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NOTES AND CORRESPONDENCE

Diurnal Variations of Surface Wind Speed Observed in the Mountainous Area of Central Japan during Sunny Summer Days

Jyunpei ISONO

Aero Asahi Co., Tokyo, Japan

and

Kenichi UENO

Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan

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Abstract

Diurnal variations of surface wind speeds during fair weather in the summer were revealed in central Japan, including data at Automated Meteorological Data Acquisition System (AMeDAS) and mountain station data above 2000 m above the mean sea level (a.s.l.) archived by an inter-university cooperative project, in relation to the altitude and concave-convex conditions around each station. AMeDAS stations belonging to Japan Meteorological Agency (JMA) are located below 1500 m, and most of them were categorized as being in concave topography with stronger daytime wind speed anomalies than in nighttime. At stations above 2000 m a.s.l. operated by each university, wind speed anomalies at night were stronger than those during the day except at the station without convex topography within a 1–5 km scale. Nocturnal enhancement of wind speeds at representative mountaintop stations appeared with prevailing Pacific Highs in synoptic pressure patterns, but it did not always appear in the same day and the absolute nocturnal wind speed varied day by day. The degree of concavity was not clearly related to the wind speed anomaly, and the degree of convexity was linearly related to the wind speed anomaly at a scale of approximately 10 km.

Keywords surface wind; diurnal variation; fair weather; mountainous area; central Japan

1. Introduction

Diurnal variations of surface wind speeds during fair weather generally increase during the day and decrease at night. One reason is the development of the planetary boundary layer (PBL) due to the downward transfer of momentum from the mixing layer caused by daytime surface heating (Arya 2001). Kondo (1983) called these increased daytime wind speeds thermal convective winds. Kusaka et al. (2011) also reported that strong local surface winds on the Kanto Plain during winter, so-called Karakkaze, have a clear diurnal variation and show a strong correlation with the upper-level wind speed but a weak correlation with the daily sunshine duration. The wind speed near the top of the PBL is relatively weak in the daytime, but it is strengthened at night because the development of a stable atmosphere decouples low-level winds, and general winds flow over the PBL

Corresponding author: Kenichi Ueno, University of Tsukuba, 1-1-1 Teno-dai, Tsukuba, Ibaraki 305-8572, Japan
E-mail: ueno.kenichi.fw@u.tsukuba.ac.jp

(Blackadar 1957). Increases in the nocturnal wind speed were observed at the top of the meteorological observation tower, such as at levels of 150–200 m, according to the Meteorological Research Institute, Tsukuba, Japan (Fujitani 1985). Haginoya et al. (1984) found the reverse of the diurnal wind speed phase at Mts. Tsukuba (869 m), Ibuki (1376 m), and Gozaisho (1200 m), such as stronger winds during the night and weaker winds during the day; they suggested that this might be caused by the fact that the daytime PBL height reaches the level of those mountains. Diurnal variations of the surface wind speeds are also affected by the local circulations caused by meso-scale land surface thermal contrasts and topography. For instance, Fujibe (1985) clarified that daytime wind-speed increases in the Kanto Plain are controlled by sea breezes when the general winds are calm. Drainage flows from the mountain valleys also cause strong nocturnal surface flows (e.g., Orgill et al. 1992). However, the behavior of the diurnal component of the surface wind speed at different altitudes is not sufficiently clarified in central Japan, due to insufficient observation points at higher elevations.

The formation of nocturnal low-level jets (LLJs) had been revealed around the Great Plains in the United States of America since the 1950s. LLJs have been observed worldwide in different seasons (Stensrud 1996; Karipot et al. 2009) with several causes, such as the barrier effect of large-scale mountain ranges, baroclinicity produced by a sloping terrain, or wind speed strengthened by a mountain gap (Wexler 1961; Holton 1967; Macklin et al. 1990). In Japan, Harada (1981) identified a LLJ with south-southwest or west-northwest components over the Kanto Plain using aerological data. Kimura and Arakawa (1983) simulated a LLJ by numerical experiments in cases of synoptic wind from the southwest direction in August and suggested that the primary factor of the LLJ was the mechanical effect of the mountains in central Japan, not inertial oscillation. However, there is still uncertainty about the relation between the nocturnal LLJ over the plain and the diurnal variation of wind speed observed at mountain sites.

In central Japan, large-scale mountain ranges with 3000 m levels such as Hida, Kiso, and Akashi and major basins with connections of small valleys such as Nagano, Ina, Ueda, and Takayama compose complex topographies. The Automated Meteorological Data Acquisition System (AMeDAS) operated by the Japan Meteorological Agency (JMA) covers a wide range of countries with uniform instruments for monitoring meso-scale weather conditions. However, the highest AMeDAS station is Nobeyama, at 1350 m a.s.l., in central Japan; most stations are distributed at lower elevations along valleys, which causes gaps in continuous mountain weather records (Suzuki 2013). Therefore, previous surface wind analyses in central Japan using AMeDAS data (e.g., Suzuki and Kawamura 1987) mostly reflect the land-sea and mountain-valley circulations along the valleys. Recently, the JMA wind profiler network has detected diurnal wind components in the lower troposphere, and the contribution of return currents of the local wind system was investigated at the 1- to 3-km level (Sakazaki and Fujiwara 2010). To assess the influence of global warming on environmental changes in the Japanese Alps region, an inter-university cooperative project (JALPS) was established in 2010 at the University of Tsukuba, Shinsyu University, and Gifu University. The climate change research group in JALPS archived meteorological data observed at high-elevation stations operated in conjunction with each university's research center or university forests (Ueno et al. 2013). This study analyzed three years of JALPS and AMeDAS surface wind data to uncover the relation between the altitude and diurnal wind speed components with an assessment of concave-convex conditions around the stations in central Japan.

2. Data

The analysis area covered 35–37°N, 137–139°E on the main island of Japan, and the analysis periods were set in July and August from 2010 to 2013. The black circles in Fig. 1 mark 80 JMA observation points where hourly 10-minute averaged wind-speed data were archived. The 21 observation sites under the JALPS project are marked as black triangles, where the hourly wind-speed data were reconstructed from the original data format (http://www.geoenv.tsukuba.ac.jp/~jalps-atm/), including a TKY site operated by the AsiaFlux project (Yamamoto et al. 1999). In the domain, the AMeDAS station with the highest elevation is Nobeyama (NOB, 1350 m). In addition, all the JALPS stations were located above 800 m, with Mt. Yarigatake (YAR) having the highest elevation at 3079 m. Data at temporary summer observation sites, such as stations on a top (2207 m) and middle slope (1750 m) of Mts. Neko (NEK) and Sanada (SAN, 843 m), were included. Digital elevation data with a 1-km interval from the National Land Numerical Information download service (http://nlftp.mlit.go.jp/ksj/index.html) were used to assess the topographic conditions around the stations.

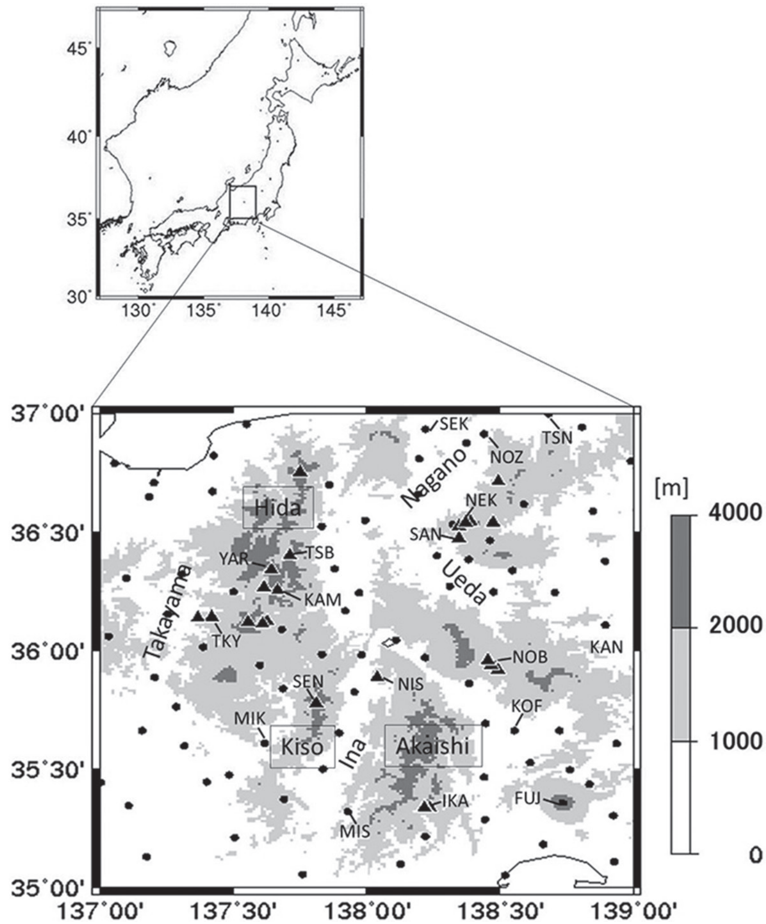

Fig. 1. Location of the analysis area (upper) and distribution of AMeDAS (●) and JALPS (▲) observation sites (lower) with major mountain ranges, basins, and abbreviations of the station names.

3. Selection of analysis days

This study focused on summer days with fair weather that might plausibly develop the PBL. In a target area, the development of convective clouds was frequently observed over mountains. To avoid cloudy days with synoptic scale disturbances, a target day is defined as having "fair weather except in the afternoon (12–21, Japan Standard Time, JST)" and is nominated using Japanese Multi-functional Transport Satellite (MTSAT) infrared brightness temperature (TBB) data. At first, the threshold TBB for discriminating the cloud top temperature from the land surface temperature was experimentally defined on a grid over Mt. Neko (138.38°E, 36.54°N; NEK), where the land scale is composed of wide-ranging pastures. TBB time sequences showed clear daytime diurnal variations, such that a sudden decrease below 280 K occurred in the evening caused by cumulus cloud development after abrupt warming in the morning by land-surface heating. In the night, TBB values were concentrated around the TBB with 286–290 K through the observation period, and air temperatures at approximately 03–05 JST measured by an in situ Automatic Weather Station (AWS) at NEK agreed with this TBB range. Namely, the TBB range of 286–290 indicates the surface temperature for a night without cloud cover at the 2000-m level. Then, a TBB temperature of 287 K, the most frequent value, was simply adopted as a threshold for discriminating cloud cover in the mountain areas. Second, days were nominated as fair days when they had no grids of TBB below 287K, except from 12 to 21 JST in an analysis domain with an evident increase of area-averaged TBB during the morning (06–12 JST). Consequently, 71 days were nominated for analysis, corresponding to 52 % of the total candidates (136 days).

4. Diurnal variation of standardized wind speed and elevations

Absolute wind speeds differ, depending on a site's location and elevation. Also, there are varieties of instrument types for wind-speed measurements at the JALPS sites. To detect the relative amplitude of diurnal wind speeds, hourly wind-speed data were standardized at each point by the following formula:

$$u' = \frac{u_i - \bar{U}}{\sigma},$$

where u_i is an hourly wind speed, $\bar{U}$ is the average wind speed for the 71 fair days, σ is the standard deviation, and u' is a standardized wind speed anomaly (SWSA). In the following sessions, the SWSAs were averaged at each time for 71 days and used for analysis.

Figure 2 shows the distributions of SWSA at 03, 09, 12, and 18 JST, representing night, morning, noon, and evening, respectively. Warm (cool) colors indicate relatively stronger (weaker) wind speeds than the daily averages at each station. At night (03 JST), almost all stations show negative SWSAs. However, stations over the mountain ranges, such as the Hida mountain range (A), the Mt. Neko area (B), and the Sekiyama (SEK)/Tsunan(TSN) stations in Niigata Prefecture, showed positive signals, indicating that relatively stronger wind speeds prevailed at night. The nighttime positive signals found at the mountaintop stations correspond to the results of Haginoya et al. (1984). Regarding to the positive signals at SEK and TSN, Ohashi and Kawamura (2006) detected nocturnal land-breeze flows starting from the southern edge of the Niigata Plain. Therefore, we speculate that nocturnal strong winds at SEK and TSN indicate the prevailing Katabatic wind channel from the backbone ranges. At noon (12 JST), signs are reversed, indicating stronger wind speeds except at high elevations. As an exception, the Kofu (KOF) station in Yamanashi Prefecture indicated negative signs indicating weaker wind speeds at Noon. This signal might indicate calm condition at the bottom of the Kofu Basin before starting a wind channel along the Fuji River from the Pacific side in the afternoon as analyzed by Kanda and Tsunoi (1995) in sunny summer days. In the morning (09 JST), most of the stations showed negative SWSA; some stations with positive SWSAs may indicate the start of up-slope winds. In the evening (18 JST), positive signals lined along major valleys that indicate large-scale valley wind channels and winds over the mountains were weakened, as indicated by the blue color.

Relations between the SWSA and the altitude are shown in Fig. 3, at the same time slots as in Fig. 2. First, it is clear that there is no station at approximately 2000 m. The reason for the lack of stations in this altitude zone is speculated to be that this altitude is below the timber line with steep slopes but is high enough for a residential area to prevent the establishment of a meteorological observatory in central Japan. At night (03 JST), a clear trend, such as weaker (stronger) wind speeds in lower (higher) altitudes, appeared with a turning altitude at approximately 2000 m a.s.l., except at SEK, STN, and Senjyo-jiki (SEN) stations. In the morning (09 JST), positive and negative SWSA were mixed at below 2000 m. The relation became reversed at noon as compared to nighttime (12 JST). The amplitude of SWSA variations at lower elevations indicates that the daytime valley wind speed was not as a function of absolute altitude but depended on the location. In the lower-elevation sites, the KOF station recorded the lowest SWSA at noon. The SWSA at the SEN station became positive at 9 JST and noon. The cause of the outstanding feature at the SEN station will be discussed in the next paragraph.

The tendency of synoptic scale weather patterns on days with a clear diurnal variation of SWSA at four mountain stations (Mt. Neko, Tsubakuro, Yari, and Nishi-hodaka) was examined from July 18 to August 31 in 2010. In summer of 2010, a Pacific High was extended and strengthened from the end of July to August, causing record-breaking hot summer days in central Japan. Days with stronger nocturnal (averaged between 01 JST and 01–05 JST) than daytime (averaged between 10 JST and 14 JST) winds were nominated at the four stations (Fig. 4a) with surface pressure patterns categorized each day (Fig. 4b). For instance, a black box on July 20 corresponds to a stronger nocturnal wind speed after midnight (around 03 JST on July 20) than in the daytime on July 19. Pressure patterns were classified into six categories, using surface weather analysis maps in the morning, such as prevailing Pacific Highs, traveling anticyclones, Okhotsk anticyclones, traveling extra-tropical cyclones, fronts, and tropical cyclones. Typical days with strong nocturnal winds prevailed from July 20 to 28 and August 17 to 25 with prevailing Pacific Highs, but those days were not always the same at all mountain stations. Absolute amplitude of nocturnal wind speed increases also changed day-by-day even in the similar synoptic weather pattern of Pacific

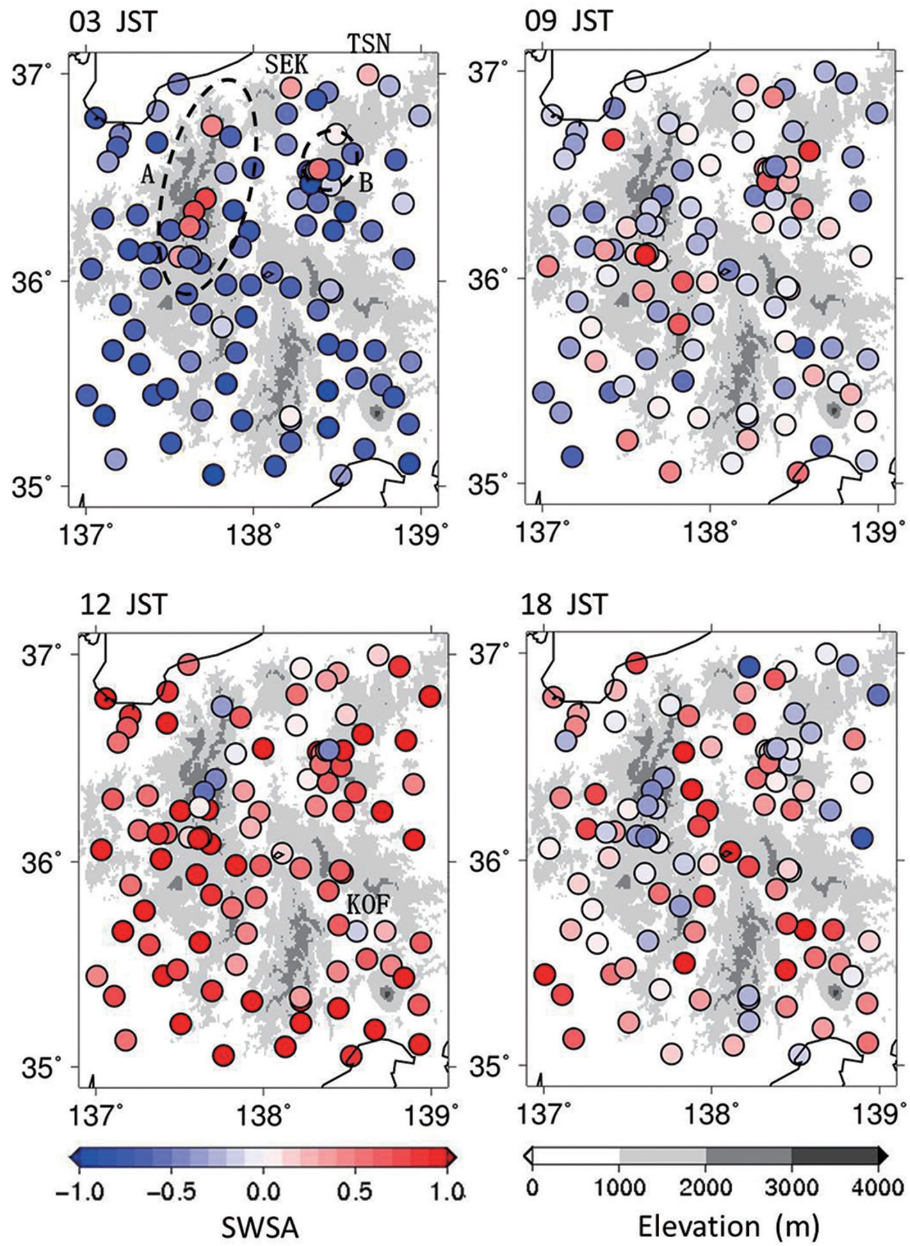

Fig. 2. Distribution of averaged SWSA at 03, 09, 12, and 18 JST. A and B at 03 JST correspond to the Hida Mountain Range and the Mt. Neko area, respectively.

Highs. Days with less diurnal wind speed variation appeared from July 29 to August 1 and from August 11 to 16 when synoptic disturbances, such as cyclones and fronts, existed. Namely, occurrences of stronger nocturnal winds at mountain tops were plausible on fair days under Pacific Highs, but the appearance tendency was dependent on the location and day.

5. Assessment of concave/convex topography conditions around the stations

Surface winds in the mountainous areas are strongly affected by the local topography, such as valley basins, slopes, ridges, etc., even when absolute elevations are the same. Haginoya et al. (1984) pointed out that concave/convex (CC) conditions

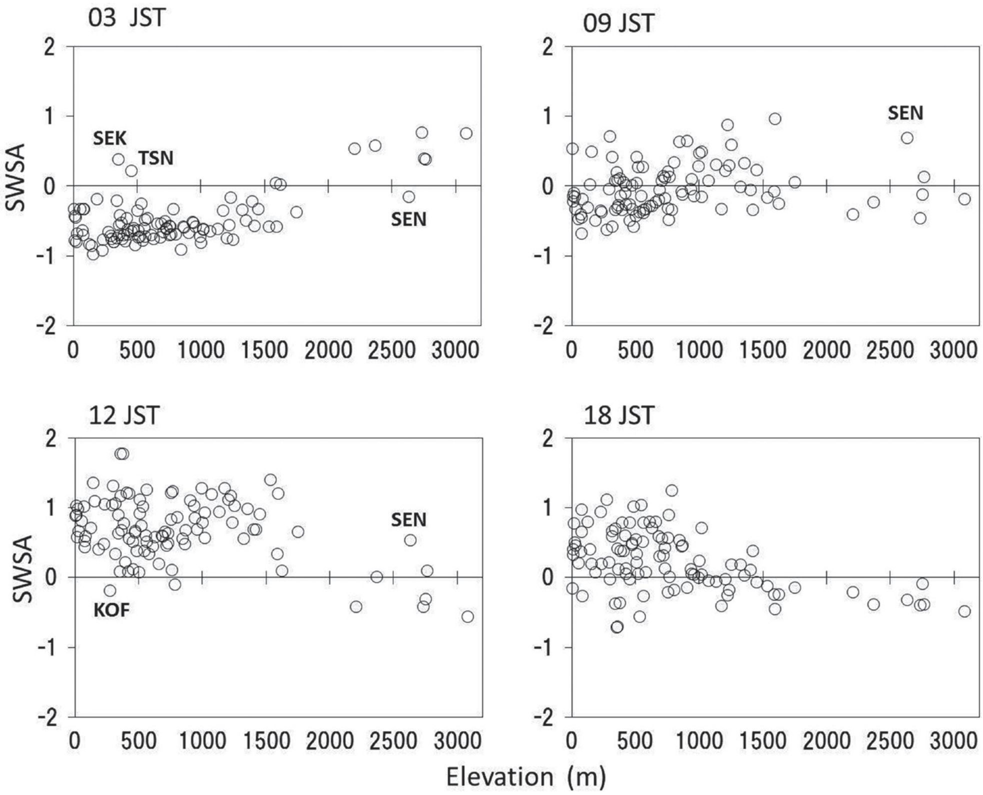

Fig. 3. Scattering diagrams between elevation (m) and SWSA at four times. Abbreviations stand for the station names, as indicated in Fig. 1.

around the stations especially determine the effect of upper general winds, even at stations in the mountains. This study assessed the CC condition following the methods of Suda (1990). Six spatial scales, such as 1, 5, 10, 15, 25, and 40 km, were established, each centered around a station. Then, a difference between the elevation of the station and the spatially averaged elevation was calculated as the CC index (unit: m) in each scale. If the CC index is positive, the station is located over convex topography, such as a ridge, hill, or mountaintop; if it is negative, it is in concave topography, such as the bottom of a valley or basin.

Figure 5 shows the relation between the elevation and the CC index. Most of the AMeDAS stations are located below the 1500-m level and are categorized as flat places in a 1-km scale and as a concave place in more than a 5-km scale. For stations with low elevations, the Kanna (KAN), Minami-shinano (MIS), Ikawa (IKA), and Sanada (SAN) stations were associated with relatively large concave topographies below −200 m in a 1-km scale (Fig. 5a). Those with relatively large positive CC indices are Nozawa Onsen (NOZ), Minami Kiso (MIK), and TSN, but the index was below +70 m (not shown in Fig. 5). Both the TSN and SEK stations showed strong prevailing nocturnal winds (Fig. 3), but their CC indices were +57 m and −10 m, respectively. This feature suggests that the nocturnal flows in the major valley from the Nagano Basin were deeper than 100 m and were not affected by the relative differences of local altitudes around the station. The lowest station with a significant positive CC index was the TKY site (1420 m, Fig. 5c) because the data were recorded at the top of a meteorological tower above the forest canopy on hilly topography (Yamamoto et al., 1999). However, nocturnal wind speeds at the TKY site were below the daily average, with no indication of nocturnal winds. On the other hand, most high-elevation stations were categorized with positive CC indices. The SEN station (2630 m), where nocturnal wind speeds were below the daily average, as shown in Fig. 3, was categorized as having a concave condition at 1 km, an almost-flat area at 5 km, and a convex condition above a 10-km scale (Fig. 4b). Besides, the CC index of the

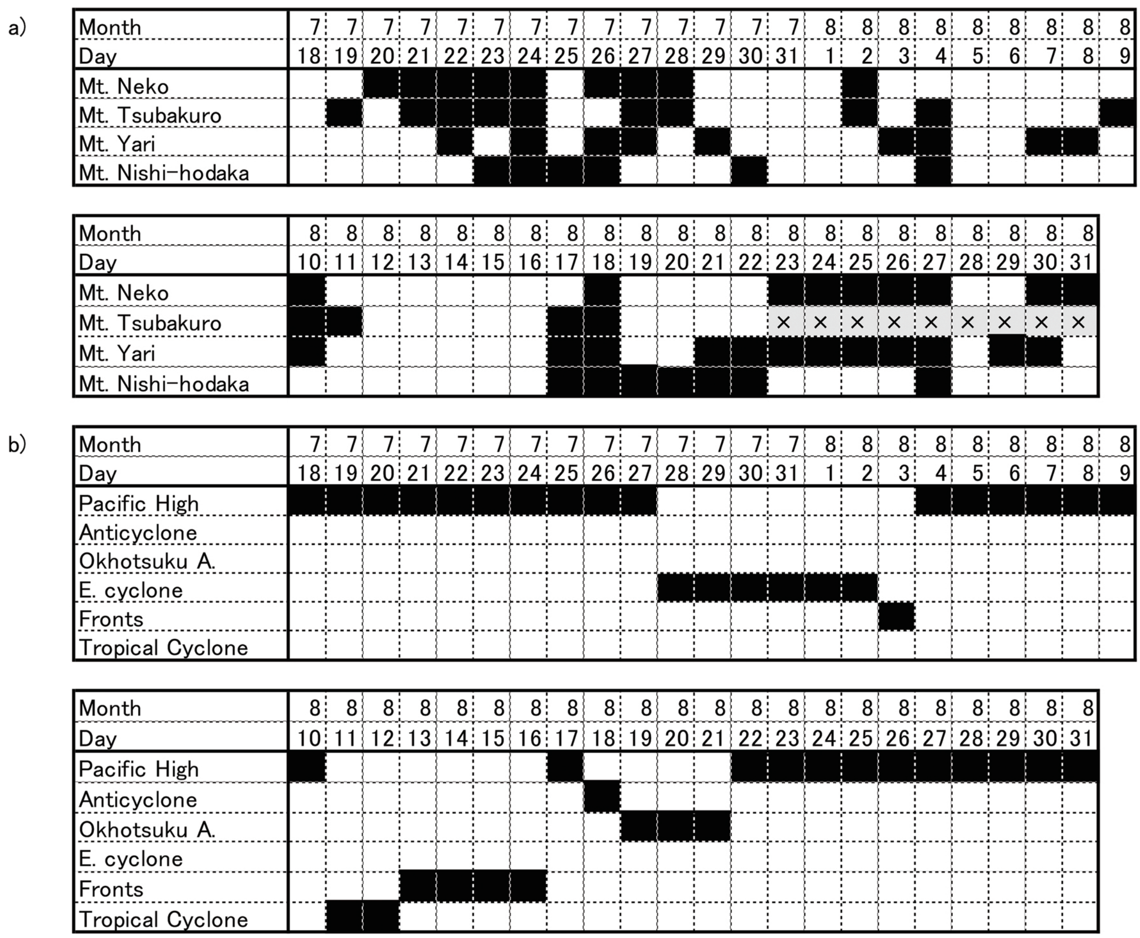

Fig. 4. a) Representative days with strong nocturnal winds (solid black boxes) at four mountain stations, and b) corresponding surface pressure patterns in 2010. Cross marks indicate days with missing data.

Nishi-Komagatake station (NIS, 2368 m) became relatively lower at 25 km (Fig. 5e), but stronger winds were found at night. Kamikochi (KAM, 1530 m) is a unique station that shows a concave topography condition in a 10-km scale (Fig. 5c) with a relatively high elevation because it is surrounded by ridges in the Hida mountain range, and the SWSA became positive during the day. Namely, wind speed anomalies at night were stronger than those during the day at stations with convex topography within a 1–5 km scale above 2000 m a.s.l.

Next, relations between the CC index and the SWSA were investigated in different spatial scales at midnight (03 JST) and noon (12 JST). Figure 6 shows the scatter diagram for 1-, 10-, 15-, and 40-km scales of the CC index. At midnight, the SWSA increased as the CC index (concave topography) increased, especially for scales of more than 10 km. The borderline for a CC index to change the SWSA from a positive to a negative signature was 200 m at a 1-km and 500 m at a 10-km scale. For stations with negative CC indices (concave topography), the relation between CC and SWSA was not clear, indicating that stations at the bottom of a deeper valley (basin) did not always record a weaker wind speed. Above the 15-km scale, positive and negative SWSAs coexisted at the same CC-index levels, indicating that stronger nocturnal winds at high elevations appeared with concave topographies at less than approximately a 10-km scale. At noon, the larger CC index provided a smaller SWSA. In concave topographies (negative CC values), this relation was more evident at approximately a 15-km scale. Additionally, negative and positive SWSA coexisted at more than 15-km scales, indicating that isolation of the station point should not be evaluated on such a large scale.

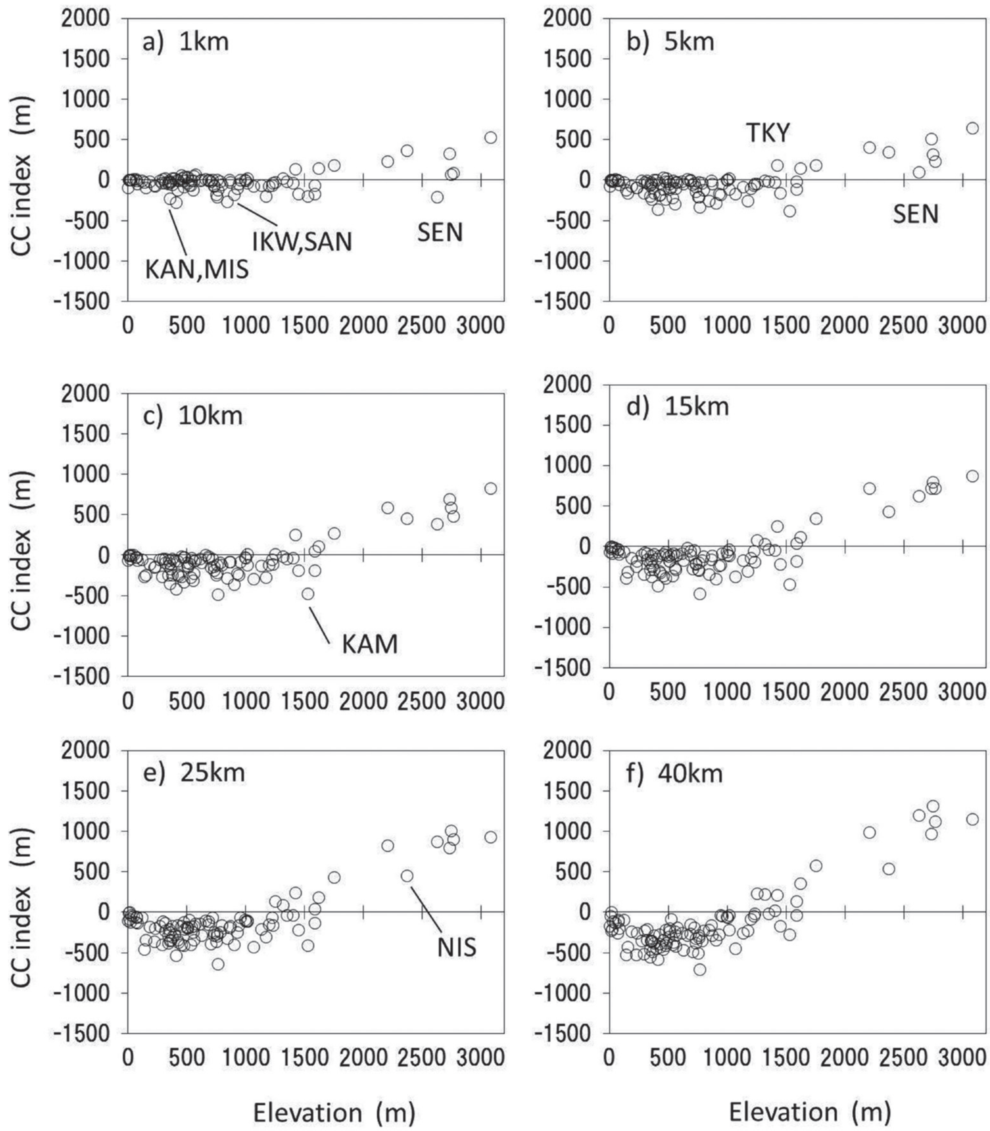

Fig. 5. Relations between elevation (m) and CC index calculated in six different spatial scales. Abbreviations stand for the station names, as indicated in Fig. 1.

6. Conclusion

Diurnal variations of surface wind speeds were examined in central Japan using the JALPS mountain observation network together with AMeDAS data for 71 fair days in July and August, 2010–2013. AMeDAS stations were located below 1500 m and mostly recorded stronger (weaker) daytime (nighttime) wind speeds. However, most station data from above 2000 m archived by the JALPS project showed reversed relations, such that wind speeds were stronger at night than during the day. The CC index in different spatial scales was defined around each station. Most of the AMeDAS stations were categorized as having flat or concave topography within a 5-km spatial scale. The TKY site at 1420 m is located in the convex condition, but the daytime wind speeds were higher than at night. Stations above 2000 m were located in convex topography, except that Senjyo-jiki at 2630 m was categorized as having concave topography within a 5-km scale, and wind speeds were lower at night than during the day. The

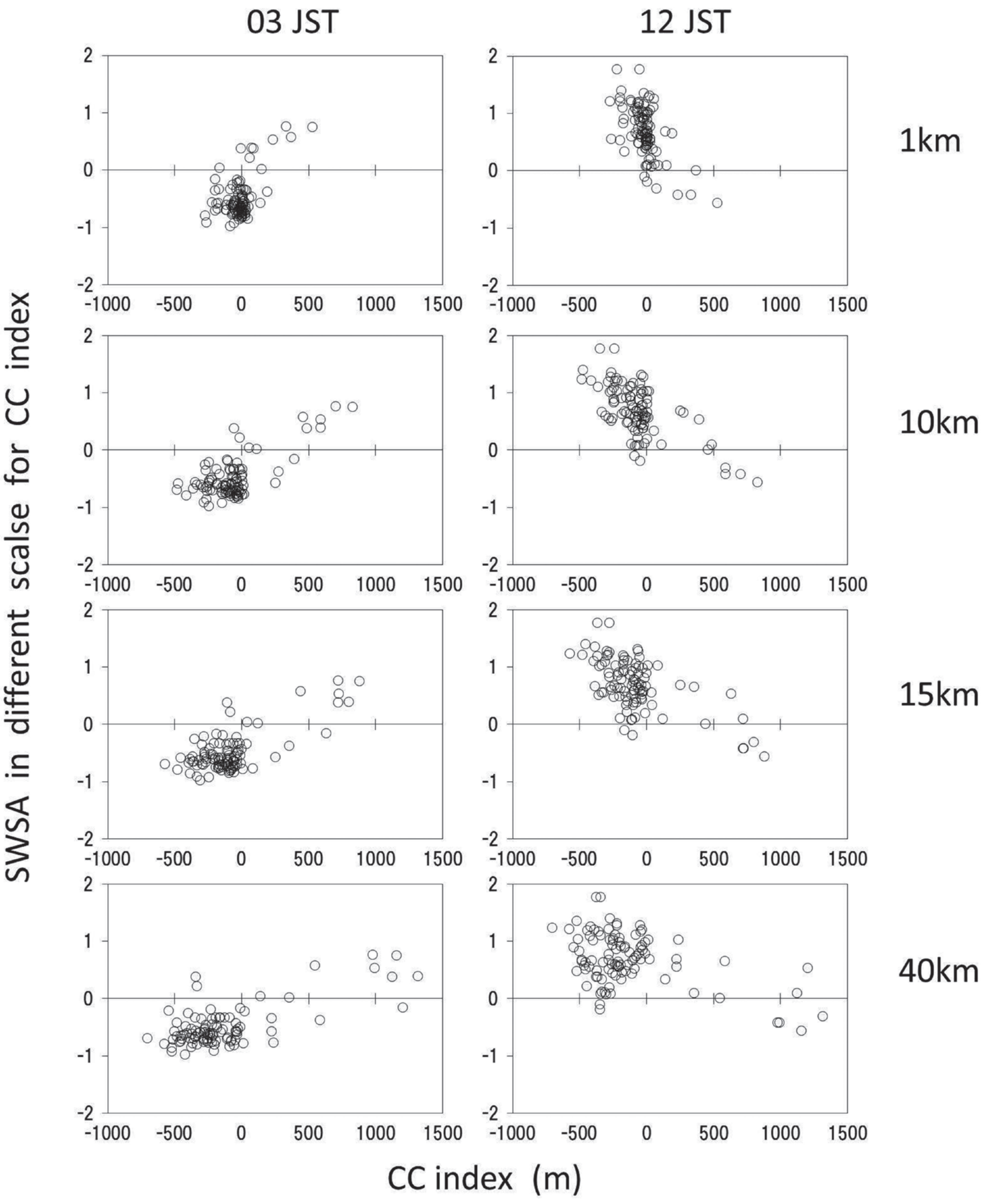

Fig. 6. Relations between the CC index and averaged SWSA at 03 JST (left) and 12 JST (right) in 1-km, 10-km, 15-km, and 40-km spatial scales.

seesaw of daytime and nocturnal wind speeds was not only defined by the absolute elevation but was affected by the concave-convex topographical condition. Especially, nocturnal wind enhancement is difficult to detect at stations with convex conditions in the 1- to 5-km scale above 2000 m because the surface boundary layer, due to the local topography, will become an obstacle to upper general winds. Unfortunately, clear altitudinal borders for changing the sign of wind speed anomalies from daytime to nighttime were not determined because of the lack of observation points near the 2000-m level; further data archives from different organizations, such as prefectures or private facilities, are expected.

At night, larger positive CC indices caused more positive SWSAs, especially in a 10-km spatial scale. Only for stations with concave topographies (negative CC indices), such as AMeDAS stations, did the magnitude of the CC index not relate to the wind speed, indicating that stations in deeper valleys are not always associated with weaker nocturnal winds due to katabatic flows. At noon, both positive and negative SWSAs prevailed at concave stations in more than 15-km scales, indicating that the isolation at a station point should not be evaluated in such large scales. Nocturnal-positive SWSAs at representative mountaintop stations appeared on fair days with prevailing Pacific Highs, and synoptic disturbances disturbed the diurnal variation of SWSA. Representative days with strong nocturnal winds at the mountain top stations were not always the same for the four stations, and the amplitude of SWSAs also differed day by day, even in similar synoptic weather patterns. Comparisons between the general wind speeds and in-situ data considering wind directions for the mountain ranges and their placement are expected using objective analysis data.

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