Marvellous self-consistency inherent in wind waves — Its origin and some items related to air–sea transfers

Yoshiaki Toba

Tohoku University (Emeritus); Home: 228-91 Iwakura-Nakamachi, Sakyo-ku, Kyoto, 606-0025 Japan, E-mail: y_toba@nifty.com

Abstract. There exists conspicuous self-consistency inherent in wind waves which are in local equilibrium with the wind, or in the wind–windsea equilibrium. From my long-term concern, I will review such aspects based on my present ideas. Aspects of the self-consistency are: (1) the 3/2-power law for significant waves, (2) the wave spectral form proportional to the friction velocity and the frequency to the minus fourth power, (3) proportionality of the Stokes drift with the friction velocity, and (4) the existence of the downward bursting boundary layer (DBBL), where turbulent intensities are proportional to the friction velocity. These aspects have very simple forms, and are mutually convertible, to form a holistic nature. The origin of these characteristics is discussed with the concept of the *wave breaking adjustment*. In relation to the air–sea transfers of momentum and gas, importance of the windsea Reynolds number is stated, and direction of further researches is recommended.
Key words: 3/2-power law, wave spectrum, Stokes drift, friction velocity, DBBL, wave breaking adjustment, windsea Reynolds number

1. Aspects of self-consistency in wind waves

1.1 The 3/2-power law

The *3/2-power law* is expressed as:

$$H^* = BT^{*3/2}, \quad B = 0.062, \tag{1}$$

where $H^* = gH_s/u_*^2$, and $T^* = gT_s/u_*$, with H_s, the significant wave height, T_s, the significant wave period, u_* the air friction velocity, and B is a constant. (1) was found (Toba 1972), by eliminating nondimensional fetch from empirical fetch graph formulas by Wilson (1965), Mitsuyasu *et al*. (1971) and Hasselmann *et al*. (1973), together with dimensional considerations.

Equation (1) may alternatively be expressed by a dimensional form:

$$H_s = B(gu_*)^{1/2} T_s^{3/2}, \quad B = 0.062, \tag{2}$$

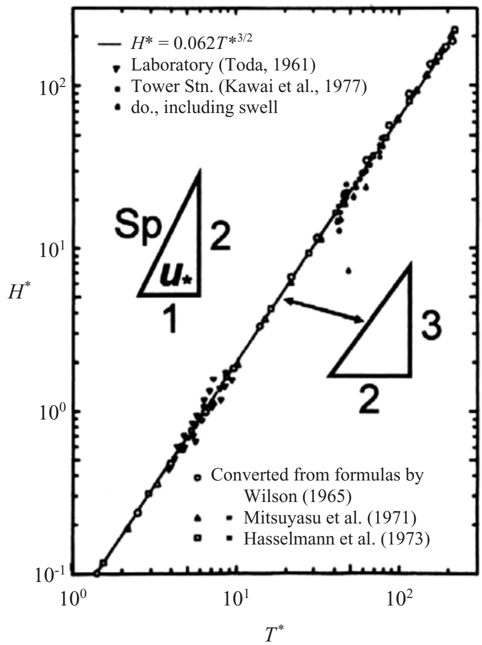

Figure 1 The 3/2-power law for windsea in local equilibrium with the wind in the form of (1), cited from Toba, Suzuki and Komori (2008). The data was originally taken from Kawai, Okada and Toba (1977), and the spurious triangle for u_* and a triangle for the slope of data-point distribution are added. Closed symbols indicate observation data, and open symbols are used to show three continuous lines, which are very close to one another, converted from three empirical formulas.

or, by using total energy E and the spectral peak angular frequency σ_p,

$$E^* = B_\sigma \sigma_p^{*-3}, \quad B_\sigma = 0.051, \tag{3}$$

where $E^* = g^2 E/u_*^4$, $\sigma_p^* = u_* \sigma_p / g$ (Toba 1978). Also, Bailey, Jones and Toba (1991) converted (1) to a relation between significant wave steepness and the wave age.

In the actual sea, variability of the wind, and more or less swell exist. In the observation data, the above coefficient B in (1) or (2) actually has deviation within 20% or so (Toba *et al* 1990). Also, Ebuchi *et al.* (1992) investigated the effect of swells and changing winds, by using data from ocean data buoy stations. This variation of B may also be caused in the estimation of u_*, since it includes the sea surface drag coefficient C_D in many cases in course of the estimation.

As seen in Figure 1, this law (1) was also applicable to laboratory data by Toba

(1961) and to tower station data compiled by Kawai *et al*. (1977). More recently, e.g., Lamont-Smith and Waseda (2008) reported, by using observation data, that this law is satisfied effectively, throughout from a wind wave tunnel and to the ocean, though the wave height and the frequency develop by their respective laws.

The empirical formulas of the wind sea growth by Wilson (1965) had complex forms as functions of the nondimensional fetch, where wind sea approaches the fully developed state. Nevertheless such a complicated form was converted to be a straight line as shown in Figure 1. This led us to a concept of the *wind sea in local equilibrium with the wind* or the *wind–windsea equilibrium*, as described in Section 2.

1.2 The $gu_*\sigma^{-4}$-type power spectrum

The high frequency side of self-similarity one-dimensional spectral form of wind waves is expressed by the following form, including u_*-proportionality:

$$\varphi(\sigma)=\alpha_s g_* u_* \sigma^{-4}, \quad \sigma>\sigma_p, \quad \alpha_s=0.062\pm0.010 \tag{4}$$

where α_s is a constant, σ_p the peak angular frequency, $g_*=g\ (1+S\kappa^2/\rho_w)$ is the acceleration of gravity extended to include the effect of surface tension S for high frequency part, with κ the wave number and ρ_w is the water density (Toba 1973). This spectral form was derived in order for the integral of (4) to correspond to (1), and at the same time in accordance with observations by Toba (1961) and Kawai *et al*. (1977).

Kitaigorodskii (1983) and Phillips (1985) re-proposed this spectral form theoretically, and (4) was widely accepted by many observations by Mitsuyasu *et al*. (1980), Kahma (1981), and others, as reviewed by Janssen (2004). Phillips (1985) named α_s Toba's constant, and stated that the observed values were ranged from 0.06 to 0.11. Janssen (2004) reported a value of 0.127 based on many observations. More recently Romero and Melville (2010) have presented observational data showing an increasing trend from 0.06 to 0.11 with the increasing wave age.

It should be noted, however, that as was clearly shown in Toba, Okada and Jones (1988), α_s has fluctuating values caused by unsteadiness of the wind, showing undersaturation and oversaturation of the spectral level, since it takes some time for wind waves to reach the wind–windsea equilibrium to the new wind. Consequently, α_s varies inversely to the fluctuation of u_*. Also, for decreasing wind speed, the spectral peak shifts to a little lower frequency side with higher values. For increasing wind, it shifts to a little higher frequency side to have a little lower value, as we reported in the same paper. Hanson and Phillips (1999) supported this by new observation data.

Zakharov and Filonenko (1966) had predicted theoretically that the one-dimensional spectral form of wind waves should be proportional to σ^{-4}, for surface gravity wave interactions, and (4) is in accordance with this theory. However, present day importance of the spectral form (4), which includes the u_* -proportionality, is that it has become the basis of satellite observations of the sea surface wind (see, e.g., Kawamura, 2003).

1.3 Stokes drift–friction velocity proportionality

The Stokes drift of wind waves as the water waves, u_0, is expressed by

$$u_0=\pi^3 H_s^2/gT_s^3 \ . \tag{5}$$

Combining (5) with (2), we get immediately its u_*-proportionality (Toba 1972):

$$u_0=\pi^3 B^2 u_*=0.12u_* \ . \tag{6}$$

This u_*-proportionality should be applicable from laboratory to ocean waves, and by the self-similar spectral form of (4), for all the stages of developing wind waves, and also to the individual waves in a sense shown by Tokuda and Toba (1981).

Bye (1988) also reported that u_0 is proportional to u_* for the spectral form (4), and predicted theoretically with observation that the wind drift surface current u_s is approximately twice u_0.

1.4 Friction velocity–turbulence intensity proportionality within DBBL

Turbulence characteristics also have proportionalities with u_*. From our laboratory experiment data (Yoshikawa *et al*. 1988), Toba and Kawamura (1995) found a special boundary layer below the wind waves: the *downward-bursting boundary layer (DBBL)*, where (7) holds:

$$(\overline{u_a'^2})^{1/2} \propto (\overline{u_w'^2})^{1/2} \propto u_{*w} \propto u_* \propto u_0 \ , \tag{7}$$

where $(\overline{u_a'^2})^{1/2}$ is the intensity of air turbulence, $(\overline{u_w'^2})^{1/2}$ that of water turbulence, and u_{*w} is the water friction velocity. DBBL has observationally a thickness of about 5 times H_s, and in DBBL the u_*-proportionality of turbulence intensities and Reynolds stress holds.

Figure 2 shows, cited from Toba and Kawamura (1995), the depth distribution in z/H_s, of turbulence intensities (a) and Reynolds stress (b) in water, showing the existence of this DBBL. In (b), the value of 0.33 of the abscissa, shown by the vertical line, almost exactly corresponds to (6), since $u_{*w}/u_0=0.33$ of the Figure correspond to $u_0/u_*=0.12$.

Figure 3 shows, cited also from the same paper, four data sets of the depth of the DBBL. Five thin segments of the Figure were taken from Toba *et al*. (1975)

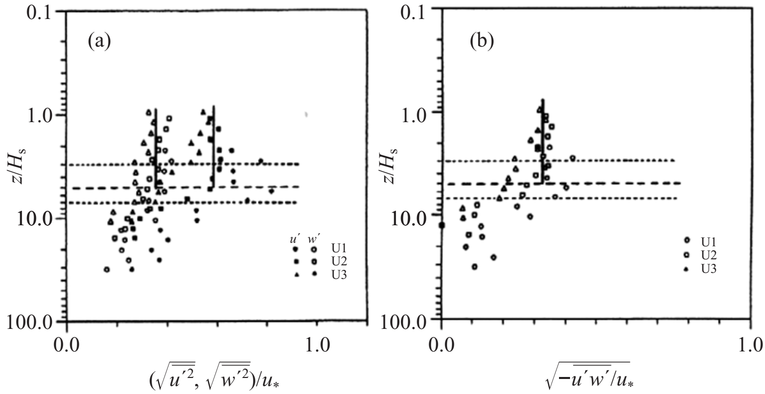

Figure 2 The depth distribution, in z/H_s, of turbulence intensities (a) and Reynolds stress (b) in water, showing the existence of this DBBL. Cited from Toba and Kawamura (1995), which reanalyzed Yoshikawa *et al.* (1988) data.

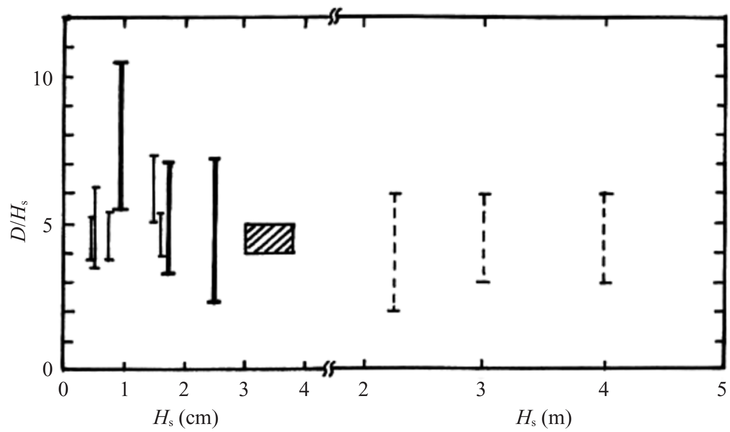

Figure 3 Four data sets of the depth of the DBBL, D, normalized by H_s, cited from Toba and Kawamura (1995). The data set includes, from the left to the right, a laboratory no bubble entrainment case by Toba *et al.* (1975), the turbulence measurement data by Yoshikawa *et al.* (1988), the air–water CO_2 exchange data by Komori *et al.* (1995) in a laboratory, and observations of bubble clouds in the sea cited from Thorpe (1986; 1992).

of a wind-wave tank, where DBBL developed as soon as wind waves were generated, in spite that no air-entrainment occurred yet, as seen from their Photos 1 to 3. A rectangle in the middle part is from an experiment of air–water CO_2 exchange in a wind wave tank by Komori *et al.* (1995). The three broken segments show observations of bubble clouds in the sea cited from Thorpe (1986; 1992).

Kitaigorodskii *et al.* (1983), using Donelan's data in Lake Ontario, reported the two-layer structure, with the upper layer of the order of ten times the rms. wave amplitude, having intense turbulence generation by wind waves. This should just correspond to the DBBL. More recently, Yoshioka *et al*. (2003) made detailed observations of wind sea, breaking waves, swell, together with bubble entrainment depth, and reported a similar structure with our DBBL.

2. Origin of the self-consistent aspects – *Wave-breaking adjustment*

The above described four aspects of wind sea are all in very simple forms, and yet they are mutually consistent or convertible. Thus the wind sea seems to have a holistic structure. Now what is the origin of this marvellous self-consistent nature. Toba (1988; 1996) gave some comprehensive discussion at that time, and Csanady (1997), Badulin *et al*. (2005; 2007), Kukulka and Hara (2008a; 2008b), for example, seem to have pursued their own approaches.

From my present time idea, the simplest form among the above characteristics will be (6) and (7). The water surface is driven by the wind stress, represented here by u_*, and the water surface elements of individual waves must always adjust themselves to move with the same speed u_0. This should be performed by the *wave breaking*, whether or not bubble entrainment is taking place. Here u_0 should be taken relative to the water layer below the DBBL.

In the *wind–windsea equilibrium* or in *wind waves in local equilibrium with the wind*, waves and turbulence are coupled by strongly nonlinear processes, including the skin friction distribution along the phase of waves (Okuda *et al*. 1977; Banner and Peierson, 1998), local shear flows caused by it, wave breaking (with or without bubble entrainment), ordered motions in the air and water (Kawamura and Toba 1988), bursting and turbulence (Ebuchi *et al*. 1993). If the velocity of some wave element exceeds the above speed u_0, it breaks to satisfy this requirement. This situation may be expressed as the *wave-breaking adjustment*.

The above characteristics of wind waves were also derived in a quite different manner (Toba 1974). Dimensionally obtained Kolmogoroff and Obukhov's law in turbulence was expressed by

$$V^3/\Lambda = \text{constant}, \tag{8}$$

where V is the velocity difference over a distance Λ of the size of an eddy. When this was applied to wind waves as Λ: $2a = H$, V: $2u = 2\sigma a = H\sigma$, where a is the wave amplitude, and using a dimensional supposition of $H^2\sigma^3 = u_* g$, we immediately arrive at

$$H^* = (T^*/2\pi)^{3/2}\,. \tag{9}$$

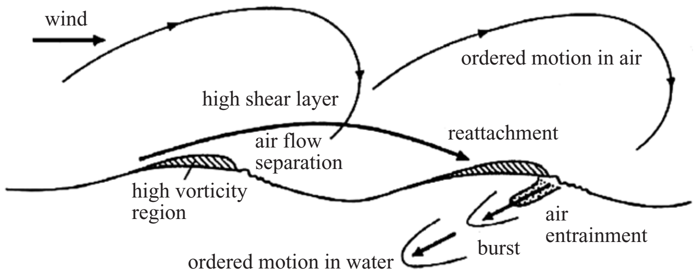

Figure 4 Schematic picture of the microphysical processes at the air–water interface. (Cited from Toba 1996).

This is equivalent to the 3/2-power law with

$$B=(2\pi)^{-3/2}=0.0635(\approx 0.062) \text{ and } u_0=\pi^3 B^2 u_*=(2)^{-3} u_*=0.125 u_* . \quad (10)$$

Wind waves thus seem to have *duality of wave and turbulence*.

It should be noted that Tulin (1996) suggested that the 3/2-power law can be explained by a simultaneous consideration of wave energy and wave momentum change rates resulting from wave breaking, keeping the water-wave relation: $M=E/C$, where M is the wave momentum, E the wave energy, and C is the phase speed. This leads to the necessary *downshifting of wave frequency*, to satisfy the 3/2-power law, keeping a balance between the wind input and dissipation by wave breaking.

Observationally, the part of momentum, that is retained as the wave momentum, is 6% in short fetch wind-wave tanks, and it decreases with the wave age by an error functional way down to zero value for the fully developed sea (Toba 1978). However, a purely theoretical approach from these elementary processes, including the wind, wave breaking and turbulence, may not be easy, because of their strongly nonlinear holistic nature. Elucidation of how the stress or works by the wind remains in waves and goes through the DBBL to the lower layer, would be future works.

3. Windsea Reynolds number R_B and air–sea transfers

By the above story of consistency, H^*, T^*, or the wave age, $\sigma_p^*=u_*\sigma_p/g$, are unified one nondimensional quantity describing the state of wind sea for given u_*. There is the other quantity that should describe the fluid dynamical state of wind-sea surfaces. It is the *windsea Reynolds number*:

$$R_B=u_*^2/\nu\sigma_p , \quad (11)$$

where ν is the kinematic viscosity of air.

The R_B was originally introduced by Toba and Koga (1986) as a nondimensional parameter describing the overall conditions of air–sea boundary processes, including the percentage of the breaking wave crests, the whitecap coverage, and the concentration of sea-salt particles on the sea surface. Iida, Toba and Chaen (1992) presented further data showing that the production rate of sea water droplets on the sea surface can be expressed well by using this. Toba, Suzuki and Iida (1999) used R_B in the estimates of global distribution of whitecap coverage and sea-salt production on the sea surface, using the terminology of the *breaking wave parameter* for R_B.

Synthesizing these studies, Figure 5 clearly shows that the percentage α of breaking crests among individual waves of windsea passing a fixed point on the water surface are widely distributed when plotted against U_{10}, and it collapses

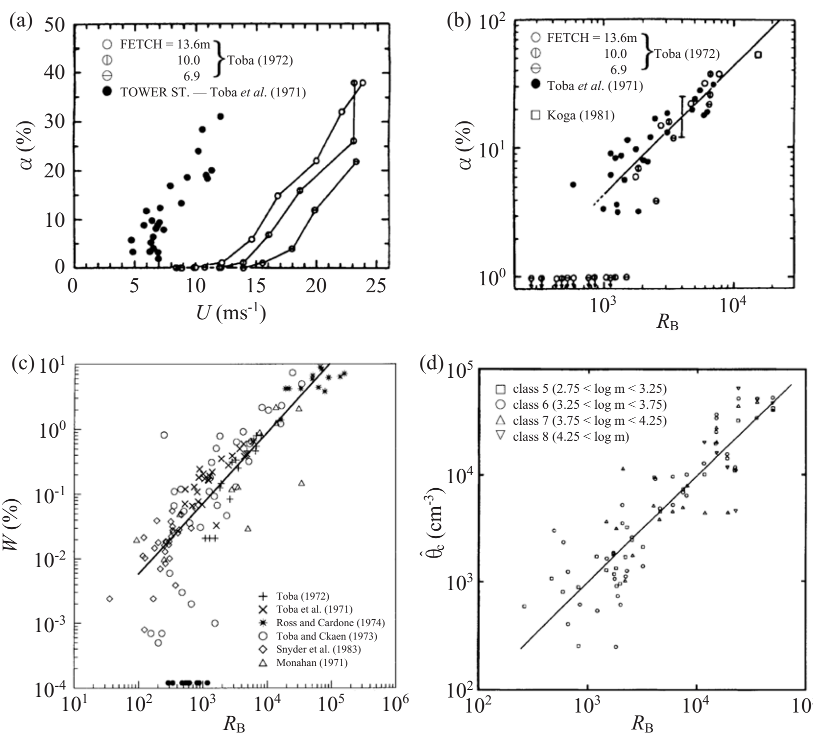

Figure 5 Cited from Toba *et.al.* (2006), (a) Percentage α of breaking crests among individual waves of wind sea passing a fixed point on the water surface, plotted against U_{10}, and (b) plotted against R_B (from Toba and Koga 1986). (c) Whitecap coverage percent, W, plotted against R_B (from Zhao and Toba 2001). (d) Sea-water droplet concentration observed near the sea surface, plotted against R_B (from Iida *et al.* 1992).

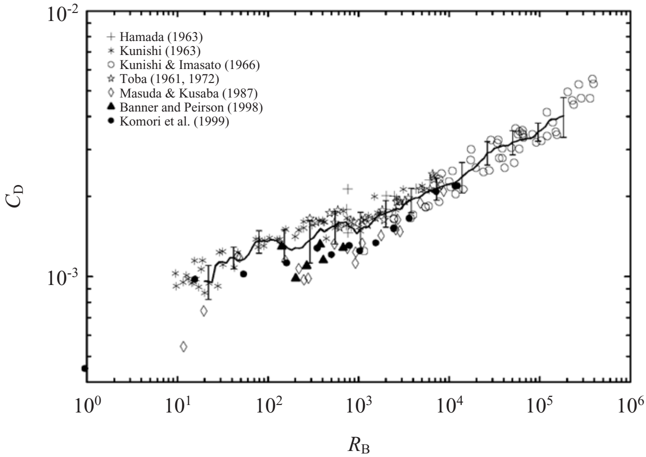

Figure 6 Data set of the drag coefficient C_D, measured by wind-wave tank experiments in fetch-limited conditions, plotted against the *windsea Reynolds number* R_B. (Cited from Toba *et al.* 2006.)

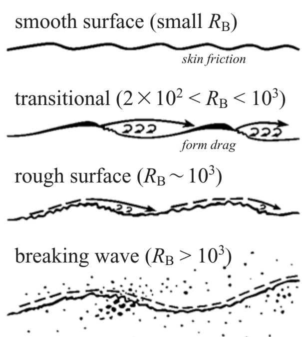

Figure 7 Schematic representation of the regime shift of the windsea boundary layer conditions as a function of R_B, cited from Toba *et al.* (2006).

when plotted against R_B. At the same time it is seen that there is a clear critical value of R_B at 10^3, where breaking wave and drop production begin to take place. Further, Zhao and Toba (2001) showed the clear advantage of R_B over U_{10} , u_* and the wave age, in describing observed data sets of whitecap coverage. Toba *et al.* (2006) presented synthesizing review of the derivation and physical interpretation of R_B, and gave the new terminology of the *windsea Reynolds number*. As a matter of fact, R_B may be interpreted as a Reynolds number, since it contains u_* as a representative scale of speed, and $L_s = u_* T_s$ $(=2\pi u_*/\sigma_p)$ as a representative length scale of the phenomenon under consideration, and ν.

This is an appropriate quantity also to study and describe air–water momentum or gas transfers. Zhao *et al.* (2003) effectively expressed the CO_2 transfer velocity as a function of R_B, and Suzuki *et al.* (2001) attempted a global mapping of the air–sea CO_2 exchange by using this kind of formula. Zhao *et al.* (2006) presented a now sea-spray generation function for spume droplets as a function of R_B. Soloviev *et al.* (2007) reported further researches using R_B.

Figure 6 shows measured values of C_D in laboratory tanks by many authors (cited from Toba *et al.* 2006). We can see two critical points in the distribution of C_D, at $R_B = 2 \times 10^2$ and at $R_B = 10^3$, where the data indicates two downward points, which bracket a bulge region. Beyond $R_B = 10^3$, C_D values become large. The latter point corresponds well to the critical point of wave breaking shown in Figure 5.

Figure 7 shows, from Toba *et al.* (2006), schematic representation of the regime shift of the windsea boundary layer conditions as a function of R_B. The transitional regime between 2×10^2 and 10^3 in R_B corresponds to the regime where flow separation is large with the form drag leading over the skin friction, in accordance with data by Banner and Peirson (1998).

When we add data observed in the sea where some swells usually exist, point distribution in Figure 6 becomes less sharp, as Toba *et al.* (2006) had shown. Nevertheless C_D vs. R_B expression seems much better than, e.g., the nondimensional roughness parameter v.s. wave age expression proposed in Jones and Toba (Eds.) (2001) book. Suzuki *et al.* (2010) has further investigated the effect of swell, using observation tower data including two-dimensional wave spectra. In this sense, well-designated studies of gas transfer as well as momentum transfer should be necessary in the future, especially for cases where various swells coexist.

4. Concluding remarks

Throughout the whole stages of wind sea development, the strokes drift of individual waves adjust themselves to go with the same velocity, $u_0 = \pi^3 B^2 u_*$ in the mass, performed by the *wave-breaking adjustment*. This results in the 3/2-power law, the $g u_* \sigma^{-4}$-type power spectrum, and the DBBL below wind sea having a special turbulence structure. These altogether constitute the self consistent, holistic nature of the wind sea.

The *windsea Reynolds number* R_B acts as a good parameter to describe the hydrodynamic regime of the surface of the wind sea, and can serve to describe characteristics of variation of air–water transfer coefficients of momentum and gasses. However, where there are prevailing swells, they affect largely the exchange coefficients. Therefore we should accumulate more data of air–sea fluxes by further intentional experiments and observations, in which two-dimensional wave spectra are included.

References

Badulin, S.I., A.N. Pushkarev, D. Resio and V.E. Zakharov (2005), Self-similarity of wind-driven seas. *Nonlinear Processes in Geophysics*, *12*, 891-945.

Badulin, S.I., A.V. Babanin, .E. Zakharov and D. Resio (2007), Weakly turbulent laws of wind-wave growth. *J. Fluid Mech*. *591*, 339-378.

Bailey R.J., I.S.F Jones and Y. Toba (1991), The steepness and shape of wind waves. *J. Oceanogr. Soc. Japan*, *47*, 249-264.

Banner, M. and W. Peirson (1998), Tangential stress beneath wind-driven air–water interfaces. *J. Fluid Mech*., 364, 115-145.

Bye, J.A.T. (1988), The coupling of wave drift and wind velocity profiles. *J. Marine Res. 46*, 457-472.

Csanady, G.T. (1997), The "ship law" of the free surface. *J. Oceanogr*. *53*, 67-80.

Ebuchi, N., Y. Toba and H. Kawamura (1992), Statistical study on the local equilibrium between wind and wind waves by using data from ocean data buoy stations. *J. Oceanogr*., *48*, 77-92.

Ebuchi, N., H. Kawamura and Y. Toba (1993), Bursting phenomena in the turbulent boundary layer beneath the laboratory wind-wave surface. In *Natural Physical Sources of Under Water Sound.* (Ed. B. Kerman), Kluwer Acad Pub., 263-276.

Hasselmann, K. *et XV al.* (1973), Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). *Deut. Hydrogr. Z., Suppl.*, *A48*, 95pp.

Hanson, J.L. and O.M. Phillips (1999), Wind sea growth and dissipation in the open ocean. *J. Phys. Oceanogr*., *29*, 1633-1648.

Iida, N., Y. Toba and M. Chaen (1992), A new expression for the production rate of sea water droplets on the sea surface. *J. Oceanogr. 48*, 439-460.

Janssen, P. (2004), *The Interaction of Ocean Waves and Wind.* Cambridge Univ. Press, 300pp.

Jones, I.S.F. and Y. Toba (Eds.) (2001), *Wind Stress over the Ocean*. Cambridge Univ. Press, 307pp.

Kahma, K.K. (1981), A study of the growth of the wave spectrum with fetch. *J. Phys. Oceanogr*., *11*, 1603-1515.

Kawai, S., K. Okada and Y. Toba (1977), Field data support of the three-seconds power law and the $u_*\sigma^{-4}$-spectral form for growing wind waves. *J. Oceanogr. Soc. Japan*, *33*, 137-150.

Kawamura, H. (2003), Satellite remote sensing of the air–sea interface. In *Ocean–Atmosphere Interactions*. (Ed. Y. Toba), TERRA PUB/Kluwer, 239-298.

Kawamura, H. and Y. Toba (1988), Ordered motion in the turbulent boundary layer over wind waves. *J. Fluid Dyn., 197,* 105-138.

Kitaigorodskii, S.A. (1983), On the theory of the equilibrium range in the spectrum of wind-generated gravity waves. *J. Phys. Oceanogr*., *13*, 816-827.

Kitaigorodskii, S.A., M.A. Donelan, J.L. Lumley and E.A. Terray (1983), Wave–turbulence interactions in the upper ocean. Part II: Statistical characteristics of wave and turbulent components of the random velocity field in the marine surface layer. *J. Phys. Oceanogr*., *13*, 1988-1999.

Komori, S., T. Shimada and Y. Murakami (1995), Laboratory estimation of CO_2 transfer velocity across the air-sea interface. In *Biogeochemical Processes and Ocean Flux in the Western Pacific*. (Eds. H. Sakai and Y. Nozaki), Terra Sci. Pub. Co., Tokyo, 69-81.
Kukulka, T. and T. Hara (2008a), The effect of breaking waves on a coupled model of wind and ocean surface waves. Part I: Mature seas. *J. Phys. Oceanogr*., *38*, 2145-2163.
Kukulka, T. and T. Hara (2008b), The effect of breaking waves on a coupled model of wind and ocean surface waves. Part II: Growing seas. *J. Phys. Oceanogr*., *38*, 2164-2184.
Lamont-Smith, T. and T. Waseda (2008), Wind wave growth at short fetch. *J. Phys. Oceanogr*. *38*, 1597-1606.
Mitsuyasu, H., R. Nakamura and T. Komori (1971), Observations of the wind and waves in Hakata Bay. *Rep. Res. Inst. Appl. Mech*., *Kyushu Univ*., *19*, 37-74.
Mitsuyasu., H., F. Tasai, T. Suhara, S. Mizuno, M., Ohkusu, T. Honda and K.R. Kiishi (1980), Observations of the power spectrum of waves using a cloverleaf buoy. *J. Phys. Oceanogr*., *10*, 286-296.
Okuda., K., S. Kawai and Y. Toba (1977), Measurement of skin friction distribution along the surface of wind waves. *J. Oceanogr. Soc. Japan*, *33*, 190-198.
Phillips, O.M. (1985), Spectral and statistical properties of the equilibrium range of wind generated gravity waves. *J. Fluid Mech*., *156*, 505-531.
Romero, L. and K. Melville (2010), Airborne observations of fetch-limited waves in the Gulf of Tehuantepec, *J. Phys. Oceanogr*., *40*, 441-465.
Soloviev, A., M. Donelan, H. Graber, B Haus and P. Schlüssel (2007): An Approach to estimation of near-surface turbulence and CO_2 transfer velocity from remote sensing data. *J. Marine Systems, 66*, 182-194.
Suzuki, N., Y. Toba and S. Komori (2010), Examination of drag coefficient with special reference to the windsea Reynolds number – Condition with counter and mixed swell –. *J. Oceanogr.*, *66* (to be published).
Suzuki, Y., S. Komori, D. Zhao and Y. Toba (2001), Global mapping with seasonal variation of air-sea CO_2 exchange by using wind and wind-wave distribution. *Extended Abstracts, 6th International Carbon Dioxiside Conference, Sendai*, Vol. II, (Ed. K. Nakazawa), 756-759.
Thorpe, S. A. (1986), Measurements with an automatically recording inverted echo sounder; AIRES and the bubble clouds. *J. Phys. Oceanogr*., *16*, 1462-1478.
Thorpe, S. A. (1992), Bubble clouds and the dynamics of the upper ocean. *Quart. J. Roy. Meteor. Soc*., *118*, 1-22.
Toba, Y. (1961), Drop production by bursting air bubbles on the sea surface (III) Study by use of a wind flume. *Mem. Coll. Sci. Univ. Kyoto, Ser. A*, *29*, 313-344.
Toba, Y. (1972), Local balance in the air–sea boundary processes I. On the growth process of wind waves. *J. Oceanogr. Soc. Japan*, *28*, 109-120.
Toba, Y. (1973), Local balance in the air–sea boundary processes III. On the spectrum of wind waves. *J. Oceanogr. Soc. Japan*, *29*, 209-220.
Toba, Y. (1974), Duality of turbulence and wave in wind waves. *J. Oceanogr. Soc. Japan*, *30*, 241-242.
Toba, Y. (1978), Stochastic form of the growth of wind waves in a single-parameter representation with physical implications. *J. Phys. Oceanogr.*, *8*, 494-507.
Toba, Y. (1988), Similarity laws of the wind wave and the coupling process of the air and water turbulent boundary layers. *Fluid Dyn. Res*., *2*, 263-279.
Toba, Y. (1996), Physical processes of the local air–sea interactions — Current

understanding and outstanding questions. Twentieth Symposium on Naval Hydrodynamics. (Ed. M.P. Tulin), National Academy Press, 588-597.

Toba, Y., N. Iida, H. Kawamura, N. Ebuchi and I.S.F. Jones (1990), Wave dependence of sea-surface wind stress. *J. Phys. Oceanogr*., *20*, 706-721.

Toba, Y. and H. Kawamura (1995), Wind wave coupled downward-bursting boundary layer below the sea surface — In relation to penetration depth of bubble clouds, In *Air–Water Gas Transfer* (Eds. B. Jähne and E.C. Monahan), AEON, 177-183.

Toba, Y. and M. Koga (1986), A parameter describing overall conditions of wave breaking, whitecapping, sea-spray production and wind stress. In *Oceanic Whitecaps*, (Eds. E.C. Monahan and G. MacNiocaill), D.Reidel Pub. Co., Dordrecht, 37-47.

Toba, Y., S. Komori, Y. Suzuki and D. Zhao (2006), Similarity and dissimilarity in air-sea momentum and CO_2 transfers: the nondimensional transfer coefficients in light of the windsea Reynolds number, in *Atmosphere–Ocean Interactions Vol. 2*. (Ed. W. Perrie), WIT Press, 53-82.

Toba, Y., K. Okada and I.S.F. Jones (1988), The response of wind–wave spectra to changing winds. Part I: Increasing winds. *J. Phys. Oceanogr*., *18*, 1231-1240.

Toba, Y., N. Suzuki and S. Komori (2008), Discrimination of spurious self-correlation in nondimensionalized analyses of fluid dynamical data. *J. Oceanogr*., *64*, 393-397.

Toba, Y., Y. Suzuki and N. Iida (1999), Study on global distribution with seasonal variation of the whitecap coverage and sea-salt aerosol production on the sea surface. In *The Wind-Driven Air–Sea Interface — Electromagnetic and Acoustic Sensing, Wave Dynamics and Turbulent Fluxes.* (Ed. M.L. Banner), School of Math., Univ. of New South Wales, Australia, 355-356.

Toba, Y., M. Tokuda, K. Okuda and S. Kawai (1975), Forced convection accompanying wind waves. *J. Oceanogr. Soc. Japan*, *31*, 192-198.

Tokuda, M. and Y. Toba (1981), Statistical characteristics of individual waves in laboratory wind waves. I. Individual spectra and similarity structure. *J. Oceanogr. Soc. Japan*, *37*, 243-258.

Tulin, M.P. (1996), Breaking of ocean waves and downshifting. *Waves and Nonlinear Processes in Hydrodynamics*. (Eds. J. Grue, B. Gjevich and J.E. Weber). Kluwer, 170-190.

Wilson , B.W. (1965), Numerical prediction of ocean waves in the North Atlantic for December, 1959. *Dtsch. Hydrogr. Z., 18*, 114-130.

Yoshikawa, I., H. Kawamura, K. Okuda and Y. Toba (1988), Turbulent structure in water under laboratory wind waves. *J. Oceanogr. Soc. Japan*, *44*, 143-156.

Yoshioka, H., M. Matsumoto, S. Serizawa and T. Takayama (2003), Acoustically observed characteristics of bubble entrainment due to wave breaking. *Proceedings of Coastal Engineering, JSCE*, *50*, 116-120.

Zhao, D. and Y. Toba (2001), Dependence of whitecap coverage on wind and wind-wave properties, *J. Oceanogr*., *57*, 603-616.

Zhao, D., Y. Toba, Y. Suzuki and S. Komori (2003), Effect of wind waves on air–sea gas exchange: Proposal of an overall CO_2 transfer velocity formula as a function of breaking-wave parameter. *Tellus*, *55B*, 478-487.

Zhao, D., Y. Toba, K. Sugioka and S. Komori (2006), New sea spray generation function for spume droplets. *J. Geophys. Res., 111*, C02007, 1-11.

Zakharov, V.E. and N.N. Filonenko (1966), Energy spectrum for stochastic oscillation of the surface of a liquid. *Doklady Akademii Nauk SSSR*, *170*, 1291-1295.