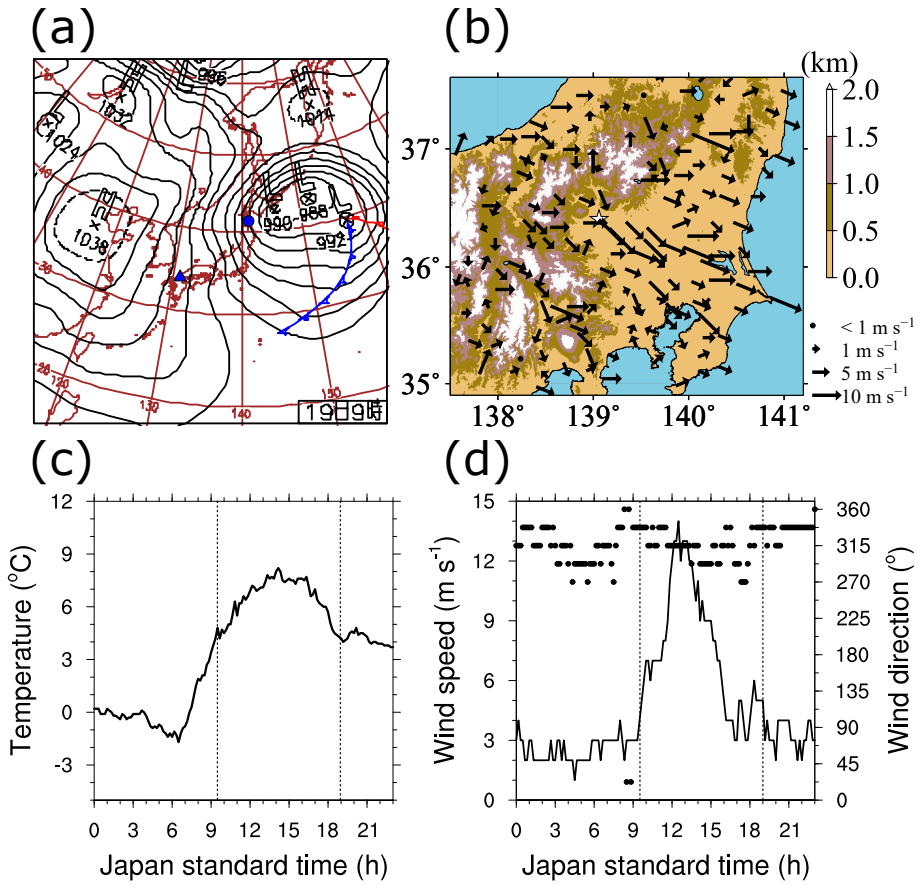

Fig. 1. Typical example of a type Foehn-D on 19 February 2002. (a) Synoptic weather chart at 0900 Japan Standard Time (JST) on 19 February 2002 (adapted from Japan Meteorological Agency 2019a). The contours show the sea level pressure with the intervals of 4 hPa. The circle and triangle indicate the position of Oma and Shimonoseki, respectively. (b) Surface wind distribution at 1300 JST 19 February 2002. Shading represents the terrain elevation. The star indicates the location of Maebashi. (c) Time series of temperature at Maebashi on 19 February 2002. (d) Time series of wind speed (line) and wind direction (dots) at Maebashi on 19 February 2002. The Karakkaze occurred between two broken lines in (c) and (d).

wind at Maebashi (Table 1). In the first type of Karakkaze, both the wind speed and temperature increase in the morning and decrease from afternoon to evening (Fig. 1). These wind and temperature changes are similar to the diurnal changes of wind and temperature accompanying the development and decay of a convective boundary layer (an ordinary boundary-layer wind). This first type corresponds to the Karakkaze described by Yamagishi (2002). In the second type, both the wind speed and temperature increase during the night (Fig. 2). However, the second type may also involve increasing wind speed and a cessation of the temperature decrease during the night. This combination of the temporal evolutions of wind and temperature is similar to that of south foehns in the Alps and Chinooks in the Rocky Mountains and corresponds to the Karakkaze described by Watarai et al. (2015). In the third type, the wind speed increases in the morning, but the temperature decreases (Fig. 3). However, this third type may also involve an increase in wind speed and a halt in the temperature rise during the morning. This combination of the temporal evolutions of wind and temperature is similar to that of the bora in the Dinaric Alps and corresponds to the Karakkaze described by Yoshino (1975). In this study, the first type is referred to as a "type Foehn-D", the second as a "type Foehn-N", and the third as a "type Bora".

Table 1. The types of Karakkazes and the features of each type.

		Number of events in the cold half-year (the winter season)	Appearance rate in the cold half-year (the winter season) (%)
Foehn	-D	103 (72)	43 (46)
	-N	56 (34)	24 (22)
Bora		79 (51)	33 (32)

In the present study, we classified the Karakkaze events into three types on the basis of five parameters: (1) the start time of the Karakkaze, (2) the end time of the Karakkaze, (3) the temperature change during the first hour of the event (ΔT_a), (4) the temperature change during the hour preceding the start of the event (ΔT_b), and (5) the trend of temperature change during the four hours after the start of the event ($\partial T/\partial t$).

The criteria of the trends in our classification were based on the climatological mean trends of temperature change for the cold half-year from 2000 to 2016. The climatological mean trends were about 0.7°C hour^{-1} between 0600 and 1400 JST ($\partial T_m/\partial t$) and about −0.3°C hour^{-1} between 1400 and 0600 JST ($\partial T_n/\partial t$).

The classification criteria for each type are explained below. Type Foehn-D was defined as an event satisfied the following two criteria: (1) the Karakkaze event which started between 0600 and 1400 JST and ended between 1400 and 2400 JST and (2) $\partial T/\partial t > \partial T_m/\partial t$. In contrast, type Foehn-N was defined as an event satisfied the following three criteria: (1) the Karakkaze event which started between 1400 and 0600 JST, (2) $\Delta T_a > \Delta T_b$, and (3) $\partial T/\partial t > \partial T_n/\partial t$. Type Bora was defined as an event satisfied the following three criteria: (1) $\Delta T_a < \Delta T_b$, and (2) $\partial T/\partial t < \partial T_n/\partial t$ when (3) the Karakkaze event started between 1400 and 0600 JST or (2) $\partial T/\partial t < \partial T_m/\partial t$ when (3) the Karakkaze event started between 0600 and 1400 JST.

Among the 238 Karakkaze events that we analyzed, we found 103 events of type Foehn-D (43%), 56 events of type Foehn-N (24%), and 79 events of type Bora (33%). The Karakkazes have been characterized as local winds accompanied by dropping temperature (i.e., type Bora) in previous studies (Yoshino 1978; Yoshino 1975; Yoshino 1992). However, the present study revealed that Karakkaze events accompanied by rising temperature (type Foehn-N and type Foehn-D) are more frequent than those accompanied by dropping temperature (type Bora). It is noteworthy that the definition of a Karakkaze in the present study is consistent with Yoshino (1975) and Kusaka et al. (2011).

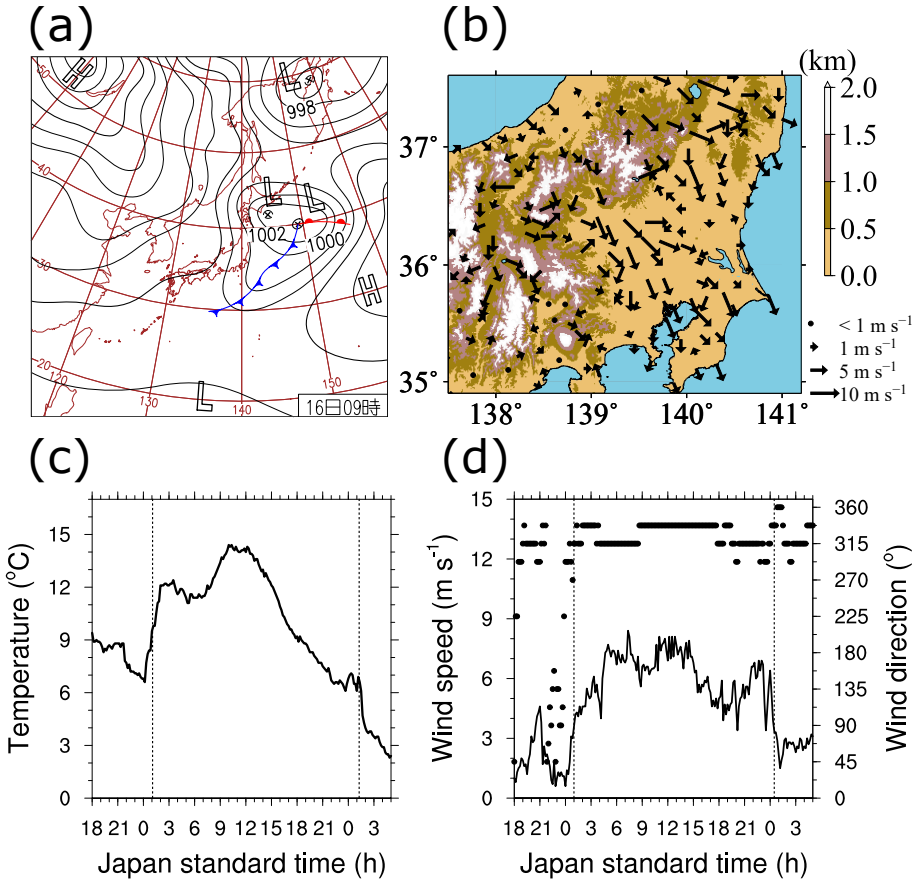

Fig. 2. Typical example of a type Foehn-N on 16 December 2012. (a) Synoptic weather chart 0900 JST on 16 December 2012 (Japan Meteorological Agency 2019c). The contours show the sea level pressure with the intervals of 4 hPa. (b) Surface wind distribution at 1100 JST on 16 December 2012. Shading represents the terrain elevation. (c) Time series of temperature at Maebashi from 2100 JST on 15 December 2012 to 0600 JST on 17 December 2012. (d) Time series of wind speed (line) and wind direction (dots) at Maebashi from 2100 JST on 15 December 2012 to 0600 JST on 17 December 2012. The Karakkaze occurred between two broken lines in (c) and (d).

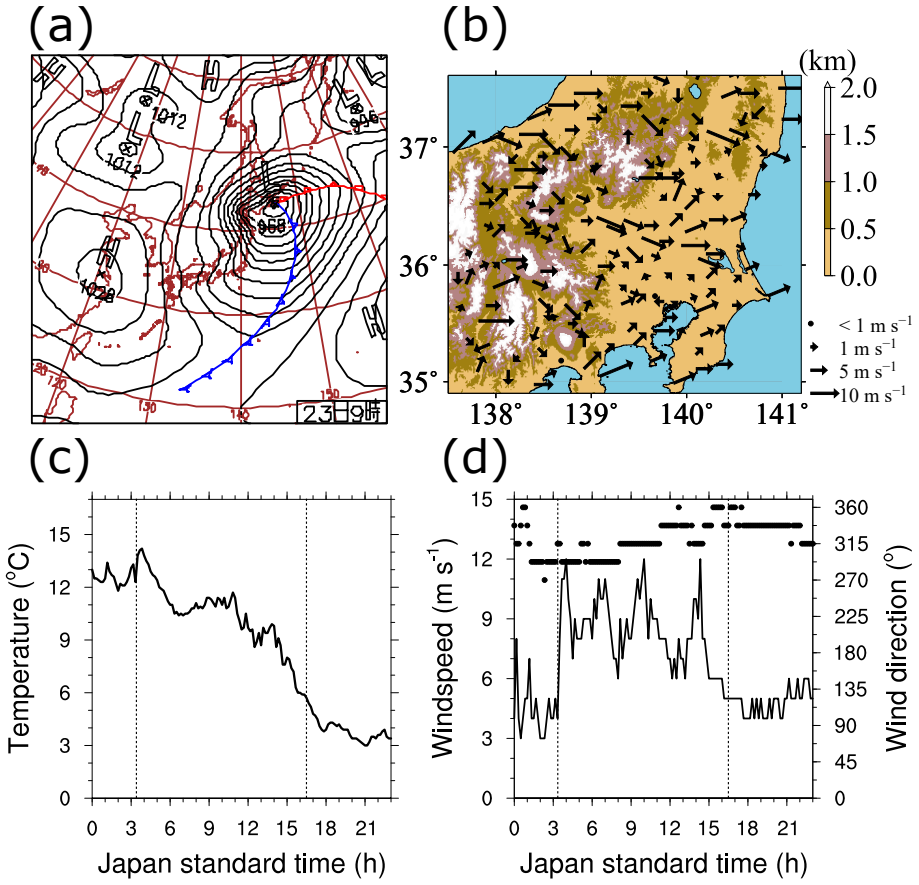

Fig. 3. Typical example of a type Bora on 23 February 2004. (a) Synoptic weather chart at 0900 JST on 23 February 2004 (Japan Meteorological Agency 2019b). The contours show the sea level pressure with the intervals of 4 hPa. (b) Surface wind distribution at Maebashi at 0400 JST on 24 February 2004. Shading represents the terrain elevation. (c) Time series of temperature on 23 February 2004. (d) Time series of wind speed (line) and wind direction (dots) on 23 February 2004. The Karakkaze occurred between two broken lines in (c) and (d).

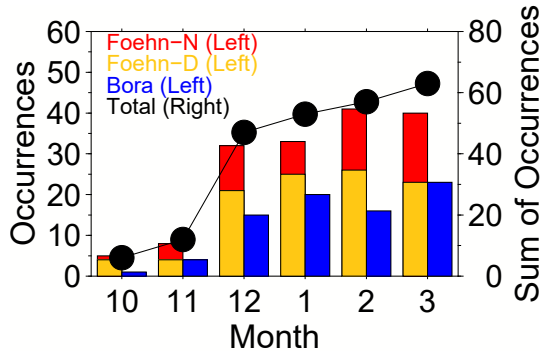

Fig. 4. Frequency of Karakkaze events. The circles denote the overall frequency of Karakkaze events in each month (right vertical axis). Orange bars denote the frequency of type Foehn-D, red bars the frequency of type Foehn-N, and blue bars the frequency of type Bora (left vertical axis).

The seasonal frequency of local winds has traditionally been a concern in the field of geographical climatology (Yoshino 1975). We, therefore, examined the frequency of each type of Karakkaze. The results indicated that the seasonal frequency differed among the three Karakkaze types. The type Foehn-D tended to occur in January (Fig. 4). In contrast, the type Foehn-N and type Bora occurred most frequently in March. Previous studies have suggested that Karakkazes occur mainly in the winter (Yoshino 1975, 1978; Kusaka et al. 2011). However, we found that Karakkazes occurred in early spring as well as in winter, even Karakkazes that satisfied the definition of Yoshino (1975) and Kusaka et al. (2011).

To clarify the sea level pressure (SLP) pattern associated with the three types of Karakkaze event, we examined the temporal change of the pattern depending on each type of event using the pattern in the weather charts before and during the Karakkaze event. Strengthening of SLP pattern was defined as the case when the difference of SLP between at north and west ends of the main island of Japan (Oma and Shimonoseki in Fig. 1a, respectively) during the Karakkaze event was 4 hPa or larger than that before the starting of the event. In addition, maintaining of SLP pattern was defined as the case when the difference of SLP during the Karakkaze event changed within ±4 hPa, compared with that before the starting of the event.

In about 72% (74 events) of type Foehn-D, the SLP patterns were similar before and after the Karakkaze (Table 2). In most of these 74 events (73 events), the typical winter SLP pattern over Japan (high pressure to the west and low pressure to the east) was maintained without apparent strengthening. In contrast, in 53% (42 events) of type Bora, the SLP pattern before and after the Karakkaze differed. These included 33 events where an extratropical cyclone passed through the Japanese archipelago and 9 events where the typical winter SLP pattern over Japan was strengthened. Similarly, in the majority (66%, 37 events) of type Foehn-N, the SLP pattern before and after the Karakkaze differed. Even when the period of analysis was winter, the occurrence frequency of each type of Karakkaze was the same as during the cold half-year.

We confirmed the change of the daily maximum temperature. We can classify 238 Karakkaze events into 92 events where the daily maximum temperature increased at least 1°C from the previous day, 43 events where the temperature did not change by more than 1°C, and 103 events where the temperature dropped over 1°C. Yoshino (1975) has noted that the daily maximum temperature on a Karakkaze day is at least 1°C lower than the daily maximum temperature on the previous day, but our result showed that Yoshino's concept did not apply to all cases. In the next section, we will compare the result of Yoshino (1975) and the present study in more detail.

3.2 Comparison with the results of Yoshino (1975)

Yoshino (1975) defined the Karakkaze as bora-type local winds because of a lower daily maximum temperature than the previous day. However, our results showed that the Karakkaze events can have the features not only of bora-type local winds (i.e., the type Bora) but also of foehn-type local winds (i.e., the type Foehn-D and the type Foehn-N).

What accounts for the difference between our conclusions and those of Yoshino (1975)? One reason is the temporal resolution of the temperature observation data. Yoshino (1975) examined the relationship between the Karakkaze and temperature change in terms of the difference between daily maximum temperatures on Karakkaze day ($Tmax_k$) and the previous day ($Tmax_p$), whereas the present study examined this relationship in terms of surface air temperature over 10-minute intervals. Yoshino (1975) concluded that the Karakkaze was a bora-type local wind based on the change of maximum temperature simply because hourly or 10-minute observation data, such as AMeDAS, had not yet been developed (from the 1960s to the early 1970s). Therefore, the criterion used by Yoshino (1975) cannot capture the rise in temperature due to the direct effect of the Karakkaze. In addition, it is not clear whether the criterion used by Yoshino (1975) captured the drop in temperature due to the direct effect of the Karakkaze. It is possible that the criterion captured the drop in temperature on the whole main island of Japan due to the synoptic-scale inflow of cold air.

In fact, we could classify the Karakkaze events satisfying Yoshino's criterion for maximum temperature (103 events) into 70 events with a rise in the temperature after the start of the event and 33 events with a drop in the temperature. The implication is that the temperature did not always decrease, even if the event otherwise satisfied Yoshino's criterion ($Tmax_k - Tmax_p < -1$°C). Therefore, to clearly show that the Karakkaze is not solely characterized as type Bora, we need surface observation data over 10-minute intervals.

Table 2. Changes of the SLP pattern during each type of Karakkaze. The numbers in the parenthesis are those of each category of SLP pattern in DJF.

Type of Karakkaze		Change of the weather chart before the Karakkaze versus during the Karakkaze		
		Without change	With change (i.e. typical winter type is strengthened or an extratropical cyclone moves over Japan)	Others
Foehn	-D	74 (54)	27 (18)	2 (0)
	-N	19 (14)	37 (20)	0 (0)
Bora		33 (24)	42 (24)	4 (3)

3.3 Analysis limited to events with the typical winter SLP pattern over Japan

Previous studies (e.g., Yoshino 1975; Yamagishi 2002; Kusaka et al. 2011) have considered the Karakkaze as the dry wind from the northwest at the typical winter SLP pattern over Japan. We will now assess how the results of the analysis in the previous section changes when the SLP pattern exhibits a "typical winter pattern" regardless of the time of year. As a result, we identified 164 Karakkaze events with the typical winter SLP pattern over Japan. Of these events, 92 events (56%) were type Foehn-D, 31 events (19%) were type Foehn-N, and 41 events (25%) were type Bora. Namely, the characteristics of the temperature changes that accompanied the Karakkaze were divided into three patterns, and the relative proportions of those events did not change greatly even when the object of the analysis was limited to the events consistent with the typical winter SLP pattern over Japan. The implication is that the wind speed cannot be associated with a certain temperature change when a Karakkaze blows (i.e., the temperature may rise or fall at the start of increasing wind speed starts to increase).

4. Conclusions and remarks

The present study investigated the relationship between temporal changes in the wind and temperature during Karakkaze. By focusing on the temporal evolution of temperature and wind, we determined that Karakkaze events could be classified into the following three types: type Foehn-D in which the wind speed and temperature both increase in the morning and decrease in the afternoon (like an ordinary boundary-layer wind), type Foehn-N in which the temperature increases (or stops decreasing) during the night (like a Foehn), and type Bora in which the temperature decreases (or stops rising) in the morning (like a Bora). The 238 Karakkaze events that we studied included 103 type Foehn-D events, 56 type Foehn-N events, and 79 type Bora events.

In addition, we found that each Karakkaze type had different characteristics with respect to seasonality and changes of the SLP pattern. In the type Foehn-D, the wind speed increased despite the absence of a large change in the SLP pattern. In contrast, the type Foehn-N and type Bora were caused by movements of low-pressure systems, and a typical winter SLP pattern over Japan was strengthened at the time of occurrence. These results showed that each type of Karakkaze blew under a different SLP pattern.

Karakkazes have been considered to be local winds accompanied by dropping temperature (i.e., type Bora) in previous studies. However, the present study revealed that Karakkaze events accompanied by rising temperature (type Foehn-N and type Foehn-D) are more frequent than those accompanied by dropping temperatures (type Bora). These results suggest that the criteria used for identifying the Karakkaze in previous studies were incomplete; they focused on background cold air inflow and neglected the cold air inflow that is a direct effect of the Karakkaze.

The present study clarified the geographical aspects of Karakkazes. Use of a numerical model in future studies would give better insights into the fluid dynamical and thermodynamical aspects of Karakkazes.

Acknowledgments

We thank Dr. Asuka Suzuki-Parker of Rissho University for her help in improving the manuscript. This work was supported by the Council for Science, Technology, and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Technologies for creating next-generation agriculture, forestry, and fisheries" (funding agency: Bio-oriented Technology Research Advancement Institution, NARO). We used the Generic Mapping Tools (GMT) and NCAR Command Language (NCL) to draw the figures in the present study.

Edited by: T. Takemi

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Manuscript received 3 March 2019, accepted 1 June 2019
SOLA: https://www.jstage.jst.go.jp/browse/sola/