Indices of Cool Summer Climate in Northern Japan: Yamase Indices

Teruhisa SHIMADA
Graduate School of Science, Tohoku University, Sendai, Japan

Masahiro SAWADA
Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Japan

and

Toshiki IWASAKI
Graduate School of Science, Tohoku University, Sendai, Japan

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Abstract

This study examined seven indices of the cool summer climate in northern Japan in terms of spatial representativeness and interannual variability using weather observation station data and reanalysis data from the Japanese 25-year Reanalysis/Japan Meteorological Agency Climate Data Assimilation System in June–August for 1979–2010. The indices are constructed using sea level pressure (SLP) and surface air temperature (SAT): area-average SLP over the Okhotsk Sea; north–south SLP difference in northern Japan; east–west SLP difference along the Tsugaru Strait; east–west SLP difference along the Soya Strait; SAT anomaly from climatology at a location along the coasts of the Pacific and the Okhotsk Sea; diurnal variance of SAT at a location along the coasts of the Pacific and the Okhotsk Sea; and time coefficient of the east–west oscillation mode of SAT in northern Japan. The last two are newly proposed. The atmospheric fields represented by the indices commonly show the following features: the developed Okhotsk high at the surface and a mid-troposphere ridge to its northwest; southward extensions of low SAT, high SLP, low specific humidity, and high cloud water content along the Pacific coast of northern Japan and along the Japan Sea coast of the Eurasian continent; and strong easterly/northeasterly winds to the east and west of northern Japan. Furthermore, these indices show consistent interannual variabilities and clearly detect cool summers in northern Japan in the past. Meanwhile, differences between the indices lie in the location of the ridge in the mid-troposphere and the vertical structure of the Okhotsk high, the center locations of low SAT and enhanced easterly/northeasterly surface winds, and the degree of the southward extensions of the cool air along the Pacific coast of northern Japan and along the Japan Sea coast of the Eurasian continent. Based on these characteristics, we can choose a suitable index for the intended use.

Keywords cool summer climate; climate index; Okhotsk high; Yamase; northern Japan

1. Introduction

The summer climate in northern Japan (Tohoku and Hokkaido; Figs. 1 and 2) is characterized by the intermittent development of a high-pressure system over the Okhotsk Sea (the Okhotsk high) (e.g., Kudoh
The developed Okhotsk high induces a low-level cool easterly wind blowing toward northern Japan (e.g., Ninomiya and Mizuno 1985a, b; Takai et al. 2006). This cool easterly wind, commonly known as Yamase in Japan, is accompanied by low-level stratus clouds and fog; it is blocked by the mountain ranges in northern Japan (Fig. 2) owing to the stable stratification of the lower atmosphere (e.g., Kojima et al. 2006; Kodama et al. 2009). The cool air and clouds/fog covering the low-altitude area on the east (the Pacific and the Okhotsk Sea) side of northern Japan keep the surface air temperature (SAT) low and suppress air temperature increases during the daytime through reduced solar insolation (e.g., Kanno 2004; Shimada et al. 2010). These conditions of low SAT can persist for more than several days in the case of a stagnant Okhotsk high. In addition, the activity of the Okhotsk high shows large interannual variability (e.g., Tachibana et al. 2004; Sato and Takahashi 2007), and frequent occurrences of the Okhotsk high have induced record cool summers in northern Japan.

Thus, an understanding of the summer climate associated with the cool easterly wind has been an important issue in Japan since the early twentieth century. Nowadays, studies of the cool summer climate in northern Japan are entering a new phase: studies have started to meet social demands for assessing the frequency and severity of cool summer under future climate change.

To systematically assess the variability in the present and future climate, measures representing climate or climate indices are useful. The following are examples of widely used climate indices: the El-Niño and Southern Oscillation indices (e.g., Trenberth 1997), the East Asian winter monsoon index (e.g., Yasuda and Hanawa 1999), the North Atlantic Oscillation index (e.g., Hurrell 1995), and the Indian dipole index (e.g., Saji et al. 1999). These indices have allowed researchers to simply and objectively delimit the intended climate signals and to quantify their variability. Thus, the use of indices is also effective for a unified and long-term analysis of the summer climate in northern Japan.

Some previous studies have proposed measures of
Fig. 2. Map of northern Japan with topography (gray shade) and geographical names referred to in this study. The spatial pattern of the third EOF mode of the SATs observed at the weather observation stations (solid circles) is also shown. The color (dark gray, positive; light gray, negative) and size (see legend inside this figure) of the circles indicate the sign and value, respectively. Abbreviations in the immediate vicinity of the selected circles are for names of the weather observation stations: Wakkanai (WK), Kitamiesashi (KE), Haboro (HB), Suttsu (ST), Hiroo (HO), Hakodate (HK), Fukaura (FK), Hachinohe (HC), Miyako (MY), and Sendai (SD).
the cool summer in northern Japan to identify periods and the degree of low temperature and to compile their statistics. Definitions of the measures vary widely depending on the intended goals of the studies. For example, low-temperature periods are defined as negative SAT anomalies from a climatological mean at weather observation stations along the Pacific coast, such as stations Hachinohe (HC; e.g., Kanno 1997; Takai et al. 2006) and Miyako (MY; Kon 1984) (Fig. 2). Some studies impose additional conditions such as prevailing wind direction and duration of the easterly wind at the weather observation stations (e.g., Kon 1984; Kanno 1997). Sea level pressure (SLP) has been used for representing the synoptic development of the Okhotsk high (e.g., Ogi et al. 2004; Kanno 2004). In addition, local SLP differences across northern Japan enhanced by the low-level cool air on the east work as an indicator of cool summers (Shimada et al. 2010; Shimada and Kawamura 2011).

However, no consensus has been reached on the definition of indices for the cool summer climate in northern Japan, and previously proposed measures are not generally recognized as climate indices. This is because spatial representativeness and temporal variation of the measures have not thoroughly examined and compared with those of other measures. Therefore, this study examines the characteristics of previously or newly proposed measures for cool summers in northern Japan and the possibilities for their use as climate indices or Yamase indices. We first explore the synoptic-scale atmospheric fields represented by the indices and then compare variabilities of the indices during the last 32 years. Because the indices represent the same phenomena, their spatial representativeness should display similar characteristics, and their temporal variations should be correlated. Meanwhile, because the indices approach the same phenomena from a number of different angles, the indices should exhibit individual characteristics in terms of spatial representativeness and temporal variation. Thus, a comparative verification of the indices increases the options for study and can form the basis for a consistent assessment of the variability in summer climate from observations, reanalysis or downscaled data, and projections of future climate change.

We give brief descriptions of the data in the following section. In Section 3, we describe previously and newly proposed indices. In Section 4, the spatial representativeness and interannual variability of the indices are investigated. Section 5 is devoted to a summary and discussion.

2. Data

We used weather observation station data and reanalysis data for summer months (June–August) over 32 years (1979–2010) for the definition of the indices and for composite analysis. We used hourly SLP and SAT obtained at weather observation stations operated by the Japan Meteorological Agency (JMA). Three-hourly data before 1990 were interpolated into hourly data by linear interpolation. Forty-five stations in northern Japan were used for this study (Fig. 2). We used 6-hourly reanalysis data from the Japanese 25-year Reanalysis (JRA-25)/JMA Climate Data Assimilation System (JCDAS) on a 1.25° horizontal grid (Onogi et al. 2007). The following parameters were used: geopotential height, SLP, SAT at 2 m, surface wind at 10 m, specific humidity at 2 m, and cloud water from 1000 hPa to 300 hPa.

3. Indices

3.1 Definitions

We describe seven indices adopted from previous studies or those newly proposed in this study. These indices are chosen or proposed under the following two concepts: (1) Data used for defining the indices are fundamental variables of surface weather observations or reanalysis data and are available over a long period. (2) An index is defined by one parameter for simple definition and easy application, such as the well-established climate indices mentioned in Section 1. Table 1 summarizes the indices dealt with in this study. Details of the indices are described below, and the words in parentheses at the beginning of the following paragraphs are short names of the indices referred to hereinafter.

a. Area-average SLP over the Okhotsk Sea (Okhotsk high index)

The evolution and decay of the Okhotsk high, which plays a key role in the summer climate of northern Japan, can be represented by the area-average SLP over the Okhotsk Sea, the so-called Okhotsk high index. The areas for averaging SLP differ somewhat according to the study; for example, they are defined as 50°–60°N and 140°–160°E (e.g., Ogi et al. 2004), and as 45°–60°N and 140°–155°E (Isobe et al. 2005; Shimada et al. 2010). However, the correlation between the indices defined in the two areas amounts to 0.96 in the case of the 6-hourly JRA-25/JCDAS data for June–August for 1979–2010. This study adopts the latter definition because the defined area covers the southern Okhotsk Sea (Fig. 1).
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<td>North-south SLP difference in northern Japan (North-south index)</td>
<td>Strength of the Okhotsk high relative to its possible southern limit</td>
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b. North-south SLP difference in northern Japan (north–south index)

Kanno (2004) showed that a large north–south difference of the surface pressure in northern Japan provides an indication of the synoptic pressure pattern favorable for the cool easterly wind blowing toward northern Japan; the strength of the Okhotsk high is measured relative to the surface pressure at a possible southern limit of the Okhotsk high. The north–south surface pressure difference is defined as the pressure difference between stations Wakkanai (WK) and Sendai (SD) about 800 km apart (Fig. 2). Station WK is located almost on the southern coast of the Okhotsk Sea, and station SD is located in the southern part of northern Japan. Instead of using in situ pressure at the stations (Kanno 2004), we used SLP at the stations for consistency with the following two indices based on SLP. Thus, a positive (negative) SLP difference represents high (low) pressure to the north.

c. East–west SLP difference along the Tsugaru Strait (Tsugaru Strait index)

Shimada et al. (2010) demonstrated the potential of the east–west SLP difference along the Tsugaru Strait (Fig. 2) as an index of the cool summer climate. Low-level cool air dammed on the east (the Pacific) side of the mountain ranges in northern Japan creates the east–west SLP difference on a regional scale during the prevailing period of the cool easterly wind. This SLP difference reflects the low-level air temperature difference between the east (the Pacific side) and west (the Japan Sea side) across the mountain ranges, and the depth of the low-level cool layer on the east. Shimada et al. (2010) showed that the SLP difference along the Tsugaru Strait can be represented by that between a pair of stations, Hakodate (HK) and Fukaura (FK), located on the east and west of the strait, respectively (Fig. 2). A positive (negative) SLP difference indicates higher (lower) SLP at station KE on the Okhotsk Sea coast than at station HB on the Japan Sea coast.

d. East–west SLP difference along the Soya Strait (Soya Strait index)

On the basis of the same concept as with the east–west SLP difference along the Tsugaru Strait, Shimada and Kawamura (2011) proposed a similar measure along the Soya Strait: the east–west SLP difference along the Soya Strait is represented by the SLP difference between stations Kitamiesashi (KE) and Haboro (HB) (Fig. 2). High SLP to the east of the Soya Strait is induced by the blocking of low-level cool air over the Okhotsk Sea owing to the topography of Hokkaido and Sakhalin. A positive (negative) SLP difference indicates higher (lower) SLP at station KE on the Okhotsk Sea coast than at station HB on the Japan Sea coast.

e. Surface air temperature anomaly (air temperature index)

Many studies have conventionally used a SAT anomaly from the climatological mean at a given weather observation station along the Pacific coast of northern Japan (e.g., station HC) for defining periods and the degree of low SAT owing to the prevailing cool easterly wind (e.g., Kon 1984; Takai et al. 2006). The choice of the station is important because this index is defined by data at a single station. We examine the dependence of this index on station location in the next section because few studies have paid attention to this aspect. In this study, we first removed diurnal variations from hourly SAT data at the station by using low-pass filter with a cutoff period of 1.5 days. Then, we calculated the hourly climatological mean of SAT from the data at the station over 32 years and defined hourly anomalies relative to the climatological mean.

f. Diurnal variance of surface air temperature (diurnal index)

In addition to low SAT, the small diurnal amplitude of SAT along the coasts of the Pacific and the Okhotsk Sea is a distinctive feature during periods of the prevailing cool easterly wind (e.g., Shimada et al. 2010). We newly propose the wavelet variance of SAT at a single station in a period range of 0.5–1.5 days as an index for the prevailing cool easterly wind condition following the method of Torrence and Compo (1998). Candidate stations whose observations are suitable for defining this index are those along the coasts of the Pacific and the Okhotsk Sea (e.g., station HC), as is the case for the air temperature index.

g. Time coefficient of the east–west oscillation mode of surface air temperature (EOF index)

The prevailing cool easterly wind and accompanying low-level clouds enhance the SAT contrast between the east (the Pacific/Okhotsk Sea side) and west (the Japan Sea side) across the central mountain ranges of northern Japan. Takai et al. (2006) and Shimada et al. (2010) applied empirical orthogonal function (EOF) analysis based on the correlation matrix method to the SATs observed at stations in parts of northern Japan and identified an EOF mode with an east–west contrast of SAT across the mountain ranges of northern Japan. These studies prove that this mode is important for SAT
variations in northern Japan. Thus, the time coefficient of this mode can be used as a cool summer index.

Based on these previous studies, we expanded the study area to cover the whole of northern Japan and applied the EOF analysis to the hourly SAT data for the weather observation stations (Fig. 2). In this instance, the east–west EOF mode was identified as the third mode with positive (negative) values on the east (west) side (Fig. 2). Here the signs of the spatial pattern and time coefficient of this EOF mode were selected such that a negative time coefficient corresponds to a negative anomaly of SAT on the coasts of the Pacific and the Okhotsk Sea. Incidentally, positive values are exceptionally found at stations WK and Suttsu (ST) along the coast of the Japan Sea. This is because these stations are located downwind of the terrestrial gap through which cool air passes from the east (Shimada et al. 2010; Shimada and Kawamura 2011). The spatial pattern and contribution ratio (3.1%) of this third or east–west EOF mode are consistent with the corresponding results of Takai et al. (2006) and Shimada et al. (2010), as well as those of the second or north–south EOF mode (6.5%) and the first EOF mode representing the variation across the whole study areas (77.0%). The areal selection for EOF analysis determines whether the east–west EOF mode appears as the second or third mode. To use the time coefficient as an index, we applied the low-pass filter described above to the time coefficient to remove its diurnal variation.

3.2 Time series

We illustrate the seven indices described above with the example of June–August 2003 (Fig. 3). In 2003, northern Japan experienced a record cool summer. After the end of June, except during early August, the Okhotsk high index continuously exceeded 1010 hPa, and the north–south index, the Tsugaru Strait index, and the Soya Strait index generally had positive values (Figs. 3a, b). During this period, the air temperature index showed negative values, or air temperature was lower than the climatological mean (Fig. 3c). On the whole, the diurnal index was small (< 1.5 (°C)^2), and
the EOF index was negative. From these associations among the index variations, we can confirm the following points. During a period of the prevailing cool easterly wind, the developed Okhotsk high is recognized, and the north–south SLP difference over northern Japan is enhanced. Simultaneously, the east–west SLP differences are also enhanced along the Tsugaru Strait and Soya Strait. Then, SAT decreases, and diurnal SAT rising is suppressed along the coasts of the Pacific and the Okhotsk Sea. Consequently, the SAT contrast across the central mountain ranges between the east (the Pacific/Okhotsk Sea side) and the west (the Japan Sea side) becomes prominent.

4. Results

4.1 Composite analysis

a. Method

We first examine the variability of the indices to consider the conditions of the subsequent composite analysis. Figure 4 shows histograms of the normalized indices for comparison. To define the air temperature index and the diurnal index, we hereinafter used data for station HC because the data have been conventionally and effectively analyzed for cool summers (e.g., Kanno 1997; Takai et al. 2006). For the diurnal index, normalization is done only by dividing the index by its standard deviation. All the histograms, except for that of the diurnal index, generally exhibit Gaussian distributions (Figs. 4a–e, and 4g). In contrast to these nearly Gaussian distributions, the histogram for the diurnal index follows a nearly exponential distribution (Fig. 4f). On the other hand, we can confirm that the monthly frequencies in June–August are almost the same for each index. This indicates that the variabilities of these indices are free of the influence of seasonal variation. However, the only exception is the EOF index in August, which shows less frequency in August than the other indices or the EOF index in June–July.

We then investigate synoptic-scale atmospheric fields represented by the indices using composites of the following six parameters obtained from the JRA-25/JCDAS data for June–August over 32 years (1979–2010): geopotential height, SLP, SAT, surface wind, surface specific humidity, and cloud water integrated vertically from 1000 hPa to 300 hPa. We select 6-hourly data for making the composites when the normalized index is greater than one standard deviation, except for the diurnal index: the selected data are those with the normalized indices in Fig. 4 greater than 1.0 for the four indices based on SLP and less than −1.0 for the air temperature index and the EOF index. These conditions account for 15–17% (about 1900 6-hourly

Fig. 4. Histograms of the seven normalized indices in June–August for 32 years (1979–2010). For the diurnal index in (f), the indices are only divided by the standard deviation. Color legend is shown in (a).
data) of the total data in June–August, because the histograms of the indices generally exhibit Gaussian distributions (Fig. 4). For the diurnal index, data for the composite are selected below a level at which the accumulated relative frequency is 16%. Thus, in Figs. 5–11, we show mean composites for the selected data and their anomalies from the climatological means in June–August for 32 years (1979–2010). While this study focuses on one side of the index histograms as described above, it is worth noting that the opposite side of the index histograms also represents significant atmospheric fields with warm condition around northern Japan.

b. Composites

Composites of geopotential height at 500 hPa commonly show a ridge to the north of the westerlies over Japan (Fig. 5) and vertical structures of the Okhotsk high tilting westward (Fig. 6) and northward (not shown). Split westerlies and a ridge over the Far East accompany the surface Okhotsk high (e.g., Ninomiya and Mizuno 1985a), and the Okhotsk high has a tilting vertical axis (Tachibana et al. 2004; Nakamura and Fukamachi 2004). Meanwhile, the composites have differences in the central longitudes of the blocking ridges and in the curvatures of the westerlies. The ridges lie at 134°E, and the southward curvatures of the westerlies are seen for the north–south index, the Soya Strait index, the air temperature index, and the diurnal index (Figs. 5b, d, e, f). For the other indices, the locations of the ridges shift to the east and lie at 142°E, and the westerlies show northward curvatures (Figs. 5a, c, g). In regard to the vertical structure of the Okhotsk high, Tachibana et al. (2004) showed that there are two types—the shallow and deep Okhotsk highs—and concluded that the shallow Okhotsk high significantly contributes to the cool summer around Japan. The composites have maxima of positive anomalies of the geopotential height in the lower atmosphere.
for all of the indices (Fig. 6), and these maxima indicate a shallow core of the Okhotsk high. The Tsugaru Strait index, the diurnal index, and the EOF index may suggest a deep structure at 50°N. Although the composites in Figs. 5 and 6 may combine both types, the impact of the Okhotsk high on summer climate of Japan is apparent in the subsequent analyses.

The developed Okhotsk high and its tongue-shaped extensions along the Pacific coast of northern Japan and along the Japan Sea coast of the Eurasian continent are features typical of the synoptic patterns inducing cool summer in northern Japan (Kudoh 1984) and are common in the composites of SLP (Fig. 7). These patterns of SLP reflect those of low-level air temperature, as we shall see in the next paragraph. Another common feature in the composites is northeastward tongue-shaped SLP contours to the east of Japan, which indicate frequent passages of low-pressure systems in the Baiu frontal zone. However, the anomalies highlight the differences between the indices. The Okhotsk high index represents large positive anomalies covering all of Japan or the developed Okhotsk high extending to the south (Fig. 7a). In contrast, the other indices represent dipole patterns of SLP anomaly or the developed Okhotsk high to the north (Figs. 7b–g). The north–south index, the Soya Strait index, the air temperature index, and the diurnal index enhance a north–south dipole pattern of SLP anomaly (Figs. 7b,d,e,f). The Tsugaru Strait index shows that large positive anomalies shift to the east and that the centers of positive and negative SLP anomalies are aligned with the northeast–southwest axis (Fig. 7c).

The EOF index further enhances the northeast–southwest alignments of the dipole structure (Fig. 7g). These northeast–southwest alignments of the dipole structure result in more coverage of high SLP along the Pacific coast of northern Japan. In addition, the three indices based on SLP differences represent larger SLP gradients over northern Japan than the other indices. These larger SLP gradients are reflected in the wind fields as will be shown later.

Composites of SAT (Fig. 8) commonly show tongue-shaped extensions along the Pacific coast of northern Japan and along the Japan Sea coast of the Eurasian continent in June–August for 32 years (1979–2010) along 50°N (contours and color shades). Contour interval is 5 m. Color shades indicate statistically significant differences from the climatological mean at the 95% level.
continent. These extensions of low SAT correspond to those of SLP (Fig. 7). Negative anomalies around Japan are common to all the indices, and the southern boundary of the negative anomalies roughly corresponds to the northeastward low-pressure extension or the Baiu frontal zone (Fig. 7). However, the anomalies reveal different characteristics. The negative anomalies extend southward along the Pacific coast of northern Japan for the Okhotsk high index, the Tsugaru Strait index, and the EOF index (Figs. 8a, c, g). These three indices enhance the SAT contrast across the mountain ranges between the Pacific/Okhotsk Sea and the Japan Sea. In particular, the Tsugaru Strait index shows the most enhanced east–west contrast in SAT (Fig. 8c). On the other hand, the largest negative anomalies (< −2°C) are seen over the entire region of northern Japan for the air temperature index (Fig. 8e); they are confined to the east of Hokkaido for the north-south index, the Soya Strait index, and the diurnal index (Figs. 8b, d, f).

Common characteristics of surface wind composites (Fig. 9) are enhanced easterly/northeasterly winds (with magnitudes of the anomaly vectors greater than 2 m s⁻¹) to the east and west of northern Japan. These results confirm that an enhanced easterly/northeasterly wind is a key for a cool summer in northern Japan. The differences between the indices lie in the location of the enhanced winds and the prevailing wind direction. Only the north–south index and the Soya Strait index (Figs. 9b, d) enhance northeasterly winds over the southern Okhotsk Sea. This is in contrast to the enhanced winds confined to the Pacific for the other indices (Figs. 9a, c, e, f, g). Meanwhile, over the Japan Sea, the Tsugaru Strait index and the EOF index represent enhanced easterly winds to the west of the Tsugaru Strait (Figs. 9c, g). The other indices represent northeasterly winds over the Japan Sea (Figs. 9a, b, d, e, f). These enhanced winds over the Japan Sea suggest the outflow of the cool air from the Pacific and the Okhotsk Sea (Shimada et al. 2010; Shimada and Kawamura 2011).

Composites of specific humidity and cloud water show contrasting patterns. Composites of surface specific humidity have similar distributions to those of SAT for all the indices (Fig. 10): negative anomalies of surface specific humidity correspond to those of SAT. This means that the low-level cool air accompanying the easterly winds has a small amount of water vapor because of low saturation vapor pressure. Composites

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**Fig. 7.** The same as Fig. 5 except for SLP. Contour interval is 1 hPa, and the bold contours represent 1012 hPa.
of vertically integrated cloud water also show negative anomalies in the southern Okhotsk Sea, along the Kuril Islands, and to the north of the Japan Sea, where cloud water amounts are less than $10 \times 10^{-2}$ kg m$^{-2}$ (Fig. 11). However, all the indices commonly enhance positive anomalies to the south. In particular, the north–south index, the Tsugaru Strait index, the Soya Strait index, and the diurnal index represent enhanced cloud water formations to the east of northern Japan (Figs. 11b, c, d, f). These positive anomalies possibly reflect water vapor transport by the strong easterly winds to the east of Japan and by the southerly winds to the south of Japan (Fig. 9). Moreover, it is noteworthy that well-defined maxima of the positive anomalies are anchored in the east of the mountain ranges. Above all, the Okhotsk high index, the Tsugaru Strait index, the air temperature index, and the EOF index especially enhance band-shaped positive anomalies along the Pacific coast of northern Japan and along the Japan Sea coast of the Eurasian continent to the Korean Peninsula (Figs. 11a, c, e, g). These maxima indicate cloud formation owing to orographic lifting of the cool air as the easterly/northeasterly winds impinge on the coastal mountains. This is supported by the fact that composites of low-level relative humidity have similar patterns of positive anomalies (not shown).

The negative anomalies of the cloud water amount over the southern Okhotsk Sea, along the Kuril Islands, and to the north of the Japan Sea seemingly contradict the fact that the Okhotsk Sea is frequently covered by low-level clouds in summer. The Okhotsk Sea has mechanisms for increasing the formation of low-level clouds/fog (Kato 1985; Tachibana et al. 2008; Tokinaga and Xie 2009; Koseki et al. 2012). Cool sea surface temperature in the Okhotsk Sea leads to the formation of low-level clouds/fog, which in turn cools low-level air through longwave radiation at the cloud tops (Kato 1985; Koseki et al. 2012), and cold-water patches induced by ocean tidal mixing especially enhance the occurrence of the fog (Tokinaga and Xie 2009). Note here that the negative anomalies in Fig. 11 just show that the cloud water content under the developed Okhotsk high is smaller than the climatological mean. When the Okhotsk high develops, the air temperature is particularly reduced, and the water vapor content decreases. Moreover, cloud water content also decreases, and the cloud water is confined to the shallow layer (~500 m) capped by the inversion.

Fig. 8. The same as Fig. 5 except for SAT at 2 m. Contour interval is 2°C, and the bold contours represent 16°C.
We have confirmed that consistent results with Fig. 11 are obtained from the satellite observations of vertically integrated cloud water by Advanced Microwave Scanning Radiometer for Earth Observing System and Atmospheric Infrared Sounder onboard Aqua.

c. Dependence on station location

Finally, we explore the dependence of the representativeness of the synoptic atmospheric fields on station location for the air temperature index and the diurnal index, which are defined by data for a single station. Figure 12 compares composites of SLP represented by the two indices defined at representative stations (KE, Hiroo (HO), and SD from north to south) along the coasts of the Okhotsk Sea and the Pacific. Concerning the air temperature index, as we choose more southern stations to define the indices, the center of the Okhotsk high moves southward in the Okhotsk Sea (Figs. 7e and 12a–c). The tongue-shaped high SLP along the Pacific coast of northern Japan as well as along the Japan Sea coast of the Eurasian continent extends southward. These results are true for the diurnal index (Figs. 7f and 12d–f), although the overall SLP patterns represented by the diurnal index depend more strongly on station location than those by the air temperature index. Thus, we can say that the station location determines the degree of the southward extensions of the cool air represented by these indices.

4.2 Interannual variations

We look into interannual variations of the indices. Figure 13 shows monthly means of the normalized indices (Fig. 4) in July for 1979–2010. The diurnal index is plotted against the right-hand ordinate, and the signs of the air temperature index and the EOF index are reversed. The interannual variations of the seven indices are generally consistent with each other with statistically significant correlations, as summarized in Table 2. High indices, except for the diurnal index, and low indices for the diurnal index coincidentally correspond to the commonly recognized years (1980, 1983, 1988, 1993, 1998, and 2003) when northern Japan experienced record cool summers. Incidentally, the record cool summer in 1980 dominated in August (not shown). Although the general perception of these cool summers has depended partly on the impact of cool summers on society (e.g., agricultural yields), these indices enable the assessment of summer climate

Fig. 9. The same as Fig. 5 except for wind at 10 m (vectors) and magnitude of the anomaly vectors (color shade).
in northern Japan from a climatological viewpoint. Furthermore, consistent variations of the multiple indices enable the clear detection of cool summers.

Most pairs of the indices are also correlated significantly in June and August (Table 2). Above all, the correlations between the four indices based on SLP are high (at least 0.58 and up to 0.92) with little dependence on month. However, the correlations with the indices based on SAT have a dependence on month. The air temperature index shows slightly low correlations with the indices based on SLP in August. The diurnal index is uncorrelated with the other indices in June. These may reflect changes in SAT variability with seasonal advance. Thus, we can say that the indices based on SLP have the advantage of being free from seasonal variation. Meanwhile, we need to pay attention to the fact that the indices based on SAT are subject to its seasonal variation and do not work well in some months.

5. Summary and discussion

This study examined seven indices of the cool summer climate in northern Japan associated with the cool easterly wind or Yamase in terms of spatial representativeness and interannual variability. These indices allow for a systematic evaluation of the summer climate in northern Japan by considering the following characteristics of the indices. Table 1 summarizes the points in this section.

Atmospheric fields represented by the indices show the following features in common: (1) northwestward tilting of the vertical axis of the Okhotsk high, a ridge in the mid-troposphere, and the developed Okhotsk high at the surface; (2) southward extensions of low SAT, high SLP, low specific humidity, and high cloud water along the Pacific coast of northern Japan and along the Japan Sea coast of the Eurasian continent; and (3) high speeds of the easterly/northeasterly surface winds to the east and west of northern Japan. The spatial representativeness of these features is comparable between the indices, regardless of whether the index is defined regionally or locally. Consequently, we can conclude that these indices can represent features typical of synoptic patterns inducing cool summer in northern Japan. Moreover, time variations of the indices are generally correlated. Thus, we can say that these indices work as a climate index of cool summer in

Fig. 10. The same as Fig. 5 except for specific humidity at 2 m. Contour interval is $2 \times 10^{-3}$ kg kg$^{-1}$, and the bold contours represent $10 \times 10^{-3}$ kg kg$^{-1}$.
On the other hand, the differences between the indices lie in (1) locations of the ridge in the mid-troposphere and the vertical structure of the Okhotsk high, (2) center locations of the low SAT and the enhanced easterly/northeasterly surface winds, and (3) degree of the southward extension of the cool air along the Pacific coast of northern Japan and the resulting SAT contrast between the Pacific/Okhotsk Sea and the Japan Sea. In particular, the Okhotsk high index enhances a southward advance of the Okhotsk high completely covering northern Japan. The air temperature index represents low SAT over the entire region of northern Japan. The north–south index and the Soya Strait index represent the center of the cool air located in the northern part of northern Japan (Hokkaido). Meanwhile, the Tsugaru Strait index and the EOF index enhance the southward extensions of low SAT, high SLP, low specific humidity, and high cloud water along the Pacific coast of northern Japan. The diurnal index is more sensitive to cloud water than to air temperature. In addition, the indices based on SLP are less influenced by seasonal variation. Taking advantages of these different features of the indices, we can use different indices in accordance with the intended goal. It is important to bear in mind that one feature of an index can be both an advantage and a disadvantage according to the purpose of a study.

We need to draw attention to characteristics of the data used to define the indices. For the Okhotsk high index, the spatiotemporal resolution of the data is not critical, and we generally use global reanalysis data, global climate model data, or regional climate model data covering the Okhotsk Sea. The north–south index can be defined by data from reanalysis data or climate model data with a horizontal grid increment less than or equal to about 100 km to resolve the distance between stations WK and SD, as well as data from weather observation stations. However, to define the other indices using model output, we need higher-resolution data or downscaled data. In the case of the Tsugaru Strait index and the Soya Strait index, we must use data with a spatial resolution that is sufficiently high to resolve the topography around the straits. We have confirmed that a horizontal grid increment of less than or equal to 10 km is desired. To define the other three indices based on SAT, a sufficiently high

Fig. 11. The same as Fig. 5 except for vertically integrated cloud water from 1000 hPa to 300 hPa. Contour interval is $2 \times 10^{-2} \text{ kg m}^{-2}$, and the bold contours represent $12 \times 10^{-2} \text{ kg m}^{-2}$. northern Japan.
spatial resolution is required to reproduce local-scale air temperature variations. In addition to spatial resolution, a high temporal resolution is required to define the diurnal index. Meanwhile, because the air temperature index largely depends on the climatological mean of SAT, the period of the dataset to construct the climatological mean is important. Above all, an increasing trend of SAT associated with climate change can result in an apparent decrease in the occurrences of negative anomalies of SAT in the latter years of an analysis.

The indices examined in this study are expected to be used mainly for addressing the following two challenges. One is to investigate the long-term variability of summer climate in northern Japan associated with climate change.
the cool easterly wind, or Yamase, under present and future climate conditions. This reflects the growing social demands for assessing the impact of climate change on Yamase. The indices allow for the objective and systematic assessment of climate variability, and the multiple indices representing different aspects of the summer climate in northern Japan allow robust assessment. The other is to examine what accounts for the differences between the indices at the same time. Investigating the causes of the differences leads to

Table 2. Monthly correlations between monthly mean indices in June–August (from top to bottom in each field) for 32 years (1979–2010). Asterisks indicate statistically insignificant correlations below the 95% confidence level according to Student’s t test.

<table>
<thead>
<tr>
<th>Okhotsk high index</th>
<th>North-south index</th>
<th>Tsugaru Strait index</th>
<th>Soya Strait index</th>
<th>Air temperature index</th>
<th>Diurnal index</th>
<th>EOF index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Okhotsk high index</td>
<td>–</td>
<td>0.79</td>
<td>0.58</td>
<td>0.83</td>
<td>–0.67</td>
<td>–0.10*</td>
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<td></td>
<td></td>
<td>0.68</td>
<td>0.74</td>
<td>0.70</td>
<td>–0.67</td>
<td>–0.43</td>
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<td></td>
<td></td>
<td>0.80</td>
<td>0.73</td>
<td>0.82</td>
<td>–0.57</td>
<td>–0.66</td>
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<tr>
<td>North-south index</td>
<td>–</td>
<td>–</td>
<td>0.71</td>
<td>0.92</td>
<td>–0.77</td>
<td>–0.28*</td>
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<td>0.87</td>
<td>0.85</td>
<td>–0.85</td>
<td>–0.71</td>
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<td></td>
<td>0.86</td>
<td>0.85</td>
<td>–0.64</td>
<td>–0.52</td>
</tr>
<tr>
<td>Tsugaru Strait index</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.63</td>
<td>–0.76</td>
<td>–0.33*</td>
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<td>–</td>
<td>0.62</td>
<td>–0.70</td>
<td>–0.54</td>
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<tr>
<td>Soya Strait index</td>
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<td>–</td>
<td>–</td>
<td>–0.68</td>
<td>–0.15*</td>
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<td>–</td>
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<td>–0.72</td>
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<tr>
<td>Air temperature index</td>
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<td>–</td>
<td>–</td>
<td>–</td>
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<td></td>
<td>–</td>
<td>–</td>
<td>0.46</td>
<td>0.30*</td>
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<tr>
<td>Diurnal index</td>
<td>–</td>
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</tbody>
</table>
addressing the differences in synoptic situations and in the impact of the cool easterly winds on local climate. For example, in Fig. 13, the air temperature index in July 1983 shows a low SAT in northern Japan, but low indices based on SLP suggest a pressure pattern different from that in the other cool summers. The relatively high diurnal index in 1993 may suggest more cloudless days than in the other cool summers. The high Tsugaru Strait index and the low Soya Strait index in June 2003 may indicate a dominant southward advance of the cool air from the developed Okhotsk high. Research is ongoing to achieve these purposes by the downscaling of climate datasets.

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