Numerical Simulations of Wind Wave Growth under a Coastal Wind Jet through the Kanmon Strait

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ABSTRACT

The development of a coastal wind jet flowing through the Kanmon Strait and the associated wind wave growth are investigated from a case study on 24–26 July 1999. This study presents a realistic example of fetch-limited wave growth under a developing wind jet outflowing from a terrestrial gap of a coast. A series of numerical simulations are used by one-way coupling between a mesoscale meteorological model and a shallow-water wave model with high spatiotemporal resolutions of 2 km and 1 h. The simulated fields of wind and wave are compared with satellite and in situ observations and it is confirmed that they coincide with observations. A complete picture of the wind jet is obtained from the wind simulations, and wave simulations demonstrate the areal extent of higher waves growing with the development of the wind jet. The wind maximum region is localized and extends downwind. The maximum wave height region is highly localized but located more downwind of the wind speed maximum. The high wave region completely reaches the southern coast of the Korean Peninsula before the strong wind. In the lee of the islands, waves are blocked. The conventional fetch growth of waves holds in waves at the more upwind locations than the highest wave region. The forecasting of localized waves under a coastal wind jet is a case in which adequately high spatiotemporal resolution is required for both the wave simulation and wind input.

1. Introduction

A gap-exiting wind over the ocean is a strong wind blowing from terrestrial gaps such as straits, mountain gaps, and chains of mountainous islands. The low-level strong wind, called a wind jet hereafter, is generally characterized by its short duration, high spatial variability, and highly localized strong wind in the gap exit region, depending on the terrain configurations and atmospheric structures. The wind jets have been an area of investigation for a long time (e.g., Overland 1984). Recently high-resolution capability has been utilized in these studies by means of numerical simulations (e.g., Steenburgh et al. 1998; Colle and Mass 2000) and satellite images (e.g., Sandvik and Furevik 2002; Lee et al. 2005).

Under the wind jet, wind waves are expected to react to its evolution. Wave development comes under the influence of the expansion of higher winds at the gap exit region and their downwind extension, as well as wind variation due to the internal boundary layer effect. Some studies have partially demonstrated wind wave responses to wind jets (e.g., Shimada and Kawamura 2004). However, little attention has been given to wave growth under a developing wind jet outflowing from a terrestrial gap of a coast. In fact, conventional studies of fetch-limited wave growth have been based on the ideal situation of a constant wind blowing over...
the ocean. A new question has arisen as to what degree
the wave development satisfies the conventional fetch
growth.
Recently, Isoguchi and Kawamura (2007, referred to
hereafter as IK2007) have presented an attempt to re-
solve a coastal wind jet through the Kanmon Strait in
Japan (Fig. 1). While the Kanmon Strait itself is a nar-
row intricate channel separating Honshu and Kyushu
Islands with a width of about 700 m, the strait and the
surrounding topographic features form a southeast–
northwest isthmus with 30- km-wide and 500-m-high
mountainous lands on both sides. Hereafter, we treat
the Kanmon Strait as this isthmus. The wind jet occurs
frequently during the summertime under the prevailing
southeasterly winds associated with the East Asian
monsoon. IK2007 have examined the dependence of
the wind jet enhancement on the upstream wind direc-
tion and the Froude number by employing idealized
sensitivity experiments of a high-resolution atmos-
pheric community model. These conclusions are veri-
ﬁed for the cases in which high-resolution wind fields
derived from Synthetic Aperture Radar (SAR) capture
the wind jets. Additionally, using altimeter-derived sig-
niﬁcant wave height (SWH) data and ship-based climati-
ological wave data, this study has pointed out the lo-
calized effects of the wind jet on the wave field.
While that study takes the initiative in examining
wind jet events near the Japanese coast by using a com-
bination of high-resolution SAR observations and nu-
merical simulations, it directs its attention to the wind
jet formation under the steady idealized flow only. The
time evolution of the wind jet is not investigated. It is
important to investigate how strong the wind jet is in
real situations. There is also the remaining problem of
examining the wind wave growth under the wind jet.
On the other hand, the spatial resolution of the meteo-
rological simulations of IK2007 is relatively low (5 km).
To get a complete picture of the wind jet and wind wave
developments, higher-resolution simulations are re-
quired. High-resolution simulations can improve the
geometry of the coastline and topographical features,
and reproduce the sharp contrast of the wind and wave
ﬁelds (Cavaleri and Bertotti 2004). While it has been
veriﬁed that the recent wave models have applicability
to high-resolution simulations of coastal waves due to
the technical improvements (e.g., Gorman and Neilson
1999; Wornom et al. 2001; Signell et al. 2005; Rogers et
al. 2003), it is a crucial challenge to obtain wind input
whose resolution is comparable to the wave model per-
formance.
Against such a background, we build on the work of
IK2007 to investigate real situations of the wind jet
through the Kanmon Strait and of the associated wave
growth. The wind jet event of 24–26 July 1999 is se-
lected because this case includes a full sequence of wind
jet development, from its emergence to merger with the
surrounding winds, and also because several datasets of
satellite and in situ observations are available during this example. We make use of one-way coupling of a mesoscale meteorological model and a shallow-water wave model with 2-km and 1-h resolutions in space and time, respectively. Specific questions we seek to address are: 1) What are the structural properties and temporal evolutions of the strong winds and high waves? 2) Can we obtain consistency between the satellite evidence and the numerical simulations of highly localized winds and waves? 3) How different is wave growth under a developing wind jet from that under an idealized constant wind?

This study can be considered to be a full-fledged attempt to study wave development by an outflowing wind jet and can provide local communities with knowledge of possible localized high wind and severe wave events. General global–regional weather forecasts provided by operational services still do not have the horizontal resolution of the models required to accurately forecast flow through a gap with a width of a few dozen kilometers. Thus, studies are expected on an area-by-area basis to address the local impact of the wind jet on wave development. Even if the wave simulation satisfies the required resolution, wind variability should be adequately resolved in wind data. The wave development under the gap outflow is one of the cases in which high-resolution capability is strongly required for both wind and wave simulations. On the other hand, nowadays, our understanding of wind jets and their associated severe waves is a source of growing social demand. Enhanced services relevant to strong winds and severe waves are required for shipping, marine security, and marine disaster prevention. Moreover, it is demonstrated that waves can play a key role in improving coupled atmospheric and circulation models (e.g., Powers and Stoeilinga 2000; Bao et al. 2000; Ardhuin et al. 2005). The subject of this study will serve as a stepping stone in the process of improving coupled air–sea mesoscale models.

We give brief data descriptions in the following section. In section 3, we present numerical model descriptions and their simulation frameworks. In section 4, we illustrate simulated wind and wave fields in order to investigate their evolutions. Simulated fields are also compared with observations. In section 5, the fetch growth of waves is discussed. Conclusions are given in section 6.

2. Data

The given initial and boundary conditions for the meteorological simulations were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset. The dataset contains 6-hourly data on a 2.5° horizontal grid at the surface and defined pressure levels. These reanalysis data are also used to discuss the synoptic fields during the study period. We use daily SST maps, which were made by merging several satellite SST measurements (Guan and Kawamura 2004) at 0.05° resolution. The merged SST data are well suited for input into the model simulations because there are no missing values. To represent the evidence of the atmospheric conditions, we use upper-air observations at station Fukuoka (FO) (Fig. 1b), operated by the Japan Meteorological Agency (JMA). Winds are observed every 6 h, and air temperature is basically observed every 12 h.

We use the following three datasets to verify the model simulation results. 1) Wind speeds and significant wave heights (SWHs) measured by an altimeter on board the European Remote Sensing Satellite-2 (ERS-2) along the ground track are used. The nominal distance of the observations is about 7 km. 2) We use hourly wind observations over land acquired by three meteorological stations operated by JMA (Fig. 1b). The anemometer heights are 3.3, 8.0, and 6.5 m at the Shimomonoseki (SS), Yuya (YY), and Munakata (MK) stations, respectively. One station (SS) is a weather observation station (WOS) and the others (YY and MK) are automatic observation facilities, which are part of the Automated Meteorological Data Acquisition System (AMeDAS). Wind speeds are in units of 0.1 m s⁻¹ for WOSs and 1 m s⁻¹ for AMeDAS stations. Wind directions are in units of 22.5° in both datasets. 3) We use in situ SWH data that is recorded by wave observation stations every 2 h. The observation system employed is the Nationwide Ocean Wave Information Network for Ports and Harbours (NOWPHAS). It is operated 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. We have chosen two stations located in the study area. One (Aijima, AJ) is exactly located at the exit of the Kanmon Strait and the other (Genkai-Nada, GN) is located to the west of the strait (Fig. 1b). The SWHs of both stations are used. Wave direction data from GN are used, but AJ does not have the observational equipment necessary to measure wave direction. Water depths at the AJ and GN are 21.1 and 39.5 m, respectively.

3. Numerical models and their simulation frameworks

Model simulation efforts in this study are made with the fifth-generation Pennsylvania State University–
National Center for Atmospheric Research Mesoscale Model (MM5; Grell et al. 1995) and the third-generation Simulating Waves Nearshore wave model (SWAN; Booij et al. 1999; Ris et al. 1999). Both models are recognized as being the state of the art in the modeling community and are capable of performing simulations with high spatiotemporal resolution. Surface wind fields simulated by the MM5 are used to drive the SWAN simulation. Figure 2 outlines the one-way coupled use of the model simulations. The innermost domain of the MM5 and the SWAN model domain have a grid spacing of 2 km and an hourly temporal resolution in common in order to develop a precise picture of the coastal wind jet and associated higher waves.

a. MM5 simulation

The MM5 is a nonhydrostatic, multinested, primitive equation mesoscale meteorological model. Following studies that simulate and validate winds over oceans (e.g., Song et al. 2004), we have chosen the following physical options for all the model simulations: the cumulus parameterization of Grell et al. (1995), the simple ice scheme of Dudhia (1993), a cloud radiation scheme accounting for longwave and shortwave radiative transfers in cloudy and clear air (Dudhia 1989), a five-layer soil temperature model with a fixed substrate (Dudhia 1996), and the NCEP Medium-Range Forecast model (Hong and Pan 1996). We define four model domains with grid sizes of 54, 18, 6, and 2 km as shown in Fig. 1. Smaller grid-size domains are nested within larger grid-size domains in sequential order using two-way interfaces. The model top is set at 100 hPa. Twenty-three unevenly spaced sigma levels are used in the vertical. The innermost domain (domain 4) is a 360-km square.

The case study spans a 5-day period in July 1999. The simulation is initialized at 0000 UTC 22 July 1999 and all the domains are integrated to 0000 UTC 27 July 1999 during 120 h (Fig. 2). Initial and boundary atmospheric conditions are generated by interpolating the NCEP–NCAR reanalysis data to the model grid. The simulation results are output hourly. The daily merged SST maps during 22–26 July 2002–05 are averaged to form a climatological constant ocean surface boundary condition because the focus of this study is not SST-induced effects on wind jets but to examine the relationship between wave growth and wind jets. We regard the first 48-h simulations as a period required for model spinup (Fig. 2). We have confirmed that after 48 h the simulated wind speeds keep pace with the observed wind speeds obtained from the SeaWinds/Quick Scatterometer (QuikSCAT) and in situ meteorological stations (not shown). Thus, we analyze hourly output from the subsequent 72 h (from 0000 UTC 24 July to 0000 UTC 27 July 1999) from the innermost domain (domain 4).

b. SWAN simulation

The SWAN wave model has been used for estimating nearshore waves in coastal seas (e.g., Wornom et al. 2001), semi- or fully enclosed seas (Signell et al. 2005; Rogers et al. 2003), and an estuary (Gorman and Neilson 1999). For the main energy source terms, the following default expressions are adopted. For wind input and whitecapping, the expressions of Komen et al. (1984) are used. The quadruplet nonlinear wave–wave interactions are computed with the discrete interaction approximation (DIA; Hasselmann et al. 1985). Wave spectra are computed in 180 equally spaced propagation directions (θ) and 41 logarithmically spaced frequencies (f) between $f_{\text{min}} = 0.04$ and $f_{\text{max}} = 1.00$ Hz. We focus on only wind-generated waves. Thus, incoming waves at the open boundaries of the model domain are assumed to be zero. The bottom bathymetry is shown in Fig. 1b. The SWAN model is run in nonstationary mode to simulate wind-induced wave development during the wind jet event.

The simulation involves a 72-h integration from 0000 UTC 24 July to 0000 UTC 27 July 1999. Domain 4 of the MM5 simulation (Fig. 1a) is also a model domain of SWAN with a grid interval of 0.02°. We input hourly 10-m wind output from MM5 into SWAN. It is difficult to obtain wave observations that are sufficient to construct the initial conditions. Therefore, we assume that the equilibrium state between winds and waves is satisfied adequately before the wind jet event starts. That is, the SWAN model is run in stationary mode by inputting the wind field at 0000 UTC 24 July 1999, and we use the resulting wave field as the initial conditions. This assumption can be considered valid because the wind in the study area is weak around that time. We analyze the hourly outputs of simulated wave parameters. Judging from the wind fields simulated by MM5, we specify a time period when fetch-limited conditions...
are expected (from 1200 UTC 24 July to 1200 UTC 26 July 1999; see Fig. 2). We focus on the wind wave development during this period. In this study, we have chosen to neglect the effects of currents on wave development. While the current speed associated with the Tsushima Warm Current is 0.8 m s\(^{-1}\) at most, to employ a complex current field in the Tsushima Strait (e.g. Yoshikawa et al. 2006) would take us beyond the scope of this study.

4. A coastal wind jet event at the Kanmon Strait and associated wave growth

In this section, we present a comprehensive overview of the wind jet through the Kanmon Strait and its associated wave growth from a case study. We first see the synoptic conditions around the study area. Figure 3 shows the NCEP–NCAR realanysis fields of sea level pressure (SLP) and 10-m winds. While western Japan was covered by a westward extension of the Pacific high on 25 July, a typhoon was located to the east of Taiwan (Fig. 3a). At this time, southerly winds were dominant in the study area. Later, as the typhoon moved north-eastward, the pressure gradient continued to intensify between the area northeast of the typhoon and to the southwest of the Pacific high extension (Fig. 3b). During the time, a strong southeasterly wind persistently blew toward the region around the Kanmon Strait (Fig. 3c). It was confirmed by IK2007 that the southeasterly wind blowing on the upstream (south of western Japan) was important for the generation of the wind jet. At 1200 UTC 26 July (Fig. 3d), the typhoon edge hit the Kanmon Strait region and easterly winds became dominant. Based on this synoptic-scale background, we will delve into the simulation results and the observations.

a. The wind jet event captured by meteorological station data

In this section, we show that the wind jet event has been captured in the meteorological station data. Fig-
ure 4 shows time series of the southeasterly wind speed components acquired at the three meteorological stations (SS, YY, and MK) during 1200 UTC 24 July–1200 UTC 26 July 1999. The southeasterly components of wind speed have been selected because the Kanmon Strait is a southeast–northwest-oriented isthmus and because the wind jet axis was aligned with the strait. Because station SS is located at the exit of the Kanmon Strait, it is an appropriately positioned meteorological station to capture the wind jet event. The southeasterly component of the wind speed was almost constant for 12 h before 0000 UTC 25 July. The wind speed gradually increased after 0000 UTC 25 July. After a temporal maximum (4.5 m s\(^{-1}\)) at 0600 UTC 25 July, a rapid increase in wind speed was observed, up to 7 m s\(^{-1}\) at 1400 UTC 25 July. This is a local wind maximum observed over land during this wind jet event, and this period (1200–1600 UTC 25 July) corresponds to the matured stage of the wind jet over the sea as described in the next subsection. The high winds lasted almost 6 h, until 2000 UTC 25 July, accompanying large variability in the wind speed. After that, the southeasterly component of the wind speed decreased gradually.

Wind speed observations at SS are compared with the MM5-simulated wind speeds that have been logarithmically reduced from 10 to 3.3 m. While the general trend and the variations mentioned in the previous paragraph are seen in the simulated wind time series, the simulated wind speeds are generally overestimated. This may be because the model resolution is not sufficient to reproduce the topography and surface characteristics of the narrow intricate channel and the resulting station wind. These differences between the observations and the simulations are in contrast to the consistencies of the vertical profile comparison and of a comparison over the sea afterward. The differences between the observations and the model become a little larger after 0600 UTC 26 July. This may be local effect of the dominant easterly wind at the anemometer height or of accumulating model errors.

In contrast, the other stations (YY and MK) do not show any sign of the wind jet generation. Before (~1200 UTC 25 July) and after (0000 UTC 26 July)—the mature stage of the wind jet—the two stations observed gradual increases. However, a peak is not observed between 1400–1800 UTC 25 July. This is in marked contrast to the rapid increase in wind speed at SS. These results indicate that the topographic features of the Kanmon Strait play a distinctive role in the formation of the local wind jet and that the observations at the Kanmon Strait do not represent the surrounding wind field.

In Fig. 5, we show vertical profiles of the potential temperature and wind at 1200 UTC 25 July to supplement the characteristics of the matured stage of the wind jet and to show the comparison between the observations and the simulations. The wind vector profile (Fig. 5a) shows the southeasterly wind below 2500 m. This feature is common to all of the profiles after the wind jet formation. The slope of the potential temperature was constant below 1500 m at 1200 UTC 25 July (Fig. 5b). These observations are compared with the results of the MM5 simulation. While the profile of the
potential temperature derived from the MM5 outputs is generally lower by about 3 K, the slopes and their changes are well represented. Wind vectors from the observations and model results are quite consistent.

**b. Developments of wind jet and wind wave**

Figures 6 and 7 show sequences of the simulated wind and wave fields during 25–26 July 1999. A total of nine fields of winds and waves are selected every 3 (first seven) or 6 (last two) h for describing the time evolution of the wind jet and wave. This period covers completely the range from the generation of the wind jet to the ending stage of the wind jet merging with the synoptic easterly wind.

At 0000 UTC 25 July, we can find a moderate wind jet with speeds of less than 10 m s$^{-1}$ flowing through the Kannon Strait (Fig. 6a). At 0300 UTC 25 July, the wind speeds have increased up to 11 m s$^{-1}$ within about 80 km from the exit of the strait (Fig. 6b). However, between 0600–0900 UTC 25 July (Figs. 6c and 6d), a wind...
jet with speeds $> 9$ m s$^{-1}$ extends and almost reaches Tsushima Island. In turn, between 1200–1500 UTC 25 July (Figs. 6e and 6f), the tip of the wind jet with speeds $> 8$ m s$^{-1}$ has reached the southern coast of the Korean Peninsula. The wind jet has broadened out and the area of wind speed $> 9$ m s$^{-1}$ has increased.

At this point in the developing stage, the wind jet shares the following characteristics. First, the wind jet has straight anterior faces. Second, the maximum wind speed regions are highly localized, and the wind speeds increases rapidly in the core of the wind jet up to 12 m s$^{-1}$. In contrast, the wind speeds are lower ($< 9$ m s$^{-1}$) on both sides of the wind jet and on the other side across the straight anterior faces of the wind jet. Third, we can see a narrow wind jet blowing from a small terrestrial gap in the northeast of the Kanmon strait and merging with the main wind jet, which is also confirmed by the SAR-derived wind fields (Fig. 3 in IK2007). Fourth, wind blowing through and around Tsushima Island is clearly represented in the simulated wind fields. Strong winds are seen after passing through the northern and southern tips of Tsushima Island and
a narrow wind jet extends from the terrestrial gap at the midpoint of Tsushima Island. These detailed wind structures mentioned above are not represented in the simulated wind field with 5-km spatial resolution using the idealized atmospheric conditions by IK2007. Only the main wind jet is reproduced in Fig. 6 of IK2007. To represent detailed wind jet structures more than the main wind jet, it is verified that higher spatial resolutions are required.

Turning now to the SWH fields, well-defined high SWHs are ascertainable in the jet region at 0000–0300 UTC 25 July (Figs. 7a and 7b). The SWH was about 1 m around the core of the jet. On both sides of the jet, SWH was quite low (<0.3 m). At 0600 UTC 25 July, the localized region of higher SWH reaches the eastern coast of Tsushima Island (Fig. 7c). The SWH increased up to 1.3 m by 0900 UTC 25 July (Fig. 7d). At the same time, wave blocking by Tsushima Island became more marked. This feature is common to all of the subsequent simulations. Wave blocking by Iki Island also became more marked hereafter. Between 1200–1500 UTC 25 July, the core of the high SWH region extended westward and reached the southern coast of the Korean Peninsula beyond Tsushima Island (Figs. 7e and 7f). The high wave region widened, and this timing concurs with the wind jet broadening. The maximum SWHs increased up to 1.6 m. Common features so far are that the wind jet brings about a well-localized high SWH region and that the maximum SWH positions are located more downwind than those of the maximum wind speed.

While the area of high winds temporarily decreased at 1800 UTC on 25 July (Fig. 6g), the wind speeds over the Tsushima Strait became larger at 0000 UTC 26 July. Winds over the Tsushima Strait shifted to the east, and easterly winds started to dominate (Fig. 6h). This results from the typhoon’s approach, as shown in Fig. 3c. The easterly wind jet blew toward Tsushima Island. The winds intensified at the northern and southern tips and blocked in the lee. At 0600 UTC 26 July, the wind jet exiting from the Kannon Strait extended westward toward the southern tip of Tsushima Island (Fig. 6i) and lost its localization around the Kannon Strait. During this time, the wind flow from the Kannon Strait merged with easterly winds, and strong winds were distributed southwest of the study area. This is in stark contrast to the lower winds on the northeast side of the study area.

The higher SWH region extended much more downwind than the wind jet region during the 6 h after 1800 UTC 25 July (Figs. 7g and 7h). After 0000 UTC 26 July, the wave direction started to shift to the east in response to the wind shift (Fig. 7h). Higher SWHs (1.1 m) extended westward from the channel between Tsushima and Iki Islands (Fig. 7h). Wave blockings due to Tsushima and Iki Islands are noticeable. These islands left long traces of lower wave heights (<0.6 m) at these times. At 0600 UTC 26 July (Fig. 7i), the maximum SWH reached up to 2.3 m to the east of Tsushima Island. Higher SWHs went completely around Tsushima Island and the waves grew even in the lee of the islands due to the strong wind. It is noted that wave height difference along the Korean Peninsula is large. While SWHs >1.5 m reached the coast of Korean Peninsula, the SWHs were about 1.0 m along the coast in the lee of Tsushima Island and are <1.0 m along the northern part of the coastline.

c. Comparison with altimeter-derived observations

We now compare the simulated wind and wave fields with the ERS-2 altimeter observations along track 382 at 1326 UTC 25 July. The simulated wind and wave fields at 1300 UTC 25 July (Figs. 8a and 8c) are used, which correspond to the mature stage of the wind jet. The altimeter track intersects the front edge of the wind jet and the high SWH region when passing through the Tsushima Strait from Kyushu to the Korean Peninsula. Along the altimeter ground track, wind speeds and SWHs are compared between altimeter the observations and simulated fields in Figs. 8b and 8d, respectively. Commonly used statistical parameters [the bias, the root-mean-square error (RMSE), and the linear correlation coefficient ($r$)] are calculated.

As to wind speeds, the simulated and observed wind speeds are coincident (Fig. 8b). The altimeter observes a sharper wind jet with lower wind speeds on both sides of the wind jet core and the wind speed differences are relatively large near the coast of the Korean Peninsula outside of the wind jet. The bias and RMSE are 1.7 and 1.5 m s$^{-1}$, respectively. However, we can say that the wind jet structure is well reproduced by the model simulation in general ($r = 0.89$). While the altimeter-observed SWHs have fluctuations and rapid declines at several points (bias = 0.17 and RMSE = 0.29), the simulated SWHs generally agree with the envelope curve of the observed SWH ($r = 0.75$). The maximum SWH along the section is well reproduced by the model simulation.

d. Wind wave development captured by coastal wave station data

We evaluate the model reproducibility of the time evolution of waves by using in situ measurements at two nearshore stations (Fig. 1b). Figures 9a and 9b show a comparison between time series of the in situ
Figure 8. (a) Simulated 10-m-height wind speeds (colors, m s$^{-1}$) and directions at 1300 UTC 25 Jul 1999. Wind vectors are plotted at 0.1° intervals for clarity. (b) The simulated wind speeds and the altimeter-observed (obtained at 1319 UTC 25 Jul 1999) wind speeds are plotted along the track. (c) Simulated SWH (colors, m) at 1300 UTC 25 Jul 1999; vectors indicate mean wave direction. (d) The simulated SWH and the altimeter-observed SWH plotted along the ground track. Gray dots in (a) and (c) are sampled data points from the ERS-2 altimeter along the ground track. Triangles in (c) indicated sampled data points shown in Fig. 9 along the main axis of the wind jet. For clarity, larger triangles are used every five locations.

SWHs and the simulated SWHs at the corresponding grid points while the fetch-limited conditions are expected (from 1200 UTC 24 July to 1200 UTC 26 July 1999). Figure 9a shows in situ SWH data acquired at AJ, located in the exit region of the Kanmon Strait at offshore distance of 10 km. Figure 9 shows in situ SWH data acquired at GK, located 30 km west of the strait. The observed SWH at AJ (Fig. 9) was almost constant at 0.2 m until 0000 UTC 25 July 1999. After that, SWH gradually increased and reached a peak (0.65 m)
5. Wave growth under the developing wind jet

In this section, we evaluate the wave growth under the developing wind jet outflowing from the coast. Fetch growth of wind waves has been studied intensively for half a century, as summarized by, for example, Young and Verhagen (1996). However, most of these studies assume that their conditions approximate the idealized situation of a constant. Thus, wind wave growth under realistic wind outflowing from the coast has not been discussed.

The simulated fetch-limited wave growth under the developing wind jet is compared with a guideline for fetch growth. We adopt more generalized growth curves of SWH and wave periods as derived by Breugem and Holthuijsen (2007) based on the results of Young and Verhagen (1996). The formula for deep water is

\[ \tilde{H} = \tilde{H}_o \left[ \tanh(k_2 \tilde{F}^{m_2}) \right]^{p} \]

and

\[ \tilde{T} = \tilde{T}_o \left[ \tanh(k_2 \tilde{F}^{m_2}) \right]^{q} \]

where \( \tilde{H}_o, \tilde{T}_o, k_1, k_2, m_1, m_2, p, \) and \( q \) are constant. The fetch-limited wave growth has been represented in dimensionless terms. These terms are the dimensionless SWH, \( \tilde{H} = gH/H_{10}^{\infty} \) the dimensionless peak period, \( \tilde{T} = gT_p/U_{10}^{\infty} \) and the dimensionless fetch \( \tilde{F} = gF/U_{10}^{\infty} \), where, \( H \) is SWH, \( T_p \) is the spectral peak period—that is, the inverse of the peak frequency of the spectrum, \( F \) is the fetch, \( g \) is the gravitational acceleration, and \( U_{10} \) is the 10-m wind speed. Following Young and Verhagen (1996), we adopt the 10-m wind speed averaged over the downwind fetch:

\[ U_{10} = \frac{1}{x} \int_0^x U_{10}(x) \, dx. \]
alized curve. However, after the data plots reach the maximum value, $\tilde{H}$ decreases with $\tilde{F}$. These declines in $\tilde{H}$ suggest that waves are not fully developed due to the inadequate duration time at the tip of the wind jet and the shorter wind jet extension. This may partly contribute to the decrease of $\tilde{H}$ as that wave is half blocked by Tsushima Island for the most upwind locations near the Korean Peninsula. The same results are confirmed in the dimensionless wave energy $\tilde{E} = g^2 E/U_{10}^4$ and $\tilde{F}$ domain (not shown). In Fig. 10b, it seems that $\tilde{T}$ at each time increases with the fetch almost linearly. This means a downshift of the spectrum peak frequency according to the wave growth. However, as is the case in Fig. 10a, the values of $\tilde{T}$ lower than the curve of Eq. (4) are plotted at the large $\tilde{F}$. It is especially obvious in the plots for 0000–0600 UTC 25 July.

To compare the extension of the localized high winds and waves, latitude–time plots of wind speeds and SWHs are shown in Fig. 11. The wind speed and SWH are sampled along the defined fetch indicated in Fig. 8c and plotted as a function of latitude. We can easily identify the fronts of the extension of the high winds and waves, which are indicated by the gray dashed lines. The rate of the front extension is larger for waves than winds. This means that high waves locally arrive at the coast of the Korean Peninsula before the strong wind. The wind speed plot (Fig. 11a) shows that the wind jet extends with time, and it is difficult to define the locations of the local wind speed maxima. On the
other hand, the locations of the maximum SWHs are located at the center of the high SWH region. In the downwind region beyond the highest wave region, it seems from the results in Fig. 10 that the waves are not fully developed. These differences in the extension of the localized winds and waves are an issue to be considered in future research.

6. Summary and concluding remarks

We have used a meteorological model to simulate the wind jet flowing through the Kanmon Strait from a case study during 24–26 July 1999. The simulated surface wind fields are input into a wave model to simulate wave fields while the fetch-limited condition is expected. Both models are configured to having domains with 2-km spatial resolution and to outputing hourly fields of winds and waves. The simulations with high spatiotemporal resolution enable us to describe the development and the areal extent of the highly localized strong winds and high waves. First, this study has considered the wave growth under the developing gap-exiting wind, and can be considered to be the most complete example of the localized wind and wave fields yet available for this region. The results are summarized below.

1) The simulation with a meteorological model produces a sequence of the development of a wind jet through the Kanmon Strait. The synoptic southeasterly wind speed increases as the typhoon approaches. A well-defined wind jet has developed with straight anterior faces. The region of the wind speed maximum is highly localized. Strong winds are seen after passing through the northern and southern tips of Tsushima Island, and a narrow wind jet extends from the terrestrial gap at the midpoint of the island. The developing wind jet can reach the southern coast of the Korean Peninsula. We can also see a narrow wind jet blowing from the small terrestrial gap near the Kanmon Strait and merging with the main wind jet. These are possible wind distributions under southeasterly winds in this study area.

2) The simulated wave fields represent a well-defined higher wave region associated with the wind jet through the Kanmon Strait. The areal extent of the higher waves grows with the development of the wind jet but the high wave region is highly localized. The maximum wave height appears more downwind of the wind speed maximum. The high wave region reaches the southern coast of the Korean Peninsula before the strong winds. In the lee of Tsushima and Iki Islands, the waves are strongly blocked.

3) Simulated fields of winds and waves are compared with satellite and in situ measurements. While the simulation overestimates the wind speed in the narrow channel, comparisons show general agreement between them. The simulated wind and wave fields are evaluated with the altimeter measurements at the mature stage of the wind jet. Time series wave data at observation stations are compared with those of the simulated wave fields.

4) The wave growth under the developing wind jet is compared with a conventional growth curve of SWH and peak period. The conventional fetch growth of waves holds in waves at the more upwind locations than the highest wave region. Downwind of the wind jet core, waves are not fully developed.

Looking back on the results above, we can draw the following conclusions. First, utilization of numerical models at high spatiotemporal resolution offers the first step to revealing the various phenomena with smaller-scale variations of winds and waves. This study has simulated wave fields using simulated wind fields, which are verified by high-resolution satellite observations. The present study has shed light on wave growth under the wind jet. This attempt has succeeded at high-resolution simulated wind fields. It should be noted here that satellite evidence of highly localized winds and waves has been a starting point for several of our simulations. For further consideration of air–sea interaction, it is expected that improving atmosphere–wave two-way coupled models will be more successful. Then, we can be surer that we have the resolution required to describe winds and wind waves in the study area. A 10-km isthmus can form a wind jet extending over 200 km and such a wind jet can reach the other side of the strait. A 10-km island can block the wave and leave a tail of lower wave heights. These topographic features must be resolved adequately in the simulations. Finally, we should note that the monitoring of the wind jet development and high waves is only possible at limited locations. An understanding of strong winds and severe waves is also important for practical uses such as shipping, marine security, and marine disaster prevention.

The transmission of such information is becoming more important for the appropriate agencies or communities. A collaborative observation network is also required to evaluate the localized impacts of the wind jet and waves in the marginal seas.

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