Structures and Seasonal Variations of Surface Winds Blowing through the Tsushima Strait

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

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ABSTRACT

Surface winds blowing through the Tsushima Strait are statistically investigated using satellite wind measurements and atmospheric reanalysis data. This study first presents structures and seasonal variations of the northeasterly and southwesterly along-strait winds by imposing newly proposed conditions for defining them. Although the speeds of the northeasterly along-strait winds are generally high within the entire strait, the maximum wind speeds are located downwind of the two channels. The southwesterly along-strait winds start to accelerate at the west exit within the strait. Weak-wind regions are formed in the lee of Tsushima Island in both cases. The occurrence frequencies of the northeasterly and southwesterly along-strait winds are high (low) in the warm (cool) season. The northeasterly along-strait winds are more often observed than the southwesterly along-strait winds. The frequency of the northeasterly along-strait wind is extraordinarily high in September, but the averaged wind speed is comparable to those in the other months. Most of the southwesterly along-strait wind cases fall within low-Froude-number regimes, suggesting the significant effects of Tsushima Island on the wind in the strait. Synoptic situations favorable for the along-strait winds are investigated. Correlations between the along-strait wind component and sea level pressure (SLP) indicate that the along-strait winds are induced by SLP perturbations primarily over the Japan Sea and secondarily on the south of the strait. In addition, cluster analysis of the SLP fields shows four representative SLP fields favorable for the along-strait winds and their monthly occurrence frequencies.

1. Introduction

Surface winds blowing through a strait or a channel (hereinafter referred to as along-strait winds) play a profound role in regional air–sea–land interaction. A variety of studies have investigated the along-strait winds, which are one form of gap winds, for a long time in terms of observations, theories, and numerical simulations. The following serve as examples of wind studies in the world’s straits or sea level channels: the Strait of Juan de Fuca (e.g., Overland and Walter 1981; Colle and Mass 2000), the Shelikof Strait (e.g., Lackmann and Overland 1989; Bond and Stabeno 1998), the Strait of Gibraltar (Dorman et al. 1995), the Gulf of Mannar (e.g., Luis and Kawamura 2000), the Cook Strait (Reid 1996), and the Mozambique Channel (Bigg 1992). They have shown that the along-strait winds are characterized by orographic effects causing high spatial variability and highly localized strong winds. Therefore, the along-strait winds can be a key factor in determining the weather, the climate, the sea state, and the ocean circulation, both within and adjacent to the strait.

The Tsushima Strait is a generic term used by some to indicate the sea area between the Korean Peninsula and the Japanese archipelago (Fig. 1). The Japanese islands of Honshu, Kyushu, and the Goto Islands form the southern boundary of the strait (Fig. 2). In the center of the strait is the slender Tsushima Island, oriented along the strait. This island principally consists of two mountainous islands, with a terrestrial gap in the central region. Tsushima Island divides the strait into two channels. The width and maximum depth are, respectively, 140 km and 110 m in the eastern channel and 40 km and 200 m in the western channel. Both channels connect the two marginal seas, that is, the East China Sea and the Japan Sea. From these geographical conditions, the Tsushima Strait acts as a determinant boundary condition to understand ocean circulations in the

Corresponding author address: Teruhisa Shimada, Ocean Environment Group, Center for Atmospheric and Oceanic Studies, Graduate School of Science, Tohoku University, Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi PREF 980-8578, Japan. E-mail: shimada@ocean.caos.tohoku.ac.jp

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two marginal seas. Therefore, this strait is an important sea area where continuous and intense monitoring research is required and indeed is currently ongoing, responding to social demands from oceanographic and meteorological points of view as well as a marine security point of view (e.g., Takikawa and Yoon 2005; Yoshikawa et al. 2006; Senjyu et al. 2008).

In stark contrast to those hydrographic observation studies in the Tsushima Strait, little attention has been given to surface wind monitoring in this strait. Like case examples in the above-mentioned studies, the Tsushima Strait can induce strong along-strait winds. In addition, its unique terrain configurations, characterized by Tsushima Island and two channels, can enhance the features of the along-strait wind within the strait. However, it is difficult to infer the complete picture of the wind from the sparse distribution of in situ wind observation stations. Conventional 25-km scatterometer wind measurements cannot get to the central region of the strait where Tsushima Island is located. Therefore, structural details of the along-strait winds in the Tsushima Strait are poorly documented at the present stage. Statistical studies have not yet been conducted to obtain seasonal variations of the along-strait winds and to consider their forcing mechanism. Moreover, the synoptic settings favorable for inducing the along-strait winds have not been investigated. As a consequence, higher-resolution and wider-area wind observations are required for grasping the structure of the along-strait wind and for describing their seasonal variation.

Moon et al. (2009) have recently mentioned the importance of the along-strait wind in the Tsushima Strait. They have shown that the minimum volume transport through the strait in September arises from the prevailing northeasterly wind in the strait. The northeasterly along-strait wind, especially persistent in September, produces a sea level increase along the Korean coast, resulting in a geostrophic balance across the strait. This geostrophic balance decreases the volume transport and forms a minimum in September. At the same time, this study has proved that little is known about the structure and seasonal variation of the along-strait winds in the Tsushima Strait. Therefore, we need a fundamental understanding of climatological behavior of the along-strait winds on a year-round basis. This leads to a better understanding of oceanographic and meteorological environments not only in the strait but also in the marginal seas, as illustrated by Moon et al. (2009).

The scope of this study is to investigate the structure of the surface winds blowing through and along the Tsushima Strait and to characterize the statistics of their variability. In the Tsushima Strait, the along-strait winds mean the northeasterly wind blowing from the Japan Sea to the East China Sea and the southwesterly wind in the opposite direction. This study first presents a detailed picture and climatological description of the along-strait winds in the Tsushima Strait using high-resolution satellite wind observations and atmospheric
reanalysis data. This study addresses four specific questions: 1) What is the detailed picture of the along-strait winds within the strait? 2) What are the seasonally varying magnitudes of the along-strait winds? 3) What are the favored seasons for the along-strait winds in the Tsushima Strait? 4) What synoptic conditions are favorable for generating the along-strait winds?

The following section gives brief descriptions of data. Section 3 shows the diversity of the along-strait winds. Section 4 presents the statistical characteristics of the along-strait winds in the Tsushima Strait. In section 5, synoptic conditions favorable for the along-strait winds are discussed. A summary and conclusions are given in section 6.

2. Data

High-resolution wind fields are derived from two synthetic aperture radars (SARs) to examine the wind structures within the strait. The Environmental Satellite (Envisat) Advanced Synthetic Aperture Radar (ASAR) operates at C band and in horizontal and/or vertical polarization. This study uses wide-swath mode images with a 500-km swath and a pixel size of 75 m. The ScanSAR Narrow mode image acquired by the Canadian Space Agency’s “RADARSAT” functioning in C-band horizontal polarization has a 300-km swath with a pixel size of 25 m. Wind speed maps are derived from the Envisat ASAR and RADARSAT images by applying SAR wind retrieval with the C-band scatterometer model function CMOD5 (Hersbach et al. 2007). In cases of horizontal polarization images, a polarization ratio conversion factor (e.g., Thompson and Beal 2000) is applied. We use 6-hourly objectively analyzed data, called Grid Point Value (GPV), at a 10-km grid interval produced by the Mesoscale Nonhydrostatic Model of the Japan Meteorological Agency (JMA) to give wind directions. It has been shown by numerous studies that the Japan Meteorological Agency (JMA) to give wind speeds can be retrieved from wind statistics are derived from wind measurements acquired by the SeaWinds scatterometer on the National Aeronautic and Space Administration (NASA) Quick Scatterometer (QuikSCAT) for 9 yr (2000–08). This study uses the products with 12.5-km resolutions, and the accuracy of the retrieved wind is approximately 1 m s$^{-1}$ in speed and 20° in direction (e.g., Tang et al. 2004). A total of 5204 swath data fully covering the Tsushima Strait are analyzed.

To consider the stability effect and the synoptic situations favorable for the along-strait winds, we use reanalysis data products called the Japanese 25-year Reanalysis (JRA-25) based on the JMA Climate Data Assimilation System (Onogi et al. 2007). The 6-hourly sea level pressure (SLP), air temperature, and 10-m wind data on a 1.25° horizontal grid are used for 9 yr (2000–08).

3. SAR-derived wind fields in the Tsushima Strait

It is desirable to describe the real picture of the along-strait winds in the Tsushima Strait before moving to the statistical analyses (e.g., Loescher et al. 2006). Figure 3 provides representative examples of the along-strait winds derived from SAR. The northeasterly wind cases at 0123 UTC 8 December 2002 and 0132 UTC 10 November 2003 are shown in Figs. 3a and 3b. In both cases, the northeasterly strong winds blow into the Tsushima Strait from the Japan Sea. Although the general wind speeds are higher in Fig. 3b than in Fig. 3a, the two cases have a number of common features. The winds flowing into the strait are detached at the promontories of the Korean Peninsula and the Japanese archipelago, and weak-wind regions ($<6$ m s$^{-1}$) are formed inshore along the both sides of the strait. This may result from the open coastlines of the Korean Peninsula and the Japanese archipelago on the upwind side and from their sharp points at the entrance. The winds are accelerated in passing through the northern and southern tips of Tsushima Island, and the stronger winds extend into the channels. Meanwhile, we can track the weaker-wind regions extending southwestward about 200 km in the lee of Tsushima Island, as is more distinct in Fig. 3a.

On the other hand, Figs. 3c and 3d show the southwesterly wind cases at 2125 UTC 3 June 2001 and 1308 UTC 13 September 2003. There are also similarities between them. The westerly winds blowing into the Tsushima Strait rush through the northern and southern tips of Tsushima Island with wind speed maxima in excess of 12 m s$^{-1}$. The accelerated winds in both cases extend northeastward from the tips along the strait. Another remarkable characteristic is strong winds extending from the terrestrial gap in the middle of Tsushima Island, as is clearer in Fig. 3c. The wind splits into three strong winds on the eastern side of Tsushima Island, and weak-wind regions with speeds less than 9 m s$^{-1}$ are apparent in the lee of the northern and southern mountains of Tsushima Island. As a consequence, a number of sharp wind shear lines arise downwind of the island.

The results show that the along-strait winds in the Tsushima Strait are characterized by complex orographic effects on the surface winds. The entire strait may have an impact on convergence of the inflowing wind. The two channels can induce gap winds (e.g., Pan and Smith 1999). Tsushima Island can leave wakes with weak winds...
in the lee (e.g., Smith et al. 1997). At the same time, the northern and southern tips accelerate the winds because of the expansion fans (e.g., Samelson 1992; Doyle and Shapiro 1999; Haack et al. 2001). Strong wind shear lines extend from the tips, and reverse wind flow can generate in the lee of the island (e.g., Smith and Grubišić 1993; Yang et al. 2008). Future studies have to investigate the mechanisms contributing to the spatial variability of the along-strait winds within the strait. Furthermore, it is noteworthy that any signs of the strong along-strait winds can be observed at the limited sites over land and that the along-strait winds can have large wind speed gradients between nearshore areas and central areas of the channels. In Figs. 3a and 3c, strong winds are completely located within the strait. We need to examine the possibility of monitoring of the along-strait wind from in situ observations in further studies. Although detailed investigation into these two points is out of the scope of this study, we take into account those observational features of the along-strait winds in Fig. 3 to move on to the statistical analyses.

4. Statistical features of the along-strait winds

This section shows statistical features of the along-strait winds in the Tsushima Strait. To discuss the wind statistics in the strait, we define two square areas indicated by “E” and “W” in Fig. 2 to represent the winds at the east and west exits of the strait. The two square areas of 1.2° in latitude and longitude entirely cover the

![Fig. 3. Wind fields derived from (a), (b), (d) Envisat ASAR and (c) RADARSAT. The observation time is plotted on the top of each panel. The arrows with a fixed length represent the wind directions obtained from the GPV data. These wind directions are used for SAR wind retrieval. For clarity, they are plotted at 0.5° intervals.](http://journals.ametsoc.org/doi/pdf/10.1175/2010JAMC2301.1)
inside of the strait on both sides of the island and are intended to include the winds in the two channels and in the lee of Tsushima Island, where the wind has high spatial variability, as shown in Fig. 3. The winds averaged over these square areas are used for the statistical analyses hereinafter.

Different climatological winds between the east and west exits are confirmed by annual wind roses (Fig. 4). With regard to the east exit (Fig. 4a), two main peaks greater than 10% lie northeast and southwest, and the wind rose has a nearly two-dimensional structure. This means that the wind at the east exit has strong directionality under the influence of surrounding orography throughout the year. Incidentally, the secondary peak of the northwesterly wind mostly reflects the wintertime east Asian monsoon. During the outbreak of the winter monsoon, the wind completely crosses the strait from northwest to southeast. On the other hand, the shape of the wind rose at the west exit is totally different from that at the east exit (Fig. 4b). The wind rose is bimodal, with winds coming most frequently from northeast and northwest. The frequencies of the northeasterly wind at the west exit are similar to those at the east exit. This means that the northeasterly winds blow throughout the strait from northeast toward southwest. In contrast, there is a significant peak corresponding to the wintertime northwesterly winds and no distinct peak of the southwesterly winds (6%), as seen in Fig. 4a. This means that at the west exit the wind blows into the strait mostly from the west. This is consistent with the snapshot wind fields in Figs. 3c and 3d.

The wind variability is estimated from the velocity variance ellipses and eddy kinetic energy (EKE) of the surface wind field (Fig. 5). The EKE is defined as

\[ EKE = (u'^2 + v'^2)/2, \]

where \( u' \) and \( v' \) are the respective zonal and meridional wind components obtained by removing the respective means \( \bar{u} \) and \( \bar{v} \) from each record; that is, \( u' = u - \bar{u} \) and \( v' = v - \bar{v} \). The velocity variance ellipses are anisotropic within the strait, and the two channels are characterized by large eddy kinetic energy (\( >33 \text{ m}^2\text{s}^{-2} \)). This indicates high variability of the winds passing through the channels in two directions, as seen in Fig. 3. At the east exit of the strait, the major axes of the velocity variance ellipses are aligned northeast–southwest with the coastlines. Although the velocity variance ellipses tend to be less anisotropic at the west exit, we can track the major axes westward from both channels to the common point, the Cheju Strait. The EKE is especially large around Cheju Island, reflecting its topographic effects on the wind. At both exits, the wintertime northwesterly winds completely crossing the strait from the Korean to the Japanese coasts increase the wind variability in the northwest–southeast direction to a certain degree. Nevertheless, the above-mentioned features show that the switching along-strait winds are prevailing within the strait.
Now let us examine further the along-strait wind that is a focus of this study. We propose a condition for defining the northeasterly/southwesterly along-strait wind blowing throughout the Tsushima Strait in consideration of the different wind variabilities between at the east and west exits. First, we compute the major-axis wind components, which Chelton et al. (2000a) have used to investigate the statistics of the wind jets, at both exits as follows. From snapshot ocean surface wind fields observed by QuikSCAT, we first compute mean wind vectors in the defined square areas (two squares in Fig. 2). Their velocity variance ellipses (two ellipses in Fig. 2) are also computed at the two square areas. Then, we derive the angle differences between the mean wind vectors from each snapshot wind field and the major axes of the velocity variance ellipses. The mean wind vector is projected onto the major axis to compute the major-axis wind components. A positive (negative) major-axis wind component indicates the wind speed toward the northeast (southwest). The black and gray arrows and numbers near the ellipses in Fig. 2 indicate the mean winds, the major-axis wind components, and the angle differences, respectively.

The along-strait wind on each snapshot wind field is defined if the following two conditions are met at the same time: 1) the major-axis wind components at the east and west exits have the same sign and 2) the sum of the angle differences is less than a threshold, which is proposed below. The first condition decides between the northeasterly and southwesterly winds blowing throughout the strait. When the first condition is not fulfilled, the wind inflows and outflows from both exits. The second condition permits some deviations of the wind blowing throughout the strait. When the second condition is not satisfied, it is difficult to identify well-organized wind flows along the strait. The examples are the wind crossing over the strait in the northwest–southeast direction, which is often seen in winter, and a wind jet locally generated from the isthmus between Honshu and Kyushu Islands toward the Korean Peninsula (Isoguchi and Kawamura 2007). Figure 6 shows a relative frequency of the sum of the angle differences for all the QuikSCAT observations. The threshold is set to 60°, at which there is a rapid drop. A total of 2287 snapshots out of 5204 are defined as ones capturing the along-strait winds. Of the total, 1383 and 904 are the northeasterly and southwesterly along-strait winds, respectively. Figure 2 gives an example of a wind field satisfying the two conditions. We can say that the southwesterly wind completely blows throughout the strait. To impose these conditions extracts the winds switching between northeasterly and southwesterly along the strait and allows discussion on the statistics of the along-strait winds. Otherwise, it would be difficult to analyze the switching along-strait winds.

The wind vector average, the velocity variance ellipses, and the EKE of the surface wind field are separately computed for the two regimes of the northeasterly and southwesterly along-strait winds (Fig. 7). Although high-wind regions are usually characterized by large EKE (e.g., Chelton et al. 2000a), small EKE is seen in the center of the Tsushima Strait, where the wind speeds are high. This is because these analyses are based on each regime of the northeasterly or southwesterly along-strait wind. That is, low wind variances indicate the area in
which similar wind structures are often observed. For the northeasterly along-strait-wind case (Figs. 7a,b), the wind directions are well aligned throughout the strait. High wind speeds are limited to the narrowest section of the entire strait, and we can see nearly symmetric distribution of the wind acceleration and deceleration on the upwind and downwind sides, respectively. This is quite a contrast to common gap winds with maximum wind speeds at the gap-exiting region (e.g., Chelton et al. 2000a). Small EKE is seen not only within the strait but also on the upwind side, indicating the uniformity of the inflowing winds and the importance of the upwind wind convergence due to the topography on the coasts. Meanwhile, the maximum wind speeds (9 m s\(^{-1}\)) are seen downwind of each channel, which is consistent with the common gap winds. This shows that the two channels work as gaps. For the southwesterly along-strait-wind case (Figs. 7c,d), wind accelerations apparently start at the west exit within the strait. At the downwind east exit, the high winds extend along the Japanese coast, but the maximum wind speed is seen downwind of the western channel. This indicates a channeling effect of the western channel (e.g., Pan and Smith 1999) and/or flow accelerations at the corner of the Korean Peninsula (e.g., Samelson 1992; Doyle and Shapiro 1999; Haack et al. 2001). Low EKE (<10 m\(^2\) s\(^{-2}\)) and highly anisotropic velocity variance ellipses are confined to the center of the strait.

We turn now to seasonal variation of the along-strait winds. Figure 8 shows monthly mean major-axis wind components at the east and west exits, which are computed only from the data satisfying the conditions for the along-strait winds. In both northeasterly and southwesterly along-strait-wind cases, the monthly variations at the east and west exits are similar to each other. The
monthly mean major-axis wind components are generally larger for the northeasterly along-strait winds than for the southwesterly along-strait winds. Meanwhile, the downwind wind speeds are larger by 1.0–2.0 m s\(^{-1}\) than the upwind wind speeds throughout the year at both exits, indicating the acceleration of the winds in the strait. This tendency is more distinct in the wintertime southwesterly along-strait wind case. The variabilities of the wind speed in a month are relatively large in the northeasterly along-strait-wind case (Fig. 8a), but there are three maxima in January, April, and September and minima in March, July, and October. In the southwesterly along-strait-wind case (Fig. 8b), seasonal variation of the major-axis wind components can separated into two terms: the mean major-axis wind components are smaller (about 6 m s\(^{-1}\)) in May–October and larger (about 8 m s\(^{-1}\)) in November–April.

Moon et al. (2009) have shown the seasonal variation of the along-strait wind speed. A few features of their result are the same as those of this study. Namely, the peak of the northeasterly wind speed in September is clear, and the monthly wind speed is minimum in July. However, the wind variation of their result is so small throughout the year, except the peak in September, when compared with the results presented here (Fig. 8a). Because Moon et al. (2009) use ordinary monthly averaging of wind vectors, the along-strait winds switching between northeasterly and southwesterly are not assessed in their results. This is true of their monthly composites of the wind. The present results (Figs. 7 and 8) consider the along-strait winds switching between northeasterly and southwesterly and enhance their features. Figure 8a shows that possible strong speeds of the northeasterly along-strait wind in September are not so extraordinary if the duration time is not considered.

To consider the duration times of the northeasterly and southwesterly along-strait winds, we look into their monthly occurrence frequencies (Fig. 9). Seasonal variations are clear, with high (low) frequencies during the warm (cool) season for both along-strait winds. The northeasterly along-strait winds account for 26.6% of the total dataset (5204 swath data) and are more often observed than the southwesterly along-strait winds (17.4%). Above all, an extraordinarily high peak of the northeasterly along-strait winds is seen in September. Meanwhile, there is a remarkable drop in July. The occurrence frequencies of the southwesterly along-strait winds are high in March–August and very low in September–February. There is a slight drop in June but a high peak in July. It would be difficult to obtain these seasonal variations of the along-strait winds from ordinary composite analysis without the above-mentioned conditions defining the along-strait winds. We shall return to these seasonal variations in section 5 to discuss occurrence frequencies of synoptic situations favorable for the along-strait winds.

A difference is seen in the atmospheric stability between the northeasterly and southwesterly along-strait
winds. Figure 10 shows scatterplots of the major-axis wind component $U$ versus the Brunt–Väisälä frequency $N$ at the upwind sides. These plots indicate the regimes of different Froude numbers ($Fr = U/HN$), where $H$ is the height of the island. The Froude number provides a measure of the relative importance of potential and kinetic energy in flow around and over obstacles. For the northeasterly along-strait wind (Fig. 10a), the plots have a wide and uniform distribution ranging from low to high stability and wind speed. The plots with Froude number higher than 1.0 account for 56% of the total northeasterly along-strait wind cases. On the other hand, most of the plots for the southwesterly along-strait winds (Fig. 10b) fall within the low-Froude-number regimes. Of the data plots, 68% have Froude number less than 1.0. This indicates that the southwesterly along-strait winds can be often blocked strongly by Tsushima Island and produce local high winds, as inferred from Figs. 3c and 3d. For the northeasterly along-strait winds, effects of high topography of the entire strait may have more impact on the wind.

5. Synoptic SLP fields favorable for the along-strait winds

To supplement the seasonal variation of the along-strait winds presented in the previous section and to give some suggestions on their generation mechanisms, synoptic SLP and wind fields favorable for the along-strait winds are considered in this section. The role of the synoptic SLP field is first investigated by cross-correlation analysis between the SLP of JRA-25 and the major-axis wind component at the east exit of the strait after the fashion of Chelton et al. (2000b) (Fig. 11). This result is essentially the same with the case using the major-axis wind component at the west exit of the strait. The correlation map shows a north–south dipole structure with a boundary on the south of the Tsushima Strait at 32°N. Negative concentric contours extensively cover the Yellow Sea, the eastern coast of the Eurasian continent, the Japan Sea, northern Japan, the sea on the east of northern Japan, and the Okhotsk Sea. High negative correlations ($<-0.6$) are located at the northwest of the Japan Sea (42°N, 133°E). On the other hand, positive contours entirely cover the southern seas: the East China Sea and the northwest Pacific Ocean south of 32°N. No positive contours reach to the continent. The positive contours are also concentric, with a maximum correlation ($>0.2$) with a center at 26°N, 131°E. Note that the center of the positive contours is not over the East China Sea, which corresponds to the immediate area of the strait. Although the correlation contours are not completely perpendicular to the northeast–southwest direction of the strait, the correlation patterns on the two sides indicate the contribution of the along-strait pressure gradient to the generation of the along-strait wind. Moreover, the correlations show that the along-strait winds are induced by pressure perturbations primarily over the Japan Sea and secondarily over the sea on the south of the strait.
Fig. 11. Map of the cross correlation between the major-axis wind component at the east exit of the Tsushima Strait and SLP at each 1.25° grid for 9 yr. Positive (negative) contours are drawn by black dashed (gray solid) curves. This result is essentially the same with the case using the major-axis wind component at the west exit of the strait.

Also examined are the representative synoptic SLP fields favorable for the along-strait winds and their seasonal occurrences based on cluster analysis. The cluster analysis is a multivariate statistical technique designed to divide data into clusters, with the goal that all elements within a cluster have similar characteristics, whereas distinct differences exist among the clusters (e.g., Everitt et al. 2001). This study uses a hierarchical cluster analysis for classifications of the SLP field, which is often used in the field of atmospheric science (e.g., Weber and Kaufmann 1995). The hierarchical cluster analysis first assigns a cluster to each element and merges two clusters until one single cluster remains, using a linkage method. Similarity or dissimilarity is defined by a distance based on the linkage method. The complete linkage method (or farthest-neighbor method) is selected here to make homogeneous and compact clusters. The number of clusters is determined from the behavior of the distance at which two clusters are merged. The distance in merging two clusters increases with decreasing number of clusters. A sudden increase of the distance indicates a strong loss of information and a possible candidate for determining appropriate number of clusters.

This study takes concrete steps as follows. First, the SLP fields in the area of interest (22°–50°N, 120°–148°E) are temporally interpolated at the corresponding times of the QuikSCAT observations satisfying the conditions of the along-strait winds. That is, a total of 2287 SLP fields are obtained. Next, SLP anomaly fields are derived from each SLP field. The SLP anomaly \( p' \) is derived by removing a spatial mean \( \bar{p} \) over the entire area of interest from SLP \( p \) at each grid: that is, \( p' = p - \bar{p} \). Then, the distance between the SLP anomaly fields at two times \( A \) and \( B \), which is the similarity or dissimilarity measure between the two SLP anomaly fields, is defined by

\[
d_{AB} = \frac{1}{N} \sum_{j=1}^{N} (p'_{Aj} - p'_{Bj})^2,
\]

where \( j \) denotes the grid point and \( N \) is a total number of grid points. Thus, the hierarchical cluster analysis is applied to the dataset. This analysis method relies solely on the spatial similarity of the SLP fields and does not take into account the temporal variance. Figure 12 shows a few sudden increases of the distance when decreasing the number of clusters, for example, from six to five and four to three. The numbers like six or four can be candidates for cluster numbers suitable for discussion. In the case of six clusters, there are still similar clusters whose differences are not discussed effectively. In the light of the simplified but fundamental discussion hereafter, we choose the number of clusters to be four in the subsequent analysis. All the SLP fields are assigned to one of the four clusters. We hereinafter refer to the dataset assigned to a cluster as Cluster \( X \), where \( X = 1, 2, 3, 4 \).

We proceed to a discussion based on the cluster mean fields or averages of the dataset assigned to each cluster. Figure 13 shows the cluster mean SLP anomaly fields. Mean fields of 10-m wind fields from JRA-25, which correspond to the SLP anomaly fields assigned to each cluster, are overlaid. The percentage on each panel indicates a relative frequency of the data assigned to the cluster. We can see that no very small clusters occur. Figure 14a shows monthly relative frequencies of the SLP anomaly fields assigned to the four clusters. Features of the SLP anomaly fields and seasonal variation of the occurrence frequencies are discussed individually.

The SLP anomaly fields assigned to Cluster 1 account for 55.9% of the total SLP dataset (Fig. 13a). This type of SLP anomaly field appears more frequently than other types (Fig. 14a). The occurrence frequencies have two distinct peaks, in May–June and in August–October. The positive SLP anomalies cover the southern Okhotsk Sea, northern Japan, a part of the northwestern Pacific, and the entire Japan Sea. These characteristics are mainly associated with the appearance and development of a high pressure system over the Okhotsk Sea, often called the Okhotsk high (e.g., Ninomiya and Mizuno 1985), which induces the cool northeasterly winds over the Japan Sea. The cool air is easily blocked by the coastal mountain range of the Eurasian continent and the
Japanese archipelago and sometimes induces cold-air damming, enhancing the northeasterly wind. The negative SLP anomalies and the high occurrence frequencies in August–October, especially in September, also result from the low pressure systems frequently approaching the strait from the south, such as typhoons and tropical cyclones. The resulting large SLP gradient around the Tsushima Strait can induce the strong northeasterly along-strait winds toward the East China Sea.

Cluster 2 also represents the northeasterly along-strait winds in the Tsushima Strait and accounts for 8.7% of the total (Fig. 13b). This SLP anomaly field is characterized by large positive SLP anomalies over Eurasia, the Japan Sea, and the Yellow Sea, and negative SLP anomalies over the Pacific Ocean and the Okhotsk Sea. This pattern is typical of the SLP field in winter. Whereas the northwesterly wind crossing the strait from northwest to southeast is prevailing during the outbreak of the winter monsoon, the wind shifts to northeast during the decline stage of the outbreak and blows through the strait toward the southwest. This is confirmed by the higher occurrence frequencies of this cluster in the cool season (September–March; Fig. 14a). The SLP gradient along the strait is the largest, and the resulting winds are the strongest among these four cluster mean fields. In contrast with the wind acceleration downwind of the strait, as seen in Cluster 1 (Fig. 13a), we can see the strong winds even upwind over the Japan Sea.

The total percentage of Cluster 3 is 20.9%. The primary feature of this pattern is negative SLP anomalies over the Japan Sea and positive SLP anomalies over the Pacific Ocean and the Okhotsk Sea. This SLP anomaly field corresponds to a representative SLP pattern in midsummer, and the Pacific high induces the east Asian summer monsoon. The southwesterly winds blow into the Tsushima Strait along the western edge of the positive SLP anomalies. High frequencies in May–August support this (Fig. 14a) and are well reflected in the occurrence frequencies of the southwesterly along-strait wind shown in Fig. 9. This SLP anomaly field also represents an SLP pattern typical of the rainy season in June–July, accompanied by the baiu front between the Pacific high and the Okhotsk high (e.g., Ninomiya and Akiyama 1992).

Cluster 4 accounts for 14.5% of the total. This SLP anomaly field is characterized by positive SLP anomalies mainly over the East China Sea and the Yellow Sea and negative SLP anomalies on the northeast of the study area, with large SLP gradient. The occurrence frequencies of this cluster are higher in spring (March–May). This reflects frequent moving anticyclones in the south during spring, and high pressure over the East China Sea induces the southwesterly along-strait winds in the Tsushima Strait. In fact, the anticyclonic winds are clear over the East China Sea. The wind pattern suggests rapid acceleration in the Tsushima Strait. This SLP anomaly pattern also reflects the cyclone passages in the north.

Last, we examine the consistency of the monthly frequencies derived from the cluster analysis. The SLP anomaly fields assigned to Clusters 1 and 2 and Clusters 3 and 4 can induce the northeasterly and southwesterly along-strait winds, respectively. For the northeasterly and southwesterly along-strait winds, Fig. 14b compares the monthly frequencies of sum of the clusters (line graphs) with those of the along-strait winds derived from the QuikSCAT wind measurements (bar graphs) shown in Fig. 9. As a result, both monthly frequencies are completely consistent with each other. It is verified that the frequency drop of the northeasterly along-strait winds in July is significant. These results prove the validity of the results of the cluster analysis and the primary importance of the SLP distribution represented by each cluster for the formation of the along-strait winds.

6. Summary and conclusions

This study has investigated the structures and seasonal variations of the along-strait winds or the northeasterly and southwesterly winds blowing through the Tsushima Strait. The statistical analyses based on the conditions for defining the along-strait winds have shown enhanced wind distributions in the strait and seasonal variations of the along-strait winds, and they have allowed the discussion on the synoptic SLP fields favorable for inducing the along-strait winds. The following conclusions are obtained.

1) The surface wind structures are obtained for the northeasterly and southwesterly along-strait winds. The norheaterly along-strait winds tend to blow throughout the strait, and the wind speeds are generally high within the entire strait. The maximum wind
speeds are seen downwind of the two channels. On the other hand, the southwesterly along-strait winds start to accelerate at the west exit within the strait. The terrestrial gap in the middle of Tsushima Island as well as the two channels can produce strong winds. Wind speeds tend to be large at the exit of the western channel and at the corner of the Korean Peninsula. For both cases, weak-wind regions are formed in the lee of Tsushima Island and along the coast on both sides of the strait.

2) The monthly mean downwind wind speeds are larger by 1.0–2.0 m s\(^{-1}\) than the upwind wind speeds throughout the year. The monthly mean speeds of the northeasterly along-strait winds show three peaks in January, April, and September, and they are comparable. The monthly mean speeds of the southwesterly along-strait winds are generally smaller in May–October and larger in November–April.

3) The occurrence frequencies of the northeasterly and southwesterly along-strait winds are high (low) in the warm (cool) season. This seasonal contrast is clearer for the southwesterly along-strait winds. The northeasterly along-strait winds account for the 26.6% of the total and are more often observed than the southwesterly along-strait winds (17.4%). Above all, the occurrence frequency of the northeasterly along-strait wind is extraordinarily high in September.

FIG. 13. Cluster mean fields of SLP anomalies assigned to the four clusters (Clusters 1–4) and corresponding 10-m wind vector fields. The relative frequency of a cluster is shown on the top of each panel. The contour interval is 1.0 hPa. Gray shading indicates positive SLP anomalies.
The along-strait winds are significantly associated with a north–south dipole structure of SLP across the south of the strait. This structure results from SLP perturbations primarily over the Japan Sea and secondarily in the south of the strait. Based on the cluster analysis of the SLP fields, the four representative SLP fields favorable for inducing the along-strait winds are obtained. Cluster 1 mainly reflects the appearance and development of the Okhotsk high in May–June and August–October. Cluster 2 is characterized by positive SLP anomalies over the Japan Sea and the Eurasian continent, associated with the wintertime east Asian monsoon. These two contribute to the north-easterly along-strait winds. Cluster 3 shows positive SLP anomalies over the Pacific Ocean and parts of the Okhotsk Sea and represents the SLP pattern in midsummer. This pattern induces the southwesterly along-strait winds along the western edge of high pressure. Cluster 4 shows that anticyclones over the East China Sea can induce the southwesterly along-strait winds mainly in March–May.

Based on these results, we now realize that the following will be our future tasks. First, it is necessary to investigate the three-dimensional dynamic and thermodynamic structures associated with the along-strait winds and the wind acceleration mechanisms. The SAR-derived wind fields (Fig. 3) can serve as observational evidence for surface wind distributions. Then, we have to examine oceanic responses to the along-strait winds such as wave development, surface current, eddy generations, and sea level changes. It is necessary to carefully assess sharp wind shear lines and large wind speed contrast within the strait. High-resolution capability is essential to achieve these two points. We also need to examine effective ways of monitoring the along-strait wind from in situ observations.

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