1. Introduction

The atmospheric conditions near the Earth’s surface exhibit variations over a wide range of time scales. The wind speed spectrum of Brookhaven, NY, had spectral peaks corresponding to fluctuations of approximately 1 min and 4 d, which apparently correspond to atmospheric turbulence and synoptic changes, respectively (van der Hoven 1957). Turbulent variations in air temperature can be as rapid as 1 K/s or more (Ibbetson 1978). Numerous theoretical and observational studies have been conducted to understand the detailed features of atmospheric turbulence.
Kudoh et al. 1982; Yoshino 1984; Toritani 1985). Ookubo et al. (2005) reported large temperature variations on time scales of approximately 1 h around Lake Suwa (Fig. 8 shows the location of the Suwa station) under strong cooling during winter nighttime. Nitta and Sakata (2007) made a similar analysis for the former Ina station. Generally, studies on sub-hourly temperature variations are limited to case studies. Compared with the vast knowledge about atmospheric turbulence on shorter time scales and atmospheric meso- to synoptic-scale systems on longer time scales, knowledge about the statistical features of sub-hourly temperature variations are limited. Therefore, the dominant types of variations at different times of the day and under different atmospheric conditions are unknown, as well as whether the temperature variations documented in the case studies are a common feature of the boundary layer or limited to a specific location and atmospheric condition.

The Automated Meteorological Data Acquisition System (AMeDAS) provided 1 min surface air temperature, wind, sunshine duration, and precipitation data dating back to 2010 from approximately 1000 stations. These data enabled us to investigate the statistical features of temperature variations on time scales of 1 h or less. This study aims to analyze the sub-hourly variations of surface air temperature by using these data from a climatological viewpoint to identify the regional and seasonal features of such variations. This analysis combines spectral analysis with statistical procedures.

Given that the atmospheric processes in the boundary layer are complex, many types of sub-hourly temperature variations with various causal mechanisms can exist. However, this study focuses on the representative features of sub-hourly temperature variations that can be detected by statistical procedures. This is the first step toward acquiring basic knowledge about the climatological features of sub-hourly temperature variations in Japan. Considering that it is likely that the mechanisms of sub-hourly temperature variations are too complicated to be covered in this study, we have not investigated these in detail. However, a brief analysis was conducted to investigate the relationship between temperature and wind speed variations.

2. Data and representative cases of temperature variation

2.1 Data

One-minute data covering the period from March 2011 to February 2015 from the AMeDAS were used in this study. Air temperature, wind direction, wind speed, sunshine duration, and precipitation were recorded in units of 0.1°C, 36 points of the compass, 0.1 m s⁻¹, 1 min, and 0.5 mm, respectively. On the basis of the criteria that missing data should be less than 10% during the 4-year period, 917 stations were selected for the analysis (Fig. 1).

Temperature observations were made using two types of platinum resistance thermometers. The JMA-10 type equipment with a 3.2 mm (diameter) protective tube around the thermometer is installed at staffed stations, special automated weather stations, and aviation weather stations. The response time, defined by the e-folding time for stepwise temperature changes, is approximately 20 s (Japan Meteorological Agency 2011). Temperature was measured every 10 s and was processed into 1 min running averages. For example, the temperature at 1500 JST is the average of temperature measurements taken from 14 h 59 m 10 s to 15 h 00 m 00 s, which is an average of temperature measurements of more than 1 min because the
response time of the thermometer is approximately 20 s. Among the 917 AMeDAS stations used for the analysis, 232 stations have thermometers of this type. The other stations have the JMA-04B type equipment with a 6 mm (diameter) protective tube around the thermometer having a response time of approximately 90 s. Temperature was measured every 10 s and the data were used without time averaging. Both types of thermometers filter out turbulent variations on time scales less than 1 min, although those on longer time scales may be retained. In Appendix A, the results of the analysis of data from stations equipped with different types of thermometers are compared to check for systematic differences.

The thermometer is installed 1.5 m above the ground at most stations. However, some JMA-04B type stations, particularly those located in the region extending from the western coast to the inland area of northern and central Japan, have thermometers installed at higher levels to avoid problems due to deep snow cover. The results obtained with data from stations with different thermometer heights are compared in Appendix B to check for possible biases due to the difference in thermometer height.

The 1 min data of wind speed and wind direction give the range of their variations during each minute measured using a vane anemometer. The anemometer height at most stations is 10 m or less. However, it is higher than 10 m at 200 stations, out of which 23 stations have anemometer heights greater than 30 m. Given that bias due to the difference in anemometer height is possible, the results of wind speed analysis for stations with anemometer heights of 10 m or less and stations with anemometer heights over 10 m are shown separately.

2.2 Representative cases of temperature variation

Figure 2 shows the time series of daytime temperature and wind on August 3, 2014, at the Narita station (see Fig. 8 for location), which is located in the Narita International Airport. The weather was sunny under the dominance of the subtropical high with temperature variations on time scales of 5–10 min and amplitudes of ~0.5 K. Additionally, short-term wind speed and direction variations were observed. However, the relationship between wind and temperature variations is complicated. For example, the temperature minima at approximately 1140 and 1300 JST corresponded to low wind speeds, as indicated by the solid arrows in Fig. 2, whereas those at approximately 1225 and 1340 JST did not correspond to low wind speeds, as indicated by the dashed arrows.

Figure 3 shows three representative cases of nighttime variations observed under strong cooling at (a) Narita, (b) Sugadaira, and (c) Taiki. These variations have larger amplitudes and longer time scales than those shown in Fig. 2. The relationship between wind and temperature variations is different for different cases. The high temperature at Narita was accompanied by high wind speed, although the wind direction varied between west and northwest. The high temperature at Sugadaira corresponded to a moderate wind speed of ~1 m s$^{-1}$ with the wind direction varying from north to east, and the low temperature corresponded to weak winds from the south or west. The correspondence between temperature and wind is not obvious at Taiki, where the temperature minimum at approximately 0235 JST corresponded to the minimum wind speed, whereas the temperature minima at approximately 0210 and 0300 JST occurred under high wind speeds. It should be noted that the relationship between wind and temperature at a station can be different for different cases. At Narita, for example, the correspondence between temperature and wind speed is not always so obvious as in the case shown in Fig. 3a.
3. Procedure of statistical analysis

3.1 Time filtering

To isolate the short-term components of temperature variations, a time filter was used in the form

\[ T'(t) = T(t) - \bar{T}(t), \]

where \( T(t) \) is temperature at time \( t \), and \( \bar{T}(t) \) is the time averaged temperature defined as

\[ \bar{T}(t) = \frac{\int T(t')G(t' - t)dt'}{\int G(t' - t)dt'}, \]

where \( G(t) \) is a Gaussian weight function defined as

\[ G(t) = \exp\left[-\left(\frac{t}{\tau}\right)^2\right]. \]

The window length (\( \tau \)) was set to 60 min to capture variations on time scales of approximately 1 h or less. Additionally, an analysis based on \( \tau = 30 \) min was made for the comparison of results obtained with different values of \( \tau \).

3.2 Calculation of the power spectrum

The power spectrum of \( T'(t) \) was calculated using fast Fourier transform (FFT) (Hino 1977) for each 2 h interval (0000–0200, 0200–0400, …, 2200–2400 JST) during the analysis period. An interval length of 2 h was chosen because it was long enough to capture relatively slow variations on time scales of up to 1 h and short enough to resolve the diurnal cycle of the variation. Considering that FFT requires a data length of \( 2^n \), where \( n \) is an integer, it was applied to 128 values extending into the next interval by 8 min (for example, values obtained from 0001 to 0208 JST were used to calculate the power spectrum for the period of 0000 to 0200 JST). Hereafter, the power spectrum is denoted by \( E(f) \), where \( f \) is the frequency. Frequency smoothing was not applied to \( E(f) \) because the statistical analyses described in Section 3.3 are expected to have a smoothing effect.

It should be noted that the integral of the power spectrum, which is given by

\[ V_0 = \int_{0}^{\infty} E(f) df, \]

is equal to the variance of \( T'(t) \), and the partial integral, which is calculated as

\[ V(f_1, f_2) = \int_{f_1}^{f_2} E(f) df, \]

gives the variance accountable for variations in the frequency range between \( f_1 \) and \( f_2 \). In subsequent analyses, \( V(f_1, f_2) \) was temporally averaged over the specified season and time interval of the day.

Fig. 3. Representative cases of nighttime temperature and wind variations. The arrows indicate the times at which temperature maxima and minima occur (see text).
To examine the sensitivity of the spectrum to the filter width (τ), the \( V(f_1, f_2) \) values calculated with \( τ = 60 \text{ min} \) and \( τ = 30 \text{ min} \) were compared. Figure 4 shows the relationship between the \( V(f_1, f_2) \) values at each station calculated with the two values of \( τ \) for 1000 to 1600 JST (hereafter referred to as daytime) of June to August (hereafter referred to as summer) and those for 2200 to 0400 JST (hereafter referred to as nighttime) of December to February (hereafter referred to as winter). The calculation was made for three frequency ranges corresponding to periods of over 64 min, 64 to 16 min, and 16 min or less. The variances calculated with \( τ = 30 \text{ min} \) for periods of over 64 min, 64 to 16 min, and 16 min or less are 27–28 %, 66 %, and 90–92 %, respectively, of those calculated with \( τ = 60 \text{ min} \) for the respective periods. Therefore, the spectra for periods shorter than 64 min calculated with \( τ = 60 \text{ min} \) and \( τ = 30 \text{ min} \) are not significantly different. The subsequent analysis is based on the variance calculated with \( τ = 60 \text{ min} \) for periods of 64 min or less given by

\[
V(1/64, \infty) = \int_{1/64}^{\infty} E(f) df,
\]

which will be denoted by \( V_{64}^{(T)} \) hereafter. Filtering with \( τ = 30 \text{ min} \) leads to the underestimation of variance to a certain extent; however, the main features of the results are unchanged.

### 3.3 Statistical analysis

The climatological features of temperature variation were examined by averaging \( E(f) \) and \( V_{64}^{(T)} \) over stations, days, and time intervals of the day.

The analysis of the dependence of temperature variation on weather conditions was based on the categorization of cases according to temperature and wind speed averaged over each 2 h interval and according to the sunshine duration and amount of precipitation during the 2 h interval. The temperature and wind speed quantiles defined for each station and each 2 h interval of the day of each month were used. High and low temperature cases were defined as the upper one third and lower one third of the total cases, respectively. Similarly, high and low wind speed cases were defined as the upper one third and lower one third of the total cases. Sunny and no-sunshine cases were defined as sunshine durations of 90 % or more and 0 %, respectively. Precipitation cases were defined by precipitation of 0.5 mm or more during the 2 h interval and 2 h preceding this interval to avoid cases of isolated showers under mostly sunny weather.

### 3.4 Analysis of wind speed variations

The power spectrum of wind speed was calculated following the same procedure as that of the temperature power spectrum calculation described in Sections 3.1 and 3.2. The integral of the power spectrum for periods of 64 min and less, defined as in Eq. (6), is denoted by \( V_{64}^{(W)} \) hereafter.

The cross spectrum of temperature and wind speed was calculated using FFT to examine the relationship between temperature and wind variations. The integral of the power spectrum for periods of 64 min and less is denoted by \( C_{64} \) hereafter. \( C_{64} \) is a complex variable; a positive real part corresponds to an in-phase vari-
ation of temperature and wind speed and a positive imaginary part indicates a phase advance of wind speed over temperature. In this study, $C_{64}$ is used in a normalized form as

$$C'_{64} = C_{64}/\sqrt{V'^{2}_{64}/V^{2}_{64}}.$$  \hspace{0.5cm} (7)

Note that the absolute value of $C'_{64}$ is coherence, which is unity if temperature and wind speed variations are exactly in phase.

4. Results

4.1 Seasonal and diurnal variations of temperature variance

Figure 5 shows the boxplots of annual daytime and nighttime variation of $V^{(t)}_{64}$. The daytime $V^{(t)}_{64}$ is large from March to September with a smaller amount of scatter among stations than the nighttime $V^{(t)}_{64}$. The nighttime $V^{(t)}_{64}$ from November to April has a large amount of scatter with large mean values, corresponding to the presence of a small number of stations having exceptionally large variances. In other words, the large variations shown in Fig. 3 are not a common feature. Nighttime temperature variations at many other stations are much weaker.

Figure 6 shows the diurnal variation of $V^{(t)}_{64}$ during summer and winter. In summer, $V^{(t)}_{64}$ is larger during daytime than during nighttime. In winter, nighttime $V^{(t)}_{64}$ shows a large amount of scatter from 1600 JST to 0800 JST, during which some stations show extremely large temperature variations, although the mean value of $V^{(t)}_{64}$ is almost independent of the time of the day.

4.2 Regional features

Figure 7 shows the $V^{(t)}_{64}$ values during summer daytime and winter nighttime for the four regions of Japan (defined in Fig. 1). There is little regional difference between the summer daytime values. However, winter nighttime $V^{(t)}_{64}$ values increase toward the north.

Figure 8 shows the location of the 46 stations with values of $V^{(t)}_{64}$ above the 95th percentile of $V^{(t)}_{64}$ during winter nighttime (0.148 K^2). Among the 46 stations, 6 are located in central Honshu. These stations are Nobeyama, Sugadaira, and Tateshina, which are located on the mountainsides in the inland region at...
1350, 1253, and 715 m, respectively, above the mean sea level, and Narita, Kita-ibaraki, and Namie, which are located along the east coast at 41, 5, and 47 m, respectively, above the mean sea level. The other 40 stations are located in Hokkaido, mainly in the eastern part. However, some stations, including those located in eastern Hokkaido, show relatively small values of $V_{64}^{(T)}$, as shown in the bottom right panel of Fig. 8 for the Tokachi Plain. Therefore, nighttime temperature variation is a highly localized feature.

Figure 9 shows the topography around Narita, Sugadaira, and four stations in the Tokachi Plain having large $V_{64}^{(T)}$ values. The Narita station is located near the edge of a hill that is oriented in the NNE–SSW direction and is intruded by a valley from the northwest. The Sugadaira station is located on a ridge extending

![Topographic maps of the 10 km × 10 km area surrounding each station at the center (indicated by a dot) with the station name and the respective $V_{64}^{(T)}$ value during winter nighttime indicated at the bottom of each map. Contours are drawn at an interval of 2 m for (a), 40 m for (b), and 10 m for (c) to (f). Elevations are shown in meters.](image-url)
from the east and divided by valleys in the NW–SE direction. Therefore, the two stations are located on a col, although the topographic steepness differs by more than an order of magnitude. Regarding the stations in the Tokachi Plain, Obihiro-izumi is located on a col formed by a NE–SW oriented ridge and a NW–SE oriented valley, whereas Taiki, Kamisatsunai, and Ikeda are located on downward slopes in the SE, NE, and SW directions, respectively. Figure 10 shows the topography around Urahoro and Nukanai, which are located in the Tokachi Plain and have relatively small values of $V_{64}^{(T)}$ for comparison. These stations are located in the center of a valley extending southward and northeastward, respectively.

Another analysis was conducted to investigate the possible effects of water surface. Land-use data on grids of $30^\circ$ in latitude and $45^\circ$ in longitude were obtained from the “Digital National Land Information” website of the Ministry of Land, Infrastructure, Transport and Tourism of Japan for this analysis. The fraction of water surface around a station ($\alpha$) was calculated using a Gaussian weight in the form

$$\alpha = \frac{\sum_i \exp \left(-\frac{(r_i)^2}{R^2} \right) w_i}{\pi R^2},$$

where $w_i$ is fraction of water surface in the grid $(i)$, $r_i$ is the distance from the station to the center of the grid $(i)$, and $R$ is a given parameter that controls the domain size for calculation. Given that nighttime temperature variations seem to depend on topography on the scale of one to several kilometers, three values of $R$ (1, 3, and 10 km) were used (Figs. 9, 10). Only the results obtained for $R = 3$ km are shown because the results obtained for all the three $R$ values were qualitatively the same.

Figure 11 shows the box plots of $V_{64}^{(T)}$ for stations with $\alpha \geq 0.5$, $0.05 \leq \alpha < 0.5$, and $\alpha < 0.05$, corresponding to 93 coastal stations, 433 intermediate stations, and 391 inland stations, respectively. The value of $V_{64}^{(T)}$ tends to decrease with increasing $\alpha$ during both summer daytime and winter nighttime, with a larger decrease in $V_{64}^{(T)}$ observed during winter nighttime. No station in the $\alpha \geq 0.5$ category has $V_{64}^{(T)} \geq 0.15$ K$^2$.

Among the 46 stations with $V_{64}^{(T)}$ values over the 95th percentile of $V_{64}^{(T)}$ during winter nighttime, the three stations with large $\alpha$ values are Tokoro ($V_{64}^{(T)} = 0.169$ K$^2$, $\alpha = 0.33$), Mombetsu-komukai ($V_{64}^{(T)} = 0.200$ K$^2$, $\alpha = 0.32$), and Kita-ibaraki ($V_{64}^{(T)} = 0.163$ K$^2$, $\alpha = 0.25$). These stations are located 1–2 km from the coastline (shown in Fig. 8). The Tokoro station is located near the mouth of a river facing the Sea of Okhotsk to the north, with a hill a few kilometers to the east. The other two stations are located near the foot of a hill having an inclination of 1% or more. The complex terrain in the environs implies that the topography affects the temperature variations at these stations. However, the influence of the sea may be small because land and mountain breezes are expected to dominate during nighttime under strong cooling with low ambient winds.
4.3 Dependence of temperature variation on weather conditions

Figure 12 shows $V_{64}^{(T)}$ values under different weather conditions defined in Section 3.3. The $V_{64}^{(T)}$ values during summer daytime tend to be larger in high temperature cases and sunny cases than in low temperature cases and no-sunshine cases, respectively. However, there is little difference between the $V_{64}^{(T)}$ values in low and high wind cases. As defined in Section 3.3, low/high temperature cases and low/high wind cases account for one third of the total cases, respectively. The proportions of sunny cases and no-sunshine cases are 25.8 % and 23.1 % of the total cases, respectively. Precipitation cases account for 8.0 % of the total cases on the average over stations.

The $V_{64}^{(T)}$ values during winter nighttime are larger in low temperature cases and low wind cases than in high temperature cases and high wind cases, respectively. Low temperature and low wind cases (accounting for 13.1 % of the total cases on the average over stations) show the largest mean value of $V_{64}^{(T)}$, although the 95th and 99th percentiles are almost the same as those of low temperature cases. The $V_{64}^{(T)}$ values are small for precipitation cases, which accounts for 9.8 % of the total cases.

4.4 Time scale of temperature variation

Figure 13 shows the temperature power spectra $E(f)$ for summer daytime and winter nighttime averaged for all the stations. Additionally, the average power spectrum for winter nighttime at the 46 stations with $V_{64}^{(T)}$ values above the 95th percentile of $V_{64}^{(T)}$ is shown. No spectral peaks were observed in the power spectra for summer daytime and winter nighttime, thus implying the absence of characteristic time scales in temperature variations. However, the ratio of $E(f)$ during winter nighttime to that during summer daytime decreases with increasing frequency, as shown in Fig. 14. This indicates that low frequency variations are more dominant during winter nighttime than during summer daytime; this finding is implied by the representative cases shown in Figs. 2 and 3.

Fig. 12. Box plots of $V_{64}^{(T)}$ during summer daytime and winter nighttime for each weather condition.

Fig. 13. Power spectra of temperature variations during summer daytime and winter nighttime averaged for all the stations. Additionally, the power spectrum of the average temperature variations for the 46 stations with $V_{64}^{(T)}$ values above the 95th percentile of $V_{64}^{(T)}$ is shown. Power is shown in $fE(f)$ instead of $E(f)$ (defined in Section 3.2) to mitigate its strong dependence on frequency.

Fig. 14. Ratio of the power during winter nighttime to power during summer daytime for all the stations and for the 46 stations with $V_{64}^{(T)}$ values above the 95th percentile of $V_{64}^{(T)}$. 
4.5 Variation of wind speed in relation to temperature

The box plots in Fig. 15 show the diurnal variation of $V_{64}^{(W)}$ during summer and winter at stations with anemometer heights ($H_a$) of 10 m or less. It can be seen that values of $V_{64}^{(W)}$ tend to be larger during winter daytime than during summer nighttime. The amount of scatter among stations is relatively small during summer and large during winter, particularly during nighttime. Figure 16 shows the scatter diagrams of $V_{64}^{(T)}$ and $V_{64}^{(W)}$ with the different colored dots representing stations with $H_a \leq 10$ m and $H_a > 10$ m. The values of $V_{64}^{(T)}$ and $V_{64}^{(W)}$ during summer daytime have a weak negative correlation of $-0.12$ if only stations with $H_a \leq 10$ m are considered ($-0.06$ if all the stations are considered). However, during winter nighttime these values have a positive correlation of 0.23 if only stations with $H_a \leq 10$ m are considered ($0.15$ if all the stations are considered). The correlation between $V_{64}^{(T)}$ and $V_{64}^{(W)}$ during winter nighttime is statistically significant at the 1% level. This indicates that temperature variations during winter nighttime are related to wind speed variations to a certain extent. However, the low correlation and large amount of scatter among stations imply that the relationship between temperature variation and wind variation is not strong. Twenty of the stations with $H_a \leq 10$ m and $V_{64}^{(W)}$ values over 0.4 m$^2$ s$^{-2}$ show $V_{64}^{(T)}$ values less than 0.1 K$^2$, with the exception of a station with $V_{64}^{(T)} = 0.12$ K$^2$. These stations are located either in the coastal areas or on the northwestern side of Honshu and Hokkaido, thus implying that strong northwesterly wind events during the winter monsoon is accompanied by large fluctuations in wind speed but not in temperature. By contrast, stations having large $V_{64}^{(T)}$ values show relatively small values of $V_{64}^{(W)}$ ($\approx 0.2$ m$^2$ s$^{-2}$ or less), thus indicating that the large temperature variations during winter nighttime are not accompanied by large variations in wind speed. This feature remains unchanged when $V_{64}^{(W)}$ is normalized by averaged wind speed as $V_{64}^{(W)}/u_0$, where $u_0$ is the average wind speed of the specified season and time of the day at each station (not shown).

Figure 17 shows the normalized cross spectrum ($C_x^{(x)}$) at each station during summer daytime and winter nighttime. The $C_x^{(x)}$ at most stations during summer daytime has a negative real part and a negative imaginary part. This indicates that the temperature variation in summer is related to the wind speed variation. During winter nighttime, however, the real part is positive, indicating that temperature variations during winter are not directly related to wind speed variations. This feature remains unchanged when $V_{64}^{(W)}$ is normalized by averaged wind speed as $V_{64}^{(W)}/u_0$. The correlation between temperature variation and wind variation is thus not strong.
peak will tend to coincide with or lag behind the minimum wind speed. The $C_{64}'$ during winter nighttime has a positive real part corresponding to in-phase variations of temperature and wind speed. However, the coherence is relatively low (~0.2 or less) at many stations, which is in agreement with the poor correspondence between temperature and wind speed variations in certain cases (Figs. 2, 3).

5. Discussion

The amplitudes of daytime temperature variations are larger during warm seasons than during cold seasons. These variations are observed throughout the country with a relatively small amount of scatter among stations. This indicates the existence of a common mechanism for the generation of such variations. According to the findings of a number of studies on daytime mixing layer (Monji 1981; Weijers et al. 1995a, b; Horiguchi et al. 2014), these variations are likely caused by large-scale turbulence and convective motion, although the high-frequency variations may be lost because of the long response time of thermometers (Section 2.1). The occurrence of daytime variations in both high and low wind cases and the reduction of amplitude of variation in low temperature and no-sunshine cases does not conflict with this speculation. The tendency of the temperature peak to coincide with or lag behind the minimum wind speed is indicated by the cross-spectrum analysis (Fig. 17a). This feature is in agreement with the result of Weijers et al. (1995a, b), who showed a negative relationship between temperature and horizontal wind speed by applying statistical procedures to “temperature ramp” cases.

By contrast, the temperature variation during winter nighttime has a large amount of scatter among stations. Exceptionally large variations were observed at some stations located in northern and eastern Japan, particularly at stations located in eastern Hokkaido. Regarding the effect of weather conditions, temperature variations are pronounced under low temperatures and low wind speeds. This implies that strong surface cooling is a necessary condition for large variations. Additionally, the strong localization of temperature variation implies the significance of topographical effects on the generation of temperature variation.

Stations with large nighttime variations are located on a col or a slope, as shown in Fig. 9. It is expected that the surface cold air is easily removed downslope at these sites. A number of observational studies at Sugadaira revealed repeated discharge and accumulation of surface cold air accompanied by wind and temperature variations during nighttime (Nakamura 1978; Kudoh et al. 1982; Yoshino 1984; Toritani 1985). Similar variations were observed at other mountainsides (Doran and Horst 1981; Owada et al. 1995). However, drainage winds may not be the only cause of nighttime temperature variations. Under the temperature inversion of the nocturnal surface layer, any kind of disturbance causes vertical mixing that is accompanied by an increase in temperature and wind speed; this is in agreement with the tendency for the in-phase variations of temperature and wind speed (Fig. 17b). Such disturbances can be produced by internal gravity waves (Yokoyama et al. 1981, 1984), Kelvin–Helmholtz instability (Zhou and Chow 2014), and other unspecified phenomena. Interestingly, some stations with large $V_{64}'$ values during winter nighttime

Fig. 17. Normalized cross spectra of temperature and wind speed ($C_{64}'$) during summer daytime and winter nighttime.
have relatively low correlation between temperature and wind speed (Fig. 17b), whereas stations showing large wind variations tend to show small temperature variations (Fig. 16b). Strong nocturnal inversion is likely a key factor for large temperature variations. Under weak inversion, the temperature variation is expected to be weak even in the presence of strong wind variations. However, under strong inversion, even a small disturbance can produce a large temperature variation because of the large vertical gradient of potential temperature. The high proportion of stations located in eastern Hokkaido that have large temperature variations can be explained by strong nighttime cooling in this region (Yazaki et al. 2017). This is because this region is located downwind of mountains under northwesterly winter monsoon, and therefore the temperature often drops below −20°C under clear and calm conditions.

However, large temperature variations were not observed at all the stations with strong nighttime cooling. At Nukanai, which is shown in Fig. 10, the average daily minimum temperature in January is −19.1°C, which is lower than that at Taiki (−16.9°C). Therefore, the small variance at Nukanai cannot be attributed to weak nighttime cooling. It is rather likely that well-developed cold air lakes formed in the center of the valley are so stable that they cannot be easily disturbed to generate temperature variations. This may explain why large nighttime temperature variations are limited to a small number of stations, although strong nighttime cooling is a widespread feature over land.

Regarding the spatial scale of variation, Kudoh et al. (1982) reported weakly correlated temperature variations at two sites located several hundred meters apart with an altitude difference of 50 m on a slope of Sugadaira. Ookubo et al. (2005) performed intensive observations at the Suwa Basin, where 12 stations were deployed around Lake Suwa, and found nearly in-phase variations at two pairs of sites located 500 m and 2 km apart. These cases imply that nighttime variations can have a horizontal scale of several hundred meters or more, although other cases may have different spatial features.

Another interesting result of this study is that the \( V_{64}^{(T)} \) at Suwa, for which Ookubo et al. (2005) reported some cases of large temperature variations, is only 0.035 K\(^2\) during winter nighttime. This value is below the average value of the country (0.062 K\(^2\)). Ookubo et al. (2005) observed that large temperature variations at Suwa were rare events with only 13 remarkable cases, which correspond to extremely strong cooling over the frozen surface of Lake Suwa, in 30 years. It is implied that large temperature variations can occur even at places where the temperature variation is usually weak if certain conditions are satisfied.

Although our study focuses on only the dominant features of sub-hourly temperature variations, many other types of variations that are limited to specific regions and occasions, in addition to those discussed above, may exist. For example, temperature variations at some stations are related to the boundaries of local air masses. Nagasawa and Miyakawa (1980) described the rapid temperature change observed in the northeastern part of Hokkaido due to the alteration of foehn winds and sea breezes. Large temperature variations can also occur along the boundary between cold inland air and warm maritime air (Fujibe 1990, 1992). Cooling due to isolated showers is another cause of temperature variations, particularly at stations located on the southern islands in Japan, where sunny weather with intermittent showers during summer cause temperature changes of a few degrees. It is expected that the results of the present study will serve as a guide for more detailed studies on sub-hourly temperature variations.

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**Appendix A: Comparison of results obtained with different thermometer types**

Figure A1 shows the box plot of \( V_{64}^{(T)} \) for 232 stations with the JMA-10 type equipment and 685 stations with the JMA-04B type equipment. These thermometers have different response times and use different data processing methods (see Section 2.1). There is little difference between the results obtained from the two groups of stations for both summer daytime and winter nighttime.

However, a higher proportion of stations with the JMA-10 type equipment are located near the coast and on small islands than stations with the JMA-04B type equipment. Each JMA-10 type station was paired with a JMA-04B type station located in its vicinity with similar topographical conditions to avoid possible bias due to topographical differences, except for 46 JMA-10 type stations having no suitable JMA-04B type stations in their vicinity. Figure A2 shows the box
plot of $V_{64}(T)$ for the 186 paired stations. There is little difference between the results obtained from the two groups of stations. Therefore, we can deduce that the use of different thermometer types does not affect the results obtained.

**Appendix B: Comparison of results obtained with different thermometer heights**

As discussed in Section 2.1, some JMA-04B type stations have thermometers installed at a height of 2 m or more. These stations are generally located in regions with deep snow cover in northern and eastern Japan. Here the $V_{64}(T)$ values at stations in northern and eastern Japan are compared by categorizing stations according to thermometer height ($H_t$) into three groups: $H_t < 2$ m, $2$ m $\leq H_t < 3$ m, and $H_t \geq 3$ m; the numbers of stations categorized into these three groups are 276, 131, and 45, respectively.

Figure A3 shows the box plots of $V_{64}(T)$ for the three groups of stations and all the stations. It can be seen that stations with $H_t \geq 3$ m tend to have smaller values of $V_{64}(T)$ than the stations in the other groups, during both summer daytime and winter nighttime. However, this difference is small. The results of the statistical analysis for all the stations and stations with $H_t < 2$ m are similar. Therefore, the difference in thermometer heights of different stations is not likely to affect the analysis.

**References**


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