Low-Level Easterly Winds Blowing through the Tsugaru Strait, Japan. 
Part I: Case Study and Statistical Characteristics Based on Observations

TERUHISA SHIMADA
Ocean Environment Group, Center for Atmospheric and Oceanic Studies, Graduate School of Science, 
Tohoku University, Sendai, Japan

MASAHIRO SAWADA AND WEIMING SHA
Atmospheric Science Laboratory, Graduate School of Science, Tohoku University, Sendai, Japan

HIROSHI KAWAMURA
Ocean Environment Group, Center for Atmospheric and Oceanic Studies, Graduate School of Science, 
Tohoku University, Sendai, Japan

(Manuscript received 22 January 2010, in final form 17 May 2010)

ABSTRACT
This study has investigated structures and diurnal variations of the easterly surface winds blowing 
throughout the east–west passage comprising the Tsugaru Strait, Mutsu Bay, and circumjacent terrestrial gaps 
in northern Japan during the summer months. Based on observational and reanalysis data, a representative 
case study in June 2003 and supplemental statistical analyses are presented. The cool easterly winds ac-
companied by clouds and fog are blocked by the central mountain range. This condition increases an along-
strait sea level pressure (SLP) gradient, which induces strong winds in the west of the strait. The along-strait 
SLP gradient is enhanced by the developed Okhotsk high and by low pressure systems passing along the 
southern coast of Japan or over the Japan Sea. Stronger (weaker) and easterly (east-northeasterly) winds are 
observed during the nighttime (daytime), corresponding to the cool air intrusion from the east (retreat from 
west). Differences in SLP observed at meteorological observation stations on the east and west can be a good 
indicator of wind speed in the west of the strait. Meanwhile, the winds over the land also show diurnal 
variations specific to the times of the prevailing cool easterly winds. The easterly winds over the land are 
stronger and more divergent across the strait during the daytime than nighttime. This indicates the possibility 
that the diurnal wind variations are thermally induced. Reduction of diurnal air temperature changes in the 
east increases east–west thermal contrast. Additionally, the cool air over the strait and the bay can enhance 
land–sea thermal contrast across the coast.

1. Introduction
A cool easterly wind intermittently blows toward 
northern Japan from the high pressure system over the 
Okhotsk Sea (Okhotsk high) during the summer months, 
especially in June–July. This cool easterly wind, commonly 
known as Yamase, has been an object of study since the 
early twentieth century because it has dominated sum-
mertime climate over northern Japan and sometimes 
caused severe cold-weather damage (e.g., Ninomiya and 
Mizuno 1985a,b; Kojima et al. 2006; Takai et al. 2006; 
Kodama et al. 2009). The easterly wind is accompanied 
by maritime cool and humid air, and low-level stratus 
clouds and fogs, and can persist for several days. The 
low-level atmosphere is characterized by an inversion 
capping a thin mixed layer. Consequently, the low-level 
wind and clouds are mostly blocked by the mountain 
ranges of Tohoku and Hokkaido (Fig. 1). The dammed 
clouds reduce insolation on the east (Pacific) side of the 
mountain ranges. A visible composite image in Fig. 1 
serves as an example for the above-mentioned charac-
teristics. The easterly winds prevail and the clouds cover 
the low-altitude area on the east side of northern Japan.
In stark contrast to the mountain ranges in Tohoku and Hokkaido (Fig. 1), there is the only east–west-oriented passage of low-level winds in northern Japan. It consists of the Tsugaru Strait, Mutsu Bay, and several circumjacent low-level terrestrial gaps (Fig. 2). The Tsugaru Strait is an international strait between Tohoku and Hokkaido, connecting the Japan Sea with the northwestern Pacific Ocean. The east–west distance is about 100 km and the width ranges from 20 to 40 km. A semiclosed bay, called Mutsu Bay, is open to the Tsugaru Strait through a narrow (10 km) channel on its northwest side (Fig. 2). These topographic features make low-level routes for the cool easterly winds from the Pacific to the Japan Sea. Understanding of the low-level winds blowing throughout this passage is essential for forecasts of weather and sea state and for regional climate research.

Also, the wind has important social and economic impacts. However, little attention has been given to the low-level winds in this passage, and their structure and evolution have not been documented. Because most of the previous studies of the cool easterly wind focus on the wind offshore east of northern Japan, studies on local winds in the vicinity of this passage have been left behind despite a long study history of the cool easterly winds during the summer months.

Recently, the high-resolution capability of satellite observations and numerical simulations has shed light on the structure and evolution of the cool easterly wind in the vicinity of the passage. Yamaguchi and Kawamura (2005) have shown that the southeasterly wind entering Mutsu Bay from its southeastern low-level gap blows throughout the central part of the bay, resulting in strong wind shear on both sides. Wind statistics at the center of Mutsu Bay shows high directionality in east and west throughout the year due to the topographic effect (Kawai et al. 2006). Kawai et al. (2006) have also pointed out the importance of solar heating over the land and of the distribution of land and sea for the local atmospheric circulation. Shimada and Kawamura (2007) have first mentioned the strong easterly winds exiting from the Tsugaru Strait and their diurnal variation with stronger (weaker) and easterly (east-northeasterly) winds during the nighttime (daytime). This diurnal variation is quite a contrast to that of winds over the land with stronger (weaker) winds during the daytime (nighttime; Rikiishi and Sasaki 1990). The impact of the strong winds on wave development is examined by using numerical simulations (Shimada and Kawamura 2009).

However, we have not yet had a comprehensive vision of the structure and evolution of these winds in the passage. First, the previous studies on the winds in this region have conventionally focused only on one side of the strait (e.g., Rikiishi and Sasaki 1990; Yamaguchi and Kawamura 2005; Takai et al. 2006; Kawai et al. 2006). We have to capture the entire picture of the low-level winds blowing throughout the Tsugaru Strait, Mutsu Bay, and circumjacent low-level terrestrial gaps. Also, no studies have ever tried to investigate the generation mechanism of the strong winds in the west of the strait and to obtain a measure for the prediction of strong winds. The atmospheric and orographic settings of the present...
study subject are favorable for the generation of gap-exiting winds, which are induced by a large pressure gradient along a gap mostly due to cold air surges (e.g., Bond and Stabeno 1998; Colle and Mass 2000; Sharp and Mass 2004). Furthermore, the diurnal variations over the land and sea have been pointed out merely based on slight evidence (Rikiishi and Sasaki 1990; Shimada and Kawamura 2007). We have to compile wind data in the entire study area to examine causes of different diurnal variations of the low-level winds over the land and sea while the cool easterly winds are prevailing.

This study investigates the structure and evolution of the easterly low-level winds blowing throughout the passage consisting of the Tsugaru Strait, Mutsu Bay, and the circumjacent low-level terrestrial gaps. Using observational and reanalysis data, we present a case study in June 2003 and statistical analyses. We especially focus on the sustained easterly wind event on 5–10 June 2003 based on the previous studies (Shimada and Kawamura 2007, 2009). Specific questions we would like to address are the following: 1) What are the typical structural properties of the low-level winds around the Tsugaru Strait and Mutsu Bay? 2) What is the generation mechanism of the strong winds in the west of the strait? 3) How do the low-level winds vary diurnally over the land and sea?

We give brief descriptions of data in the following section. Section 3 presents a case study, and section 4 gives statistical analyses. Section 5 is devoted to the summary and conclusions. We use Japan Standard Time (JST, UTC + 9 h) for descriptions hereafter because this study deals with diurnal variation.

2. Data

The following satellite observations are used. We use 10-m wind measurements with 12.5-km resolution acquired by the SeaWinds onboard the Quick Scatterometer (QuikSCAT) and the Advanced Earth Observing Satellite 2 (ADEOS2). The root-mean-square error of the retrieved wind is approximately 1 m s⁻¹ in speed and 20° in direction (e.g., Tang et al. 2004). Combined use of their observations almost 4 day⁻¹ by two essentially identical sensors allow examination of diurnal wind variation. By applying the wind retrieval method from Synthetic Aperture Radar (SAR; e.g., Monaldo et al. 2004), we derive a wind field with 100-m grid interval from the Canadian Space Agency’s RADARSAT-1 ScanSAR wide image. The wind speeds can be typically retrieved from RADARSAT-1 with a root-mean-square error of less than 2 m s⁻¹ and with negligible bias (e.g., Monaldo et al. 2004). The method uses the C-band scatterometer model function CMOD5 (Hersbach et al. 2007), a polarization ratio conversion factor (Horstmann et al. 2000), and wind direction from the objective analysis data called grid-point value (GPV). The GPV data are output from the Mesoscale Nonhydrostatic Model (MSM) of the Japan Meteorological Agency (JMA) with 10-km and 6-hourly spatiotemporal resolutions. In Fig. 1, we show a visible composite image from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board Aqua at 1216 JST 8 June 2003 (R/G/B: band 1/4/3) together with the SeaWinds wind vectors.

We use in situ data from two types of meteorological observation stations operated by JMA over the land. One is called a weather observation station (WOS) and the other is a station that has automatic observation facilities called Automated Meteorological Data Acquisition System (AMeDAS). There are 6 WOSs and 25 AMeDAS stations in the study area (Fig. 2). Hourly surface winds and air temperatures are observed at these stations. The WOSs also observe hourly air pressure. We also use 12-hourly upper-air observations at station Hachinohe (HC). Wind observations during June 2003 are also obtained from a buoy located at the center of Mutsu Bay operated by Aomori Prefectural Fisheries Research Center Aquaculture Institute (Fig. 2).

To discuss synoptic situations, we use reanalysis data known as the Japanese 25-yr Re-Analysis (JRA-25), which are produced by the Japan Meteorological Agency Climate Data Assimilation System (Onogi et al. 2007). The 6-hourly sea level pressure (SLP), 2-m and 1000-hPa air temperatures, and 10-m wind data on a 1.25° horizontal grid are used.

3. Case study example in June 2003

Figure 3 shows 6-hourly fields of SLP, 2-m air temperature, and 10-m winds on 8–9 June 2003 to describe the typical synoptic situation. During the passage of the low pressure to the southeast of Japan, the easterly wind persistsently blows toward northern Japan (Figs. 1 and 3). The cool air extends southwestward along the east coast of northern Japan and of the Eurasian continent. The patterns of SLP roughly correspond to those of the tongue-shaped cool air masses around the Okhotsk high. This means that the low-level cool air temperatures dominantly determine the SLP. Thus, the east–west SLP gradient across northern Japan is maintained during the prevailing period of the cool easterly wind. Figure 3 also shows clear diurnal variations of the two tongue-shaped cool air masses. While the southwestward extension of the cool air (≈10°C) along the east coast of northern Japan reaches the vicinity of the Tsugaru Strait during the nighttime (Figs. 3a,d,e), it retreats during the daytime to the east of Hokkaido (Figs. 3b,c). Radiative cooling at the top of the clouds is one of the
important factors in diurnal variation of air temperature (e.g., Kojima et al. 2006; Kodama et al. 2009). Associated with the air temperature variations under the prevailing easterly wind, the SLP becomes higher (lower) during the nighttime (daytime). Thus, the cool air extension (retreat) during the nighttime (daytime) increases (decreases) the east–west SLP gradient across northern Japan.

We take a closer look at the 12.5-km wind fields on the same day. In the early morning (Fig. 4a), we can identify well-organized strong winds (>8 m s\(^{-1}\)) in the west of the Tsugaru Strait with a spatial extent of about 120 km and a width of 80 km. The spatial extent of the strong winds decreases and the winds slightly shift to the south during the daytime (Figs. 4b,c). The winds in the west of the strait start to evolve again and the wind directions shift back to the west during the nighttime (Figs. 4d,e). Thus, the stronger (weaker) and easterly (east-northeasterly) winds are observed during the nighttime (daytime) in the west of the Tsugaru Strait. Strong winds along the Hokkaido coast vary in accordance with this variation. Additionally, stronger (weaker) winds in the west of the strait during the nighttime (daytime) correspond to the cool air intrusion (retreat) as shown in Fig. 3. This suggests that increase of the pressure gradient due to the cool air intrusion induces the stronger winds during the nighttime. This diurnal variation along the Japan Sea is in stark contrast with emergence and disappearance of the strong winds in the lee of the upwind cape (42.0°N, 143.2°E; Shimada and Kawamura 2007). In the analysis hereafter, we represent winds in the east and west of the strait by mean winds in the two squares indicated in Fig. 4a. Meanwhile, the winds over the land in the vicinity of the Tsugaru Strait and at the buoy in Mutsu Bay become stronger during the daytime (Figs. 4b,c) than nighttime (Figs. 4a,d,e). During the daytime, the winds shift toward inland and become more divergent across the strait.

We look into the detailed wind field derived from the RADARSAT-1 image acquired at 0544 JST 9 June 2003 (Fig. 5). This time corresponds to the fully developed stage of the winds in the west of the strait as shown in Fig. 4e. The easterly wind blowing into the strait forms a wind speed maximum (7 m s\(^{-1}\)) at the narrowest point (41.6°N, 140.9°E). The easterly wind blowing from the southeast of Mutsu Bay also reaches up to 7 m s\(^{-1}\) in the west of the bay, leaving weak wind region in the lee of the Shimokita Mountains. Figure 5 verifies that the strong winds observed by SeaWinds in the west of the strait (Fig. 4e)
are confluence of three smaller-scale strong winds extending from the upstream terrestrial gaps. The wind speeds increase rapidly up to 12 m s\(^{-1}\) after passing over the southern tip of the Matsumae Peninsula. This is possibly due to a decrease of the marine atmospheric boundary layer height and resulting wind accelerations, called an expansion fan (e.g., Haack et al. 2001). Meanwhile, the wind speeds between the wind jets and behind the mountainous peninsulas are quite low (<3 m s\(^{-1}\)). Thus, routes of the low-level winds are strongly influenced by the topography.

We show that this event is represented in the meteorological stations over land. Figure 6a shows a time series of SLP difference between stations Hakodate (HK) and Fukaura (FK) in June 2003, together with sign-reversed zonal wind components in the west of the strait. The positive SLP difference indicates higher SLP at station HK than station FK. Noticeably significant correlation between them is apparent. The zonal component is useful here to show the wind switching in east–west direction, but we have confirmed the same degree of correlations between the SLP differences and wind speeds in the west of the strait for the times of the easterly winds. The air temperature differences between stations HK and FK are inversely correlated with the SLP differences (Fig. 6b). Namely, the SLP differences are positive when the air temperatures are lower on the east than west due to the inflowing cool air. The inflowing cool air is confirmed from a time–height diagram of potential temperature at station HC (Fig. 6c). Lower potential temperatures are seen when the SLP difference is positive. While the potential temperatures are especially low below 300-m height, the cool air reaches up to 1500-m height. The above results indicate that the cool air associated with the easterly winds increases the SLP on the east side of the strait and the SLP gradient along the strait, and the increased SLP gradient induces strong winds in the west of the strait. These results are consistent with typical characteristics of gap-exiting winds (e.g., Sharp and Mass 2004). We discuss suitable pairs of WOSs for representing SLP gradient along the

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**Fig. 4.** Ocean surface winds at 12.5-km resolution measured by SeaWinds/QuikSCAT and SeaWinds/ADEOS2. The label at the top of each indicates the observation time of SeaWinds. Wind vectors over the land are obtained from meteorological observation stations. A wind vector observed at the buoy in Mutsu Bay is also shown. For clarity, the wind vectors over the land and at the buoy in Mutsu Bay are twice longer than those from SeaWinds. Color scales are common to the winds over the land and sea. (a) The two squares indicate areas for wind averaging for statistical analysis of the winds in the east and west of the strait.
strait and for monitoring the strong winds in the west of the strait from statistical point of view in section 4.

While the Okhotsk high is important to induce the positive SLP difference, its sustainability depends on the tracks of low pressure systems. The sustained positive SLP difference on 5–10 and 23–28 June are induced by low pressure systems passing along the southern coast of Japan (Fig. 3). The resulting easterly winds continuously advect the cool air from the Okhotsk high toward northern Japan. On the other hand, short durations of the positive SLP difference are apparent on 12–13, 16–17, 20, and 28 June. The approach of the low pressure systems over the Japan Sea toward the Tsugaru Strait rapidly increases the SLP difference. After passing over the strait, the pressure difference reverses, switching the wind from easterly to westerly. Consequently, the positive SLP difference lasts only one or two days at most. In section 4, we will be examining statistics of the tracks of low pressure systems.

So far, we have seen that the easterly winds in the west of the strait are dominantly induced by an along-strait SLP gradient. The cool easterly winds accompanied by clouds and fog are blocked by the central spine of the mountains and are dammed on the east side (Fig. 1). This condition enhances a regional- to synoptic-scale SLP gradient along the strait (Fig. 3). The SLP gradient can also induce strong winds exiting from the other terrestrial gaps (Figs. 4 and 5). On the other hand, we are also interested in the diurnal variation of the winds in the west of the strait and over the land (Fig. 4). The diurnal variation of the cool air intrusion into the strait plays an important role on the wind diurnal variation in the west of the strait (Fig. 3). We need to investigate what makes a difference in the diurnal variation of winds over land and in the west of the strait. To address the questions posed in this section, we show statistical analyses of the data in section 4.

4. Statistical analyses

a. Wind climatology

We show wind climatology in the vicinity of the Tsugaru Strait where the wind speed and direction are greatly influenced by the topography. Figure 7 illustrates wind roses in June–July for 9 yr (2000–08). The wind roses in the east and west of the Tsugaru Strait are composed from SeaWinds/QuikSCAT (Figs. 7a,b) and first presented by using the 12.5-km wind data. The wind rose in the west of the strait shows a primary peak of cumulative frequency of 15% lying east and east-northeast (Fig. 7a). This directional range reflects the direction of the strait and the wind diurnal variation as shown in Fig. 4. The high percentage of speeds greater than 5 m s\(^{-1}\) indicates the frequent occurrence of strong winds blowing from the east through the Tsugaru Strait. On the other hand, the wind rose for the east of the strait shows the prevailing winds from the east and east-southeast directions (Fig. 7b). The high wind speeds in the east of the strait occur much less frequently than in the west. As well as the easterly winds, the westerly winds are also dominant in both sides of the strait, reflecting the direction of the strait. However, it is noted that the speeds of the exiting winds are significantly different between the easterly and westerly winds; namely, the speeds of the easterly wind in the west are much higher than those of the westerly winds in the east of the strait. This suggests that the background conditions of the cool easterly winds are favorable for enhancing the easterly winds in the strait in these months.

The wind roses composed from the hourly observations at the meteorological stations generally have linear shapes along the terrestrial gaps (Fig. 7c). This confirms that there are many small-scale passages for wind. Alternatively, peaks of the wind roses are aligned with the coast as seen at the stations at the southern tip of the Matsumae Peninsula and at the northern and southern tips of Mt. Osorezan. Wind speeds over the land are quite low compared with those in the east and west of the strait. Higher speeds than 5 m s\(^{-1}\) do not significantly change the wind roses over the land. Moreover, the shapes of the wind roses in the west and east of the strait (Figs. 7a,b) are not the same with those even at the nearest stations over the land. This means that it is difficult to infer the sea surface winds from the winds over the land.

b. Estimation of wind speed in the west of the strait

To estimate the zonal component or the speed of the easterly wind in the west of the strait, we have shown...
that the SLP differences at two WOSs are useful (Fig. 6a). We here decide which pair of stations is suitable for monitoring the strong winds in the west of the strait from 9-yr statistics. The east-side stations should be subject to the cool air accompanying the easterly winds, and the west-side stations should be apart from the routes of the cool winds. Judging from the SAR-derived wind field (Fig. 5), three WOSs [HC, HK, and Mutsu (MU)] can be candidates of the east-side stations because they are located in the eastern plains. The other three WOSs [Aomori (AO), Esashi (ES), and FK] can be candidates of the west-side stations because they are located on the west of the mountains and the blocking of the easterly wind is expected at the locations. Thus, we have nine possible pairs of stations to obtain the SLP difference for estimating the strength of the wind in the west of the strait.

Using the data in June–July for 9 yr, we compare correlations between the SLP differences between the east- and west-side stations and wind speeds in the west of the strait for the times of the easterly winds. While the following results are essentially the same with use of the zonal wind component in the west of the strait, the wind speeds in the west of the strait reflect the along-strait wind component more directly. We also have confirmed that the correlations become maximum if the time lag is within $\pm 2$ h, but no significant and systematic changes around zero time lags are found from the dataset. Thus, we hereafter show the results with a zero time lag. Figure 8a is an example in case of stations HK and FK. Table 1 summarizes the correlations for the nine pairs of stations. We can conclude that the SLP difference between the WOSs with significantly high correlations (e.g., correlations $>0.8$) can be effectively used to estimate the strength of the easterly winds. While it is difficult to estimate the SLP gradient accurately along the strait, appropriate pairs of stations can characterize the along-strait SLP difference on the whole. It is worth mentioning that significant correlations exist throughout the year. Monthly correlations are above 0.72 in case of stations...
HK and FK. However, the correlations are highest in June–July. This means that pressure gradient along the strait become a dominant factor for the strong winds in the west of the strait in June–July.

Additionally, local-scale pressure perturbations intimately tied to topography can be inferred from the differences of the correlations between stations (Table 1). There is not so much of a difference in the correlations for
choice of an east-side station. This means that the SLPs at the locations of the east-side stations respond to the cool air intrusion. Above all, the correlations are higher for stations HK and MU than station HC. The SLP at station HC may not always represent that at the inlet of the strait due to the location away from the inlet. Meanwhile, the correlation is sensitive to choice of a west-side station. The correlations are lowest in the case of station ES because station ES is located between two strong winds extending northwestward from the terrestrial gaps (Fig. 5). While station AO is located at midway point between the east and west coasts, it is apart from the winds blowing through Mutsu Bay. Thus, the SLP variation at this station is substantially unaffected by the cool air. The easterly wind completely goes around the location of station FK due to the high mountains. Actually, choice of station FK as a west-side station gives high correlations (>0.85) for each of the east-side stations. Above all, a pair of stations HK and FK shows the highest correlation. Because a line connecting the stations is well aligned with the direction of the western strait, a SLP gradient is well represented by the SLP differences between the stations.

Let us now attempt to examine the possibility of estimating the wind in the west of the strait using the analytical model of gap flows (Overland 1984; Mass et al. 1995). Given steady and one-dimensional conditions with an imposed along-strait pressure gradient and frictional force proportional to the surface wind speed squared, Mass et al. (1995) give the solution as follows:

\[
u^2(x) = \left[ u^2(0) - \frac{P_s}{K} \right] e^{-2Kx} + \frac{P_s}{K}, \quad (1)
\]

where \(u\) is the along-strait component of the wind, \(x\) is the distance along the strait, \(P_s\) is the along-strait pressure gradient force, and \(K\) is proportional to the drag coefficient. For sufficiently large \(x\), the initial wind speed \(u(0)\) is relatively unimportant and the first term of the right-hand side is negligible. This is true to the present case. Using the available parameters here, the Eq. (1) can be reduced as

\[
u^2(x) = \frac{\Delta P}{\rho K \Delta x}, \quad (2)
\]

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<th>Table 1. Correlation coefficients for pairs of WOSs between their SLP differences and wind speeds in the west of the strait for the times of the easterly winds in June–July for 9 yr (2000–08).</th>
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Fig. 8. (a) Scatterplots between SLP differences between stations HK and FK and wind speeds in the west of the Tsugaru Strait for the times of the easterly wind in June–July for 9 yr (2000–08). (b) As in (a), but for squared wind speeds. Both (a) and (b) include a correlation coefficient \(R\). The solid lines in (b) indicate a regression line based on the prediction formula. (c) Scatterplots between observed and estimated wind speeds in the west of the strait.
where $\Delta P$ is SLP difference between stations (e.g., stations HK and FK), $\rho$ is air density, and $\Delta x$ is the distance of the strait.

Using the data shown in Fig. 8a, we now inversely estimate $K$ suitable for the present case, and evaluate the accuracy of estimated wind speeds. Figure 8b shows the relationship [see Eq. (2)] and the slope (i.e., 0.32) indicates the $1/\rho K\Delta x$. The correlation amounts to 0.91 as is expected from Fig. 8a. Assuming that the SLP differences between stations HK and FK represent the SLP differences over the distance of the strait and that the distance $D_x$ is about 100 km, $K$ is $2.5 \times 10^{-5}$ m$^{-1}$. This value is 3.0–3.8 times larger than that used in Shelikof Strait by Bond and Stabeno (1998). In the present case, $K$ may not represent the surface friction only. The SLP difference $\Delta P$ tends to be large because the SLP at station FK can be locally lower due to lee troughing and because the SLP difference between stations HK and FK include the north–south SLP gradient components. The large $K$ may also arise from effective distance of the curved strait and the terrain configuration of this study area. Figure 8c compares the observed wind speeds with those estimated using the $K$ value. The root-mean-square error is 1.42 m s$^{-1}$ and the bias is 0.22 m s$^{-1}$. These relatively small errors imply that the SLP differences between the stations can be used to estimate the wind speeds in the west of the Tsugaru Strait.

c. Tracks of low pressure systems and synoptic situation

This subsection shows that tracks of low pressure systems have an important role to induce the along-strait SLP gradient. Using the 6-hourly SLP fields from the JRA-25 reanalysis data, we track all the low pressure systems in June–July for 9 yr (2000–08; Fig. 9). Twenty-two tracks are extracted on an average per year in the area. The SLP differences between stations HK and FK are indicated on the tracks. Two main tracks of the low pressure systems are evident, and, on each track, the plots indicating large SLP differences are localized in an area, which can be called a triggering area. The first is a track extending northeastward along the southern coast of Japan, including the tracks of low pressure systems developing on the baiu front. The large SLP differences are continuously induced before and after the low pressure systems leave the Japanese coast (138°–146°E). The resulting easterly winds in the west of the strait can last for several days. The second is a track over the Japan Sea, extending from the East China Sea. The low pressure systems approaching to the Tsugaru Strait can rapidly increase a SLP difference when they are situated on the

![Fig. 9. Tracks of all the low pressure systems in June–July for 9 yr (2000–08). They are manually tracked from the 6-hourly JRA-25 SLP fields whose grid interval is reduced 4 times (0.31°) by interpolation. Circles on the tracks denote the 6-hourly positions of the low pressure systems, and their colors indicate the SLP differences between stations HK and FK at the positions.](image-url)
southeast of the Japan Sea. Duration time of the easterly wind in the west of the strait is typically short (about 1 day). The low pressure systems passing through these two triggering areas effectively induce a large along-strait SLP difference or strong easterly winds in the west of the strait.

The two main tracks of low pressure systems are well reflected in composite and anomaly fields of SLP and 1000-hPa air temperature for the times when the SLP differences between stations HK and FK are greater than 1.0 hPa (Fig. 10). A large tongue-shaped low pressure extends eastward along the southern coast of Japan and a small tongue-shaped low pressure extends northeastward over the Japan Sea (Figs. 10a,c). These tongue-shaped low pressures correspond to the triggering areas of the easterly winds in Fig. 9, and enhance the Okhotsk high, which is a prerequisite for the easterly winds. The tongue-shaped high pressures extend along the east coast of the Eurasian continent and northern Japan from northeast (Figs. 10a,c), corresponding to cool air anomalies (Fig. 10b). The cool air anomalies indicate the continuous cool air extension toward the east coast of northern Japan (Fig. 10d). Warm air anomalies on the southeast of the Japan Sea indicate the warm air advections due to the low pressure systems located in this triggering area (Fig. 10d).

The previously mentioned pattern of high and low pressures form a large SLP difference (about 2 hPa on average) along the Tsugaru Strait. For the composite fields, we examine the contribution of low-level cool air to the SLP gradient along the strait. The similar patterns between the SLP and 1000-hPa air temperatures means that the low-level cool air temperatures dominantly determine the SLP (Figs. 3 and 10a,b). To calculate the depth of the cool air responsible for the hydrographic pressure changes along the strait, we use the Schoenberger’s equation (Schoenberger 1984):

$$\Delta P = (P g \Delta Z \Delta T_v)/(RT_v T_v),$$

where $\Delta P$ is an estimate of the hydrostatic surface pressure difference due to the cool air depth change ($\sim 2$ hPa), $P$ is the environmental pressure ($\sim 1010$ hPa), $g$ is gravity, $\Delta Z$ is the depth of the cool air, $T_v (\sim 291$ K) is the mean
virtual temperature of the warm air, $T_{vc}$ (~288 K) is the mean virtual temperature of the cold air, $\Delta T_v = T_{vw} - T_{vc}$ (~3 K), and $R$ is the gas constant for dry air. By solving for $\Delta Z$, the equivalent depth of cold air to account for the pressure difference is about 1600 m. This depth is consistent with the cool air layer shown in Fig. 6c. Thus, the increase in SLP may be explained by the arrival of the low-level cool air. However, further studies are required to investigate SLP variations, including its diurnal variations and the effect of surface conditions (sea or land).

**d. Diurnal variations of wind and air temperature**

This subsection considers the implications for the diurnal variations of winds over the land and sea. Hereafter, we define the times of the prevailing easterly wind as the SLP differences between stations HK and FK greater than 1.0 hPa. Composite analysis confirms the different diurnal variations of the surface winds over the land and in the west of the strait under the prevailing easterly winds (Fig. 11). Mean surface winds are derived from SeaWinds/QuikSCAT and meteorological observation stations at 0500 and 1700 JST in June–July for 9 yr (2000–08). These times roughly correspond to the local passing times of QuikSCAT. The winds are easterly at 0500 JST (Fig. 11a) and east-northeasterly at 1700 JST (Fig. 11b) in the west of the strait. The area with high wind speeds (>8 m s$^{-1}$) is wider at 0500 than 1700 JST. The easterly winds are generally seen over the land at both times. However, the speeds are larger and the directions are more divergent by shifting toward inland at 1700 than 0500 JST. These confirm the results of the case study (Fig. 4) and are consistent with the results of the southern land part of Rikiishi and Sasaki (1990). For 2003, the composites of SeaWinds/ADEOS2 winds at the local passing times around 1000 and 2200 JST support the previously mentioned diurnal wind variation.

To the west of the strait, the wind speeds and direction change diurnally. The change in speeds results from the diurnal variation of the SLP gradient as seen in Fig. 3; namely, the SLP gradient along the strait is relatively small (large) during the daytime (nighttime) because of the higher (lower) temperature of the inflowing air. While the SLP difference between the WOSs is a good indicator of the wind speeds in the west of the strait, it may not reflect the diurnal variation of SLP differences responsible for the air temperature of the inflowing air. This is because the SLPs at the meteorological stations over the land are dominantly affected by land heating/cooling. It is necessary to analyze the inflowing air over the sea. Meanwhile, it is speculated that the change in direction partly results from larger Coriolis force due to the large wind speeds during nighttime, which shifts the winds to the west from the west-southwest. Similar effects of the gap-exiting winds are seen in the previous studies (e.g., Chelton et al. 2000). Additionally, the north–south pressure gradient can diurnally vary reflecting the cool air outflowing from the strait and temperature rising in the lee of the Matsumae and Tsugaru Peninsulas. These points will be addressed using high-resolution mesoscale model simulations.

On the other hand, to consider the diurnal variation of the winds over the land, we look into mean air temperatures at the meteorological observation stations for 9 yr (2000–08) under the prevailing easterly wind (Fig. 12a). The air temperatures are generally lower (higher) on the east (west) side. Inferring from this figure, a virtual isotherm of 17.0°C may correspond to the boundary of the east side subject to the cool air and the west side free from it. Lower air temperatures (<17.0°C) are distributed along the coast of the strait and Mutsu Bay which are main routes of the cool wind. This study first
shows the detailed east–west contrast of air temperature in Hokkaido as well as in Tohoku, Japan.

To examine variation of the east–west thermal contrast, we apply empirical orthogonal function (EOF) analysis to the hourly air temperatures at the stations in June–July for 9 yr (2000–08) based on the correlation matrix method. The spatial pattern of the first EOF mode shows a variation of the whole study area (not shown). The spatial patterns of the second and third EOF modes show variations of east–west and north–south oscillation patterns. The contribution ratios of the first three modes are 83.9%, 5.6%, and 2.7%, respectively. These results are consistent with the result of Takai et al. (2006). The spatial pattern of the second EOF mode (Fig. 12b) generally shows negative (positive) values on the east (west) side. The negative values are also located along the coast of the strait and the bay. This pattern is consistent with the mean air temperatures in Fig. 12a. Thus, the second EOF mode can contribute to enhance the east–west contrast of air temperature distribution.

The present analysis allows consideration of the diurnal variations because we use the hourly air temperature data. Figure 13 shows time series of reconstructed air temperature anomalies of the first and second EOF modes at station HC in June 2003. Takai et al. (2006) show that the sum of the first and second EOF modes essentially represents air temperature variation associated with the cool easterly winds. The time series of the first EOF mode show usual diurnal variations of air temperature with maxima after noon and minima in early morning. Meanwhile, there are two types of variations in the time series of the second EOF mode. When the SLP difference between station HK and FK is negative (Fig. 6a), the time coefficients of the first and second mode are generally in phase (e.g., on 2–4, 10, 14, and 21 June). When the SLP difference is positive or the easterly wind is prevailing, they are inversely correlated (e.g., on 5–9, 12–13, 16–17, and 23–29 June). This means that the second EOF mode suppresses air temperature rising during the daytime.

To identify the stations at which these relations are found, Fig. 14 shows correlation coefficients of the reconstructed air temperature anomalies between the first and second EOF modes while the easterly wind are prevailing. The spatial pattern of the correlation coefficients is generally consistent with mean air temperatures and spatial pattern of the second EOF mode shown in Fig. 12. The stations on the west side and apart from the routes of the easterly wind have positive correlations. Negative correlations are found at the stations on the east side and along the coast of the strait and the bay. In contrast to the results in Fig. 12b, the station at the southern tip of the Matsumae Peninsula has negative correlation. This may be because the air temperature variation is affected by the cool easterly wind directly rushing through the southern coast of the peninsula (Fig. 5). At the locations with negative correlation, diurnal variations of air temperature are suppressed by the cool easterly winds.

Based on the above results, we speculate about the different diurnal winds over the land and sea. The cool easterly winds accompanied by clouds and fog are blocked by the central spine of the mountains and are dammed on the east side (Fig. 1). This condition features an along-strait SLP gradient on a regional to synoptic scale (Fig. 10a). The along-strait SLP gradient induces strong winds exiting from the terrestrial gaps (Figs. 4 and 5). The cooler air during the nighttime increase the SLP gradient or the wind speed (Fig. 3). These are background conditions. At the same time, the cool easterly winds directly blow into the Tsugaru Strait. The cool air in the strait and

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**Fig. 12.** (a) Mean air temperatures at the meteorological observation stations in June–July for 9 yr (2000–08) when the SLP differences between stations HK and FK are greater than 1.0 hPa. (b) Spatial pattern of the second EOF mode of air temperatures.
warm air over the Japan Sea can produce large thermal contrast or large SLP gradient force at the western exit of the strait, inducing the strong winds there. The timing of the strongest winds may correspond to the time when the cool air reaches the west exit (Fig. 3). On the other hand, diurnal land heating affects winds over the land. The low-level clouds and fogs on the east side associated with the easterly winds reduce insolation, decreasing daily mean air temperatures and air temperature rising during the daytime (Figs. 12, 13, and 14). This results in increases of the local east–west thermal contrast during the daytime as Rikiishi and Sasaki (1990) speculated. Moreover, the cool air over the strait and the bay and the high air temperatures over the land increase the thermal contrast across the coast, possibly strengthening sea-breeze circulation. Thus, the local SLP gradient enhances winds blowing from east to west and from sea toward land during the daytime (Fig. 11). Further study is required to investigate the diurnal wind variations over the sea surface and a process of the cool air intrusion into the strait and the bay.

e. The SLP difference as an index of summertime climate

Finally, we look into the feasibility of the SLP difference between east- and west-side stations as an index of the Okhotsk high activity or surface air temperature from a long-term viewpoint. Figure 15 shows interannual variations of the SLP difference between stations HK and FK, air temperature at station HC, and the standardized Okhotsk high index. These are averaged over June–July for each year. Many studies have adopted air temperature at station HC as a representative in northern Japan along the Pacific coast (e.g., Takai et al. 2006). The Okhotsk high index is defined as a SLP value averaged over the Okhotsk Sea (45°–60°N, 140°–155°E). While the SLP difference is locally determined, the three parameters are quite well accorded with each other. The correlation between any two of these three indices exceeds 0.72. In the peak years (1993, 1998, and 2003), northern Japan experienced a record cold summer. These variations are also consistent with another index based on the north–south air pressure difference along northern Japan (Kanno 2004). The SLP difference has the advantages that 1) it can be determined from the WOS observations at any time and 2) its absolute values are important and it is unaffected by climatology or interannual variations. Thus, the SLP difference can be a good index to investigate the summertime climate associated with the cool easterly winds (i.e., Yamase).

5. Summary and conclusions

This study has examined the structures and diurnal variations of the summertime low-level easterly winds blowing throughout the only east–west passage in northern Japan. This passage is composed of the Tsugaru Strait, Mutsu Bay, and circumjacent terrestrial gaps. The
The following conclusions are obtained from the case study and statistical analyses using the observational and reanalysis data.

1) The easterly wind blowing into the vicinity of the Tsugaru Strait splits into two flows due to the terrestrial blocking of Shimokita Mountains and Mt. Osorezan. The winds blow into the strait from the east inlet of the strait and into Mutsu Bay from a low-level gap on the southeast. The locally intensified winds are identified at the east inlet of the strait and at the center of Mutsu Bay. The strongest winds are found in the west of the strait and can extend westward about 120 km. They result from the confluence of three strong winds extending from the strait and adjacent terrestrial gaps. Maximum speeds are located in the lee of the southern tip of the Matsumae Peninsula.

2) The low-level cool air accompanied by the easterly wind increases the SLP gradient along the strait and enhances the strong winds to the west. The SLP differences between the WOSs on the east and west sides can represent the along-strait SLP gradient and can be a good indicator of the wind speed in the west. The most suitable pair of stations is stations HK and FK.

3) On the condition of the developed Okhotsk high, low pressure systems on the two main tracks can trigger the strong winds in the west of the strait. The low pressure systems passing along the southern coast of Japan and over the Japan Sea contribute to the long- and short-duration of the large SLP gradient in the vicinity of the Tsugaru Strait.

4) The winds over the land and in the west of the Tsugaru Strait show diurnal variations specific to the times of the prevailing cool easterly winds. In the west of the strait, stronger (weaker) and easterly (east-northeasterly) winds are seen during the nighttime (daytime), corresponding to the cool air intrusion from east (retrialt from west). On the other hand, the easterly winds over the land are stronger and more divergent across the coast of the strait and the bay during the daytime than nighttime. Mean air temperature and air temperature rising during the daytime are reduced on the east side because of the low-level clouds and fogs. These indicate a possible wind enhancement due to the local thermal contrast in the east–west direction and across the coast.

5) This study reveals that the SLP differences between the WOSs on the east and west sides (e.g., stations HK and FK) can also be a good index to define the times of the prevailing cool easterly wind, the so-called Yamase. The interannual variation is consistent with that of surface air temperature at station HC and the Okhotsk high index.

Additional work is required to confirm the speculation about the diurnal variations of the low-level winds over the sea surface in the Tsugaru Strait and Mutsu Bay. The dynamical mechanisms underlying the locally strong winds in the strait and the bay also merit further examination. To address these questions, we will investigate the case study during 5–10 June using high-resolution mesoscale model simulations. Analysis of the model simulation data, as well as the observational results here, will provide further insights for better understanding of regional climate and for improvement of weather forecasting.

Acknowledgments. The authors thank the members of Oceanography Groups of Tohoku University for their valuable advice on a regular basis. We downloaded the SeaWinds/QuikSCAT and SeaWinds/ADEOS2 data from the National Aeronautics and Space Administration (NASA) Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory. MODIS visible imagery was provided by Japan Aerospace Exploration Agency. We downloaded the JRA-25 data based on the cooperative research project by Japan Meteorological Agency (JMA) and Central Research Institute of Electric Power Industry (CRIEPI). The GPV, AMeDAS, and Weather Observation Station
data were provided by JMA. The buoy observations in Mutsu Bay were provided by Aomori Prefectural Fisheries Research Center Aquaculture Institute. We purchased the RADARSAT-I image from ImageONE Co., Ltd. This study was supported by Exploratory Research Program for Young Scientists of Tohoku University, and by Grant-in-Aid for Young Scientists (B) of the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

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