1. INTRODUCTION

Surface winds blowing through a strait or a channel play a profound role in regional air–sea–land interaction. A variety of studies have investigated the winds in the straits, which are one form of gap winds, for a long time in terms of observations, theories, and numerical simulations. The winds blowing through the strait can be an key factor in determining the weather, the climate, the sea state, and the ocean circulation, both within and adjacent to the strait.

Scope of this study is to investigate true state of three low-level strong winds through the straits (Tsushima, Tsugaru, and Soya Straits) in the Japan Sea. These straits are international straits connecting the Japan Sea with the East China Sea, the northwest Pacific Ocean, and the Okhotsk Sea. We use high-resolution remote sensing data, numerical wave and meteorological models, and in situ observations. Above all, we utilize high-resolution wind fields derived from synthetic aperture radar (SAR) to capture the whole pictures of the strong winds, to support statistical features, and to verify the effectiveness of numerical model simulations. This approach makes it possible to examine unprecedented aspects of air-sea-land interaction in the Japan Sea, which only high-resolution data or simulations can resolve. Based on the examination of high-resolution wind fields derived from several SARs, representative cases of strong winds in the three strait are demonstrated in this study.

2. DATA

High-resolution wind fields are derived from 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. Phased Array type L-band Synthetic Aperture Radar (PALSAR) onboard Advanced Land Observing Satellite (ALOS) operating at L band has a ScanSAR imaging mode, and the image has a 250 to 350-swath.

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 [1]. In cases of horizontal polarization images, a polarization ratio conversion factor [2] 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. For wind speed retrieval from PALSAR images, an L-band geophysical model function [3] is used. This L-band model function is derived from PALSAR data to estimate wind speeds from the PALSAR images.

This study uses wind measurements acquired by the SeaWinds scatterometer on the National Aeronautic and Space Administration (NASA) Quick Scatterometer (QuikSCAT) and the Advanced Earth Observing Satellite 2 (ADEOS2). The products with 12.5-km resolutions are used [4]. Visible composite image from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board Aqua are used (R/G/B: band 1/4/3).

3. THE TSUSHIMA STRAIT [5]

In the study of the winds within the Tsushima Strait [5], the structures and seasonal variations of the along-strait winds or the northeasterly and southwesterly winds blowing through the Tsushima Strait are investigated. High-resolution wind fields derived from SARs first show the wind structures within the strait and the impact of the Tsushima Island on the wind fields (Fig. 1). 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 main conclusions are as follows. 1) The surface wind structures are obtained from the SAR images for the northeasterly and southwesterly along-strait winds. The northeasterly along-strait winds tend to blow throughout the strait, and the wind speeds are generally high within the entire strait (Fig.1ab). 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 (Fig.1cd). 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 after passing the Tsushima Island. For both cases,
weak-wind regions are formed in the lee of Tsushima
Island and along the coast on both sides of the strait.

Fig.1 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.

2) The monthly mean downwind wind speeds derived
from the QuikSCAT data are larger by 1.0–2.0 m/s 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 (Fig. 2). 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.

4. THE TSUGARU STRAIT [6][7][8]

In the study of the winds within the Tsugaru Strait [6],
the SAR-derived wind field is used to show the detailed
structures of strong winds exiting from the strait and to
infer the passages of the low-level easterly winds within
the Tsugaru Strait and Mutsu Bay. This view of winds
shows that a wind jet observed by SeaWinds consists of a
few strong wind extensions, and leads us to identify the
appropriate pair of meteorological stations to estimate the
along-strait pressure difference, which determines the
intensity of the wind exiting from the strait. The
atmospheric structures are investigated using numerical
simulation data in the companion paper [7].

A cool easterly wind intermittently blows toward
northern Japan from the high-pressure system over the
Okhotsk Sea (Okhotsk High) during summer months,
especially in June-July (Fig. 3). This cool easterly wind,
commonly known as Yamase, has been an object of study
since the early 20th century because it has dominated
summertime climate over northern Japan and sometimes
caused severe cold-weather damage. The easterly wind
accompanies 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.3). The dammed
clouds reduce insolation on the east (Pacific) side of the
mountain ranges. A visible composite image in Fig. 3
serves as an example for the above-mentioned
characteristics. The easterly winds prevail and the clouds
cover the low-altitude area on the east side of northern
Japan.
2) The low-level cool air accompanied by the easterly wind increases the sea level pressure (SLP) gradient along the strait and enhances the strong winds to the west. The SLP differences between the weather observation stations 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 (Fig. 6). 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-durations 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 (Fig. 7). 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 (retreat 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.

5) This study reveals that the SLP differences between the weather observation stations 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 conventional indexes, surface air temperature at station HC and the Okhotsk high index.
Fig. 6 Hourly SLP differences between stations HK and FK (gray line) and sign-reversed zonal wind components in the west of the Tsugaru Strait by two SeaWinds (black circles).

Fig. 7. Mean surface winds from SeaWinds/QuikSCAT and the meteorological observation stations at (a) 0500 and (b) 1700 JST in June–July for 9 yr (2000–08) when the SLP differences between stations HK and FK are greater than 1.0 hPa. Gray shades indicate the areas with wind speeds greater than 8 m/s. For clarity, the wind vectors over the land are 3 times longer than those over seas. Color scales are common to the winds over the land and sea.

In the study [8], the impact of the strong winds exiting from the Tsugaru Strait on the wave development is examined. The SAR-derived wind field allows us to consider the required spatial resolutions to simulate the wind structure and to discuss the wave development.

The study has compared high-resolution wave simulations and operational wave forecasts under coastal wind jets in the west of the Tsugaru Strait from a case study on 5-9 June 2003. The simulated fields of wind and waves with 2-km and 1-hour spatiotemporal resolutions are compared with operational wave forecasts with 10-km and 6-hourly spatiotemporal resolutions. Model simulation efforts in this study are made with the Pennsylvania State University-NCAR (PSU-NCAR) fifth-generation Mesoscale Model MM5 and a third generation wave model SWAN (Simulating WAves Nearshore). Hourly surface wind fields simulated by MM5 are used to drive the SWAN simulation. For MM5 simulation, we define two model domains with grid size of 6- and 2-km as shown in Fig. 8. The inner domain of MM5 is the same with the SWAN model domain. They have a grid spacing of 2 km and an hourly temporal resolution in common. Because this case study satisfies the fetch-limited condition and we focus on only wind-generated waves, incoming waves at the open boundaries of the model domain are assumed to be zero. The SWAN model is run in non-stationary mode. According to the method of [9], the result in stationary mode at 0900 UTC 6 June 2003 is used as an initial condition. The MM5 simulation is initialized at 0000 UTC 5 June 2003 and integrated to 0000 UTC 10 June 2003 during 120 hours. The SWAN simulation is initialized at 0900 UTC 6 June 2003 and integrated to 0000 UTC 10 June 2003 during 87 hours.

Fig. 8 Map of the topography and geographical locations referred to in this paper. The two MM5 model domains are indicated by the rectangles. The color scale overland, in these figures and others to follow, indicates the terrain elevation. The contours are isobaths of 200, 1000, and 2000 m. The inner domain (Domain 2) of MM5 is also the domain of the SWAN simulation.

The following conclusions are obtained. 1) High-resolution wind field derived from RADARSAT with a 500-m grid interval reveals wind jets blowing from terrestrial gaps (Fig. 5). The major wind jet blowing from the Tsugaru Strait merges with small wind jets to form a large wind jet. Merging of wind jets is also observed along the Hokkaido. Wind blocking is seen in the lee of the mountainous area. Maximum wind speed differences are up to 8 m/s between the neighboring strong and weak wind regions. These features are well reproduced by the MM5 simulations (Fig. 5 and 9).

2) Simulated wave fields by SWAN with a grid interval of 2-km well reflect the features of the wind fields (Fig. 10). The simulated SWH field represents SWH peaks corresponding to each wind jet and wave
blocking in the lee of the islands. The variation of SWH is consistent with observations.

3) Wind forecasts with a 10-km grid interval from the GPV data represent only one localized strong winds in the west of the Tsugaru Strait. While the maximum wind speeds are close to the observations, the distributional shapes of the strong winds are different from those of high-resolution observations and simulations. No other small wind jets can be reproduced. While 10-km wave forecasts represent the localized high wave region, the forecasts do not show SWH peaks corresponding to the wind jets and wave blocking due to the islands. The GPV wave forecasts have difficulty replicating coastal SWH variation due to the spatiotemporal resolution.

Looking back the results of the case of the Tsugaru Strait, we can draw the following conclusions. First, consideration of high-resolution wind fields is an important starting point for accurate wave forecasts. Though we have taken this fact for granted, unpredictable distributions of coastal wind can be revealed by high-resolution observations in some cases. Wave development under a gap exiting wind is one of the cases in which high-resolution capability is strongly required for both wind and wave simulations. Then, we have proposed a resolution required to describe winds and wind waves in this study area. Terrestrial gaps with width of 5-15 km can form a wind jet extending over 100 km. A small island can block the wave and leave a tail of lower wave height. These topographic features must be resolved adequately in the simulations. Finally we should note that monitoring of the strong wind and high waves is only possible at limited locations. Examination of high-resolution observations and simulations can provide us with a chance to reconsider and improve the configurations of observation systems.

Fig. 9 Simulated wind vector field by MM5 at 18:00 UTC June 8 2003. Grayscale shade indicates wind speed.

5. THE SOYA STRAIT [10]

In the study [10], a summertime gap winds exiting from the Soya Strait is investigated using SAR-derived winds and SeaWinds measurements. In this strait, few studies have paid attention to the winds within the strait and the strong wind extension to the west. The previous studies [6] [7] demonstrated that strong gap winds occur to the west of the Tsugaru Strait and circumjacent terrestrial gaps under the summertime easterly wind conditions, and showed that the Tsugaru Strait works as a conduit for the cool air from the Pacific Ocean. Another important sea-level conduit for the cool air is the Soya (La Pérouse) Strait located between Sakhalin and Hokkaido (Fig. 11). This strait with a width of 40 km connects the Japan Sea with the Okhotsk Sea.

The SAR-derived wind field at 1248 JST 8 June 2006 clearly observes the gap winds exiting from the Soya Strait (Fig. 11). The maximum speeds of the gap winds reach up to 15 m/s due to the rapid acceleration, but minimum speeds between the gap winds are less than 4 m/s. The widths of strong winds correspond to those of the strait. The easterly winds extend more than 200 km and almost reach the coast of the Eurasia continent. Also, as is the same with the case of the Tsugaru Strait, the occurrence frequency and intensity of the easterly gap winds to the west of the Soya Strait shows significant interannual variability according to the activity of the Okhotsk high.

Fig. 10 Simulated significant wave height field by SWAN at 18:00 UTC June 8 2003. The arrows of equal length indicate mean wave direction.
6. SUMMARY

This study has shown the detailed structures of the winds blowing through the straits in the Japan Sea. The three straits (the Tsushima, Tsugaru and Soya Straits) are conduits of the Japan Sea not only for seawater but also for low-level winds. It is crucial to understand sporadic and severe winds in the straits and its impact on the ocean and atmosphere. Moreover, the environmental monitorings in these straits are especially required because they are the international straits with heavy marine traffic. To understand the importance of the wind distribution and variability within the straits that has gone unheeded, the pictures of the winds within the straits are first shown. The SAR-derived winds in the study area have suggested the efficient way to analyze other datasets to understand wind variability, the wind statistics, and formation mechanisms of the strong winds.

The results of this study may lead to further studies of air-sea-land interaction associated with highly localized strong winds. Additionally, this study can give suggestions to improve systems for environmental monitoring in the Japan Sea. It is desired to use the knowledge of the strong winds and severe waves in coastal seas for practical use such as shipping, marine security, and marine disaster prevention. The transmission of such information is becoming more important for the appropriate agencies or communities. This study reminds us of the necessity of the high-spatial-resolution capability.

7. REFERENCES

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