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Growth of Wind Waves with Fetch in the Sea of Japan under Winter Monsoon Investigated Using Data from Satellite Altimeters and Scatterometer

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By using wind vector fields observed by the NASA Scatterometer (NSCAT) and significant wave heights observed by the TOPEX/POSEIDON and European Remote Sensing Satellite-2 (ERS-2) altimeters, one-dimensional fetch growth of wind waves has been investigated under conditions of strong wind and high waves caused by the East Asian winter monsoon in the Sea of Japan. The evolution of fetch-limited wind waves can be observed by the altimeters along their ground tracks. The fetch is estimated by using vector wind fields observed by NSCAT. The derived growth characteristics of wind waves are compared with empirical relationships between the non-dimensional fetch and significant wave height proposed by previous studies. Good agreement is discernible with Toba's fetch graph formula normalized by the friction velocity, while Wilson's well-known formula normalized by the wind speed at a height of 10 m tends to underestimate the wave height under such severe conditions of high wind and very long fetch. This discrepancy is explained by the wind-speed dependence of the drag coefficient. A simple correction to Wilson's formula for the high wind conditions is proposed and compared with the observed data.

Keywords:
· Wind wave,
· altimeter,
· scatterometer,
· air-sea interaction,
· remote sensing.

1. Introduction

During the East Asian winter monsoon, outbreaks predominate. Strong winds blow constantly over the Sea of Japan from Siberia towards the west coast of Japan, usually for periods longer than one day. Under such conditions, one can expect very active air-sea interactions, including transfer of momentum, energy, heat, water vapor, gas, and other substances. Though these intensive air-sea interactions are very interesting as an extreme example, field observations in the sea are very difficult to perform under the severe conditions. Active microwave remote sensing of wind and waves is considered a powerful tool to investigate these phenomena.

Such a situation, under an almost constant wind blowing from a coastline, may be simplified as a fetch-limited, one-dimensional, time-independent problem. The growth of wind waves with fetch has been observed mainly by arrays of buoys or towers arranged along lines normal to the shoreline (e.g., Donelan *et al.*, 1985; Dobson *et al.*, 1989). The drawbacks of this method are that the spatial resolution is not high and the range of fetch is limited. Recently, the spatial distribution of wave heights and the evolution of directional wave spectra have been observed by airborne remote sensors such as a laser altimeter (Liu and Ross, 1980; Hwang *et al.*, 1998b) and a surface contour radar (Walsh *et al.*, 1989). These airborne instruments have high spatial resolutions and make rapid mapping possible over long ranges of the fetch. However, the observations are limited to short periods in the special operations.

Satellite radar altimeters can provide us with spatial profiles of significant wave heights (SWHs) along their ground tracks with high spatial resolution and temporal frequency. The altimeter-derived wave heights have been utilized in various studies of wind waves including wave climate (e.g., Bauer and Staabs, 1998), validation of wave models (e.g., Parsons, 1979; Queffeulou, 1983; Bauer *et al.*, 1992; Romeiser, 1993; Hwang *et al.*, 1998a), and assimilation into the models (Bauer *et al.*, 1992). Ebuchi *et al.* (1992) discussed fetch growth of wind waves in the Sea of Japan under the East Asian monsoon conditions using wind and wave data derived from the Geosat altimeter. In their study, however, wind speed was observed only along the altimeter ground tracks and fetch was estimated from the wind direction derived from weather charts.

Satellite microwave scatterometers provide us with surface vector winds over a wide coverage with high spatial resolution. The temporal interval of the scatterometer observations is a few days and this is too coarse to investigate the temporal evolution of the wind and wave field or to directly drive wave models. However, snapshots of wind fields observed by the scatterometers can be utilized to investigate the growth of wind waves under fetch-limited, one-dimensional, time-independent conditions.

In the present study, vector wind fields observed by the National Aeronautics and Space Administration (NASA) Scatterometer (NSCAT) are used to estimate the fetch and are combined with SWH derived from the TOPEX/POSEIDON and European Remote Sensing Satellite-2 (ERS-2) altimeters to investigate the fetch growth of wind waves in the Sea of Japan under the East Asian monsoon conditions. Section 2 briefly reviews empirical formulas for the one-dimensional fetch growth of wind waves. Altimeter and scatterometer data utilized in the present study are summarized in Section 3. Section 4 presents results on the growth of wind waves with fetch. The derived fetch growth characteristics are compared with empirical fetch formulas. The results are discussed in Section 5, followed by conclusions in Section 6.

2. Empirical Formulas for One-Dimensional Fetch Growth of Wind Waves

The growth of wind waves with fetch has been estimated using an empirical relationship between the non-dimensional fetch and SWH. The fetch F, SWH H, and total energy of wind waves E are normalized using the wind speed at a height of 10 m U_{10} as,

$$\hat{F} = gF / U_{10}^2, \quad \hat{H} = gH / U_{10}^2, \quad \hat{E} = g^2 E / U_{10}^4, \tag{1}$$

where g is the acceleration of gravity. The total energy E can be related to H by

$$E = H^2 / 16. \tag{2}$$

Empirical relationships between the non-dimensional fetch and SWH have been proposed by several researchers. Wilson (1965) proposed

$$\hat{H} = 0.30\left[1 - \left(1 + 0.004\hat{F}^{1/2}\right)^{-2}\right], \tag{3}$$

by using data observed by shipborne wave recorders under various wind and wave conditions, including severe storms. This formula has been widely utilized for prediction of wave heights. As the JONSWAP formula, Hasselmann *et al*. (1973) proposed

$$\hat{E} = 1.6 \times 10^{-7} \hat{F}, \tag{4}$$

or

$$\hat{H} = 1.6 \times 10^{-3} \hat{F}^{1/2}. \tag{5}$$

The JONSWAP formula does not express the saturation of the wave growth in a long fetch, and is applicable only for short-fetch conditions of $\hat{F} < 10^4$.

Instead of the normalization using the wind speed at a height of 10 m U_{10} in Eq. (1), the friction velocity of the atmospheric boundary layer u_* is also utilized as the scaling wind speed as,

$$F^* = gF / u_*^2, \quad H^* = gH / u_*^2, \quad E^* = g^2 E / u_*^4. \tag{6}$$

Based on data from laboratory experiments and observations in the Hakata Bay, Mitsuyasu (1968) proposed,

$$H^* = 5.24 \times 10^{-2} F^{*0.504}. \tag{7}$$

This formula is also limited to the short-fetch conditions of $F^* < 10^6$. Toba (1978) proposed a stochastic form of the wave growth as,

$$\begin{aligned} &dE^*/dF^* = 4.3 \times 10^{-3} G, \\ &G = 0.062[1 - erf(0.12E^{*1/2})], \end{aligned} \tag{8}$$

where

$$erf(x) = \frac{2}{\pi^{1/2}} \int_0^x \exp\left(-\zeta^2\right) d\zeta \tag{9}$$

and $E^* = H^{*2}/16$. The function G represents a fraction of energy transferred directly from the wind to waves. Numerical integration of Eq. (8) gives a fetch growth formula.

Since the friction velocity u_* represents the sea-surface wind stress or momentum transfer across the sea surface rather than the wind speed at a height of 10 m U_{10}, the normalization using u_* is considered to be more appropriate than that by U_{10} to express the wind-wave growth. However, accurate field measurements of u_* are too few to derive a reliable formula. In order to estimate u_* from U_{10}, the drag coefficient C_D, which is defined as,

$$C_D = (u_*/U_{10})^2, \tag{10}$$

is conventionally utilized, though there seems to be considerable disagreement about the value of C_D among investigators (e.g., Blanc, 1985). Also several studies (e.g., Toba *et al*., 1990; Donelan *et al*., 1993) reported that the value of C_D depends not only on the wind speed but also on the sea state.

In previous studies concerning the wave growth, an overall value of the drag coefficient $\overline{C_D}$ has been frequently used to convert formulas normalized by U_{10} and those by u_*. For example, Mitsuyasu (1968) converted Eq. (7) to

$$\hat{H} = 2.15\times10^{-3}\hat{F}^{0.504}, \tag{11}$$

by assuming $\overline{C_D} = 1.6\times10^{-3}$. The numerical coefficients in Toba's formula (Eq. (8)) were determined to fit with Wilson's formula (Eq. (3)) by assuming $\overline{C_D} = 1.2\times10^{-3}$. However, these conversions depend on the assumed value of $\overline{C_D}$, especially for cases of high winds and large waves.

3. Data

The SWHs observed by the TOPEX/POSEIDON and ERS-2 altimeters are obtained from the Global Near Real Time Significant Wave Height Data Host at the Colorado Center for Astrodynamic Research (CCAR), University of Colorado. Several previous validation studies (e.g., Callahan *et al.*, 1994; Cotton and Carter, 1994, 1995; Ebuchi and Kawamura, 1995; Gower, 1996; Queffeulou, 1996; Cotton and Challenor, 1997; Hwang *et al.*, 1998b) have showed that the accuracy of the SWH derived from these altimeters is better than 0.3 m. Though Ebuchi and Kawamura (1995) reported that the TOPEX altimeter overestimates SWH at low wave ranges in comparison with the ocean data buoys in the seas around Japan, the overestimation is not discernible for high wave ranges ($H > 3$ m) in their comparison.

The NSCAT High-Resolution Merged Geophysical Data Product is used to derive the vector wind fields over the Sea of Japan. The spatial resolution of the wind data is 25 km and the reference height is 10 m. The geophysical model function NSCAT-1 is used to derive the wind vectors from the backscattering measurements. The data product is distributed from the NASA Physical Oceanography-Distributed Active Archive Center (PO-DAAC) at the Jet Propulsion Laboratory (JPL), California Institute of Technology (Dunbar, 1997). In validation studies for the product (e.g., Ebuchi *et al.*, 1998; Freilich and Dunbar, 1999), it has been confirmed that the accuracies of wind speed and direction are better than 1.5 ms^{-1} and 20°, respectively.

For a period from November 1996 to February 1997, nine snapshots were selected of the wind and wave field derived from the scatterometer and altimeters where the outbreak of winter monsoon and fetch growth of waves were coincidentally observed. The date and time of the analyzed data are listed in Table 1.

4. Result

Figure 1 is a typical weather chart of the winter monsoon near Japan (Japan Meteorological Agency, 1997). High and low pressures are located in Siberia and Japan, respectively, and strong northwest winds blow over the Sea of Japan. Figure 2 shows time series of wind speed and direction, and significant wave height observed at the ocean buoy station in the Sea of Japan (37°55′ N, 134°33′ E), which has been operated by the Japan Meteorological Agency. Strong wind higher than 15 ms^{-1} blew continuously from a constant direction for more than one day. In such a condition, fetch-limited growth of wind waves can be observed in the Japan Sea, where the fetch is estimated as a distance from the Siberian coastline.

Figure 3 shows a vector wind field and profile of significant wave height observed by the NSCAT and ERS-2 altimeter on the day of the weather chart shown in Fig. 1. The solid line in the wind field panel (a) shows the altimeter ground track, where significant wave heights were observed. In this case, strong winds (over 15 ms^{-1}) blew from the northwest and waves grew up to 6 m with distance from the coast. At latitudes around 41°N, there exists a region of weaker wind and lower waves compared with the surrounding areas. This region is considered to be affected by shading effects due to mountains

Table 1. NSCAT and altimeter data analyzed in this study.

NSCAT date	Observation time (UT)	Altimeter	Observation time (UT)	Mean wind speed (ms^{-1})	Max. SWH (m)
Nov. 21, 1996	12:38	ERS-2	13:01	12.7	3.28
Nov. 21, 1996	12:38	T/P	13:43	12.2	4.60
Dec. 05, 1996	13:02	T/P	11:18	15.4	5.69
Jan. 07, 1997	01:59	ERS-2	02:09	13.6	5.67
Jan. 07, 1997	01:59	T/P	04:24	12.0	5.20
Feb. 03, 1997	12:53	T/P	13:37	11.8	3.90
Feb. 18, 1997	12:50	ERS-2	13:04	10.7	3.35
Feb. 21, 1997	01:52	ERS-2	01:53	15.9	6.26
Feb. 21, 1997	13:10	ERS-2	13:10	14.2	5.95

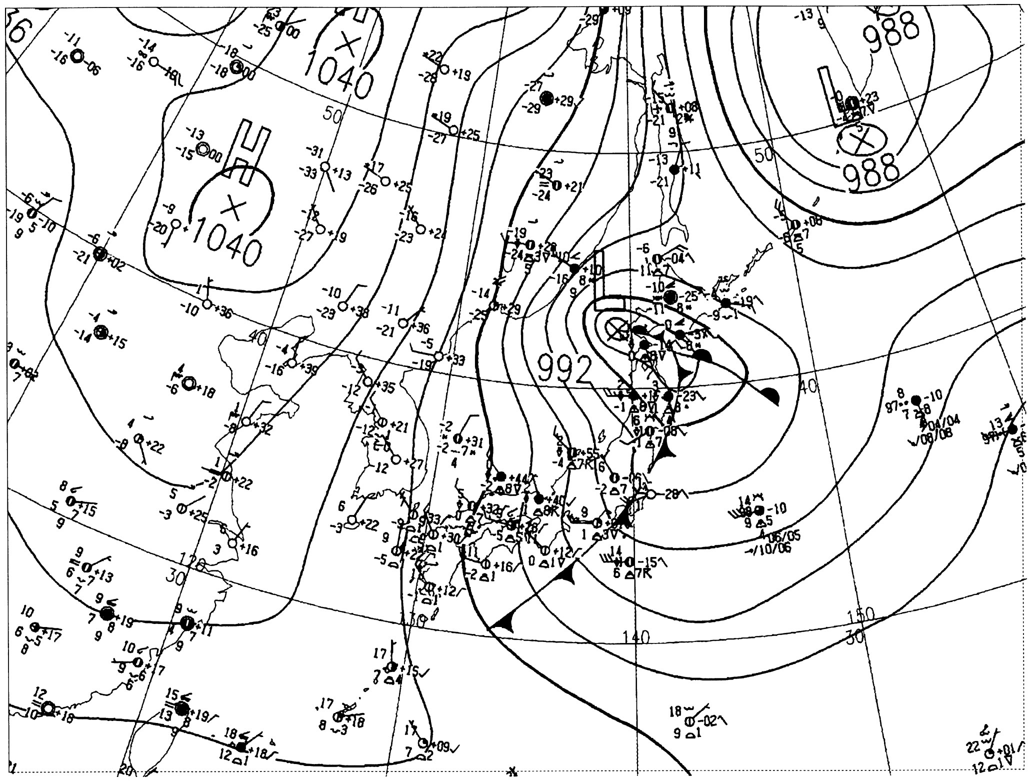

Fig. l. Weather chart at 00:00 UT on February 21, 1997 (Japan Meteorological Agency, 1997).

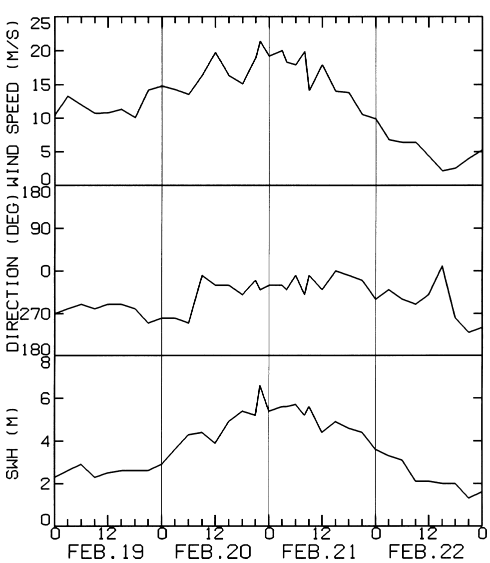

Fig. 2. Time series of wind speed and direction, and significant wave height observed at an ocean data buoy station in the Sea of Japan (37°55′ N 134°33′ E).

located on the Siberian coast. The orographic effects of the coast on the wind fields and air-sea fluxes over the Sea of Japan have been discussed by Kawamura and Wu (1998).

Using the vector wind field shown in Fig. 3, fetch at points on the altimeter ground track can be estimated by measuring length of streamlines from the coastline. Figure 4 shows the streamlines drawn from points on the ground track, estimated fetch along the ground track, and average and standard deviation of wind speed calculated along each streamline, together with the observed SWH. In the same way, the fetch and mean wind speed are calculated for each point on the altimeter ground track for the nine cases listed in Table 1. Portions of the ground tracks where large variations of the wind speed and direction are discernible along the streamline are eliminated. The standard deviation of wind speed along each streamline is less than 2 ms^{-1} for all of the data used in this analysis.

Figure 5(a) shows the relation between the non-dimensional fetch and significant wave height, calculated from H observed by the two altimeters along the ground track, F estimated from the vector wind field derived from NSCAT, and U_{10} given as an average wind speed over the fetch along the streamline as described above. In order to obtain an averaged feature, the data in Fig. 5(a) are di-

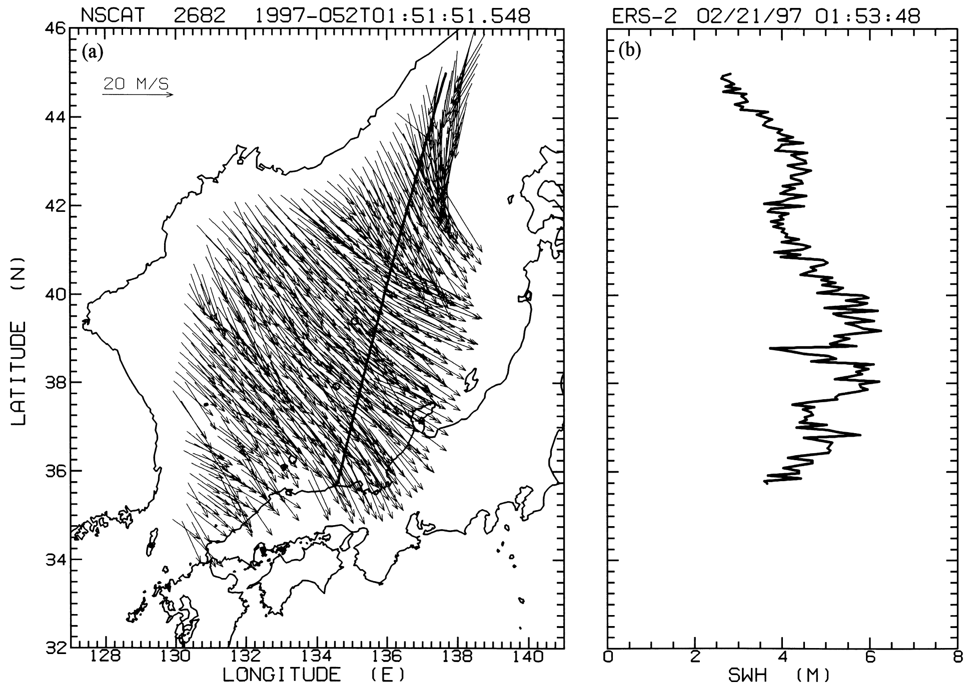

Fig. 3. (a) Wind vector field observed by NSCAT at 01:52 UT on February 21, 1997 together with the location of ERS-2 altimeter ground track at 01:53 UT (solid line), and (b) profile of significant wave height observed by the altimeter along the ground track.

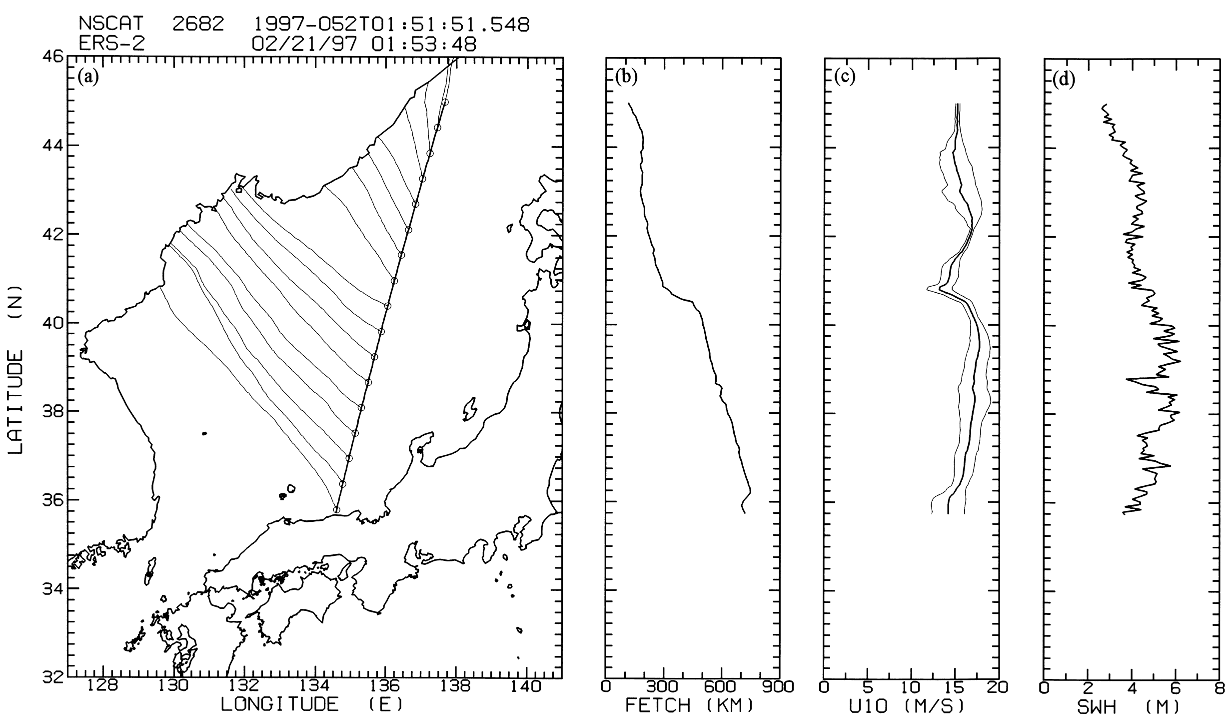

Fig. 4. (a) Streamlines from the coast line to points on the altimeter ground track, (b) the estimated fetch along the ground track, (c) the wind speed averaged along each streamline (thick line) and standard deviation (thin lines), and (d) the significant wave height observed by the altimeter along the ground track.

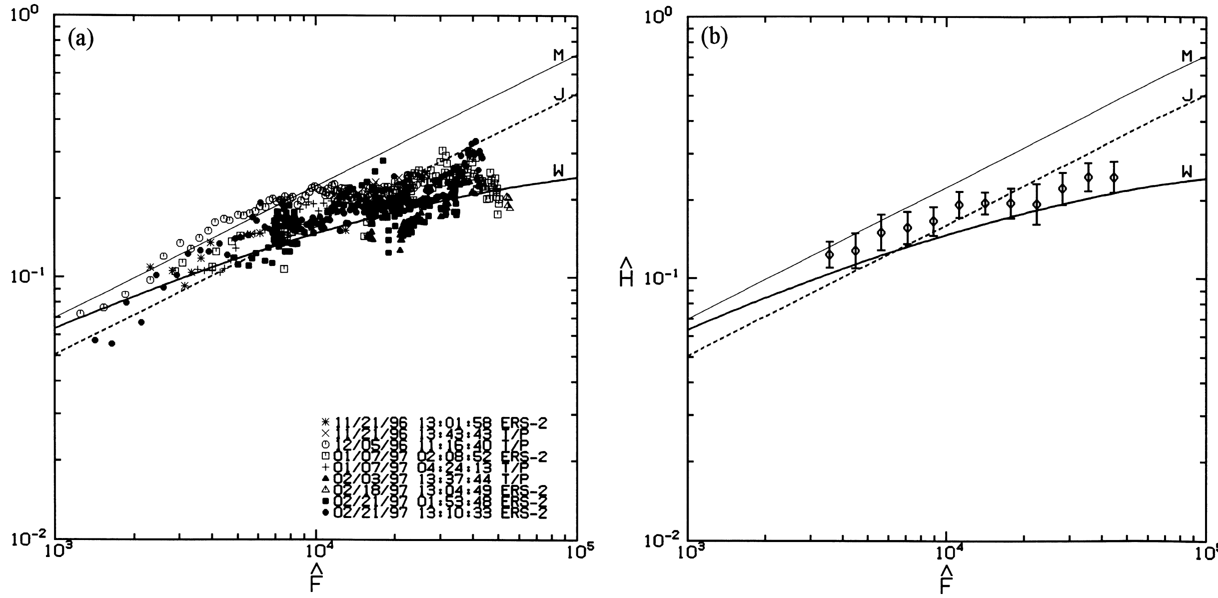

Fig. 5. The relation between the non-dimensional fetch $\hat{F}$ and the non-dimensional significant wave height $\hat{H}$. (a) All the data along the altimeter ground tracks listed in Table 1. (b) The average and standard deviation in the sections of $\hat{F}$. The solid line *W*, dashed line *J*, and thin line *M* show the empirical fetch formulas proposed by Wilson (1965; Eq. (3)), JONSWAP (Hasselmann *et al.*, 1973; Eq. (5)), and Mitsuyasu (1968; Eq. (11)), respectively.

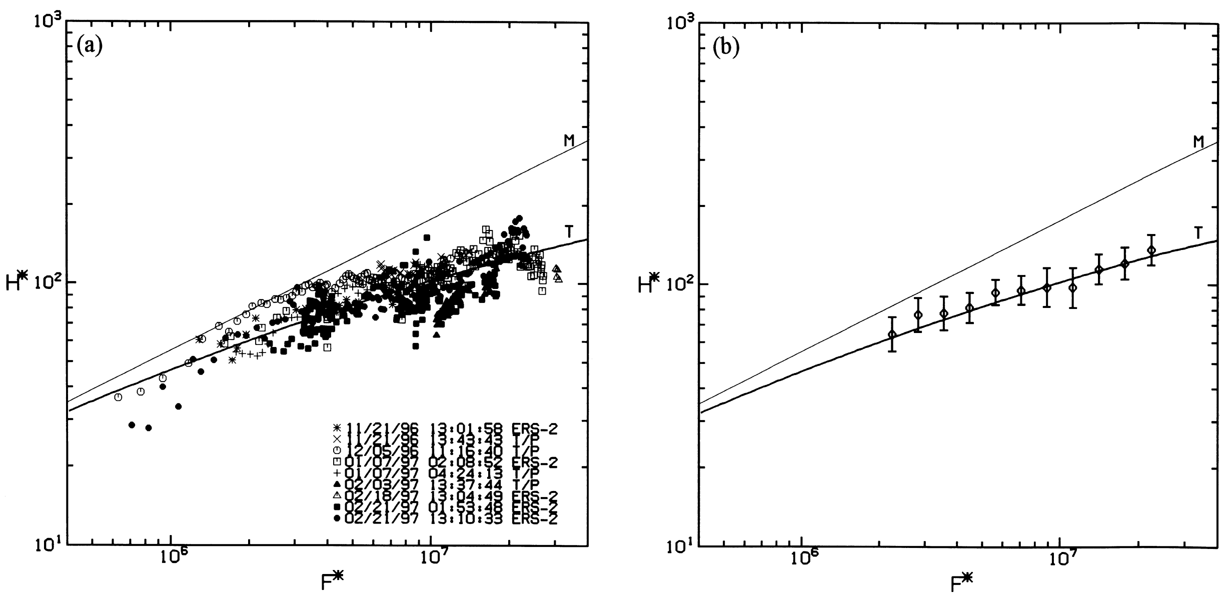

Fig. 6. The relation between the non-dimensional fetch F^* and the non-dimensional significant wave height H^*. (a) All the data along the altimeter ground tracks listed in Table 1. (b) The average and standard deviation in the sections of F^*. The solid line *T*, and thin line *M* show the empirical fetch formulas proposed by Toba (1978; Eq. (8)) and Mitsuyasu (1968; Eq. (7)), respectively.

vided into sections of the non-dimensional fetch of one tenth of a digit long in the logarithmic axis. In each section the average and standard deviation of the non-dimensional wave height are calculated as shown in Fig. 5(b). Empirical formulas proposed by Wilson (1965; Eq. (3)), JONSWAP (Hasselmann *et al.*, 1973; Eq. (5)), and Mitsuyasu (1968; Eq. (11)) are also shown in Figs. 5(a) and (b).

The qualitative trend of the wave growth with fetch derived from the data of the altimeters and scatterometer agrees well with Wilson's formula, including the saturation in a long fetch. In a short fetch, the growth rate also agrees with the JONSWAP and Mitsuyasu formulas. However, the value of non-dimensional wave height is slightly higher than that predicted by Wilson's formula in the whole range. The difference between Wilson's formula and the present data is about 20% on average. This result means that Wilson's formula, which is widely used to estimate the one-dimensional fetch growth of wind waves, may underpredict wave height for cases of strong wind and very long fetch.

Figure 6(a) shows a plot of the same data as in Fig. 5(a), normalized by the friction velocity. The drag coefficient proposed by Smith (1980) in a wind-speed dependent form as,

$$C_\mathrm{D} = (0.879 + 0.075U_{10}) \times 10^{-3} \quad (U_{10} > 5\ \mathrm{ms}^{-1}), \tag{12}$$

was used to convert the wind speed U_{10} to u_*. Figure 6(b) shows the averages and standard deviations calculated in the same way as in Fig. 5(b). Empirical formulas proposed by Mitsuyasu (1968; Eq. (7)) and Toba (1978; Eq. (8)) are also shown in Figs. 6(a) and (b). The present data agree well with Toba's formula over the whole range including the saturation in a long fetch. Mitsuyasu's formula shows systematic overestimation compared to the data, since it does not include the saturation in a long fetch. In a short fetch, both Toba's and Mitsuyasu's formulas agree with each other.

The scatter of the data points represented by standard deviations in Fig. 6(b) is almost the same as in Fig. 5(b). This result implies that the scatter of data is not caused by choice of the scaling wind speed. Strictly speaking, assumptions of fetch-limited, one-dimensional, and time-independent wave growth might not be exactly satisfied in most of the cases, and this may cause the scatter of data points shown in Figs. 5 and 6.

5. Discussion

In the previous section, we have shown that the fetch growth characteristics of wind waves derived from the altimeter and scatterometer data agree well with Toba's (1978) formula (Eq. (8)) and show systematic difference with Wilson's (1965) formula (Eq. (3)), which has been widely accepted for simple estimation of the fetch growth of wind waves. A possible reason for the underestimation by Wilson's formula might be explained in terms of an underestimation of NSCAT-derived wind speeds at high wind ranges. Freilich and Dunbar (1999) and Ebuchi *et al.* (1998) pointed out that wind speeds contained in the NSCAT wind product used in this study are a few percent lower than collocated buoy winds. However, this underestimation of the NSCAT winds cannot explain the difference of 20% between the data and Wilson's formula, as shown in Fig. 5.

Another reason might be the difference of the scaling wind parameter used in the normalization of fetch and wave height. As mentioned in Section 2, Toba's formula was originally tuned to Wilson's formula by assuming an overall constant value of the drag coefficient of $\overline{C_\mathrm{D}} = 1.2 \times 10^{-3}$ (Toba, 1978). Therefore, the difference between the present data and Wilson's formula and the agreement with Toba's formula might be caused by the difference of the scaling wind speed and the assumption of the constant overall value of the drag coefficient.

The friction velocity is considered to represent the momentum flux transferred across the sea surface and to be an appropriate parameter to describe physical phenomena of the sea surface, such as wave growth. However, the accurate measurement of the friction velocity on the sea is difficult. Therefore, the two expressions of fetch growth formulas normalized by the 10-m wind speed and the friction velocity have been conventionally converted by using an overall constant value of the drag coefficient, such as 1.0×10^{-3} (Hasselmann *et al.*, 1973), 1.2×10^{-3} (Toba, 1978), and 1.6×10^{-3} (Mitsuyasu, 1968).

As reported and modeled by several previous studies, however, the drag coefficient depends on the wind speed and atmospheric stability (e.g., Smith, 1980; Blanc, 1985). Therefore, the empirical formulas normalized by U_{10} are considered to agree with data and also with the formulas normalized by u_* under conditions of moderate winds, where the drag coefficient takes a value close to the assumed overall constant value. For cases of strong wind, such as those investigated in this study, however, the actual value of the drag coefficient is much larger than that for the moderate wind cases. This difference in the drag coefficient might be a reason for the discrepancy in the agreement between the data and the empirical formulas, as shown in Figs. 5 and 6. As discussed by Toba *et al.* (1990) and Donelan *et al.* (1993), the value of the drag coefficient may also depend on the sea state. This effect is also considered to modify the relationship.

In Fig. 7, Toba's formula is converted to formulas normalized by U_{10} using various values of the drag coefficient and plotted together with Wilson's formula and the data in Fig. 5(b). Toba's formula almost agrees with Wilson's formula if it is converted using a value of the drag coefficient of 1.5×10^{-3}, which corresponds to a wind speed of about 8.3 ms^{-1}. This value of the drag coefficient is slightly higher than that assumed by Toba (1978) for the tuning of his formula, since the tuning was done at shorter fetches. The observed data agree with the formula converted by 2.0×10^{-3}, corresponding to a wind speed of about 15 ms^{-1}. This value is close to the mean wind speed of the present data, 13.8 ms^{-1} (Table 1).

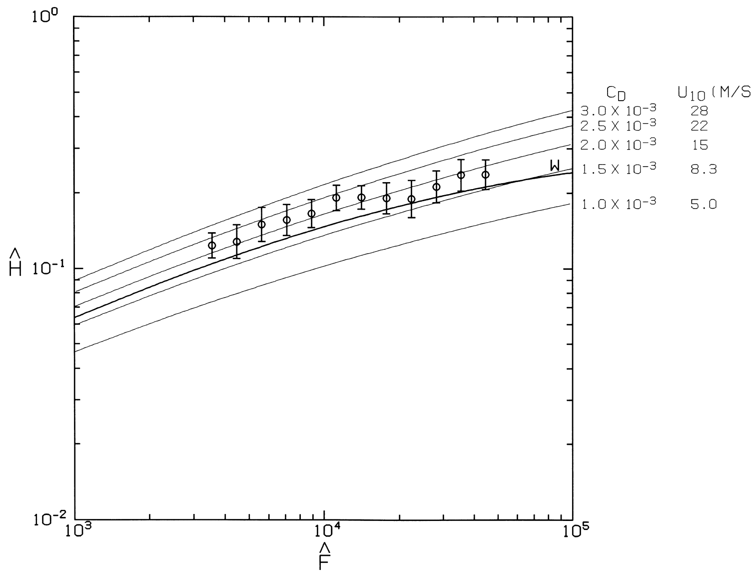

Fig. 7. Toba's formula converted to formulas normalized by U_{10} using various values of the drag coefficient (thin lines) together with Wilson's formula (solid line *W*) and the data in Fig. 4(b).

Wilson's formula agrees with Toba's formula for cases of moderate wind speeds. For very high wind speeds, however, the difference between the overall drag coefficient and the actual drag coefficient may cause the difference between Wilson's formula, Toba's formula, and the data.

Let us propose a simple method to correct Wilson's formula to predict wave growth under conditions of high wind, large waves, and long fetch. By definition of the normalized fetch and SWH in Eqs. (1) and (6), one can derive that

$$\hat{F} = \overline{C_D} F^*, \quad \hat{H} = \overline{C_D} H^*, \tag{13}$$

where the overall value of the drag coefficient $\overline{C_D}$ is a constant. Assuming that Wilson's formula in Eq. (3) represents the fetch growth of wind waves under moderate winds with the assumed constant overall value of $\overline{C_D}$, Wilson's formula can be converted to a formula normalized by u_* substituting Eq. (13) into Eq. (3) as,

$$\overline{C_D} H^* = 0.30\left[1 - \left\{1 + 0.004\left(\overline{C_D} F^*\right)^{1/2}\right\}^{-2}\right]. \tag{14}$$

This formula is considered to represent the wave growth over the whole range of wind speed and drag coefficient.

In order to obtain a new formula for practical uses, let us convert Eq. (14) to a formula normalized by U_{10} using the variable value of $C_D(U_{10})$. Following Eq. (13), new non-dimensional fetch and wave height are defined as,

$$\tilde{F} = C_D\left(U_{10}\right) F^*, \quad \tilde{H} = C_D\left(U_{10}\right) H^*. \tag{15}$$

By substituting Eq. (15) into Eq. (14), we obtain

$$\tilde{H} = 0.30\alpha\left[1 - \left\{1 + 0.004\left(\tilde{F}/\alpha\right)^{1/2}\right\}^{-2}\right], \tag{16}$$

where α is a correction factor defined by the ratio of the drag coefficients as,

$$\alpha = C_D\left(U_{10}\right) / \overline{C_D}. \tag{17}$$

The value of α can be estimated by Smith's (1980) formula in Eq. (12) as,

$$\alpha = \begin{cases} 1 & \left(U_{10} < 8 \text{ ms}^{-1}\right) \\ 0.60 + 0.05U_{10} & \left(U_{10} > 8 \text{ ms}^{-1}\right), \end{cases} \tag{18}$$

where

$$\overline{C_D} = C_D \quad \left(U_{10} = 8 \text{ ms}^{-1}\right) \tag{19}$$

is assumed as a rough estimation of the global average of the drag coefficient.

A corrected form of Wilson's formula, which depends on wind speed, is obtained by using Eq. (16) with Eq.

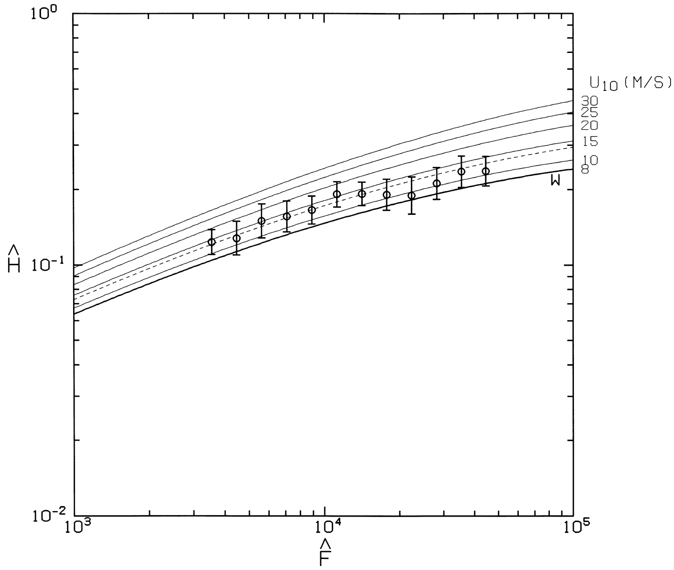

Fig. 8. Corrected Wilson's formula for various wind speeds (thin lines) together with the original Wilson's formula (solid line *W*) and the data in Fig. 5(b). The dashed line represents the corrected Wilson's formula for wind speed of 13.8 ms^{-1}, which corresponds to the mean wind speed of the present data set.

(18). In Fig. 8, the corrected Wilson's formula is plotted together with the data in Fig. 5(b). The wave height predicted by the formula increases with wind speed. The dashed line representing the formula for the mean wind speed of the present data set, 13.8 ms^{-1}, agrees very well with the observed data. The readers should note that the correction is deduced only from the consideration of the scaling wind parameter and the wind-speed dependence of the drag coefficient, and no empirical tuning was done by using the data.

6. Conclusion

By using wind vector fields observed by NSCAT and significant wave heights observed by the TOPEX/POSEIDON and ERS-2 altimeters, one-dimensional fetch growth of wind waves has been investigated under conditions of strong wind and high waves of the East Asian winter monsoon. The evolution of fetch-limited wind waves can be observed by altimeters along the ground tracks. The fetch is estimated by using vector wind field observed by NSCAT. It is shown that the two active spaceborne microwave sensors, the scatterometer and the altimeter, are very useful tools for studies of wave growth at very long fetch under strong winds, where in-situ observations are very difficult.

The derived growth characteristics of wind waves are compared with empirical relationships between the non-dimensional fetch and significant wave height proposed by previous studies. Good agreement is discernible with Toba's (1978) fetch graph formula normalized by the friction velocity, while Wilson's (1965) formula normalized by the wind speed at a height of 10 m tends to underestimate the wave height under such severe conditions of high wind and very long fetch.

The reason for this discrepancy is explained by the wind-speed dependence of the drag coefficient. Toba's formula was originally tuned to Wilson's formula by assuming an overall constant value of the drag coefficient, which relates the wind speed and friction velocity. The empirical formulas normalized by U_{10} are considered to agree with data and also with the formulas normalized by u_* under conditions of moderate winds where the drag coefficient takes a value close to the assumed overall constant value. For cases of strong wind, such as those investigated in this study, however, the value of the drag coefficient is much larger than that for the moderate wind cases. This difference of the drag coefficient might be a reason for the discrepancy of agreement of the data with empirical formulas. A simple way to correct Wilson's formula for practical uses under conditions of strong winds, high waves, and long fetches, has been proposed and compared with the observed data. The number of data used in this study is limited, since wind data from the NSCAT were interrupted by an accident. Further studies of wave growth at long fetch under strong winds are necessary to investigate the wind speed dependence of fetch-graph formulas and to validate the correction proposed by the present study.

As discussed in several studies (e.g., Toba *et al*., 1990; Donelan *et al*., 1993), the value of the drag coefficient depends on the sea state. This effect may also modify the value of the drag coefficient and the correction made to Wilson's formula. Further studies are also needed to clarify the relation between the wave dependence of the sea-surface wind stress and the fetch growth of wind waves. As demonstrated in this study, wind and wave data derived from spaceborne active microwave sensors, such as scatterometer, altimeter, and synthetic aperture radar (SAR), are very useful tools for such studies.

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