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THE INFLUENCES OF THE SEA ICE AND THE WIND FIELD ON THE WINTER AIR TEMPERATURE VARIATION IN HOKKAIDO

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Abstract: Variations of air temperature in Hokkaido during winter are characterized by the presence of two minima in ten-day normals; days 21–30 (end of January) and days 41–50 (middle of February). We name this tendency the "W-phenomenon", which is significant in the northern coastal area of Hokkaido facing the Sea of Okhotsk. The second minimum occurs when the ice cover is most extensive along the Okhotsk coast of Hokkaido. We examine this relation using rotated principal component analysis (RPCA). The RPCA results show that the second mode is a factor of the ice cover that is related to the second minimum. However, the correlation coefficient between rotated principal components of the second mode and ice concentration is rather low, −0.56. The RPCA results also show that the wind field is another factor that governs the "W-phenomenon". The relationship between the rotated principal components and wind directions shows that the drop in temperature in Hokkaido is associated with not only heavy ice cover but also northeasterly wind. Two mechanisms of the northeasterly wind system are expected: weak winds from an anticyclone over Okhotsk ice cover off Hokkaido and strong winds from a cyclone over the Pacific Ocean off the southeast coast of Hokkaido. Both these cases are possibly caused by the heavy ice cover in the Sea of Okhotsk. In the former mechanism, the wind directly carries cold air flow cooled over the sea ice. In the latter, the heavy ice cover prevents cyclones from moving into the Sea of Okhotsk.

1. Introduction

The Okhotsk coast of Hokkaido is often covered with sea ice during winter (Fig. 1). A relationship between Okhotsk sea ice and air temperature in Hokkaido has been indicated since early in the 1900s. Most of the studies were focused on the relationship between the ice cover and the weather of the following spring and summer in Hokkaido (*e.g.*, ANDO, 1915; FUKUTOMI, 1950; CHISHIMA, 1962; SCHELL, 1972; AKAGAWA, 1980). On the other hand, there have been only a few studies to examine the direct relationship between the ice cover and air temperature variations in Hokkaido during winter. CHISHIMA (1962) and OHASHI (1975) indicate that years with heavy (light) ice conditions in Abashiri are associated with below (above) average temperatures there. AOTA *et al.* (1988) shows that a drop in air temperature is seen in Mombetsu when ice concentration is high off the Okhotsk coast of Hokkaido, using ten-day mean values during February and March. CHISHIMA (1962) and OGATA (1976) indicate that the drop (rise) in air temperature is associated with the approach (retreat) of sea ice in

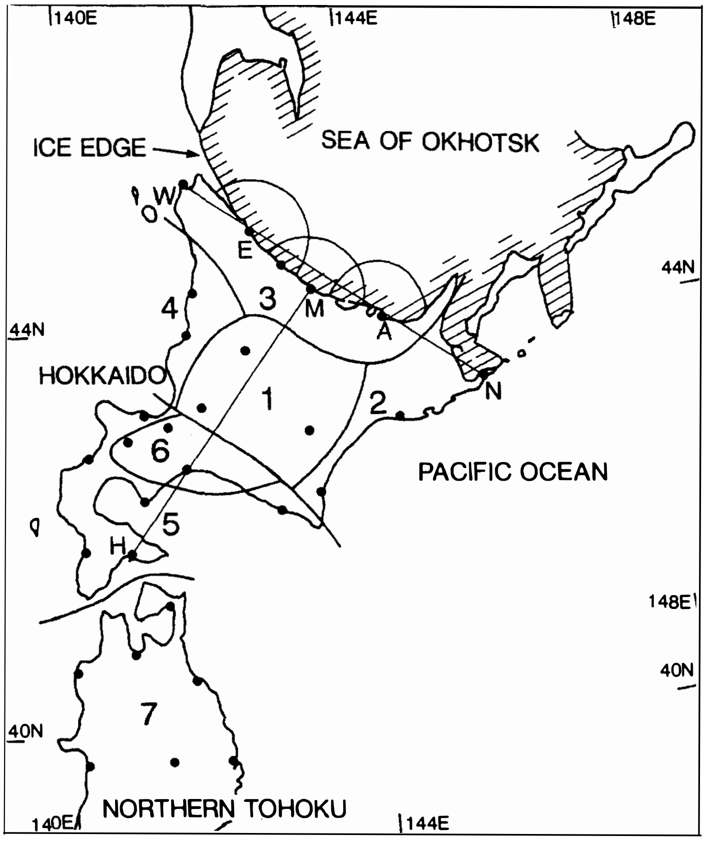


Fig. 1. A map of northern Japan. Hokkaido is divided into six areas based on a cluster analysis of daily mean air temperature, and northern Tohoku is included for comparison. Numbers (1–7) correspond to six areas of Hokkaido and an area of northern Tohoku. Weather stations are shown by solid circles. The coverage of the sea ice radar observation network is indicated by three semicircles along the Okhotsk Sea coast of Hokkaido. Mean ice edges on February 20 (1971–1990) are shown by the hatched belt. Letters indicate place names; W: Wakkanai, E: Esashi, M: Mombetsu, A: Abashiri, N: Nemuro and H: Hakodate. Two orthogonal lines (W–N, M–H) connect pairs of stations that are used to calculate surface winds in Section 5.1.

Abashiri. SATO (1983) suggests that the ice cover has an influence on the winter-air-temperature field of Hokkaido using 30-year normals of air temperature. Most of these studies were, however, performed only to examine the local relationship between the ice cover and the air temperature at a certain place (Abashiri or Mombetsu). Although the object of SATO's (1983) study is all areas of Hokkaido, this study is only based on 30-year normals.

In the present study, we use daily meteorological data in Hokkaido during winter for the years 1961–1990. The purpose of this paper is to understand the influence of sea ice on the winter-air-temperature field in Hokkaido using these data. This paper is organized as follows. Section 2 shows characteristics of winter air temperature variations in Hokkaido. In Section 3, we describe the data sets and the rotated principal component analysis used in this study. In Section 4, we show results of the rotated principal component analysis and discuss the relationship between the ice cover and variations of air temperature. We discuss the relationship between the wind field effect on the temperature field and the ice cover in Section 5. Finally, we summarize our results in Section 6.

2. Characteristics of Winter-Air-Temperature Variations in Hokkaido

Figure 2 shows 10-day normals of daily mean air temperature in Hokkaido and northern Tohoku during winter (January to March; days 1–90) based on data taken from the years 1961–1990. Hokkaido is divided into six areas (Fig. 1) based on cluster analysis of daily mean air temperature. In addition, an area of northern Tohoku is also considered for comparison, because this area is not affected by the ice cover.

Winter air temperature in most of Japan generally has a minimum during days 21–30 (end of January), and it monotonically increases after days 31–40 (early in February). This tendency is seen in northern Tohoku (Area 7). Variations of air temperature in Hokkaido, however, do not show this trend. There is another minimum during days 41–50 (middle of February). Since air temperature varies in a manner similar to the letter "W", we refer to this tendency as the "W-phenomenon". This phenomenon is most apparent in Area 3 (Okhotsk coast). The minimum during days 41–50 corresponds to a period when ice cover is most extensive along the Okhotsk coast of Hokkaido. If the ice cover simply prevents loss of oceanic heat to the atmosphere, a drop in temperature should occur only in the Okhotsk coast area near the ice cover. The minimum during days 41–50, however, also occurs in Areas 1, 2 and 4, although each of them is weaker than that of Area 3. This suggests that other meteorological elements also play some role in generating the second temperature drop.

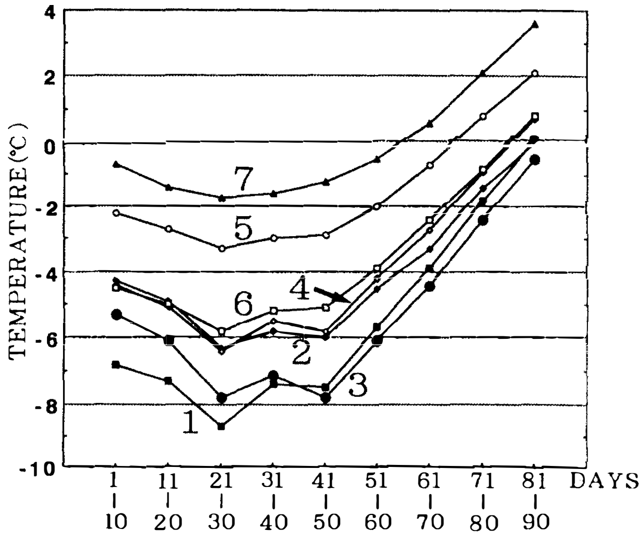


Fig. 2. Ten-day normals (1961–1990) of daily mean air temperature in winter (January to March). Numbers (1–7) correspond to seven areas shown in Fig. 1.

First, we performed rotated principal component analysis on the air-temperature data of Hokkaido to examine the influence of the ice cover on the air-temperature field. Then, we investigated the relationship between this influence and other meteorological elements.

3. Data and Analysis

3.1. Meteorological and sea ice data sets

Meteorological data used in this study are part of the Japan Meteorological Agency data sets, which consist of daily values of all surface meteorological elements for the years 1961–1990. We used data of daily mean air temperature and sea level pressure in Hokkaido (22 weather stations) during winter (January 1 to March 31; days 1–90). To obtain air-temperature-anomaly data, we first averaged values from the 30-year data for each calendar day at 22 stations. Then, we further averaged these values spatially to evaluate the Hokkaido mean values for each calendar day. Finally, we obtained the air temperature anomaly data by subtracting these Hokkaido mean values from the original data at each station. The reason that we obtained these anomaly data is to make the regional air temperature difference in Hokkaido clear. The anomaly data of 90-day time series of each year (30 years) were connected into 2700-day time series for each station (22 variables, 2700 observations) which formed the basis for the rotated principal component analysis (RPCA) described below. We calculated geostrophic winds from the daily mean pressure data in Section 4. Further, we used daily sea level pressure data from the National Meteorological Center (NMC) data sets, to examine synoptic scale patterns of the pressure field in Section 5.

The Institute of Low Temperature Science of Hokkaido University has maintained an ice-floe monitoring radar network on the northern coast of Hokkaido facing the Sea of Okhotsk since 1969. The network consists of three land-based radar stations (Esashi, Mombetsu and Abashiri, shown in Fig. 1) and allows continuous monitoring of the ice field along a 250 km coastline and 50 km seaward (AOTA *et al.*, 1988; AOTA and ISHIKAWA, 1993). We used the sea ice concentration data obtained using this radar network.

3.2. Rotated principal component analysis (RPCA)

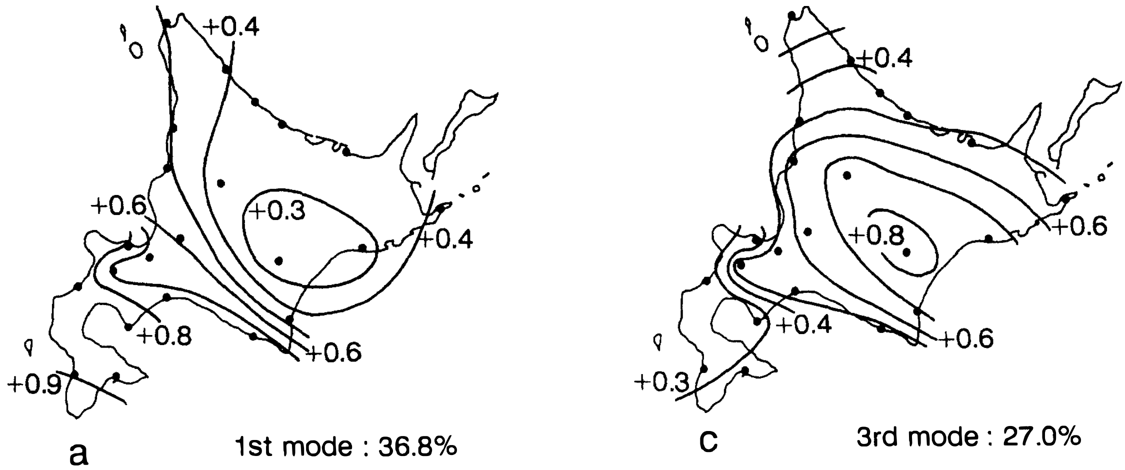
The anomaly data at each station were normalized to have mean 0 and variance 1. Then, we performed an RPCA on these anomaly data. To obtain RPCA solutions, we need principal component analysis (PCA) solutions as initial solutions. PCA is one method of multivariate statistical analysis, which reduces the original multivariate data set into the fewest number of significant independent components. The advantage of this technique in our study is that it is possible to examine the relationship between only the ice cover and air-temperature field, because we can extract the effect of the ice cover from many factors associated with air-temperature field. Since PCA solutions are sometimes difficult to interpret (HOREL, 1981), RPCA solutions are often used. RPCA solutions are obtained by transforming the initial solutions orthogonally. To obtain RPCA solutions, the proper number of principal components should be transformed. A comparison between PCA and RPCA solutions has been described in detail by HOREL (1981). Three types of results are obtained from the RPCA solutions: the rotated principal components themselves in time series, the amount of variance explained by the rotated principal components and the factor loadings, which are the spatial patterns associated with the rotated principal components and correspond to the correlation coefficients between the rotated principal components and the original time series.

In our PCA results, three principal components were valid. Nevertheless, it was difficult to interpret these solutions. Therefore, these three principal components were transformed using the varimax rotation method. We then obtained three rotated principal components.

4. Results of Rotated Principal Component Analysis

Figure 3 shows the spatial patterns of three factor loadings obtained by the RPCA. First, second and third modes account for 36.8, 27.4 and 27.0% of the total variance, respectively. Figure 4 also shows a time series of the rotated principal components based on 30-year means for each calendar day. Correlation coefficients between each rotated principal component and ice concentration are 0.02, −0.56 and −0.15, respectively (Table 1). To obtain these coefficients, we used 10-day means of data from 1969 to 1990. This result indicates that the second mode is relatively strongly related to the ice cover. Moreover, this mode has noticeably large values, close to +0.8, of the factor loadings along the Okhotsk coast (Fig. 3b). In addition, the time series of the rotated principal components of this mode has lower values during days 41–50, when ice cover is most extensive along the Okhotsk coast of Hokkaido, than those of other periods. These facts suggest that the air temperature along the Okhotsk coast is lower than that in other areas during days 41–50. Magnitudes of the drop in air temperature are proportional to values of factor loadings. This indicates that the ice cover has a weak influence on the air-temperature field in most of Hokkaido (Fig. 3b). The first and third modes are explained by other meteorological factors (Table 1). The former is related to synoptic meteorological variations, represented by the 500 hPa height. The latter is related to the regional contrast between inland and coastal areas, represented by the diurnal temperature range (daily maximum temperature–daily minimum temperature). This is because the diurnal temperature range of inland areas is generally larger than that of coastal areas.

According to RPCA results, it is possible to explain the "W-phenomenon" in Hokkaido. The minimum during days 41–50 (middle of February) is due to large, negative values of rotated principal components of the second mode. On the other hand, the minimum during days 21–30 (end of January) can be explained by normal, seasonal variations seen throughout Japan and by the third mode whose time series has large, negative values then. Therefore, the linear combination yields the two minima in Hokkaido. The second minimum is most apparent



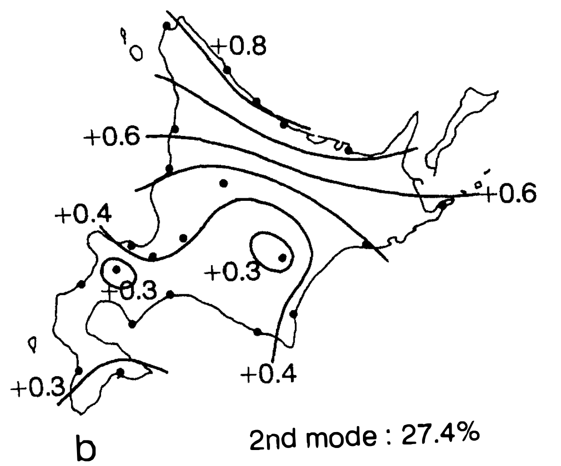


Fig. 3. *Spatial patterns of three factor loadings derived from anomaly data of air temperature in 30 winter seasons (1961–1990, January to March) by rotated principal component analysis. The factor loading at each point is the correlation coefficient between the time series of rotated principal components and the air temperature anomaly data. Percentages of variance described by factor loadings are shown for each map. The contour interval is 0.1.*

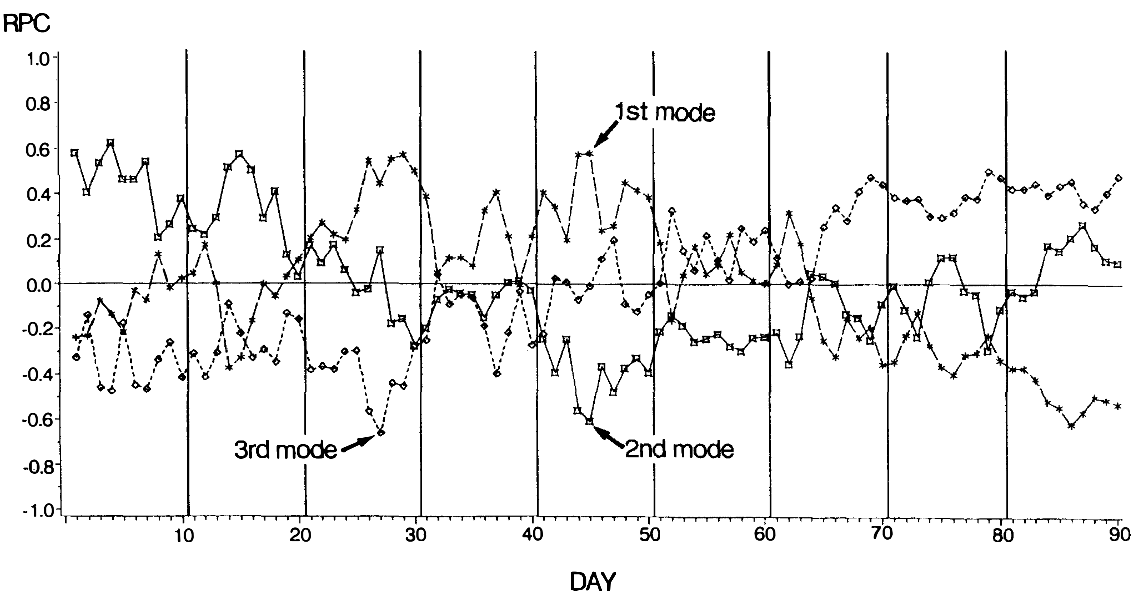


Fig. 4. *Time series of three rotated principal components (30-year means for each calendar day) derived from the same data set described in Fig. 3. RPC denotes rotated principal component.*

Table 1. Percentage of the total variance explained by each of three rotated principal components and correlation coefficients between the three components and meteorological factors; 500 hPa, ICE and DTR denote 500 hPa height over Hokkaido, ice concentration, and diurnal temperature range, respectively. For the first two factors, the correlation is taken between 10-day means of the meteorological factors and the rotated principal components (1969–1990, January to March). For DTR, the correlation is taken between 30-year means of DTR and factor loadings at each point.

Component number	Percent variance explained (%)	Correlation coefficient		
		500 hPa	ICE	DTR
1	36.8	**0.66***	0.02	−0.60
2	27.4	0.35	**−0.56***	−0.16
3	27.0	0.30	−0.15	**0.92***

*significant at 99% level.

in Area 3 (Okhotsk coast) where the second mode has large factor loadings and the first minimum is most apparent in Area 1 (inland) where the third mode has large factor loadings. In the southern part of Hokkaido (Area 5 and 6), conversely, the two minima are weak, because both second and third modes have small factor loadings in these areas.

We indicated that the second mode is related to ice cover from the RPCA results. Nevertheless, the correlation coefficient (−0.56) between the second mode rotated principal components and ice concentration is rather low, although it is significant at 99% level. This suggests that there must be other meteorological elements besides the ice cover which determine the temperature variations. To identify other elements, we examined sunshine duration, precipitation, pressure and wind. As a result, we found that wind is another important factor. We discuss this result in the next section.

5. Effects of Wind Field on Air-Temperature Field

5.1. Relationship between wind and temperature field

We derived the wind field on the scale of Hokkaido from the pressure field. First, geostrophic winds were evaluated using daily mean pressure data at two pairs of stations (Wakkanai and Nemuro, and Mombetsu and Hakodate, shown in Fig. 1). Then, these geostrophic winds (G) were converted into surface winds (U) using ALBRIGHT's (1980) values (U/G = 0.585 and turning angle of 30.0°). There are three reasons that we used the wind field calculated from the pressure field. (1) Observed wind data at each station are strongly influenced by local environment (topography, buildings, etc.). Furthermore, the statistical continuity of the data is interrupted by the renewal of instruments from cup type anemometers to propeller type anemometers in 1975. (2) Observed pressure data have high accuracy and there have been few missed observations over the 30 years. (3) This method is suitable for obtaining representative synoptic-scale winds in Hokkaido.

Figure 5 shows the dependence of the rotated principal components of the second mode on the surface wind direction. Heavy ice cases (ice concentration 90–100%) and light ice cases (0–49%) are shown in Figs. 5a and 5b, respectively. Squares show mean values of the rotated principal components in each 45-degree sector. These squares are smoothly connected by a thick curve in each case. Thin curves show the ranges of standard deviations. There is appreciable dependence

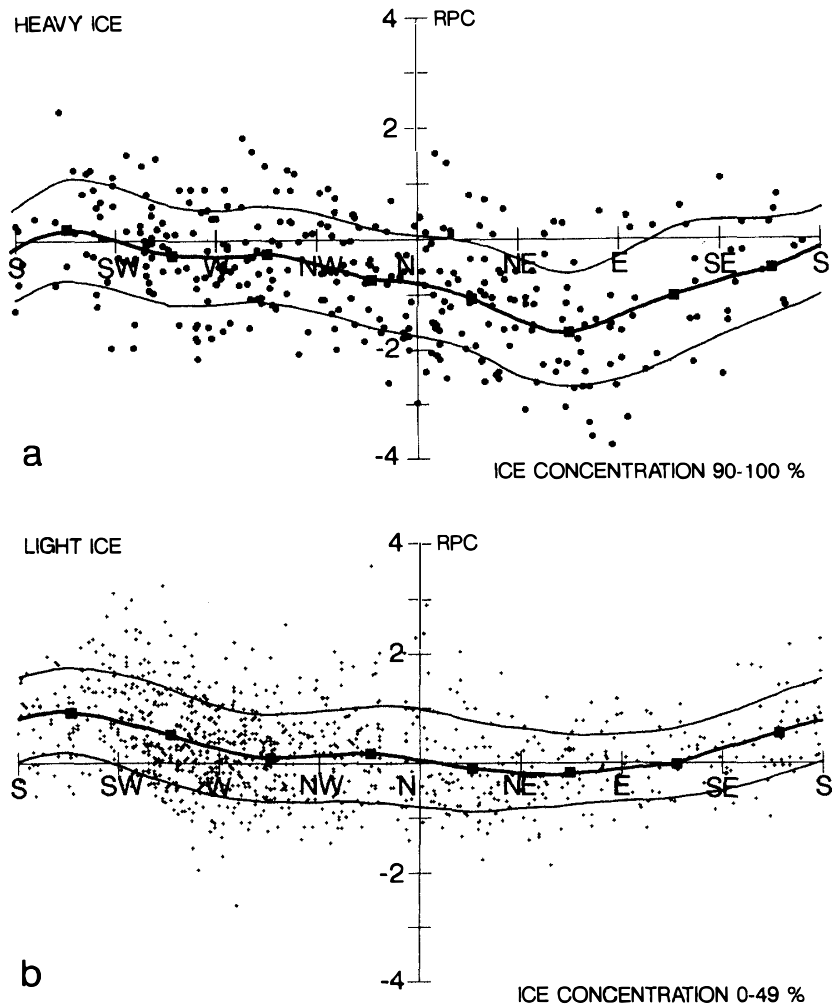


Fig. 5. Dependence of rotated principal components of the second mode on surface wind direction. (a) Heavy ice cases and (b) light ice cases are selected from daily values of the rotated principal components (1969–1990, January to March). Squares show mean values of the rotated principal components in each 45-degree sector (ex. N-NE, NE-E). These squares are smoothly connected by a thick curve in each case. Thin curves show the ranges of standard deviations. Since there are many dots on the lower panel, smaller dots are used to show all the data points clearly.

of the rotated principal components on wind directions for the heavy ice cases. In particular, most of the rotated principal components have negative values for northeasterly winds (N-ESE). In contrast, there is little dependence of the rotated principal components on wind direction for the light ice cases. For the air temperature along the Okhotsk coast to be lower than in other areas, therefore, northeasterly wind is needed as well as heavy ice cover.

Numbers of heavy ice-cover days (open circles) are shown in Fig. 6. Also shown are numbers of northeasterly wind days among the heavy ice-cover days (solid circles). These numbers for every 10 days are derived from data taken from 1969 to 1990. The heavy ice cover days generally occur during days 31–70 (from early in February to early in March). The highest numbers of northeasterly wind days among heavy ice cover days occur during days 41–50. Therefore, the above results suggest that air temperature during days 41–50 is somewhat lower than in other periods.

5.2. Northeasterly wind system

We next examine causes for the northeasterly winds. Two causes are considered: the cold air flow from an anticyclone that develops over the Okhotsk ice cover off Hokkaido and the cold air flow from a cyclone that develops over the Pacific Ocean southeast of Hokkaido. In general, the former system is characterized by weak winds and the latter is characterized by strong winds. To identify these two causes, we use composite charts of sea level pressure anomalies based on the NMC data sets (Fig. 7). First, we calculate an average sea level pressure field for days 31–70 based on 1969–1989 data (40 days × 21 years = 840 days).

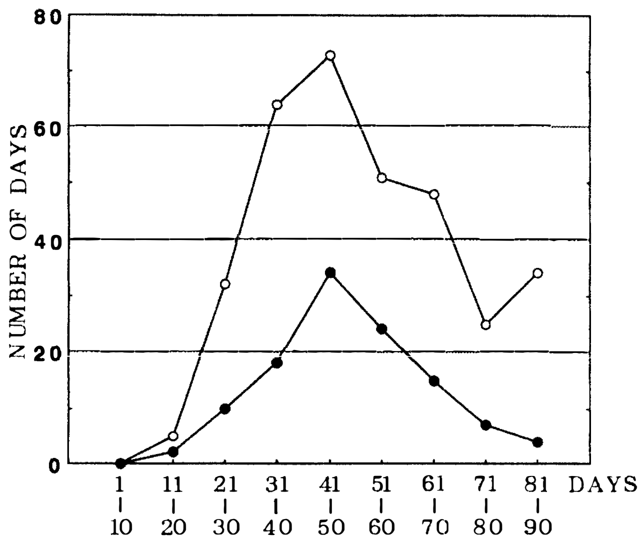


Fig. 6. Number of heavy ice cover days (open circles) and northeasterly wind (N-ESE) days among the heavy ice cover days (solid circles) (1969–1990, every 10 days). These numbers of days are selected from the total of 220 days (22 years × 10 days).

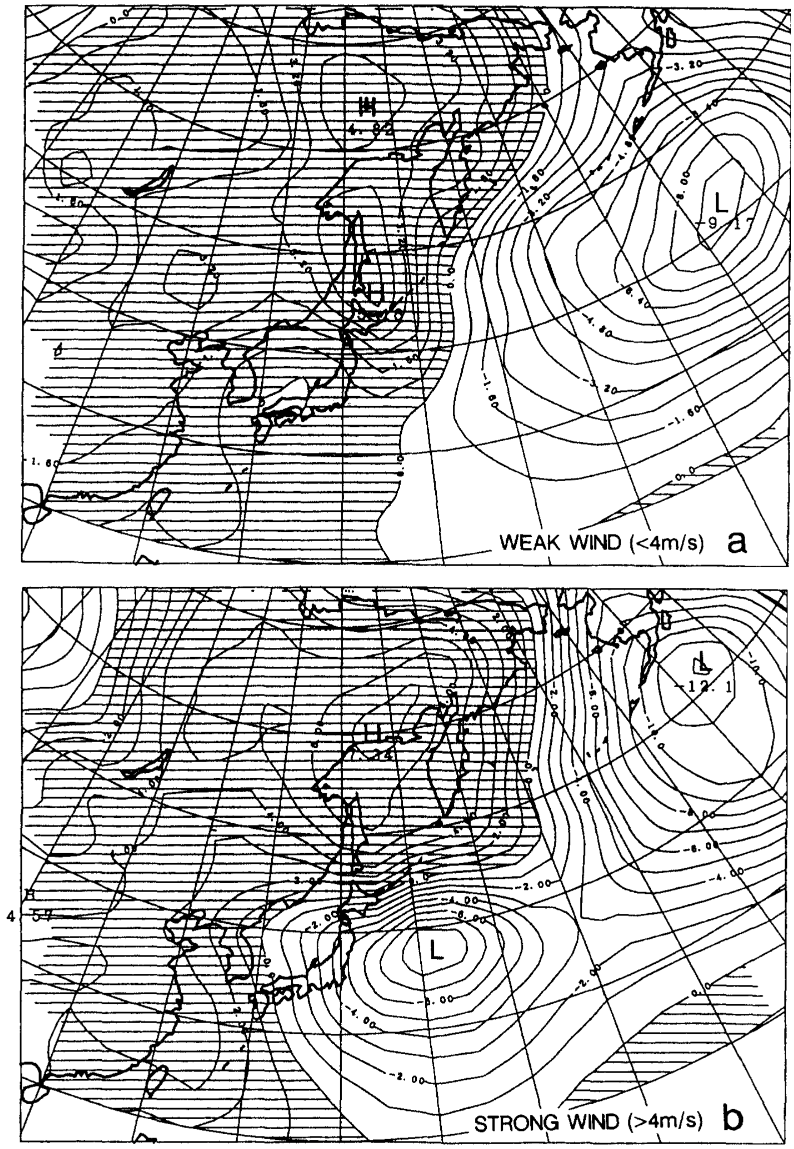


Fig. 7. Composite charts of sea level pressure anomalies for days 31-70 based on data from 1969–1989. Weak (<4 m/s, panel a) and strong (>4 m/s, panel b) northeasterly winds among heavy ice cases are shown. The contour intervals are 0.8 hPa in panel a and 1.0 hPa in panel b, respectively. Hatching indicates positive anomaly regions.

Days 31–70 coincide with the period of mean heavy ice cover (Fig. 6). Second, we select northeasterly wind days among heavy ice days from these 840 days. Third, we divide the heavy ice and northeasterly days into weak and strong wind days using a wind magnitude of 4 m/s at the surface. This is the mean value in Hokkaido during winter derived from the pressure field mentioned in the previous subsection. Fourth, we calculate average sea level pressure fields for both weak (< 4 m/s) and strong (> 4 m/s) wind days. Finally, we obtain the composite charts of sea level pressure anomalies by subtracting the average field of the 840 days from the average fields for both weak and strong wind cases (shown in Figs. 7a and 7b). These results are consistent with the two systems mentioned above: a high pressure anomaly over the Okhotsk ice cover in Fig. 7a and a low pressure anomaly southeast of Hokkaido in Fig. 7b. In both these figures, there are similar patterns with strong negative anomalies of the Aleutian Low and strong positive anomalies over the northern part of the Sea of Okhotsk. This indicates that cold air from the north blows toward the south. Furthermore, this cold air also leads to southward expansion of the Okhotsk ice cover. The Okhotsk ice extent is usually subject to variations of general atmospheric circulation (Aso, 1986; Cavalieri and Parkinson, 1987; Parkinson, 1990). This suggests that both the above causes come from similar patterns of the general circulation.

Figure 8 shows the dependence of the rotated principal components of the

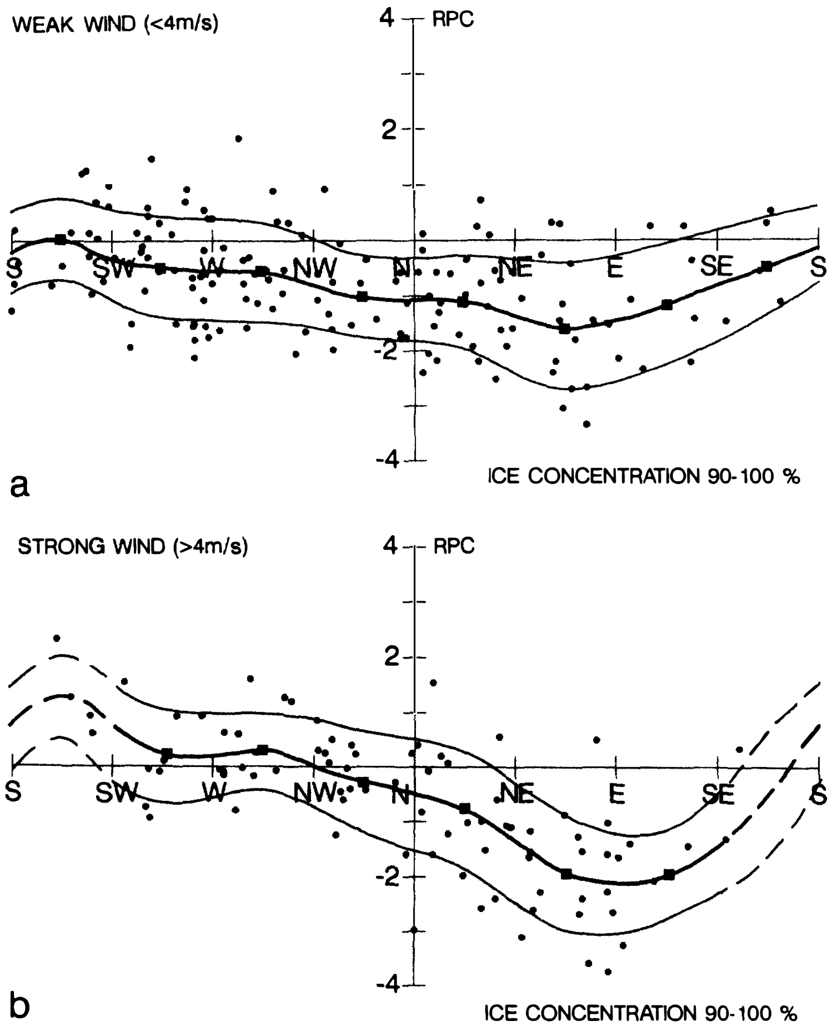


Fig. 8. Dependence of rotated principal components of the second mode on directions of surface winds for heavy ice cases in days 31-70 based on data from 1969–1990. Weak and strong wind cases are shown in panels a and b, respectively.

second mode on wind directions in the heavy ice cases; the weak and strong wind cases are shown in Figs. 8a and 8b, respectively. The period (days 31–70) is chosen as in Fig. 7, but 1990 data are also included in Fig. 8. The figures show that the dependence of the rotated principal components on wind direction is more apparent for strong winds than for weak winds. For northeasterly winds, strong winds have lower values of the rotated principal components than weak winds.

As shown in Fig. 7a, weak winds are associated with an anticyclone over Okhotsk ice cover off Hokkaido. Weak northeasterly winds from this anticyclone are cooled over the ice cover and blow toward Hokkaido. However, fine weather by the anticyclone may cause radiative cooling in all of Hokkaido (Chishima, 1962). Therefore, the drop in temperature along the Okhotsk coast compared to other areas is not as noticeable as in the case of strong winds. In contrast, strong winds, which are associated with a cyclone over the Pacific Ocean on the southeast of Hokkaido, brings cold air from the north. Since the cold air directly advances toward the Okhotsk coast as suggested by Fig. 7b, the temperature is lower there than in other areas. Ogata (1976) suggests that the heavy ice cover prevents cyclones from moving into the Sea of Okhotsk. Consequently, this cyclone is located southeast of Hokkaido as seen in Fig. 7b and northeasterly winds prevail along the Okhotsk coast. For these reasons, we suggest that heavy ice cover indirectly causes relatively low temperature along the Okhotsk coast of Hokkaido.

6. Summary

It has been believed that Okhotsk sea ice influences air-temperature variations in Hokkaido during winter. To examine this idea, we performed RPCA on the air temperature field and found the following:

1) The minimum of air temperature during days 41–50 (middle of February) is related to the Okhotsk ice cover. The "W-phenomenon" is caused by normal, seasonal temperature variations, the regional contrast between inland and coastal areas (the minimum during days 21–30) and ice cover effects (the minimum during days 41–50).

2) Periods of lower temperature along the Okhotsk coast than in other areas coincide with the occurrence of not only heavy ice cover but also northeasterly winds. These conditions are seen most frequently during days 41–50.

3) Two causes for the northeasterly wind system are identified: weak winds from an anticyclone over the Okhotsk ice cover and strong winds from a cyclone over the Pacific Ocean southeast of Hokkaido. Both of these cases are caused by heavy ice cover. In the former mechanism, the wind directly carries cold air cooled over the ice cover. In the latter the heavy ice cover prevents cyclones from moving into the Sea of Okhotsk.

The last point is still qualitative. Therefore, we need to interpret these mechanisms quantitatively using other meteorological data.

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