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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Abstract

By using wind vectors observed by NSCAT and significant wave heights observed by TOPEX/ POSEIDON and ERS-2 altimeters, one-dimensional fetch growth of wind waves is 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 the altimeters along the ground tracks. The fetch is estimated by using vector wind field 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 with the empirical fetch graph formula normalized by the friction velocity is discernible, while the formulas normalized by the wind speed at a height of 10 m tend to underestimate the wave height under such severe conditions of high wind and very long fetch.

1. Introduction

During the East Asian winter, outbreak of the monsoon from the northwest is dominant. Strong winds blow constantly over the Sea of Japan from Siberia towards the west coast of Japan usually for periods longer than one day. Such a situation under an almost constant wind from a coastline may be simplified as a fetch-limited, one-dimensional, and time-independent problem. Under such conditions, very active air-sea interactions, including transfer of momentum, energy, heat, water vapor, gas, and other substances, are expected. 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 winds and waves is considered as a powerful tool to investigate these phenomena.

Ebuchi *et al.*(1992) discussed fetch growth of wind waves under the 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. In the present study, vector wind field data observed by NASA Scatterometer (NSCAT) are used to estimate the fetch and combined with significant wave heights derived from the TOPEX/POSEIDON and European Remote-sensing Satellite-2 (ERS-2) altimeters to investigate the fetch growth of wind waves.

2. Data

In this study, the NSCAT High-Resolution Merged Geophysical Data Products are used to derive the vector wind fields over the Sea of Japan. The spatial resolution of the data is 25 km, and the reference height is 10 m. The data products are distributed from the NASA/JPL PO-DAAC. The significant wave heights observed by the TOPEX/ POSEIDON and ERS-2 altimeters are obtained from the Global Near Real Time Significant Wave Height Data Host at CCAR, University of Colorado.

For a period from November 1996 to February 1997, 9 snapshots of the scatterometer and altimeters where the outbreak of winter monsoon and fetch growth of waves were coincidentally observed are selected. The date and time of the analyzed data are listed in Table 1.

Figure 1 is a typical weather chart of winter monsoon near Japan. High and low pressures are located in Siberia and the North Pacific, respectively, and strong northwest winds blew over the Sea of Japan continuously for more than 1 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 2 shows vector wind field and profile of significant wave heights observed by the NSCAT and

ERS-2 altimeter on the day of the weather chart shown in Fig.1. The solid line in the panel of wind field shows the altimeter ground track, where the 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.

Using the vector wind field shown in Fig.2, fetch of points on the altimeter ground track can be estimated by measuring length of streamlines from the coast. In Fig.3, the streamlines drawn from the points on the ground track, estimated fetch along the ground track, and average wind speed along each streamline are shown. In the same way, the fetch and mean wind speed are calculated for each point on the altimeter ground track for the cases listed in Table 1.

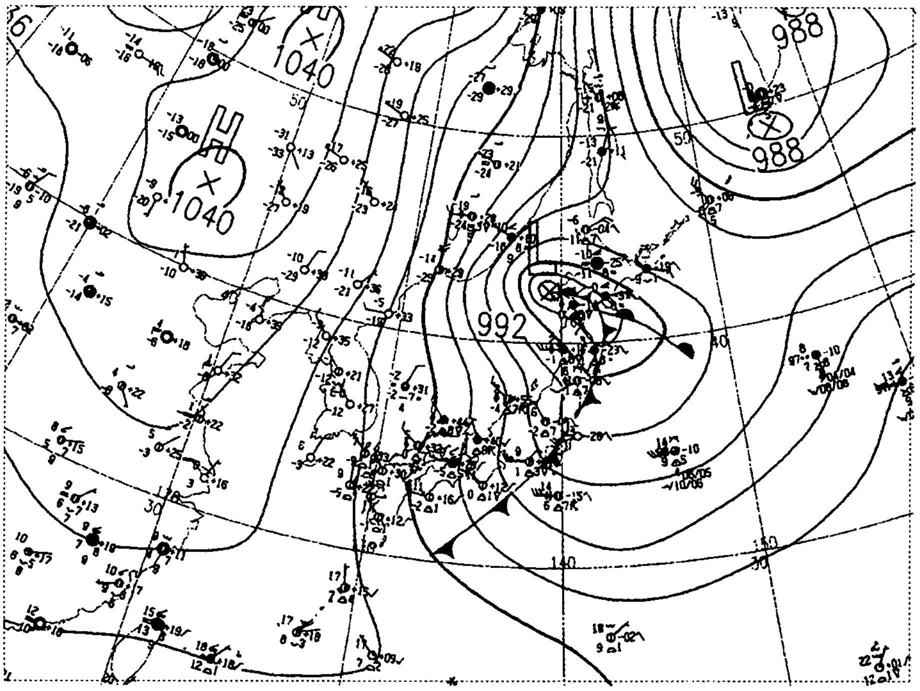

Fig.1. Weather chart at 00:00 UT on February 21, 1997.

Table 1. NSCAT and altimeter data analyzed in this study

NSCAT Observation Date	Time (UT)	Altimeter Observation ALT	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

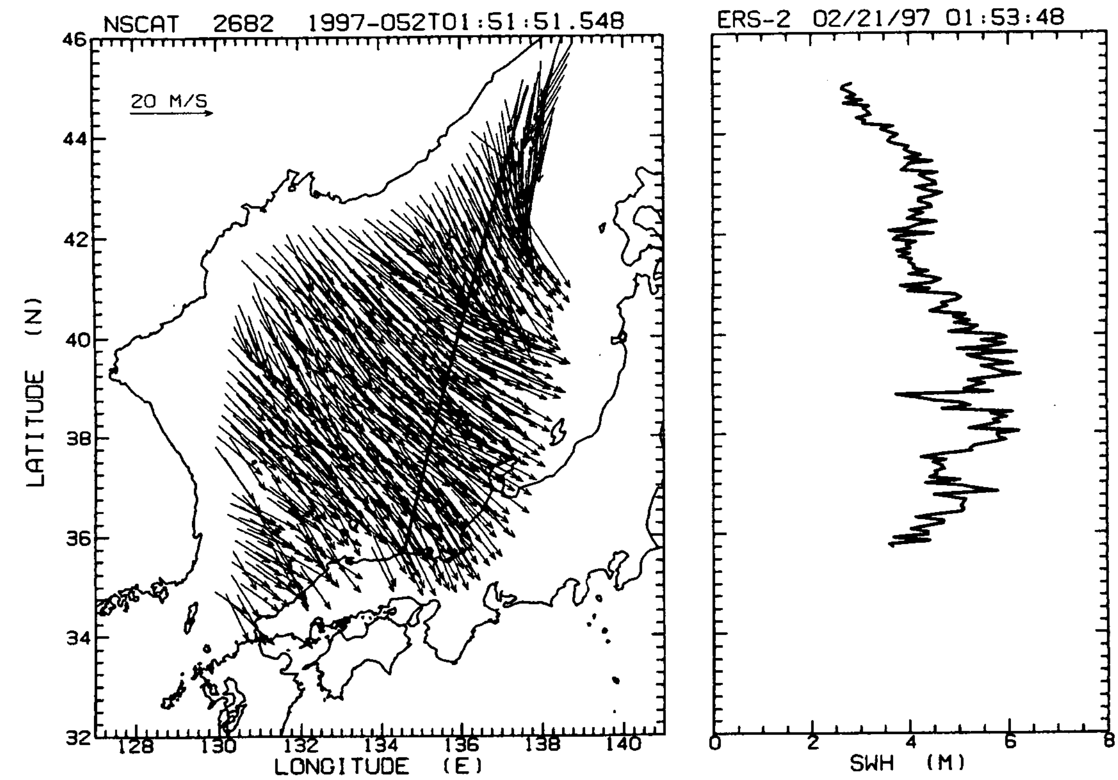

Fig.2. Wind vector field observed by NSCAT at 01:52 UT on February 21, 1997 together with the location of ERS-2 altimeter ground track at 01:53 UT (solid line), and profile of the significant wave height observed by the altimeter along the ground track.

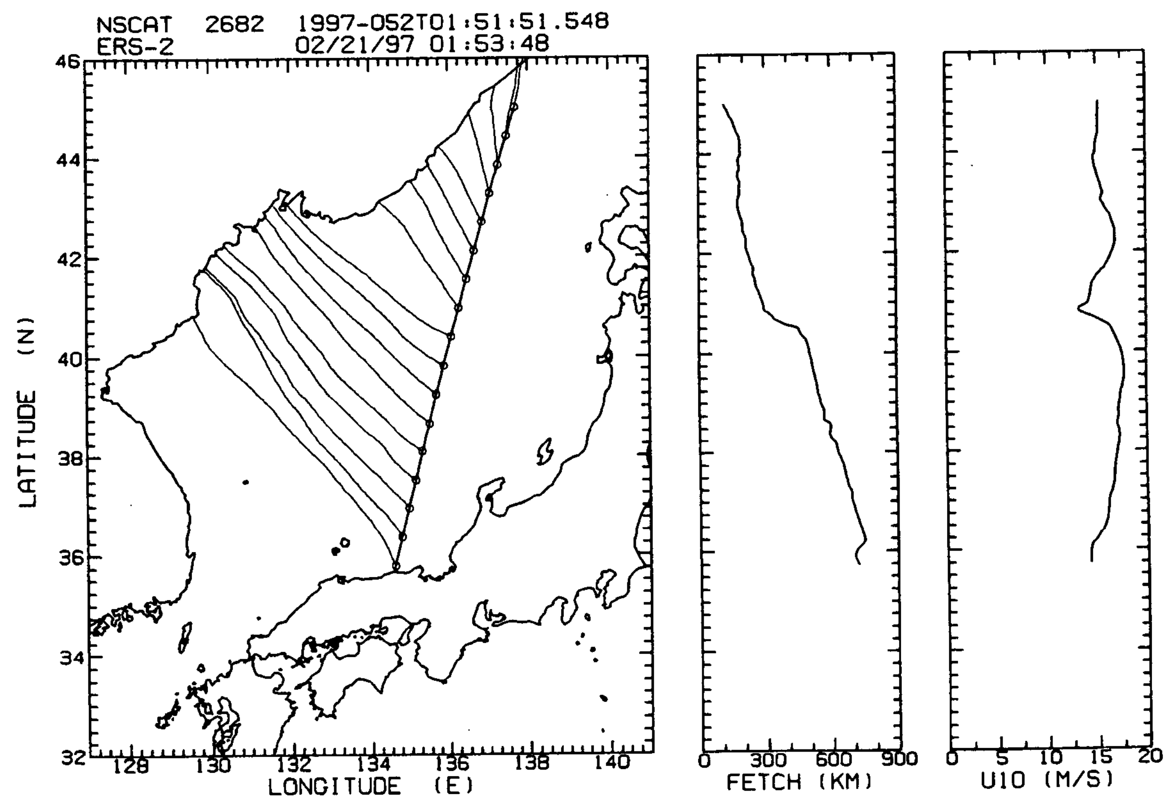

Fig.3. Streamlines from the coast line to points on the altimeter ground track, the estimated fetch along the ground track, the wind speed averaged along each streamline.

3. Result

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

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

where g is the acceleration of gravity. Several formulas which describe the relationship between the non-dimensional fetch and significant wave height has been proposed (*e.g.*, Wilson, 1965; Mitsuyasu, 1968; Hasselmann *et al.*, 1973)

Figure 4(a) shows the relation between the non- dimensional fetch and significant wave height, which are 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, as described in the preceding section. In order to obtain the average feature, the data in Fig.4(a) are divided 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.4(b). Empirical formulas proposed by Wilson (1965), JONSWAP (Hasselmann *et al.*, 1973), and Mitsuyasu (1968) are also shown in Figs.4(a) and (b).

Qualitative trend of the wave growth with fetch derived from the data of the altimeters and scatterometer agrees well with the Wilson's formula including the saturation in a long fetch. In a short fetch, the growth rate also agree with the JONSWAP and Mitsuyasu's formulas. However, the value of non-dimensional wave height is slightly higher than that predicted by the Wilson's formula in the whole range. The difference between the Wilson's formula and the present data is about 20 % on an average. This result means that the 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.

In stead 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,

$$F^* = g\,F / u_*^2, \quad H^* = g\,H / u_*^2. \tag{2}$$

In Fig.5(a), the same data in Fig.4(a) are normalized by the friction velocity and plotted. To convert the wind speed U_{10} to u_*, the drag coefficient proposed by Smith (1980) as a wind-speed dependent form is used. Figure 5(b) shows the average and standard deviation in the sections in a similar way in Fig.4(b).

Empirical formulas proposed by Mitsuyasu (1968) and Toba (1978) are also shown in Figs.5(a) and (b). The present data agree well with the Toba's formula over the whole range including the saturation in a long fetch. Originally, the Toba's formula was tuned to Wilson's formula by assuming an overall constant value of the drag coefficient of 1.2×10^{-3} (Toba, 1978). Therefore, the difference of the present data with Wilson's formula (Fig.4) and the agreement with the Toba's formula (Fig.5) might be caused by the difference of the scaling wind speed and the assumption of the constant overall value of the drag coefficient, which relates the wind speed and friction velocity.

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 expression of fetch growth formulas normalized by the 10-m wind speed and the friction velocity have been conventionally converted by using a 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). These values correspond to the range of wind speed where their observations were made.

As reported and modeled by several previous studies, however, the drag coefficient depends on the wind speed and atmospheric stability (*e.g.*, Smith, 1980). The value of drag coefficient varies with range of wind speed. For cases of strong wind as investigated in this study, the value of drag coefficient is much larger than that for the moderate wind cases and assumed as a constant overall value. This difference of the drag coefficient might be a reason for the discrepancy of agreement of the data with empirical formulas as shown in Figs.4 and 5.

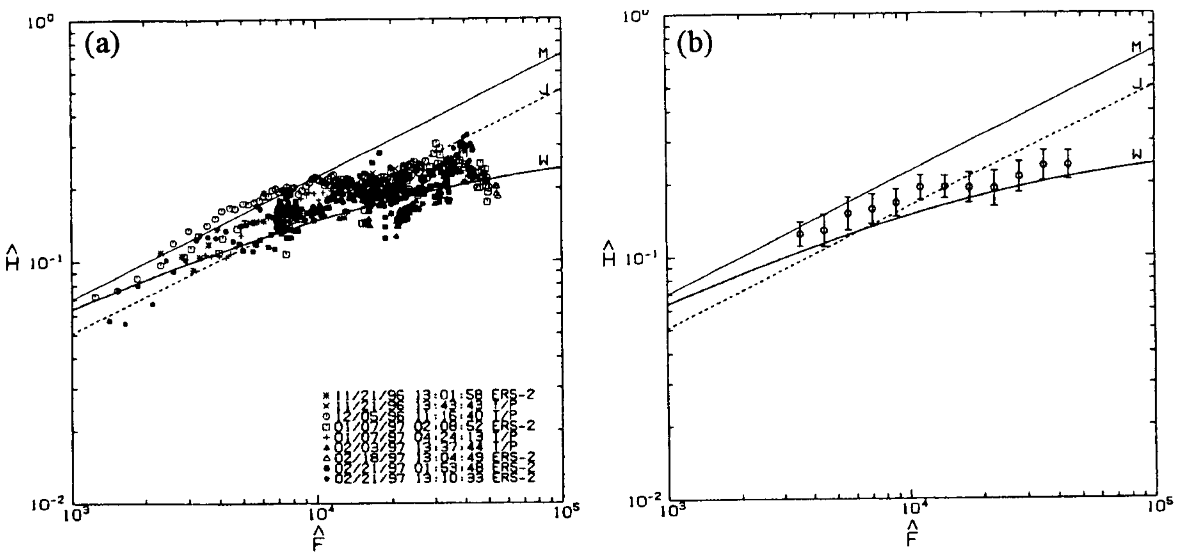

Fig.4. The relation between the non-dimensional fetch $\hat{F}$ and the non-dimensional significant wave height $\hat{H}$. (a) All the data along the altimeter ground tracks listed in Table 1. (b) The average and the standard deviation in the sections of $\hat{F}$. The solid line W, dashed line J, and thin line M show the empirical fetch formulas of Wilson (1956), JONSWAP (Hasselmann *et al.*, 1973), and Mitsuyasu (1968), respectively.

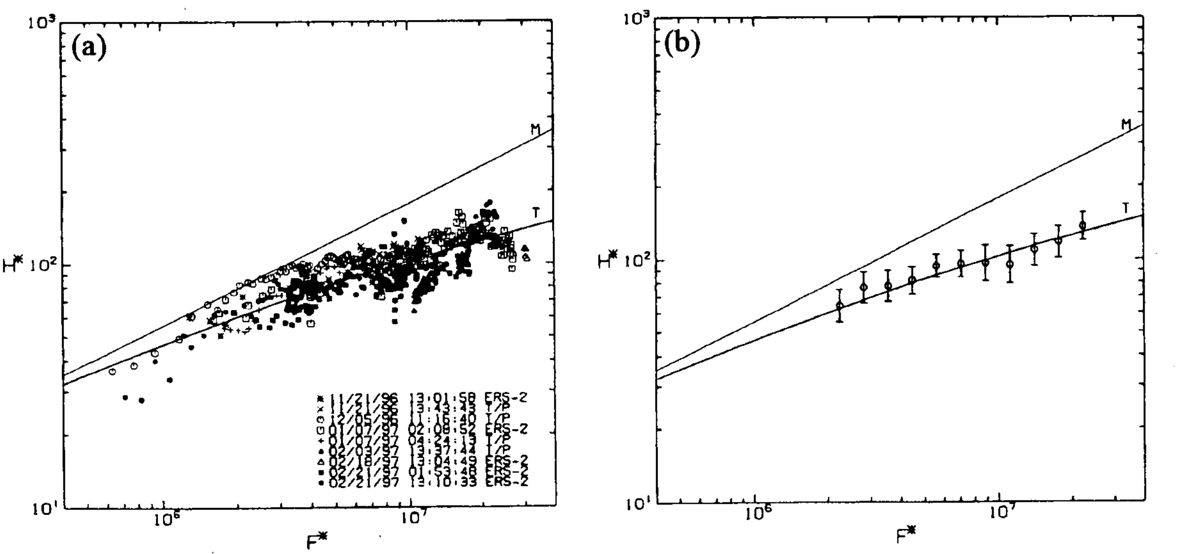

Fig.5. The relation between the non-dimensional fetch F^{*} and the non-dimensional significant wave height H^{*}. (a) All the data along the altimeter ground tracks listed in Table 1. (b) The average and the standard deviation in the sections of F^{*}. The solid line T, and thin line M show the empirical fetch formulas of Toba (1978) and Mitsuyasu (1968), respectively.

In Fig.6, the Toba's formula is converted to the normalization by U_{10} using various values of the drag coefficient and plotted together with the Wilson's formula and the data in Fig.4(b). The Toba's formula almost agrees with Wilson's when it is concerted by a value of drag coefficient of 1.5×10^{-3}, which corresponds to wind speed of about 8.3 ms^{-1}. The data agrees with the formula converted by 2.0×10^{-3}, corresponding to wind speed of about 15 ms^{-1}. This value is close to the mean wind speed of present data (Table 1). The Wilson's formula agrees with Toba's formula and observation data for cases of moderate wind speeds. For very high wind cases, however, the difference between the overall drag coefficient and the actual drag coefficient may cause the difference of the Wilson's formula with the Toba's formula and the data.

Reference

Ebuchi, N., *et al.*, 1992, *J. Geophys. Res.*, **97**(C1), 809-819.

Hasselmann, K., *et al.*, 1973, *Dtsch. Hydrogr. Z.*, **A8**(12), 1-95.

Mitsuyasu, H., 1968, *Rep. Res. Inst. Appl. Mech., Kyushu Univ.*, **16**, 459-482.

Smith, S.D., 1980, *J. Phys. Oceanogr.*, **10**, 709-726.

Toba, Y., 1978, *J. Phys. Oceanogr.*, **8**, 494-507.

Wilson, B.W., 1965, *Dtsch. Hydrogr. Z.*, **18**, 114-130.

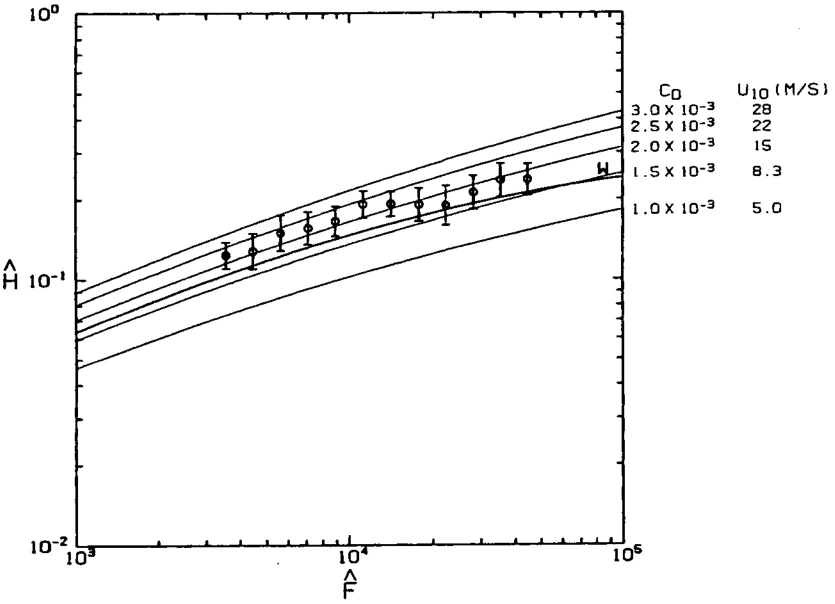

Fig.6. The Toba's formula (thin lines) converted to the normalization by U_{10} using various values of the drag coefficient together with the Wilson's formula (solid line *W*) and the data in Fig.4(b).