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GEOGRAPHICAL VARIATIONS IN SEASONAL CHARACTERISTICS OF NOCTURNAL COOLING IN CENTRAL JAPAN

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Abstract Geographical variations in nocturnal cooling are investigated using statistical analyses of routine observational data in central Japan. Seasonal variations in the relationships between nocturnal cooling intensity and topographic features are investigated in terms of synoptic atmospheric conditions and derived mesoscale circulation. Cluster analysis demonstrates that nocturnal cooling types can be classified into six main categories. Seasonal patterns of each cooling type are associated with the origin of weak wind conditions. Weak winds in inland areas are of down-slope winds that drain cold air, whereas those in coastal areas are weak synoptic winds. Nocturnal cooling is strengthened with altitude up to around 700 m during spring and summer, likely caused by the effect of water vapor gradient.

Keywords: nocturnal cooling, cluster analysis, seasonal variation, wind system, central Japan

1. Introduction

Geographical variations in the intensity of nocturnal cooling result from the horizontally nonuniform, radiative and thermal properties of land surfaces, which are known to differ strongly at various topographic scales. Local climatological studies often focus on local topographic features in basins or valleys, whose nocturnal cooling affects the formation of nocturnal atmospheric phenomena such as cold-air pools and drainage flows (Whiteman 1990). On the other hand, seasonal or daily variations in nocturnal cooling at local basins or valleys are governed by synoptic and mesoscale atmospheric conditions (Iijima and Shinoda 2000, 2004) that may be modified by surrounding large-scale topography. Several studies, therefore, have focused on geographic variations in nocturnal cooling. For example, in Japan, statistical analyses have been performed using routine observational data. Kondo and Mori (1982) suggested that variations in intensity of nocturnal cooling in the southern part of the Tohoku District depended heavily on the local-scale topography and that this increased with altitude. Maki and Harimaya (1984) performed a principal component analysis to investigate the spatial pattern of daily nocturnal cooling over Hokkaido. The principal component patterns were associated with extreme cooling over inland areas that is primarily due to the "blocking effect" of mountains against ambient winds aloft.

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As mentioned above, geographical variations in nocturnal cooling are primarily controlled by the characteristics of the surrounding terrain, which modifies atmospheric conditions. No attempt has been made to reveal geographical variations in nocturnal cooling over central Japan, however, even though it has various scales of topography. Therefore, the present study focuses on the geographical differences in nocturnal cooling in plains, basins, and mountainous areas of central Japan, and performs several statistical analyses using routine observational data to clarify the seasonal relationship between nocturnal cooling and topographical features.

2. Data

In the present study, the effect of the geography of central Japan on the nocturnal cooling characteristics is examined using hourly data from the Automated Meteorological Data Acquisition System (AMeDAS) of JMA (Japan Meteorological Agency). The study area ranges from 34.5° to 38°N and from 134° to 141°E and the analysis uses 262 stations in this region. The horizontal topographic scale, that is, the distance between the mountain ranges and the width of each basin and plain, is approximately 100 km in central Japan while the vertical scale of each mountain range is 2- 3 km.

In the present study, the nocturnal cooling intensity (NCI) used by Kondo and Mori (1982) is defined by the following equation:

$$NCI = T_s - T_{min}, \quad (1)$$

where T_s (°C) represents the air temperature at sunset and T_{min} (°C) is the minimum temperature during the night. Since astronomical sunset times differ by only approximately 15 minutes in the eastern and western ends of the region, the time at which the sun set was taken as the center of the study area (36.5°N, 138.5°E). Daily NCI values are calculated from 1990 to 1999, and mean monthly NCI is used for the cluster analysis.

3. Cluster Analysis of the Nocturnal Cooling

In order to classify the geographical variations in nocturnal cooling, a cluster analysis using the un-weighted pair-group average method is conducted for monthly averaged NCI values from 1990 to 1999 for all 262 AMeDAS stations. Cluster analysis, as principal component analysis done in Maki and Harimaya (1984), is useful for summarizing climatological data and finding the spatial factors that control variation of the samples.

Based on the cluster analysis, the 262 stations are divided into six clusters whose threshold was a Euclidean distance of 13.0 (Fig. 1a). Of all clusters, Cluster 1 shows the strongest nocturnal cooling (Fig. 1b); average NCI for this group exceeds 6°C in winter (December, January, and February). The stations in this cluster extend over the inland areas of the Kanto Plain and Kofu Basin (Fig. 1c). These areas are well-known to have a strong surface inversion layer during the cold season (Yoshino 1972). Cluster 2 exhibits a different seasonal NCI change from Cluster 1 (Fig. 1b), with biannual peaks in spring (April) and autumn (October). The stations in Cluster 2 extend widely over central Japan, especially its inland basins and plains (Fig. 1c). Cluster 3 has strong nocturnal cooling as well, while the biannual peak appearing in April and October is more apparent than in Cluster 2 (Fig. 1b). This cluster's stations are in inland basins, such as the Aizu, Fukushima, and Nohbi basins (Fig. 1c), which are influenced by the winter atmospheric conditions of the Japan Sea. For Cluster 4, distinct peaks are observed in spring (April) and autumn (October), although nocturnal cooling is weak and less than 5°C (Fig. 1b). The stations are located along the Japan Sea (Fig. 1c). Cluster 5 has seasonal variations similar to Cluster 1, with weak nocturnal cooling (Fig. 1b). This cluster is restricted to areas along the shore on the Pacific side (Fig. 1c). Finally, for Cluster 6, nocturnal cooling is weak throughout the year, and it has no clear peak (Fig. 1b). The stations of Cluster 6 are located on the shore, islands, and on mountain peaks (Fig. 1c).

Based on the intensity and seasonal variations of NCI, Clusters 1, 2 and 3 can be categorized as the "inland plain and basin type," Cluster 4 as the "Japan Sea shore type," Cluster 5 as the "Pacific shore type," and Cluster 6 as the "coastal, island, and mountain ridge type."

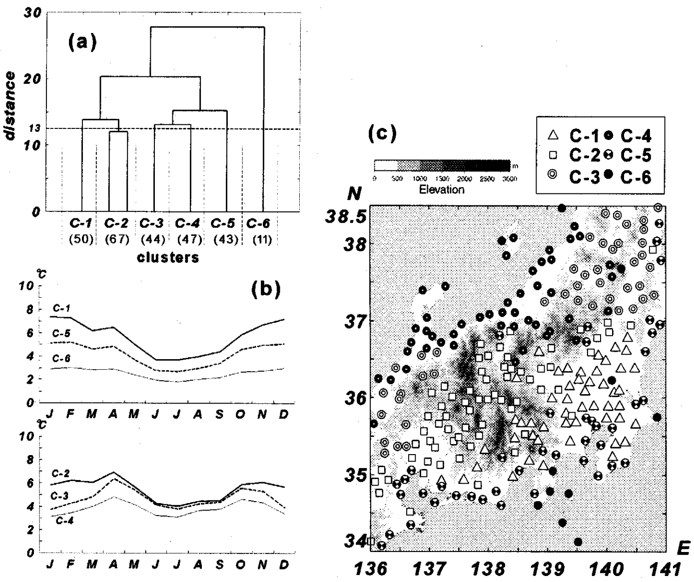

Fig. 1 Results of cluster analysis of nocturnal cooling intensity (NCI).
(a) Dendrogram of cluster analysis, (b) seasonal variation of NCI in each cluster, and (c) geographical distribution of each cluster.

4. Seasonal Changes in the Geographical Distribution of Nocturnal Cooling

The typical geographical distribution of NCI for each season is depicted by a composite of strong nocturnal cooling days (Fig. 2). In each year for 10 years, the most typical 5 days in each season with more than 8°C of regional mean NCI of Clusters 1, 2, and 3 are sampled, except in summer, when those with NCI of 6°C are sampled, giving 50 days for each season (= 5 days x 10 years). In spring, the region whose strong nocturnal cooling exceeds 10°C spreads widely over central Japan zonally along the inland area (Fig. 2a). Interestingly, the region with strong nocturnal cooling spreads beyond the topographical scale of individual basins. Although the intensity of nocturnal cooling is weakest in summer (Fig. 2b), the distribution pattern then is similar to that in spring. In particular, a horizontal gradient of nocturnal cooling clearly exists along the Pacific coast. This gradient might be associated with the sea breeze, since the gradient was mostly found in a zone that stretches inland about 30 km from the seashore. According to the numerical simulations of Ookouchi *et al.* (1979) and Kondo (1990), the effects of the sea breeze are likely to reach about 30 km inland from the shore. In addition, the sea breeze is enhanced from spring through summer (Kuwagata 1997), so that nocturnal cooling on the Pacific-side plain is likely suppressed due to intrusion of wet sea air, as also shown in Iijima and Shinoda (2004). In autumn, there is a relatively complicated distribution of areas with strong nocturnal cooling (Fig. 2c). Areas with strong nocturnal cooling whose value is more than 10°C tend to appear in each basin. In winter, the center of strong nocturnal cooling shifts southward and is restricted to the area on the Pacific side (Fig. 2d). The region with strong nocturnal cooling coincides with the area classified as Cluster 1, namely, the northern inland part of the Kanto Plain (Fig. 1c). Its strong nocturnal cooling forms under a typical synoptic pressure pattern, that is, the winter monsoon type with strong northwesterly winds. These results imply that the central mountainous basin is one of the areas with remarkable nocturnal cooling throughout the year.

Figure 2 also shows the distribution of average surface nocturnal winds in each season. In spring (Fig. 2a), winds of more than 1 m s^{-1} are observed along the coastal areas of the Tokai District and the Japan Sea, and in the north part of the Kanto Plain. These relatively strong winds might be due to a combination of synoptic winds and land breezes (Suzuki 1992; 1994). In summer (Fig. 2b), wind speed is weak in most areas. Suzuki (1993) indicated that the frequency of calm conditions inland on the Kanto Plain at night is the highest in August throughout the year, since local circulation (such as mountain winds) is not well developed because of weaker nocturnal cooling. On the other hand, a sea breeze component is shown to act in the southern coastal area of the Kanto Plain. In autumn (Fig. 2c), the wind system is similar to that in spring, while wind speeds in inland basins are relatively strong. Most wind directions in the inland plains and basins coincide with the mountain slope (probably because down-slope winds are induced by nocturnal cooling). In coastal areas, the winds coming from the land nearly perpendicular to the coast indicate a land breeze. In winter (Fig. 2d), strong northwesterly winds are found in the Kanto Plain and from the Nohbi Plain to the coastal areas of the Tokai District, westerly winds are found from the Niigata Plain to Sendai Plain, and relatively weak north winds are found in inland basins. This wind system corresponds with the Type III wind system defined by Kawamura (1966). The Type III is associated with the anticyclonic pressure pattern over central Japan formed after eastward passage of the winter monsoon pressure pattern.

Figure 3 shows the relationships between NCI and nocturnal wind speeds for the 50-day seasonal averages shown in Fig. 2. The nocturnal wind speeds denote average values from 18 to 6 JST. NCI is substantially enhanced under the weak wind conditions for all seasons. In spring, autumn and winter, extreme nocturnal cooling whose NCI exceeds 10°C forms when winds are about 1 m s^{-1} or less. Most stations that have weak wind speeds and larger NCIs are in the basin or inland plain areas (Clusters 1, 2 and 3) in all seasons. On the other hand, stations in coastal areas (Clusters 4, 5 and 6) are characterized by strong winds and low nocturnal cooling. It should be noted that differences in NCI exist between clusters, even though the wind speeds are identical. Kondo and Mori (1982) and Maki and Harimaya (1988) also analyzed the relationship between intensity of nocturnal cooling and nocturnal wind speed. They suggested that nocturnal cooling has different sensitivities toward wind speed, and the sensitivities are associated with each station's geographical position. Kondo and Mori (1982) implied that differences in nocturnal cooling depend on local topographical features less than 1 km around each station. Suda (1990) suggested that nocturnal wind directions in the inland area of central Japan changed with wind speed depending on topographic scales. That is, weak winds (about 1 m s^{-1}) are produced by thermally induced circulation that is governed by small-scale topography 10 km around the point, while strong winds (4 m s^{-1}) are associated with larger-scale topography 35 km around the area due to channeling effects on synoptic winds. Thus, it appears that the weak winds over central Japan are produced by two different conditions that both affect nocturnal cooling. Specifically, the weakened ambient (synoptic) winds have a small effect on nocturnal cooling in coastal areas, and down-slope (cold-air drainage) flow enhances nocturnal cooling in the inland plains and basins.

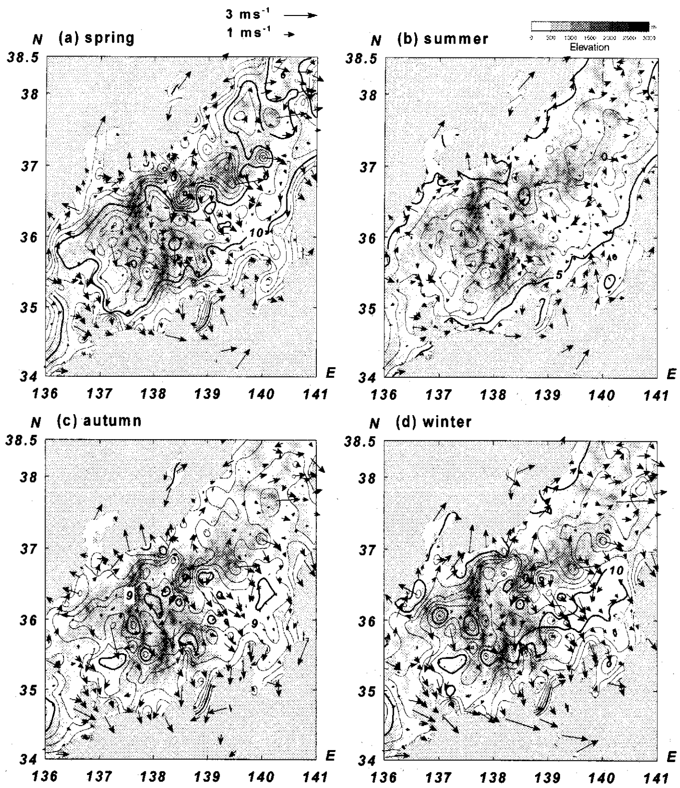

Fig. 2 Composite of geographical distributions of NCI and nocturnal wind in each season for typical 50-day mean from 1990 to 1999 (5 days in each year). The contour interval of NCI is 1°C.

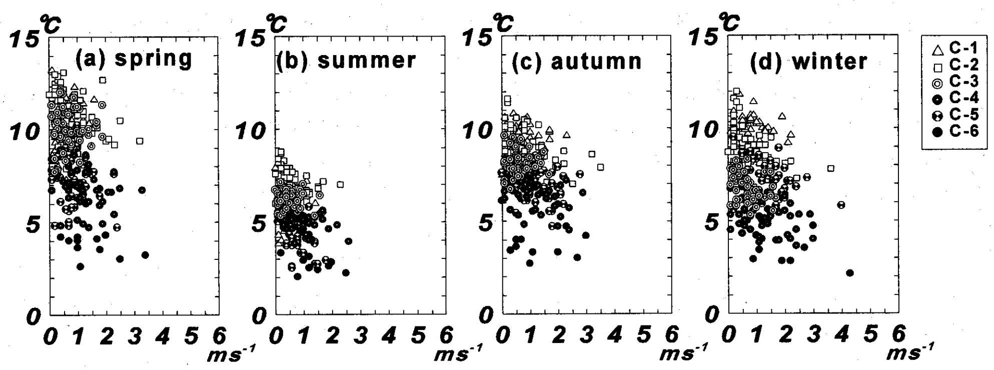

Fig. 3 The relationship between nocturnal wind speed and NCI in each season for typical 50-day mean from 1990 to 1999.

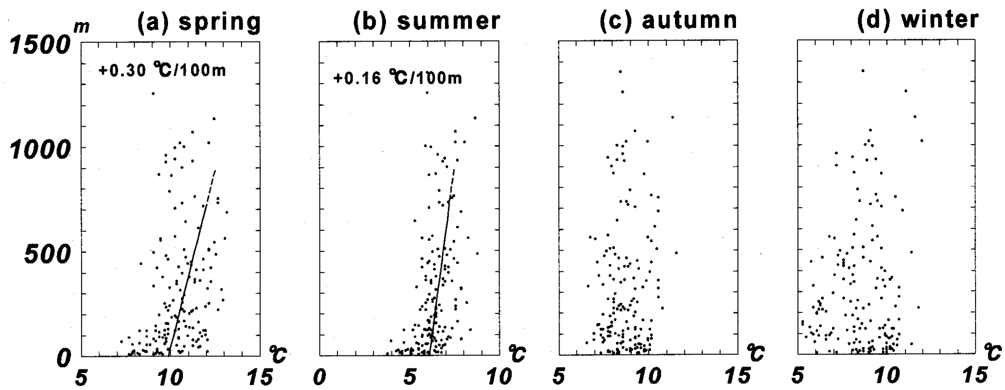

Fig. 4 The relationship between NCI and altitude in each season for typical 50-day mean from 1990 to 1999. The stations classified as Clusters 1, 2, and 3 are used in this figure. The lines in (a) and (b) represent regression lines estimated by the least square method averaging over a 50 m altitudinal interval.

5. Altitudinal Difference in the Nocturnal Cooling

The relationships between altitude of each station and the 50-day mean NCI values of each season are shown in Fig. 4. Here, in order to understand the differences in nocturnal cooling from the inland plains to mountainous basins where there are few direct effects of sea breezes and synoptic winds, we used inland stations identified as Clusters 1, 2 and 3. Nocturnal cooling for spring and summer days increases with altitude up to an altitude of around 700 m (Figs. 4a and 4b). Regression lines in Figs. 4a and 4b are estimated using the least-squares method on NCI data averaged over 50-m intervals from 0 to 700 m. The correlation coefficients between averaged NCI and altitude are statistically significant at the 1% level. The gradients demonstrate the altitudinal effect of enhanced nocturnal cooling and the gradients are 0.30℃ /100 m and 0.16℃ /100 m in spring and summer, respectively. It appears that the existence of significant gradients in spring and summer is likely due to altitudinal differences in water vapor content of the total atmospheric column, which induces a difference in atmospheric longwave radiation as theorized by Kondo (1982). In addition, since an extended sea breeze is dominant over central Japan under fine spring and summer weather conditions, water vapor is effectively transported inland (Kimura *et al.* 1997). On the other hand, nocturnal cooling and altitude do not exhibit obvious trends during autumn and winter days (Figs. 4c and d). This implies that nocturnal cooling in lower plains occurs as well as in the basins since sea breeze effects tended to be weak, while the down-slope and/or land breeze winds become dominant, even in coastal plains.

6. Conclusions

In the present study, we examine geographical variations in central Japan's nocturnal cooling among plains, basins, and mountainous areas, based on statistical analyses of AMeDAS data. Specifically, we highlight the seasonal relationship between nocturnal cooling and topographical features, which are modified by synoptic atmospheric conditions and meso-scale circulation.

A cluster analysis demonstrated that nocturnal cooling types are divisible into six areas based on seasonal variation and intensity of nocturnal cooling: the inland plain and basin type (Clusters 1, 2, and 3) with strong autumn and winter peaks, the Japan Sea shore type (Cluster 4) with spring and autumn peaks, the Pacific shore type (Cluster 5) with weak autumn and winter peaks, and the coastal island and mountain ridge type (Cluster 6) with the weakest nocturnal cooling. The center of strong nocturnal cooling is located in the inland plains and basins throughout the year. In addition, there is an increasing horizontal gradient of nocturnal cooling within several dozen kilometers from the Pacific coast during spring and summer days. These patterns are associated with surface wind conditions. In particular, nocturnal cooling under weak wind conditions differs substantially between inland (strong nocturnal cooling) and coastal (weak nocturnal cooling) areas. We conclude that this difference results from the different origins of the weak wind. Specifically, weak winds in inland areas consist of down-slope winds that drain cold air, whereas those in coastal areas consist of weak synoptic winds.

This study also shows that nocturnal cooling increases with altitude up to around 700 m during spring and summer. This altitudinal gradient is likely caused by the effect of an extended sea breeze that transports water vapor inland.

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