Case Study of Wind Jet Transition and Localized Responses of Wind Wave along the Pacific Coast of Northern Japan by Synergetic Use of Satellite and In Situ Observations

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We present a case study of low-level wind jets induced in sequence by orographic effects off the Pacific coast of northern Japan during 7–11 June 2003, and demonstrate that the transition of the wind jets causes areal differences of wave height variations along the coast. First, we describe evolution and structure of the wind jet by analyzing SeaWinds scatterometer wind measurements. Under the easterly wind, a strong wind jet formed after passing by Cape Erimo. As the wind shifted to the southeast, the wind jet started to decay. In turn, the southerly wind along the coast led to another wind jet in the lee of the easternmost tip of the Sanriku coast. We then identify onsets and decays of the wind jets from time series of wind speed at meteorological stations. Finally, we demonstrate that the transition of the wind jets has local impacts on wave height variations. Significant wave heights measured by altimeters were correlated positively with local wind energy, i.e., squares of wind speeds. Accompanying the wind jet formation/decline, significant differences of wave height variations became marked among wave observation stations located along the coast at intervals of up to 50 km.

1. Introduction

An understanding of strong surface winds over the ocean and severe waves is particularly important because they represent a significant hazard to maritime activity. Especially in coastal seas, strong winds arise locally in the form of low-level wind jets due to air-sea-land interactions. Under favorable atmospheric conditions, the low-level wind jet occurrences strongly depend on the orientation of topographic features such as terrestrial gaps and coastlines (e.g., Chelton et al., 2000a, b; Winstead et al., 2002, 2004). Moreover, the locations of strong winds vary constantly as the prevailing synoptic-scale wind shifts. In turn, higher wave regions, which are also expected to be localized, should vary with the transition of the wind jets. The subjects of this study are low-level wind jets identified after blowing along and leaving the shore, and their associated wave fields.

The previous studies have proposed some mechanisms for the formation of these wind jets which develop in the lee of promontories and bends in the coastline (e.g., Samelson, 1992; Doyle and Shapiro, 1999; Haack et al., 2001; Pickart et al., 2003; Moore and Renfrew, 2005). Above all, active efforts have been made to study winds along the California coast (e.g., Samelson, 1992; Haack et al., 2001) and around the southern tip of Greenland (Doyle and Shapiro, 1999; Pickart et al., 2003; Moore and Renfrew, 2005). As the wind blows along the coastline and passes over a tip of a coast and or a cape, it effectively moves offshore, opening a void between the flow and the coast. When this occurs and the flow remains attached, should vary with the transition of the wind jets. The flow acceleration often ends abruptly in a hydraulic jump.
The acceleration flows should be expected to persist just as long as the requisite synoptic conditions are fulfilled. Additionally, the following factors can constrain the wind flow along the coastline and enhance the wind speed increase: a lower inversion layer constrains the atmospheric boundary layer at its top. The inversion descends down toward the coast due to the presence of a low-level baroclinic structure resulting from a cool, well-mixed marine boundary layer over the ocean and warmer air over the strongly-heated land surface (e.g., Haack et al., 2001). With the base of the inversion below mountaintop level, the coastal mountains help keep the flow oriented parallel to the coastline and suppress any sea breeze that might develop. The seaward side of the flow is constrained by a large-scale pressure gradient directed onshore to prevent flow away from the coastline. Low sea surface roughness also promotes the development of the coastal wind jet.

We focus on wind jets off the Pacific coast of northern Japan in the summer season. Figure 1 shows a map of the topography of northern Japan, focusing on the present study area. The area and the season fulfill the following favorable conditions for the above-mentioned wind jet formations. The easterly wind predominates in the region from May to August, which is comparable to another dominant wind mode of the northwesterly winter monsoon (e.g., Shimada and Kawamura, 2004). The wind blows from the Pacific Ocean toward the Tohoku District (the north end of Honshu) and Hokkaido (an island on the north side in Fig. 1), associated with the high-pressure system over the Sea of Okhotsk. The dominant northeasterly wind accompanying cool, wet, low-level clouds and fogs is known as Yamase (e.g., Takai et al., 2006). The vertical structure of the typical Yamase air mass is characterized by a thin mixed layer and an upper stable layer (e.g., Ninomiya and Mizuno, 1985). The northeasterly wind usually persists for several days. The northeasterly winds converge around Cape Erimo because the Hidaka Mountain Range, which runs from north to south toward Cape Erimo, constrains the wind. The wind rushes through Cape Erimo, creating a wind jet (Arakawa, 1969). Accelerated winds then blow toward the eastern coast of the Tohoku District. On the other hand, the northeasterly wind impinges on the mountainous land (the Kitakami Highlands), and the orographic blockage splits the wind into two flows traveling around the northern and southern side of the highlands (Takai et al., 2006).

While a few studies point out the existence of low-level wind jets in this study area (e.g., Arakawa, 1969), there have been no investigations of the detailed structure of the wind jets and their transition. Though the wind jet off Cape Erimo is familiar, being one of the strongest...
local winds near the Japanese coast, few studies focus attention on the wind over the sea. If any, their data resolution is too coarse (>0.5°) to focus on wind modifications near the coast. Until now, we have been unable to comprehend the distribution of the wind jet, the transitional views of the wind jets, frequency of such wind jet events, and climatological characteristics. In addition, we have still not discussed ocean surface wave responses to the wind jets. Understanding of the wind jets and associated waves would provide significant suggestions for improvement of a local wind map, maritime disaster prevention, and maritime security.

In this study we present a case study of the wind jet transition and the localized impact of the wind jet on waves off the Pacific coast of northern Japan during 7–11 June 2003. From sequential scatterometer wind measurements we identify two low-level wind jets under the wind as it shifts from easterly to southerly. One is the famous wind jet off Cape Erimo, but the other off Sanriku coast is described in detail for the first time here. The wind jet events are confirmed by meteorological station data. Using satellite-derived wave height data and time series wave data from coastal wave stations, we present localized effects of the wind jets on waves. In the present study, the term “wind jet” is defined as a localized region of strong winds. We here summarize two advantages of this study. One is a synergy of high-resolution satellite measurements and in situ data. In particular, two scatterometers can resolve the wind jet variation. The other advantage is that we can obtain time-series wave observations from four wave stations along the Pacific coast of the Tohoku District (Fig. 1). The coast is on the opposite side, as seen from the wind jet perspective, which allows us to investigate wave responses to the wind jets. From the two viewpoints mentioned above, we can say that this case study setting is unique.

The data are briefly described in the following section. Section 3 illustrates the transition of wind jets. In Section 4, we investigate wave responses to the wind jets. Section 5 is devoted to a discussion of statistical characteristics. Conclusions are given in Section 6.

2. Data

The wind measurements analyzed in this study are acquired by the SeaWinds onboard QuikSCAT and Advanced Earth Observing Satellite 2 (ADEOS2). The SeaWinds instrument measures wind vectors with 25-km resolution over a single 1600-km swath centered on the satellite ground track (Liu, 2002). The products with 12.5-km resolution are newly released. The wind retrievals are calibrated to neutral-stability winds at a height of 10 m above the sea surface. We use the swath data of SeaWinds/QuikSCAT for April–August 2000–2005, and SeaWinds/ADEOS2 for April–August 2003. The accuracy of the retrieved wind is approximately 1 m/s in speed and 20° in direction (Ebuchi et al., 2002; Ebuchi, 2006). The combined use of the two essentially identical sensors with almost the same accuracy allows analysis with high temporal resolution.

We also use hourly wind observations over the land acquired by weather observation stations (WOSs) and automatic observation facilities, called Automated Meteorological Data Acquisition System (AMeDAS). Both observations are operated by Japan Meteorological Agency (JMA). Wind speed and direction are observed at the stations. Wind speeds are in units of 0.1 m/s for WOS and 1 m/s for AMeDAS. Wind directions are in 22.5° unit in both data. We place particular importance on observations at six selected stations indicated in Fig. 1. Station elevation is different for different stations. However, the observation height differences are not significant for capturing wind jet events because we focus on the timings of wind changes at each station.

Altimeters on European Remote sensing Satellite-2 (ERS-2) and TOPEX/POSEIDON (T/P) satellite measure significant wave height (SWH) along their ground tracks. Their repeat periods are about 35 and 10 days, and the nominal distance of observations is about 7 km.

We use in situ wave data recorded by the system called Nationwide Ocean Wave Information Network for Ports and Harbours (NOWPHAS). NOWPHAS is referred to as an observation and analyzing system for coastal waves along the coast of Japan. NOWPHAS has been in operation since 1970 by the Ports and Harbors Bureau of the Ministry of Land, Infrastructure and Transport and its associated agencies, including the Port and Airport Research Institute. The NOWPHAS system has 54 nearshore stations along the Japanese coast. We choose four stations aligning along the Pacific coast of the Tohoku District (Fig. 1). Water depths at the stations are 28–50 m. Wave observation interval is two hours. SWH data are used in the analysis.

3. Case Study of Sequential Wind Jet Events

3.1 Series of wind fields from SeaWinds measurements

In this subsection we show the diversity of prominent wind jets in the study area from a single case study, which spans a 5-day period in June 2003. Figure 2 shows a series of wind measurements from two SeaWinds during the period. This case study begins on 7 June, when a high-pressure system over the Sea of Okhotsk starts to develop and an easterly wind predominates. According to the analyzed sea level pressure charts (not shown), the center of the high-pressure system moved southward from the Sea of Okhotsk to the southeast side off Hokkaido, accompanied by an increase in sea level pressure of the high-pressure system. This resulted in an increase of
Fig. 2. Ocean surface winds measured by SeaWinds/QuikSCAT and SeaWinds/ADEOS2 during 7–11 June 2003. Detailed observation time is labeled on the top of each figure. WOS and AMeDAS wind observations closest to the SeaWinds observation time are also shown. Gray lines in (e) and (p) indicate the ground tracks of altimeters whose observation times are close to those of the SeaWinds. Details of the altimeter data are described in Subsection 4.1 and Fig. 3. Color scales of elevation and wind vectors are the same as in Fig. 3.
Fig. 2. (continued).
meridional pressure gradient. With the southward movement of the high-pressure system, the easterly wind gradually shifted to the south over the study area. These variations are one of the representative synoptic conditions in this region and in this season (May–August). Thus, the wind shifting from the east to the south favorably tends to lead wind jets. The study period first contains the evolution and decline of the wind jet in the lee of Cape Erimo. Following the wind jet, the southerly wind takes high wind speeds in the lee of the easternmost tip (around the point of station MY) of the Sanriku coast.

In the early stage of the case study, a moderate easterly wind (∼6 m/s) blew into the narrow seas between the Tohoku District and Hokkaido (Figs. 2(a) and (b)). While the wind speeds increased slightly after passing through Cape Erimo, there was no evidence of any significant wind jet around the cape. Between at 1143 UTC 7 June and 2019 UTC 7 June, a wind jet developed rapidly on the south of Cape Erimo (Figs. 2(c) and (d)). In Fig. 2(c) we find that a strong wind (11 m/s) was already observed at station CE prior to a wind speed increase over the ocean. In Fig. 2(d) we see low-level wind acceleration from approximately 6 m/s on the east side of the cape to more than 10 m/s in the lee of the cape. The spatial extent of the strong winds is quite a contrast to that of Fig. 2(c). In fact, the area of wind with speeds greater than 8.0 m/s was largest at this time.

At 0138 UTC 8 June (Fig. 2(e)), wind directions within the wind jet shifted to the northeast. While the spatial extent of the wind jet decreased slightly, the highest wind speeds (∼12 m/s) in this event were observed at this stage. Although we can continuously identify localized strong winds, winds around Cape Erimo weakened at 0833 UTC 8 June (Fig. 2(f)). At 1258 UTC 8 June (Fig. 2(g)) we see only small areas with wind speed of 8 m/s just on the south of the cape. While the easterly wind blew for the next 12 hours, there was no evidence of flow acceleration associated with the topography of the cape (Figs. 2(h) and (i)).

Here we note other local conditions. We can see other examples of gap winds exiting from straits and mountain gaps toward the Japan Sea and the Sea of Okhotsk. The wind jet at the western exit of the Tsugaru Strait (40.5–41.5°N, 139.0–140.0°E) could be ascertained while the wind jet around Cape Erimo was developing and decaying (Figs. 2(a)–(j)). The other examples are gap winds through the southwest of Hokkaido (42.0–43.5°N/139.0–141.0°E in Figs. 2(a) and (d)) and through the islands on the northeast of Hokkaido (44.0–45.5°N/145.0–146.0°E in Figs. 2(b)–(f)). These winds exiting across the coastline were quite a contrast to the wind jets addressed in this study. While synoptic wind directions changed gradually on the Pacific side, changes in these gap-exiting wind directions were small.

After a decline in intensity of the wind in the lee of Cape Erimo, moderate easterly winds (<5 m/s) still persisted with gradual changes in wind direction to south-easterly (Figs. 2(i)–(j)). The southeasterly wind blew in the sea between the Pacific coast of the Tohoku District and the southwestern coast of Hokkaido. We find that relatively strong winds (6–7 m/s) were observed off the coast of the Tohoku District around at 40.5°N/142.5°E (Figs. 2(k) and (l)). As the wind directions shifted to the south, this feature became more enhanced in the wind field at 0921 UTC 10 June (Fig. 2(m)). In Fig. 2(m), the wind directions were generally southerly. Strong winds (~10 m/s) were observed just in the lee of the easternmost tip of the Sanriku coast. No strong wind speeds are observed at land stations in this vicinity. The location of station MY in Fig. 1 corresponds to the easternmost tip of the Sanriku coast. The region with speed greater than 8 m/s was triangular in shape and strong winds were observed on the shore side of the extension of the southern Sanriku coastline. These characteristics are seen in Figs. 2(m)–(p), although two images are omitted between Fig. 2(n) and Fig. 2(o). In any case, it is noticeable that wind speeds start to increase just after passing by the easternmost tip of the Sanriku coast. Meanwhile, a southerly wind blew along the eastern Japanese coast and split into two round the Hidaka Mountain Range (Figs. 2(m)–(p)). A wind flow blew into the sea between the Pacific coast of the Tohoku District and the southwestern coast of Hokkaido. The other wind flow flashed through Cape Erimo and directly reached the southeastern coast of Hokkaido.

Let us summarize notable features of the two wind jets, using 12.5-km resolution wind measurements (Fig. 3). Figures 3(a) and (b) are close-up and high-resolution views of Figs. 2(d) and (m), and they correspond to the fully developed stage of the wind jets. In the case of the wind jet of Cape Erimo, the maximum intensity (∼12 m/s) of the wind jet appeared on the southwestern side of the cape (Fig. 3(a)). It should be noted that wind acceleration occurs after passing over the cape. The wind field had anticyclonic curvature. The region with wind speeds higher than 8 m/s was fan-shaped with a spatial extent of about 150 km, but did not reach the coast of the Tohoku District. (The overall distance is about 200 km from Cape Erimo to the coast of the Tohoku District.) No land stations apart from station CE observed the wind responding to a wind jet over the sea. In Fig. 3(a) it should also be noted that a northerly wind passed around the Kitakami Highlands and that the winds were accelerated to 8 m/s after passing the easternmost tip of the Sanriku coast. On the other hand, Fig. 3(b) shows that wind speeds start to increase just after passing the easternmost tip of the Sanriku coast. The region with speed greater than 8 m/s was triangular in shape and strong winds were observed on the shore side of the extension of the southern Sanriku
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This wind jet can be a counterpart of wind acceleration on the south of the easternmost tip of the Sanriku coast under northeasterly wind, as shown in Fig. 3(a).

### 3.2 Wind jet events captured by meteorological station data

In this subsection we show that the wind jet events are captured in meteorological station data. From the results obtained so far, it can be concluded that the key topographic features that form the wind jets are Cape Erimo and the curving Sanriku coast (Fig. 3). For each case we select one appropriately positioned meteorological station to capture the wind jet event, and two ambilateral stations for comparison. Judging from the results of the previous subsection, it is reasonable to conclude that stations located at the tips of promontories are suitable for observing the wind jets. Figure 4 shows time series of selected wind speed components at the stations. The selected projection axis corresponds to predominant wind direction and the variation of the wind speed component is roughly consistent with that of wind speed during each event.

There is an AMeDAS station at Cape Erimo (labeled CE in Fig. 1). This is the most appropriately positioned station to capture the wind jet, as inferred from Fig. 3(a). For comparison, we also show the data from WOSs on both sides of the cape (stations UK and HR in Fig. 1). In
Fig. 4. Hourly wind time series at meteorological land stations during 7–11 June, 2003. (a) Northeasterly wind speed component at the stations (HR, UK, and CE) around Cape Erimo. (b) Southerly wind speed component at the stations (MY, OF, and KJ) along the Sanriku coast. Wind speed components toward southwest and north are positive, respectively. See Fig. 1 for the locations of the meteorological land stations. Arrows with the alphabetical characters in this figure indicate the times of SeaWinds observations in accordance with Fig. 2.

By contrast, the other stations (UK and HR) observed much weaker winds with speeds less than 5 m/s throughout the data period. The stations UK and HR showed no signs of the wind jet even at station HR located on the upwind side. While northeasterly wind speed components were constantly observed at the station CE on 7–8 June, it is quite a contrast that the sign of wind speed components appeared to shift alternately at the two stations. Hence, the results above are consistent with SeaWinds wind measurements, lending credence to important role of the cape in the wind jet formation.

In the case of the wind jet off the Sanriku coast, we chose the meteorological stations along the Sanriku coast. The WOS MY (Fig. 1) is located at the easternmost tip of the Sanriku coast, and corresponds to a starting point of wind acceleration (Fig. 3(b)). The others are a WOS OF and an AMeDAS station KJ on the south and north sides of station MY along the coast, respectively (Fig. 1). Figure 4(b) shows time series of southerly wind speed component at the stations. Until 0900 UTC 9 June, southerly wind components were observed at station OF and northerly wind components were observed at stations MY and KJ. Thereafter, southerly wind components were generally observed at station MY. This time period corresponds to the time period during which wind jets were observed on the northeast of the Sanriku coast in Fig. 2. That is, southerly wind components were observed at station MY in synchrony with the formation of a wind jet in the lee of the easternmost tip of the Sanriku coast (Figs. 2(m)–(p) and 3(b)). However, onsets of the wind jets were not very clear in the wind speed variation at station MY as compared with the case of Cape Erimo mentioned above. The following factors may contribute to this. First, topographic features of valleys associated with the deeply indented coastline control the local wind flow. Second, as shown in Fig. 4(b), diurnal variations of wind speed are predominant throughout the analyzed period at the three stations. Further studies are necessary to find an observation point suitable for capturing the onset of this wind jet.
4. Localized Impacts of the Wind Jets on Wave Height Variation

4.1 Altimeter-derived SWH

In this subsection we illustrate the spatial correlation between wind and wave distribution from two representative time periods of satellite observations. In Fig. 5, altimeter-derived SWH variations are compared with squares of wind speeds, which are proportional to wind energy, along the altimeter ground tracks. We select the pairs of altimeter and SeaWinds observations with close observation times. The ground tracks are shown in Figs. 2(e) and (p) but only the data at the study area are plotted in these figures.

The first example corresponds to the most mature stage of the wind jet off Cape Erimo (Fig. 2(e)). At 0138 UTC 8 June, SeaWinds observed the wind jet in the lee of Cape Erimo (Fig. 2(e)). Throughout the SeaWinds observations during the analyzed period (Fig. 2), the maximum wind speed (12 m/s) was observed. The ERS-2 altimeter ground track intersected the edge of this wind jet region (Fig. 2(e)). Wind speeds were low near the Hokkaido coast, but increased sharply toward the coast of the Tohoku District along the track (Fig. 2(e)). This is reflected in Fig. 5(a). SWH data were obtained from ERS-2 track 74 at 0104 UTC 8 June. SWH rapidly increased from the coast of Hokkaido toward the mid point with maximum SWH at around 41.3°N. This position is coincident with that of high wind energy. Moreover, we notice that the wave with maximum SWH did not reach the coast of Tohoku District. In fact, SWH decreased toward the south (i.e., the coast of Tohoku District) down to about 1.0 m. These characteristics reflect the fact that the altimeter ground track segment intersected the boundary of the wind jet. As described above, localized higher wind energy corresponds well to the higher SWH.

The second example is the case of the wind jet evolution in the lee of the easternmost tip of the Sanriku coast (Fig. 5(b)). At 2016 UTC 11 June, SeaWinds observed the wind acceleration on the northeast of the lee of the easternmost tip of the Sanriku coast (Fig. 2(p)). While the wind speeds are around 8 m/s and comparable with strong winds in some areas, we can see localized strong winds in the lee of the tip of the Sanriku coast. The T/P altimeter ground track extended northeastward from the easternmost tip of the Sanriku coast (Fig. 2(p)) and cut across the wind jet region. The areal extent of the wind jet was confined to the northeast of the Sanriku coast. The wind energy was highest (30 m²/s²) near the coast of the Tohoku District, but gradually decreased down to 5 m²/s² at 42.0°N. SWHs were obtained from T/P track 177 at 1954 UTC 11 June (Fig. 5(b)). During this time period, southerly wind speed components are constantly observed at station MY (Fig. 4(b)). Over a ground track segment at 40.8–43.0°N, wave heights were relatively constant at around 1.2 m. However, on the southern side, wave height increased up to 1.7 m toward the Sanriku coast. The wave height increase near the coast was in synchrony with wind energy increase associated with the wind jet development.

4.2 Time series of coastal wave height

To investigate time-dependent wave height variation and their areal differences, we compare time series of SWH and wave direction acquired at four wave observation stations along the coast (Fig. 1). The wave stations are located precisely on the opposite shore, as seen from Cape Erimo, and on the lee side, as seen from the easternmost tip of the Sanriku coast. Figures 6(a) and (b) shows the time series of SWH and wave direction at the...
wave stations. Figure 6(c) shows the northeasterly and southerly wind speed component at stations CE and MY, respectively. They are the same as shown in Fig. 4. The three northern stations are located at intervals of up to 50 km (Fig. 1). Station KM is located on the south of the Sanriku coast and is far from the wind jet region. The wave height variation at station KM is approximately constant at 0.7–1.0 m with amplitude about 0.1 m during the analyzed period (Fig. 6(a)). Therefore, we principally proceed to a discussion on the assumption that wave variation at station KM can be regarded as the background condition and that swell effects do not vary too much during the period. In fact, we can confirm that wave height variations at the other stations described below are much more significant than those at station KM.

During the evolution and decay of the wind jet in the lee of Cape Erimo from 0600 UTC 7 June to 0600 UTC 9 June, the northeasterly and easterly wind blew toward the coast (Figs. 2(a)-(i)). SWHs at three stations (MO, HC, and KJ) varied in a similar manner. Before 1200 UTC 7 June, the SWH at the three stations were at almost the same level of 0.7–0.8 m. The SWHs then started to increase, to reach the maximum (1.3–1.5 m) at 0700 UTC 8 June. While the SWHs during this time were almost constant (0.7–0.8 m) at station KM, the other stations showed increases of 0.5–0.7 m for SWH. Station MO observed the lowest peak of SWH between the three stations. The reason is partly because the location of station MO is slightly offset toward the north from the core of the wind jet (Figs. 2(d) and (e)). As Fig. 6(c) shows, the
rapid increase of northeasterly wind speed component started at 1200 UTC 7 June at station CE. The time difference between the onsets of wind speed at station CE and of SWHs at the three stations was about 6 hours. It took about 18 hours for SWHs at the three stations to reach the maximum from the onset of wind speed at station CE. On the other hand, the stages at which the wind jet mostly developed were seen in Fig. 2(d) or (e) to be from 2019 UTC 7 June to 0137 UTC 8 June. The time difference between the most developed stage of the wind jet over the ocean and wave height maximum was about 6–10 h. The wave directions were almost constant until 0000 UTC 8 June. The wave directions are 100° at station MO and 90° at station HC. While the data at station KJ are sporadic and seem to be noisy, the wave direction was roughly 110°. However, the wave directions shifted to the north at 0000 UTC 8 June and maintained that direction at the three stations. On the other hand, it should be noted that only SWH at station HC was almost constant (0.7–0.8 m) and at the same level as KM. Because station HC is behind the eastward protrusion of the Sanriku coast, northwestward waves were blocked and could not reach station HC. Actually, during the analyzed time period, no northward wave directions were observed at station HC. As the wind shifted to the south (i.e., parallel to the coastline), wave height at stations (MO and KJ) also showed rapid decreases until 2100 UT 9 June.

After 1800 UTC 9 June, only SWH at station KJ increased, showing the highest SWH (about 1.3 m) at 0900 UTC 10 June. While station MO and HC data represented slight increases and decreases, the variation was much smaller than that at station KJ. The wind blew from south-southeast off the Sanriku coast at 0921 UTC 10 June (Fig. 2(m)), and wave direction seemed to change counterclockwise only at station KJ (Fig. 6(c)). During this period, the wind rushed through the Sanriku coast, resulting in wind speed acceleration in the lee of the easternmost tip of the coast. In fact, the location of station KJ corresponded to the maximum wind speed region. Therefore, the rapid increase in wave height at station KJ was associated with the localized wind jet formation. The reason why stations MO and HC did not observe high SWH is because the wind jet was highly localized and did not have far-reaching effects. At station HC, wave blocking due to the Sanriku coast is also an important factor. On 11 June, high SWH were observed only at station KJ. The same situation is expected as that inferred from the wind fields in Fig. 2(p).

5. Discussion

In this section we reflect on this case study from a statistical point of view. The characteristics of the wind
jets from the case study are representative examples. A northeasterly-southeasterly wind periodically develops and persists for several days from May to August in northern Japan (e.g., Takai et al., 2006). This is a predominant mode of wind throughout the year, as well as another dominant mode associated with northwesterly winter monsoon. Furthermore, Takai et al. (2006) closely investigated the dominant wind patterns associated with Yamase in the season (May–August). They constructed three composite wind fields for three years (2000–2002). The wind fields are composite maps of scatterometer wind measurements based on the magnitude of air temperature anomalies observed at meteorological stations. From the results, we find that the synoptic easterly and northeasterly wind fields are favorable for wind jet formation in the lee of Cape Erimo. However, they do not reveal southerly wind patterns favorable for wind jet formation in the lee of the Sanriku coast because it is out of scope of their study. This study has shown that at the end of persistent easterly-southerly wind events, a wind jet appears in the lee of the Sanriku coast.

We then examine the temporal variability of the wind from wind vector time series for April–August in 2003 at Cape Erimo and at a location off the Sanriku coast (40.25°N, 140.25°E) (Fig. 7). While hourly wind data at station CE are used in Fig. 7(a), we use SeaWinds wind measurements acquired roughly four times a day off the Sanriku coast. The unique characteristics of the wind at Cape Erimo are immediately apparent in Fig. 7(a). The winds were variable but attained much higher speed in the northeasterly wind. Moreover, the northeasterly wind tended to persist for several days. The northeasterly wind speeds were generally more than 8 m/s, sometimes increasing up to 15 m/s. It can thus be concluded that wind jet formation in the lee of Cape Erimo is extremely common. On the other hand, the winds off the Sanriku coast generally had an easterly component during the data period (Fig. 7(b)). Winds with speeds higher than 5 m/s were often northeasterly and southeasterly. In April–May, winds were rather variable. In June–August, wind variation seemed to be periodic and the wind had a larger easterly component. These characteristics reflect the wind flows passing around the Sanriku coast in two directions (Figs. 3(a) and (b)), and suggest the formation of a wind jet off Sanriku coast. However, compared with the wind at Cape Erimo, wind speeds were weak and the wind did not show a few dominant wind directions. This may mean that wind constraint due to topographic features is weaker than that around Cape Erimo.

Finally, in order to investigate the statistics of wind directionality, we present wind roses at the key locations in May–August in Fig. 8. The locations are the same as those at which wind vector time series are sampled (Fig. 7), viz. station CE and the location off Sanriku (40.25°N, 140.25°E) where the orographic effects have significant impact on wind. Note that the arrows indicate wind direction and their lengths indicate relative frequency of duration time of the wind direction. Gray scale indicates the elevation.
in the season, and the relative frequency of duration time is about 30%. On the other hand, the wind off the Sanriku coast shows a broader bimodal distribution (Fig. 8(b)). One common direction is centered on the southeast, nearly parallel to the northern coastline of the Sanriku coast. The other preferred direction is westerly. The above facts support the predominance of wind direction favorable to the wind jet events that are characterized by southeasterly-southerly flow.

6. Summary and Conclusions

We have investigated two wind jets formed in sequence off the Pacific coast of northern Japan under slowly varying wind from east to south, and their localized impacts on wave height variations from a case study during 7–11 June, 2003. A sequence of wind measurements from two scatterometers can present the transition of the wind jet evolution and decay. Coincident SWH data observed by altimeters show significant variations of wave height associated with the wind jets. Additionally, wave height time series at the coastal stations reveal the localized impact of the wind jets on wave height distribution.

We discuss the relation between the wind jet and the prospective higher wave region based on the conceptual schemes shown in Fig. 9 in order to summarize the results in this study. Figures 9(a) and (b) illustrate the typical regions with high wind speeds and dominant wind directions in the cases of Cape Erimo and the Sanriku coast at the representative time periods. Drawing an inference from the high wind regions and wave height observations by the altimeters and the stations, higher wave regions are anticipated in the strong wind regions and their downwind sides. The following conclusions are obtained in this study.

1) We described two wind jet evolutions under the easterly-southerly wind. An easterly wind tended to form a fan-shaped wind jet after passing by Cape Erimo. The maximum wind speeds were localized and did not reach the coast on the opposite side. As the wind shifted to the southeast, the wind jet started to decay. When the wind shifted to the south, another wind jet formed on the northeast of the Sanriku coast. The strong wind area was triangular-shaped and highly localized. Wind acceleration was observed after passage over the easternmost tip of the Sanriku coast.

2) Selected meteorological station data captured the two wind jet events. Enhanced signs of wind jets were confirmed by the northeasterly wind component in the case of Cape Erimo. This wind jet was characterized by rapid onset and gradual decay of wind speed. From the station data at the easternmost tip of the Sanriku coast, the onset and decay of the wind jet off the Sanriku coast was not as clear as the case of Cape Erimo. However, the wind trend was captured by the southerly wind speed component at this station.

3) Significant wave heights measured by altimeters along the ground tracks intercepting the regions of the wind jets were correlated positively with local wind energy (i.e., squares of wind speeds observed by scatterometer). Local maxima of significant wave height appeared south of Cape Erimo and near the Sanriku coast. Furthermore, wave height differences were distinguished between observations at four wave stations along the Pacific coast of the Tohoku District. The significant wave height at the three stations located on northern coast responded to the wind jet off Cape Erimo in a similar man-
ner. In case of the wind jet on the northeast of the Sanriku coast, only the station located in the lee of the easternmost tip of the Sanriku coast had sensitivity. While they are mutually located 50-km away from the others at most, significant wave height variations at the stations showed different responses to the wind jet formation/decline.

4) From the wind statistics, we can conclude that the winds at Cape Erimo in May–August are variable but attain much higher speed in a northeasterly wind. Off the northeast Sanriku coast, wind speeds are less than those at Cape Erimo but attain high speed in northeasterly and southeasterly winds. In both cases, preferred wind directions at the locations are nearly an extension of the upstream coastline.

Our results provide a striking example of the wave height variations that can occur between high-frequency, small-scale wind jet events. The present study sheds light on further studies of coastal winds and waves, and can serve as an initial step in the investigation of the wind jet dynamics and other types of oceanic responses. To investigate three-dimensional wind flow and dynamics of the flow, atmospheric numerical model approaches are efficient. Wave simulations are also required to obtain the whole wave field. On the other hand, this study’s description of a highly localized impact of wind and wind wave casts a light on disaster prevention and coastal development. Low-level wind jets can significantly impact maritime interests along the coast and offshore. They also lead to significant low-level vertical wind shear, thus presenting a hazard to aviation in the coastal zone. This study will lead to the improvement of a local wind map of Japan.

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