Review

Reminiscences on the study of wind waves

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Abstract: The wind blowing over sea surface generates tiny wind waves. They develop with time and space absorbing wind energy, and become huge wind waves usually referred to ocean surface waves. The wind waves cause not only serious sea disasters but also take important roles in the local and global climate changes by affecting the fluxes of momentum, heat and gases (e.g. CO₂) through the air-sea boundary. The present paper reviews the selected studies on wind waves conducted by our group in the Research Institute for Applied Mechanics (RIAM), Kyushu University. The themes discussed are interactions between water waves and winds, the energy spectrum of wind waves, nonlinear properties of wind waves, and the effects of surfactant on some air-sea interaction phenomena.

Keywords: wind waves, wave spectrum, growth of the wave spectrum, nonlinear energy transfer, dispersion relation, air-sea interactions

1. Introduction

The modern studies of wind waves can be said to have started with a pioneering study by Sverdrup and Munk (1947). Before their study wind waves were considered to be too disordered to be treated mathematically. It is said that Lord Rayleigh remarked, “The basic law of the seaway is the apparent lack of any law”.2)

To solve the difficult problem Sverdrup and Munk (1947)1 introduced a concept of significant waves that have a kind of mean wave height and mean wave period to describe quantitatively wind waves which show random properties. They also introduced a concept of energy balance in a wave system to understand and describe the wave evolution. Furthermore they determined empirical relationships for the evolution of wind waves by using accumulated wave data.

Although these concepts are common knowledge today, it is really surprising that such ideas were written following their initiative, and fundamental properties of wind waves were gradually clarified.

On the other hand, in the beginning of 1950s a group of New York University led by W. J. Pierson and G. Neumann started to study the spectrum of wind waves and developed a wave forecasting method by using wave spectra (Pierson, Neumann and James, 1955).3) In 1950s the progress in the study of random noise greatly affected the study of wind waves to describe their statistical properties.

As for the dynamics of wind waves, Ursell (1956)4) wrote a very important review on wave generation by wind. After the critical review of the previous studies on this problem he concluded that the present state of our knowledge is profoundly unsatisfactory. The review gave a strong impact to fluid-dynamicists and physical oceanographers. Stimulated by the review two outstanding theories on the generation of wind waves by wind were presented simultaneously by Miles (1957)5) and Phillips (1957).6) Many studies followed them to test the theories experimentally or to improve their theories, and the field of studies on wind waves became very active and exciting.

In 1965 I started fundamental studies on wind waves in the Research Institute for Applied Mechanics (RIAM), Kyushu University and continued the study until my retirement from the RIAM in 1992.
It was very gratifying that I could continue the studies on wind waves in such an active and rapidly developing field of the study.

In the present review the results of typical studies of our group in the RIAM are discussed. The following eight themes are selected chronologically and discussed: interactions between water waves and winds, nonlinear energy transfer in the spectrum of wind waves, the growth of the spectrum of wind waves, the directional spectrum of ocean surface waves, the dispersion relation of random water waves, wind-induced growth of water waves, the momentum transfer from winds to waves, and the effects of surfactant on some air-sea interaction phenomena.

In the discussion of each study, the motivation and background of the study are included as much as possible to explain the state of development of scientific knowledge in the study of wind waves at the time.

2. Interactions between water waves and winds (1)

In 1965 I moved from the Port and Harbor Research Institute, Ministry of Transportation, to the RIAM, Kyushu University. In those days I was much interested in the experimental verification of Miles’ (1957) theory for wave generation by wind, but there were no experimental facilities at all in our laboratory. In such a time I had an opportunity to use a big wave tank: 70 m long, 8 m wide and 2.9 m deep. Fortunately the tank was equipped with a mechanical wave generator and a wind blower.

By using the wave tank I began to measure the wind-induced growth of mechanically-generated regular waves. Immediately after the start of the study, however, I found that the facility was not suitable for the study: the wind diverged horizontally and vertically and wind field became non-uniform along the tank. This was due to the absence of a ceiling and side walls in the wind passage of the tank. In such a condition we lost the merit of the laboratory experiment to study the phenomenon under simple and controlled conditions.

Unexpected new findings. Although the original purpose of the study encountered the difficulty, I discovered the very interesting phenomenon that wind waves in a generation area in the tank attenuate immediately after the passage of the regular waves propagating in the direction of the wind. Furthermore, the attenuation of wind waves seemed to depend only on the local steepness H/L of the regular waves, where H is the wave height and L is the wave length of the regular waves.

In order to clarify the interesting phenomenon careful measurements were repeated by changing successively wave steepness and wind speed. A typical result is shown in Fig. 1, where the relation between a normalized wind wave energy, \( E_2/(E_2)_0 \), and the local steepness of the regular waves, H/L is shown. Here \( E_2 \) is the energy of wind waves co-existing with regular waves and \( (E_2)_0 \) is the energy of wind waves unaffected by regular waves, i.e., the energy of wind waves before the arrival of the regular waves. As shown in Fig. 1 the normalized energy of wind waves decreases gradually with the increase of the steepness of regular waves; it becomes almost negligible near the steepness 7 \( \times 10^{-2} \).

This quite new finding was published in the report of the RIAM (Mitsuyasu, 1966). Although I expected various responses to the new finding, there were no responses at all not only from Japanese researchers but also from foreign researchers.

Phillips and Banner’s mechanism. In 1974, eight years after the publication of Mitsuyasu (1966), I received a letter from Professor Phillips of the Johns Hopkins University. His letter informed me that he conducted a study similar to ours and obtained almost the same results, and asked me about the recent progress in the studies relating to our previous one.

After the study of Mitsuyasu (1966), I repeated the experiment on the same phenomena under more
controlled condition: the wind distribution was made uniform by improving the experimental setup. However, the results were almost the same to those of our previous study. I informed to Professor Phillips on this matter.

Immediately after the exchange of our letters, he published the paper, Phillips and Banner (1974)\(^8\) in Journal of Fluid Mechanics (JFM). Their experimental results were almost the same to Mitsuyasu (1966),\(^7\) but they proposed an important mechanism for the attenuation of the wind waves by steep long waves propagating in the direction of the wind. The point of the mechanism is that the wind-induced surface current is nonlinearly augmented at the crest of the long waves, and short wind waves tend to break and lose their energy at the crest of the long waves before reaching the critical breaking limit.

Theoretical estimates of the reduction of the wind wave energy showed very good agreements not only with their measurement but also our measurement. Therefore, it seemed that the problem of the attenuation of the short waves by long waves was solved, though some disagreement between the theory and experiment was reported on the wind-speed dependence of the attenuation of wind waves by long waves (Wright, 1976).\(^9\) Our later study, Mitsuyasu and Maeda (2002)\(^10\) on the interaction between winds and waves which was done in a big wind-wave tank generally supported the Phillips and Banner’s mechanism too.

**Further problems.** Mitsuyasu and Yoshida (2005)\(^11\) studied the attenuation of swell (mechanically-generated long waves) by opposing wind. In the experiment an unexpected phenomenon was found: wind waves did not attenuate but rather were augmented by the opposing swell. This is contradictory to the mechanism of Phillips and Banner (1974),\(^8\) because their mechanism predicts the attenuation of wind waves even for the opposing swell. The result showed the need for the study of another mechanism.

Chen and Belcher (2000)\(^12\) proposed another mechanism for the attenuation of wind waves by a long wave. Their idea is that when a long wave travelling in the wind direction comes into a wind area, the long wave absorbs a part of the wind momentum for its development, leading to the reduction of the momentum transferred into wind waves. The theoretical prediction obtained from their model agreed fairly well with the observations by Mitsuyasu (1966)\(^7\) and Phillips and Banner (1974).\(^8\) However, their model fails to explain the effect of the opposing swell, because the attenuation of the opposing swell requires a transfer of wind momentum, the momentum available for transfer into the wind waves is reduced, leading to the attenuation of wind waves, which contradicts the observation by Mitsuyasu and Yoshida (2005).\(^11\)

Another mechanism for the suppression of wind waves by swell, the nonlinear interaction between wind waves and swell can be considered. Masson (1992)\(^13\) studied the effects of this mechanism more than twenty years ago. However, her results showed that the interaction is generally negligible unless the two spectral peaks are so close that the spectrum can be hardly qualified as bimodal. The condition for the effective interactions is very different from that in the laboratory experiments. Furthermore, her study was concerned with the phenomenon without wind action. Therefore her results cannot explain the phenomena observed by Mitsuyasu (1966)\(^7\) and Phillips and Banner (1974).\(^8\)

Regarding the interaction between swell and wind waves, recently Tamura et al. (2009)\(^14\) published an interesting paper showing that nonlinear coupling between wind waves and swell under the wind action lead to a freakish sea state. The result suggests that if the nonlinear coupling between wind waves and swell under the wind action is studied by changing their frequency difference, their directional difference and the wind speed, we will be able to get some interesting results.

In connection with the interaction between wind waves and swell, Cheng and Mitsuyasu (1992)\(^15\) found a very curious phenomenon that the surface drift current generated by the wind was augmented by opposing swell of large steepness.

Although the studies on the interaction among the wind, short wind waves and long waves (swell) have a long history, the problem seems to be unsolved theoretically and further studies are needed: interactions between winds and waves, nonlinear interaction between short waves and long waves, and interactions between waves and currents (organized or turbulent) will provide some breakthrough.\(^16\),\(^17\)

### 3. A note on the nonlinear energy transfer in the spectrum of wind wave\(^18\)

To a first approximation wind waves which have random properties can be considered as a linear superposition of infinitely many wave components with different amplitudes, frequencies, phases and propagation directions as shown schematically in Fig. 2. Such a linear model describes fairly well
statistical and dynamical properties of wind waves and it makes the spectral description of wind waves effective.

However, there are several important phenomena which require consideration of nonlinear effects. The nonlinear energy transfer in the spectrum of wind waves is one of those that play an important role in the evolution of wind waves.

**Emergence and progress in the theory.** In 1961 a conference Ocean Wave Spectra,\(^{19}\) was held at Easton, Maryland in the US. In the conference the theories on the nonlinear energy transfer in random water waves were presented by Phillips (1963),\(^{20}\) and Hasselmann (1963).\(^{21}\) Phillips (1981)\(^{22}\) described the atmosphere of the meeting as follows: the reaction from some well-known and senior people in the field was, to my astonishment, vigorous and hostile, the flat disbelief that different components could exchange energy at all. My mathematics was certainly very primitive but Michael Longuet-Higgins, to whom I had sent a copy of the manuscript, offered his cautious and most welcome support and Klaus Hasselmann, whom I met here for the first time, was working quite independently along the same lines but with greater generality, so that sharp, encounter ended with a stand-off.

Apart from the disbelief of his theory by quite senior people, it is interesting that Phillips did not know the work of Hasselmann at all. Such a thing is difficult to appreciate in the present day when information can be transferred quickly and widely. This is probably due to the fact that Hasselmann did not publish his now-famous papers on nonlinear energy transfer (Hasselmann, 1962, 1963)\(^{23,24}\) until a year or so after the meeting.

After the meeting and the publications of the papers, Phillips (1963)\(^{20}\) and Hasselmann (1962, 1963)\(^{23,24}\) the topics of the nonlinear interaction in random water waves attracted the interests of many fluid-dynamicists and physical oceanographers and many papers were published (cf. Phillips, 1977 and Komen et al., 1994).\(^{25,26}\)

**Experimental studies.** In contrast to the progress in theoretical studies on nonlinear wave interactions, quite a few experimental studies were done to see whether the evolution of the spectrum of water waves follows to the theoretical prediction or not. Simultaneously Longuet-Higgins and Smith (1966)\(^{27}\) and McGoldrick et al. (1966)\(^{28}\) clarified theoretically and experimentally the existence and consequence of the nonlinear resonant interaction in two crossing waves. However, there were no studies which compared the Hasselmann’s theory\(^{23,24}\) with the evolution of the wave spectrum, though the inference was made later by Hasselmann et al. (1973).\(^{29}\)

One day when I was reading a paper of Uberoi (1963)\(^{30}\) on the experimental study of homogeneous turbulence, his technique in the study of turbulence gave me an idea that the same technique can be applied to the study of the nonlinear energy transfer in random water waves. His technique is that of measuring turbulence spectra at two cross sections in a wind tunnel. From the difference of the spectra at the two sections he determined the nonlinear energy transfer in the turbulence spectrum after correction for viscous energy dissipation.

Almost the same techniques can be used for the determination of the nonlinear energy transfer in the spectrum of random water waves. I selected
the data of the wave spectra measured in a decay area where the wind was not blowing (Mitsuyasu and Kimura, 1964). In this case, since the energy input from the wind to the waves and the energy dissipation due to wave breaking were absent, and the effects of the wind-induced drift current were very small, we can determine the nonlinear energy transfer in the spectrum of wind waves in the decay area by taking the difference of the spectra in two sections and by compensating for viscous energy dissipation.

Figure 3(a) shows an example of the result of our study (Mitsuyasu, 1968), where the nonlinear energy transfer in the spectrum of wind waves in decay area, which is determined through the above procedures, is compared with the theoretical computation. In the figure the wave spectrum at the upward station is also shown. As shown in Fig. 3(a) the agreement between the theory and the experiment is fairly good and we can see the important role of the nonlinear energy transfer in the evolution of the spectrum of random water waves.

However, one problem remained. At that time since I hadn’t a program for the accurate computation of the nonlinear energy transfer in the Hasselmann’s model, I used a parameterized equation by Barnett (1966) for the computation of the nonlinear energy transfer. However, the parameter-
ized equation was not necessarily specialized for our spectrum, and Barnett himself pointed out this problem in his private communication. I was very anxious about this problem for the long time after the study.

The problem was solved fourteen years later by the study of Masuda (1980).33) He developed a very accurate computation method of the nonlinear energy transfer for the Hasselmann’s model and computed accurately the nonlinear energy transfer in our measured spectra. In Fig. 3(b) wave spectrum \( \Psi(f) \) at the upward station, the observed nonlinear energy transfer determined with the same techniques used in the previous study, and the nonlinear energy transfers computed by using two different spectra: the spectrum at the upward station (dotted line) and the mean spectrum of those at the upward and the downward stations (broken line). As shown in Fig. 3(b) the agreement between the theory and the measurement is much better than that in Fig. 3(a). The result shows clearly that the nonlinear energy transfer plays an important role in the evolution of the spectrum of random water waves.

**Further problem.** After the study of Mitsuyasu (1968)18) there were quite a few similar studies. As far as I know, Zhao et al. (2006)34) is the only study similar to Mitsuyasu (1968).18) They measured the spectra of wind waves in the decay area of their laboratory tank and determined the nonlinear energy transfers using the techniques similar to those of Mitsuyasu (1968).18)

Comparisons of their measured results with the theoretical computations showed that some data agreed well with the theoretical computation but many other data were different from the theoretical computations, though the reason was not clear. Furthermore, even for the data showing good agreement between the theory and experiment, the peak frequency for the computed positive transfer is always a little higher than that for the measured one. The similar trend can be seen in the result obtained by Masuda (1980)33) shown in Fig. 3(b).

These results show the need for further theoretical and experimental studies to clarify the phenomena in the nonlinear energy transfer in the wind wave spectrum. In the laboratory experiment, in order to study the purely nonlinear energy transfer in the wave spectrum, we need to take care of other phenomena affecting the evolution of the wave spectrum, such as the drift current, the viscous energy dissipation of the composite waves and the contamination of the water surface.

In the theoretical study, we will need to develop a new theory in which the wind effects such as the wind stress and the wind-induced surface current are considered. Such wind effects are inevitable for the wind-induced waves in generation area.

**4. On the growth of the spectrum of wind-generated waves (1),35) (2)36)**

Since Neumann (1952)37) and Pierson (1953)38) introduced the use of a spectral model to describe oceanic wind waves in the 1950s, many studies had been done on the spectrum of wind waves. In addition to Phillips’ (1958)39) famous equilibrium spectrum and the Pierson and Moskowitz’s (1964)40) spectrum for the fully developed wind waves in the ocean, there were quite a few studies on the detailed properties of the wind wave spectrum and its generating conditions.

We planned to clarify the growth of the spectrum of wind waves under accurately controlled conditions (Mitsuyasu, 1968).35) The wave tank used for the study is the same wave tank used in the study of Mitsuyasu (1966).7) In this study, however, by setting a side wall and a ceiling to a part of the wave tank, it was partially converted into a conventional wind-wave flume to simplify the generating condition. Furthermore, in order to obtain the wind and wave data in the longer fetches, observations of the wind and waves were done in Hakata bay, Fig. 4(a), by using an observation platform, Fig. 4(b), where we could get the wind and wave data over the fetch of about 4.5 km in the direction of the north wind. We obtained great many data of the wind and wind waves both in the tank and in Hakata Bay.

**Fetch relations.** In order to show the growth of the wind wave spectrum by the wind quantitatively we selected two scale parameters, spectral peak frequency \( f_p \) and total spectral energy \( E \) of the wind wave spectrum, where \( E \) does not include \( \rho g \) (\( \rho \): density of water, \( g \): gravitational acceleration) and corresponds to \( \eta^2 \) (\( \eta \): elevation of the wind wave surface). These two parameters of the wind wave spectrum were related, in dimensionless forms, to the fetch \( X \) and the friction velocity of the wind \( U_* \), which was determined from the wind profile over the water surface. We obtained the following simple relations:

\[
\frac{g\sqrt{E}}{U_*^s} = 1.31 \times 10^{-2} \left( \frac{gX}{U_*^2} \right)^{0.504}, \quad [1]
\]

\[
\frac{U_* f_p}{g} = 1.00 \times \left( \frac{gX}{U_*^2} \right)^{-0.330}, \quad [2]
\]
where \( g\sqrt{E}/U_*^2 \) is a dimensionless wave energy, \( gX/U_*^2 \) is a dimensionless fetch, \( U_*f_p/g \) is a dimensionless spectral peak frequency (Mitsuyasu, 1968).\(^{35}\)

These relations are usually called the fetch relations, and the relations are satisfied almost universally for the wind waves in the generation area. Equation [1] means that the total energy \( E \) of the wind waves is proportional to the fetch \( X \) and \( U_*^2 \) (= wind stress/\( \rho_a \) density of the air), and these properties are physically reasonable. Equation [2] means that the wave age \( C_p/U_* \) (the ratio of the wave velocity and the wind friction velocity) increases slowly with the increase of the dimensionless fetch using the equation \( g/2\pi f_p = C_p \) where \( C_p \) is the phase velocity of the spectral component at the spectral peak frequency \( f_p \).

The fetch relations for the significant wave height and period were obtained firstly by Sverdrup and Munk (1946).\(^{11}\) Later Wilson (1965)\(^{41}\) improved the relations by using many reliable data of the wind and waves. In order to compare the newly obtained fetch relations for the wave spectrum, [1] and [2], with the fetch relations for the significant waves by Wilson (1965), Mitsuyasu (1973)\(^{32}\) converted the fetch relations [1] and [2] to those for the significant waves by using statistical theory and an empirical relation. It was found that the fetch relations converted from [1] and [2] were almost the same to those obtained by Wilson (1965).\(^{41}\)

**JONSWAP (the Joint North Sea Wave Project).**\(^{29}\) While we were studying the growth of the spectrum of wind waves in the laboratory tank and in Hakata Bay, a big project observing wind waves in the ocean was going on in the North Sea. The project JONSWAP was organized by Kraus Hasselmann in Germany and many well-known wave researchers in the Europe and the US attended the project.

Five years after the publication of our papers\(^{35,36}\) on the growth of the spectrum of wind waves, the results of the JONSWAP were published by Hasselmann et al. (1973).\(^{29}\) In the report they presented the fetch relations obtained by using the wind and wave data in the North Sea. In the relations they used the 10 m height wind speed \( U_{10} \) as a representative wind speed. We convert the 10 m height wind speed \( U_{10} \) into the friction velocity of the wind \( U_* \) by using the empirical relation \( U_*^2 = 10^{-3} U_{10}^2 \) (Hasselmann et al., 1973)\(^{29}\) then their relations become

\[
\frac{g\sqrt{E}}{U_*^2} = 1.26 \times 10^{-2} \left( \frac{gX}{U_*^2} \right)^{0.50}, \tag{3}
\]

\[
\frac{U_* f_p}{g} = 1.08 \times \left( \frac{gX}{U_*^2} \right)^{-0.33}. \tag{4}
\]

The fetch relations [3] and [4] obtained in the JONSWAP show surprisingly good agreements with our relations [1] and [2].

The report (Hasselmann et al., 1973)\(^{29}\) contains many important results. They proposed a standard spectrum, JONSWAP spectrum, for the fetch-limited wind waves, which simulate well the sharp spectral form in the limited fetches as compared to the fully developed spectrum obtained by Pierson and Moskowitz (1964).\(^{40}\) Furthermore they showed the important effects of the nonlinear energy transfer in the evolution of the wind wave spectrum by
examining the downwind evolution of the measured spectra and by applying the theory of Hasselmann (1962, 1963). The presentation and discussion of the energy balance equation for the evolution of the wind wave spectrum also greatly contributed to the progress in the study of wind waves.

3/2 power law. A little before the publication of the JONSWAP report, Toba (1972) clarified an important property of the wind waves in the generation area: the 3/2 power law. The law can be written, using the original expression, as

$$H' = 0.059T^{-3/2},$$  \[5\]

where $H'$ is the significant wave height, and $T$: significant wave period. The relation [5] does not include the fetch and it is satisfied universally for the wind waves in generation area.

The 3/2 power law can be obtained from the fetch relations [1] and [2] by eliminating the dimensionless fetch $gX/U_s^2$ after the approximations $0.504\rightarrow 1/2$ and $0.330\rightarrow 1/3$, and using the relations $H = 4.01\sqrt{E}$ (Longuet-Higgins, 1952) and $T = 1/1.05f_p$ (Mitsuyasu, 1968). The 3/2 power law obtained from [1] and [2] through the above procedures is

$$H' = 0.057T^{-3/2},$$  \[6\]

which is almost the same to Eq. [5]. This is due to the fact that Toba used the Wilson’s (1965) fetch relations for the derivation of Eq. [5] and the Wilson’s (1965) fetch relations are quite similar to ours.

Although the 3/2 power law is very important, we need to know its limitation. Kusaba and Masuda (1988) studied the relation between $E\omega_p^4/g^2$ and $\omega_pU_s/g$, where the former corresponds to the square of the wave steepness and the latter corresponds to the inverse of the wave age (or dimensionless wind speed). They found that the 3/2 power law is satisfied, that is, $E\omega_p^4/g^2$ is linearly proportional to $\omega_pU_s/g$, in the region $0.4 \leq \omega_pU_s/g \leq 1.0$, but in the region $1.0 < \omega_pU_s/g$, the parameter $E\omega_p^4/g^2$ tends to saturate gradually approaching the value corresponding to the breaking limit of the Stokes wave.

Recently Takagaki et al. (2012) studied the air-sea fluxes under the action of the very high wind speed up to 68 m/s (wind speed at 10 m height). They also found that the 3/2 power law was not satisfied in the wind waves under the very strong wind action. The reason is the same as that in Kusaba and Masuda (1988): the wind waves saturated due to wave breaking under the very strong wind action.

Toba’s spectrum. In 1973, when the report of the JONSWAP was published, Toba (1973) presented an important study on the spectrum of wind waves. He proposed a spectral form which has a high frequency tail proportional to $gU_*$, $f^{-4}$, which is very different from the equilibrium spectrum of Phillips (1958) which has the high frequency tail proportional to $g^2 f^{-5}$. Toba’s spectrum took a little time to be approved. This was probably because the equilibrium spectrum of Phillips (1958) was too popular and because a difference between slopes $f^{-4}$ and $f^{-5}$ in the high frequency tails of the measured spectrum was not very clear due, in many cases, to the statistical scatters of the data. However, many spectral data supported the high frequency tail of $gU_*$, $f^{-4}$ (e.g. Kawai et al., 1977, Mitsuyasu et al., 1979: Forristall, 1981: Donelan et al., 1985) and Phillips (1985) himself revised his theoretical equilibrium spectrum to show the high frequency tail proportional to $gU_*$, $f^{-4}$. Responding to such a result the JONSWAP spectrum was revised to have the high frequency tail proportional to $gU_*$, $f^{-4}$ (Mitsuyasu, 1984: Donelan et al., 1985).

5. Observation of the directional spectrum of ocean surface waves using a cloverleaf buoy

Directional spectrum $F(f, \theta)$ shows the energy distribution of the spectral components (Fig. 2) as a function of wave frequency and the directional angles for the wave propagation. It is usually expressed as

$$F(f, \theta) = \Psi(f)G(f, \theta),$$  \[7\]

where $\Psi(f)$ is the one-dimensional (frequency) spectrum and $G(f, \theta)$ is the angular distribution function which becomes 1 for the integration from 0 to $2\pi$.

Until the beginning of the 1970s, many spectral forms for the directional spectrum were presented: the Phillips’ equilibrium spectrum, the Pierson-Moskowitz spectrum, the JONSWAP spectrum and Toba’s spectrum. However, there were no reliable data for the angular distribution function. This is largely due to the difficulties in its measurement compared to the measurement of the frequency spectrum.

Wave observation project in the RIAM. In 1970 the ocean research group in the RIAM started a project to measure the directional spectrum of wind waves in open seas (Mitsuyasu et al., 1975). As a portable wave recorder to measure the directional
wave spectrum in the ocean, we selected and developed the cloverleaf buoy which was originally developed in the National Institute of Oceanography in the UK (Cartwright and Smith, 1964). The cloverleaf buoy has three floats arranged in a triangular form resembling a usual clover leaf and accurately follows to the motion of the wave surface (Fig. 5). By detecting and analyzing the motion of the buoy (heaving, pitching, rolling, etc.) by using the sensors installed in the buoy, we can determine the directional wave spectrum (Cartwright and Smith, 1964).

The reason for the selection of this buoy was its performance of high directional resolution of the directional wave spectrum. Although the technical level in electronics in Japan was not very high in 1970, fortunately the cloverleaf buoy worked more than ten years without troubles. We continued wave observation by using the buoy for about ten years in various locations including the North Pacific Ocean (Fig. 5) and the East China Sea.

A standard form of the angular distribution function. After great many trial and error we selected, as a general form for the angular distribution function, the following form proposed by Longuet-Higgins et al. (1963) and fitted it to the measured directional spectra,

\[
G(f, \theta) = G'(s)\left[\cos \theta/2\right]^{2s}.
\]

Here \(G'(s)\) is a normalizing function to make \(G(f, \theta)\) unity if integrated from 0 to \(2\pi\), \(\theta\) is the direction of the spectral component relative to the mean wave direction and \(s\) is a parameter which controls the angular spreading of the function. The form of the function \(G(f, \theta)\) can be seen from Fig. 6 for different values of \(s\) where the function \(h(\theta) = \pi G(f, \theta)\) is actually shown. With the increase of the parameter \(s\) the function becomes narrower and narrower. However, the problem is properties of the parameter \(s\).

In order to determine the properties of \(s\) and to obtain the standard form of the angular distribution function we selected, from great many wave data, the data obtained in simple conditions in which the wind continued to blow for a long time with constant speed and direction.

From the analysis of the selected data we finally obtained the following interesting properties of the parameter \(s\) (Mitsuyasu et al., 1975),

\[
s_p = \left(\frac{U_{10}}{C_p}\right)^{-2.5}.
\]

where \(s_p\) is the parameter at which \(G(f_{p}, \theta)\) is unity. The parameter \(s\) is given by

\[
s = s_p\left(\frac{f_p}{f}\right)^5 \quad \text{for} \quad f \leq f_p,
\]

\[
s = s_p\left(\frac{f}{f_p}\right)^{-2.5} \quad \text{for} \quad f_p \leq f,
\]

\[
s_p = 11.5\left(\frac{U_{10}}{C_p}\right)^{-2.5}.
\]
where $s_p$ and $C_p$ are the parameter $s$ and the phase velocity $C$ respectively of the spectral component at the spectral peak frequency $f_p$.

Properties of the angular distribution function. The form of the angular distribution function determined in the present study is given by the Eqs. [8]–[11], and it shows the following properties: the angular distribution is narrowest for the spectral component at the peak frequency $f_p$, the angular spreading becomes wider both for the low frequency side and for the high frequency side, and the angular spreading at the spectral peak frequency becomes narrower with the increase of the wave age $C_p/U_{10}$, i.e., with the development of the wind waves.

Five years later Hasselmann et al. (1980)\(^\text{57}\) presented another form of the angular distribution function which was determined from the wave data obtained by using a big wind-wave tank of his institute. Although the results on the growth of the wind wave spectrum were similar to ours (Mitsuyasu, 1967, 1968)\(^\text{35,36}\), the paper contained a very interesting result on the phase velocities of the spectral components of wind waves: the spectral components near 2 $f_p$ did not follow the linear dispersion relation.

This is a very interesting but serious problem for the spectral model of wind waves, because the linear model as shown graphically in Fig. 2 is based on the assumption that spectral components propagate with their own phase velocities depending on their frequencies. If such a curious phenomenon happens frequently applications of the linear spectral model will be limited.

The dispersion relation of random waves. In order to clarify the curious phenomenon discovered by Ramamonjiarisoa, our group started theoretical and experimental studies on this problem. Masuda et al. (1978)\(^\text{58}\) studied the nonlinear theory of two dimensional random waves and Mitsuyasu et al. (1978)\(^\text{59}\) made a laboratory experiment to clarify the phenomena.

In the experiment we measured the wind waves in a decay area where the wind was not blowing (Fig. 7). This was done to simplify the phenomenon by measuring the random waves without wind action. The phase velocities of the spectral components and the directional spectrum of the wind waves in the decay area were measured by using a linear array of wave staffs and the directional spectrum was determined by rotating the linear array.\(^\text{59}\)

The measured results were compared with the theoretical predictions of Masuda et al. (1978).\(^\text{58}\) A typical example of the result is shown in Fig. 8 where the measured phase velocity of the spectral component $C$ is compared with the theoretical computations of different approximations: [1] is the result of the one-dimensional linear theory, [2] is that of the second order approximation of the two-dimensional nonlinear theory, [3] is that of the third order approximation of the two-dimensional nonlinear theory.
From Fig. 8 we can see that our measured phase velocity $C$ has properties similar to those found by Ramamonjaireo: the phase velocities of the spectral components at around $2f_p$ ($\approx 4$ Hz) are nearly equal to those at the spectral peak frequency $f_p$ ($\approx 2$ Hz). Furthermore the curious phenomenon can be explained by the nonlinear theory of the two-dimensional random waves.

Our theory and experiment also clearly showed that the spectral components near $2f_p$ are not the free waves propagating with their own speed but mostly the nonlinear bounded waves propagating with the speed of the spectral components near the spectral peak frequency $f_p$. Even near the spectral peak frequency $f_p$ the measured phase velocity is different from the theoretical one given by the one-dimensional linear theory. This is due to the effect of the angular spreading and the phase velocity computed based on the theory of the two-dimensional random waves agrees with the measured one.

Later we measured the phase velocity of ocean waves at the oceanographic tower in Tuyazaki (Kuo et al., 1979). Although the number of the data were limited (wave steepness $H/L$: 0.02, 0.03), the measured phase velocity followed to the two-dimensional linear theory. This is due to fact that the steepness of the measured ocean waves was relatively small and the nonlinear effect for the phase velocity was negligible. Although the number of the data is limited, we are able to say that the linear dispersion relation can be used ordinarily for the ocean waves except for the special cases where very steep waves are generated by extremely strong wind.

### 7. Wind-induced growth of water wave

One of our previous studies, "Interactions between water waves and wind (1)" was originally designed to clarify the wind-induced growth of water waves. Although we found the very interesting phenomenon that the wind waves attenuate by the co-existing steep swell (Mitsuyasu, 1966), the original purpose was not attained due to the unsuitable performance of the facility. Later we built a wind-wave flume with high performance and planned again to study the same problem, the wind-induced growth of water waves, by using the new wind–wave flume.

In the experiment to clarify the fundamental properties of the wind-induced growth of water waves we planned to study the phenomena by using the following three different waves:
1) Mechanically-generated water waves co-existing with wind waves: usually the wind generates wind waves and they overlap on the mechanically-generated water waves

2) Mechanically-generated water waves with smooth surface by suppressing overlapping wind waves by using a surfactant (sodium lauryl sulfate NaC_{13}H_{25}SO_{4})

3) Mechanically-generated composite water waves with several different frequency components: simplified simulation of wind waves which have infinitely many frequency components

The third experiment was intended to clarify the following problem. In the present numerical wave model for the computation of the evolution of wind waves, we generally assume that each spectral component receives the wind energy independently without the effects of the other spectral components. That is, we assume the linear process in the energy transfer from the wind to wind waves, but this linear process is not yet proved. Regarding the third experiment, we made only a preliminary study and did not reach definite conclusions (Kusaba and Mitsuyasu, 1984). But for the first and second experiments we obtained many important results as described below.

Wind-induced growth of water waves co-existing with wind waves (1st experiment). The energy E of the mechanically-generated waves co-existing with wind waves was obtained from the wave records by using spectral filtering techniques. The energy E of the mechanically-generated wave in a wind area developed exponentially with the fetch X. The exponential growth rate \( \beta \) was determined after the correction of the viscous energy dissipation.

The exponential growth rate \( \beta \) shows a simple relation with the friction velocity of the wind \( U_* \). The relation in a dimensionless form is shown in Fig. 9 where the following best fit relation is also shown by a solid curve (Mitsuyasu and Honda, 1982);

\[
\beta/f = 0.34(U_*/C)^2, \quad 0.1 \leq U_*/C \leq 1.0, \quad [12]
\]

where \( f \) is the wave frequency and \( C \) is the phase velocity respectively of the mechanically-generated waves. In Fig. 9 a broken curve shows the data obtained by Snyder et al. (1981) for ocean waves. Although the range of \( U_*/C \) is slightly different each others, their data of \( \beta/f \) shows a slightly smaller value than ours estimated by the extension of the relation [12]. The difference will be discussed later.

Wind-induced growth of water waves with smooth surface (2nd experiment). The mechanically-generated waves with smooth surface even under the wind action were obtained by suppressing the generation of wind waves with a surfactant. Short discussions on the effect of the surfactant for the generation of wind waves will be given later in the section 9.

By the action of the wind the energy E of the mechanically-generated waves with smooth surface increased also exponentially with the fetch X, and the exponential growth rate \( \beta \) was determined after the correction of the energy dissipations due to the effects of the water viscosity and the surfactant.

The relation between the dimensionless growth rate \( \beta/f \) and the dimensionless friction velocity of the wind \( U_*/C \) for the waves with smooth surface was compared in Fig. 10 with that for the waves co-existing with wind waves. It is very interesting that the relation between \( \beta/f \) and \( U_*/C \) is almost the same for the both cases. This is due to the following reason. The measured growth rate for the waves with smooth surface was actuary smaller than that for the waves co-existing with wind waves, but the friction velocity of the wind was also smaller in this case than that for
the case of the waves co-existing with wind waves, and almost the same relation was satisfied.

From the result mentioned above we can say that the wind-induced growth of water waves is uniquely determined by the friction velocity of the wind. Here we call it as the $U^*$-similarity for the wind-induced growth of water waves. In this connection Kato et al. (2002) presented an interesting result that the $U^*$-similarity for the wind-induced growth of the water waves was satisfied even when the atmospheric stability changed. That is, the growth rate increases in such a way, $\left( \frac{\alpha}{\sigma} \right)_{\text{in stable stratification}} < \left( \frac{\alpha}{\sigma} \right)_{\text{in neutral stratification}} < \left( \frac{\alpha}{\sigma} \right)_{\text{in unstable stratification}}$, but the friction velocity $U^*$ also increases in a similar way, and the growth rate of wind waves by the wind is uniquely determined by the friction velocity.

The formulae of Plant (1982). When we submitted the paper on the wind-induced growth of the waves to Journal of Fluid Mechanics, Plant, who was working in the Naval Research Laboratory in the US, published a paper on similar topics (Plant, 1982) in Journal of Geophysical Research. He assembled the previous typical data on the growth rate of water waves by the wind, which included not only laboratory data but also oceanic data. By using the assembled data he derived the formula for the growth rate of water waves by the wind. His formula, with the same expression with ours, is given by

$$\beta/f = (0.25 \pm 0.13) (U^*/C)^2 \cos \theta,$$

where $\theta$ is the angle between the wind direction and the wave propagation direction. The formula [13] is quite similar to the formula [12] except that [13] includes $\cos \theta$, and the formula [13] gives a slightly smaller growth rate than that given by the formula [12].

Phillips’ comment. Phillips (1985) questioned the formula [12] for the growth rate which gives slightly larger values than Plant’s formula [13]. We consider that the difference in the two formulas [12] and [13] can be attributed to the difference in the range of $U^*/C$: Plant (1982) used the laboratory and the field data in the range, $0.05 \leq U^*/C \leq 3.0$, while Mitsuyasu and Honda (1982) used only their laboratory data in the range, $0.1 \leq U^*/C \leq 1.0$. When we look at the data used by Plant (1982) carefully we can see that there are some data in the range $U^*/C = 0.1$, which are much smaller than his regression line. Those data would affect the formula [13] and made the numerical coefficient in the formula smaller than that of the formula [12].

In fact the data themselves are not much different from those assembled by Plant (1982) in the same rage of $U^*/C$ (cf. Fig. 1 in Phillips, 1985). Furthermore, Kato et al. (2002) also derived a formula similar to [12] in their laboratory study.

Therefore, we can say that the formula derived from the laboratory data gives a little larger growth rate than the formula derived from the data including both laboratory and field data, and the difference can be attributed to the difference in the range of $U^*/C$: in the range, $U^*/C \leq 0.1$, the relation between the dimensionless growth rate $\beta/f$ and $(U^*/C)^2$ is not linear but curves to the lower side (to smaller $\beta/f$). Miles’ revised theory gives a curve which fits very well to the data assembled by Plant (1982).

Laboratory study by Peirson and Garcia. Peirson and Garcia (2008) made a laboratory experiment on the wind-induced growth of water waves by using a quite similar technique to that of Mitsuyasu and Honda (1982). One of the most interesting results of their study was that they found a dependence of the growth rate on the wave steepness $H/L$: with the decrease of the wave steepness $H/L$ the growth rate increases rapidly. In our study we tried to find the effect of the wave steepness on the growth rate of water waves, but we
couldn’t find any significant effect as shown in Fig. 9 (Mitsuyasu and Honda, 1982). The reason may be that according to their study the effect of the wave steepness on the growth rate is very small for the waves with relatively large steepness, and we used the waves with relatively large steepness (0.02 ≤ H/L, 0.063 ≤ ak), where a is the wave amplitude and k is the wave number defined as 2π/L.

**Some problem on the growth rate of water waves.** The growth rate of water wave by the wind is determined with various techniques. In the laboratory study the growth rate is usually determined by directly measuring the wind-induced growth of water waves along the fetch and correcting the viscous energy dissipation. In the ocean the same technique is practically impossible and we determine the momentum loss from the winds to water waves by measuring pressure fluctuation P(t) above the wave surface with a wave-following sensor simultaneously with the measurement of the water surface elevation η(t).

Both techniques are usually thought to give the same value but, as far as I know, there have been no studies that have confirmed this idea. In laboratory studies, since we can apply both techniques simultaneously for the measurement of the growth rate, we can establish whether the results agree with each other or not. Furthermore, the accurate comparison may give deeper understanding of the phenomenon of the interaction between wind and water waves.

Another problem is whether or not we can apply the growth rate given by the empirical formula to each spectral component of wind waves independently. As far as I know, there are no studies which determine the effects of interferences that the other spectral component have on the growth rate of a particular spectral components. One of the purposes of our preliminary study was to clarify this problem, but the study was terminated without reaching a definite conclusion (Kusaba and Mitsuyasu, 1984). 63)

**8. The momentum transfer from winds to waves**

In April 1983 a symposium honoring Professor Robert O. Reid of Texas A&M University was held, and his former students and colleagues attended the symposium. The author spent one year, from 1963 to 1964, in his laboratory and joined his research project on the study of air-sea interactions.

Although I could not attend the symposium, I had an opportunity to submit a paper to the Journal of Geophysical Research (JGR), where it was planned to publish the symposium papers. Mitsuyasu (1985) 69) is the paper published in that occasion.

The momentum transfer from winds to waves. Mitsuyasu (1985) 69) studied the momentum balance in the water waves under the steady wind action where the waves are locally stationary in time (cf. Fig. 11). In such a condition the momentum balance of the water waves can be shown as

\[
\frac{\Delta S_{11}}{\Delta x} = \frac{C_y}{C} \frac{\Delta E}{\Delta x} = \tau_w + \tau',
\]

where \( S_{11} = C_y E/C \) is the downwind flux of the wave momentum, \( C_y \) is the group velocity of the water waves, \( \tau_w \) is the momentum flux entering into the water waves from the wind, and \( \tau' \) is the momentum loss from the water waves due to viscous dissipation and wave breaking.

In a previous study Mitsuyasu and Honda (1982) 62) determined \( \tau_w \) by measuring directly the left-hand side in Eq. [14] and \( \tau' \) due to viscous dissipation; stable waves were used in the experiment and there was no dissipation due to wave breaking. Although the result was expressed in the form for the exponential growth rate \( \beta \) as shown in Eq. [12], by using the relation \( \tau_w = \beta E/C \), we could obtain the momentum flux \( \tau_w \) entering into the water waves from the wind as

\[
\tau_w = \left[ 2.2 \times 10^2 \left( \frac{H}{\lambda} \right)^2 \right] \tau_s,
\]

for deep water waves (Mitsuyasu, 1985). 69) In Eq. [15] \( \tau_s \) is the total downward flux of the wind
momentum given by $\rho_a U_s^2$ where $\rho_a$ is the density of the air and $U_s$ is the friction velocity of the wind.

The Eq. [15] is the relation between the total downward flux of the wind momentum $\tau_w (= \rho_a U_s^2)$ and the momentum flux entering into the water waves $\tau_w$, and the Eq. [15] shows that the momentum flux entering into the water waves $\tau_w$ increases with the increase of the wave steepness $H/L$. If we assume the wave steepness say $H/L = 0.05$ (the large side but reasonable value), it becomes

$$\tau_w = 0.55\tau_s,$$  \hspace{1cm} [16]

and more than half of the total downward flux of the wind momentum enters into the water waves. If we use Plant’s (1982)\textsuperscript{(66)} formula [13] which includes the data of ocean waves, the coefficient 0.55 in Eq. [16] changes to 0.40, which is a little smaller but still considerable percentage.

**The horizontal momentum transported by wind waves.** Mitsuyasu (1985)\textsuperscript{(69)} also computed the left-hand side of Eq. [14], the divergence of the horizontal momentum flux, for the fetch-limited wind waves, by assuming the $\cos^2\theta$ type directional wave spectrum and using the fetch relation [1]. The result was given by

$$\frac{\Delta S_{11}}{\Delta x} = 0.054\tau_s.$$  \hspace{1cm} [17]

If we use the other type directional wave spectrum the result is not much different from Eq. [17]. The Eq. [17] means that only about 5 percent of the total momentum transferred from the wind to the sea surface is advected away by the wind waves in the ocean. According to Toba (1978)\textsuperscript{(70)} $\tau_w/\tau_s$ ($G$ in his notation) depends on $T^* (= gT/U_s)$, but its upper limit was 0.062 and still very small.

From the large difference between the absorbed momentum given by Eq. [16] and the advected momentum given by Eq. [17] in the wind waves, we can get the following image on the growth of the wind waves by the wind: the large part of the momentum transferred from wind to the sea surface are absorbed by wind waves but they lose most of it through wave breaking and only a few percent of the absorbed momentum is advected away by the wind waves.

The image discussed above is shown schematically in Fig. 11. This surprising result is supported indirectly by the study of Kusaba and Mitsuyasu (1986),\textsuperscript{(71)} where the nonlinear instability and the evolution of steep water waves under wind action were studied. Their study showed that steep water waves in some transition stage did not develop even under the wind action: they kept nearly constant values of their energies or decreased their energies slowly due probably to the wave breaking (Figs. 9b and 9c in Kusaba and Mitsuyasu, 1986).\textsuperscript{(71)} Furthermore, beyond the curious phenomenon observed by Kusaba and Mitsuyasu (1986),\textsuperscript{(71)} yet more complicated processes such as studied by Tulin and Waseda (1999),\textsuperscript{(72)} and Waseda and Tulin (1999)\textsuperscript{(73)} may exist, but their detailed discussions will be left for future study.

**A study of Melville and Rapp (1985).** Immediately after the publication of our paper Mitsuyasu (1985),\textsuperscript{(69)} Melville and Rapp (1985)\textsuperscript{(74)} published a very interesting paper which support, to a certain extent, the above image on the momentum balance in the wind waves. Through an ingenious laboratory experiment they showed that nearly 30 percent of a wave momentum flux could be lost in a single large-scale wave breaking event.

**9. The effects of surfactant on certain air-sea interaction phenomena**\textsuperscript{(75)}

The motivation of this study was to clarify the role of the wind waves in the air-sea boundary processes. We used a technique to suppress the generation of wind waves by using a surfactant. Then we studied the phenomena at the air-sea boundary by using two different waters: usual tap water and the water containing a surfactant (sodium lauryl sulfate NaC\textsubscript{15}H\textsubscript{25}SO\textsubscript{4}). In the former water wind waves were generated as usual by the wind but in the latter water wind waves were suppressed by increasing the concentration of the surfactant, and we could study various phenomena at the air-sea boundary, such as the wind shear stress, water surface roughness and the wind-induced growth of mechanically-generated water waves, under the presence or the absence of the wind waves.

The experiment was done in the same wind-wave flume used in the study of the dispersion relation of random water waves (Fig. 7), though in this study the air flow was not allowed to exit the middle part of the flume. Before the studies of the phenomena mentioned above, we studied in a preliminary experiment, the effects of the concentration of the surfactant on the generation of wind waves.

The results of the study were presented in the conference *Wave Dynamics and Radio Probing of the Ocean Surface* held in Miami in 1981. However, the publication of the proceedings of the conference was much delayed until 1986 (Mitsuyasu and Honda, 1986).\textsuperscript{(75)}
Attenuation of wind waves by the surfactant. In a preliminary study we tested the effects of the surfactant on the generation of wind waves. The wind waves in the tank were gradually attenuated by increasing the concentration of the surfactant in the water as shown in Fig. 12, which is the result obtained at the fetch $X = 6$ m and the reference wind speed $U = 7.5$ m/s. Here the reference wind speed is the wind speed at the inlet of the wind-wave flume and nearly equal to the cross-sectional mean wind speed. From Fig. 12 we can see that the wind waves were almost completely suppressed at the concentration of $2.6 \times 10^{-2}\%$. Therefore we can measure various phenomena at the air-sea boundary under the condition of the smooth water surface.

It is interesting in Fig. 12 that in their attenuation stage, the spectra retain a similar form. This is contrary to our expectation that the high frequency components attenuate more strongly than the low frequency components and the spectra should therefore not keep a similar form. If we recall the $U_*$-similarity in the growth of water waves by the wind, the phenomenon seems to be due to a gradual decrease of the friction velocity of the wind. Unfortunately however, the measurement of the friction velocity of the wind in each stage was not done, and detailed analysis of the phenomenon will be left for the future study.

Wind shear stress. The wind profiles over the water surface were measured both for the smooth water surface and for the water surface covered with wind waves. By applying logarithmic profiles to the measured winds, the friction velocity of the wind $U_*$ and the 10 m height wind speed $U_{10}$ were determined for the both water surfaces: the smooth water surface and the water surface covered with wind waves, where the 10 m height wind speed $U_{10}$ was obtained by extrapolating the logarithmic wind profile.

The relations between the friction velocity of the wind $U_*$ and the 10 m height wind speed $U_{10}$ for the both water surfaces are shown in Fig. 13. The friction velocity for the water surface covered with wind waves is larger than that for the smooth water surface in a region of the relatively high speed wind, $8 \text{ m/s} \leq U_{10}$, although it is interesting that the friction velocities of the wind for the both water surfaces show similar values in a region of the low speed wind, $U_{10} \leq 8 \text{ m/s}$.

The result means that the water surface shows properties of a hydrodynamically smooth surface for the low speed wind, $U_{10} \leq 8 \text{ m/s}$, even when the small wind waves are generated on the water surface. Such a result supports the very old but interesting idea presented by Munk (1947): the water surface is
hydrodynamically smooth below the critical wind speed of about $U_{10} = 7$ m/s, but it becomes rough above the critical wind speed.

The best fit curves for the relations between the friction velocity of the wind $U_*$ and the $10$ m height wind speed $U_{10}$ were given respectively by the following equations:

for the smooth water surface

$$U_* = 4.20 \times 10^{-2} U_{10}^{0.878}, \quad U_{10} \leq 20 \text{ m/s}, \quad [18]$$

and for the water surface covered with wind waves

$$U_* = 1.61 \times 10^{-2} U_{10}^{1.327}, \quad 8 \text{ m/s} \leq U_{10} \leq 35 \text{ m/s}. \quad [19]$$

In a region, $U_{10} \leq 8$ m/s, the relation for the water surface covered with wind waves is nearly equal to [18].

Drag coefficient. A neutral drag coefficient (referred 10 m) is defined as $C_D = (U_*/U_{10})^2$. Therefore, the relations between $C_D$, and $U_{10}$ for both water surfaces can be obtained directly from the Eq. [18] and Eq. [19]:

for the smooth water surface

$$C_D = 1.77 \times 10^{-3} U_{10}^{-0.244}, \quad U_{10} \leq 20 \text{ m/s}, \quad [20]$$

and for the water surface covered with the wind waves

$$C_D = 2.60 \times 10^{-4} U_{10}^{0.654}, \quad 8 \text{ m/s} \leq U_{10} \leq 35 \text{ m/s}. \quad [21]$$

These relations are shown, with the broken curves, in Fig. 14, where the individual data of $C_D$ are also shown as a function of $U_{10}$. The straight curves in Fig. 14 are the best fit relations between $C_D$ and $U_{10}$ obtained directly from the data assuming respectively linear relation.

The relation between $C_D$ and $U_{10}$ for the usual water surface covered with wind waves is not much different from many typical previous relations shown in Mitsuyasu and Kusaba (1984), which contains concentrated discussions on the drag coefficient over water surface. Within a range of our measured wind speed, $U_{10} \leq 35$ m/s, the saturation level for the drag coefficient reported by Donelan et al. (2004) is not clear.

However, the smooth water surface, where the wind waves were suppressed almost completely by using the surfactant, clearly shows a property of hydrodynamically smooth surface, and the drag coefficient $C_D$ decreases with the increase of the wind speed.

The $C_D$ at the low speed wind and the study of Yelland and Taylor (1996). As can be seen from Fig. 13 and Fig. 14, in a region of the low speed wind, $U_{10} \leq 8$ m/s, the water surface has the drag on the wind as a smooth surface even when the wind waves are generated, and the drag coefficient in this region increases rapidly with the decrease of the wind speed as shown in Fig. 14. A similar result on the drag coefficient over the ocean was reported by Yelland and Taylor (1996) based on their observations of the wind stress in the open seas. Through the careful measurements and analysis of the sea surface wind they derived a formula for the drag coefficient over the sea surface.

Their formula for the drag coefficient shows that there is a critical wind speed at $U_{10} = 6$ m/s. In the region $6$ m/s $\leq U_{10}$, the drag coefficient increases with the increase of the wind speed as usual. However, in a region, $U_{10} \leq 6$ m/s, the drag coefficient increases rapidly with the decrease of the wind speed. In Fig. 14 their formula is shown with a short dashed curve. Their formula agrees very well with our observations particularly in a region of the low wind speed, even though their formula was obtained by using the field data and our data were obtained in the laboratory. Recent laboratory data of the drag coefficient obtained by Donelan et al. (2004) shows the property qualitatively similar to those of Yelland and Taylor (1996) and Mitsuyasu and Honda (1986).75)

10. Concluding remarks

In this review eight topics were selected from our studies which were done mostly at the RIAM, Kyushu University in the period 1965 to 1992. In
each stage of the study the selection of the topic was done depending on my interest and it was not necessarily systematic. Concluding the discussions I would like to talk about the significance or perspective of the selected topics in the study of wind waves.

The evolution of the wind waves in space and time is governed by the energy balance equation,

$$\frac{\partial F}{\partial t} + C_g \cdot \nabla F = S = S_{in} + S_{nl} + S_{ds}, \tag{22}$$

where $F(f, \theta; x, t)$ is the two dimensional spectrum of wind waves, $C_g(f, \theta)$ is the group velocity of the spectral components, and $S$ is the energy source function usually represented as the sum of the input $S_{in}$ by the wind, the nonlinear energy transfer $S_{nl}$ by resonant wave-wave interactions and the energy dissipation $S_{ds}$ mainly due to wave breaking.

Our studies on the wind waves were designed to identify and quantify the source functions represented in Eq. [22] by $S$. Since the source functions are based respectively on the complicated dynamical processes we need to clarify each elementary process and express it in a computable form. Many studies on wind waves completed or still continuing follow this approach.

Taking this viewpoint, we conclude our studies discussed in this review as follows:

1) The study in the section 2, the interactions among wind, wind waves and mechanically-generated regular wave (swell) is of a very complicated phenomenon which includes all the processes relating to $S_{in}$, $S_{nl}$, and $S_{ds}$. We clarified an important property of the phenomenon but the mechanism controlling the phenomenon is not clarified yet.

2) The study in the section 3 is an experimental study to confirm the effects of the nonlinear energy transfer $S_{nl}$ in the evolution of the wave spectrum. We could clarify experimentally an important role of $S_{nl}$ in the evolution of the wave spectrum, but quantitatively there still remains a problem in the applicability of the theory to the actual phenomena. It will be related to the assumed idealized conditions. Further experimental and theoretical studies are needed. In particular, we need an extremely accurate experiment to confirm the theory without the effects of other phenomena. On a theoretical side, we need to clarify the effect of the wind actions including that of the wind-induced drift current on the nonlinear energy transfer in random waves.

3) In the studies of sections 4 and 5 we clarified the structure of the directional wave spectrum (frequency spectrum and angular distribution function) in the generation area of wind waves. The observed spectra showed the important properties of the wind waves in the laboratory and in the ocean. They can be used not only for the engineering applications but for the test of the performance of a numerical wave model: particularly the accuracies of the source functions, because the observed wind wave spectra are nothing but the results given by the energy balance equation.

4) The study in the section 6, the nonlinear effect in the dispersion relation for random water waves, is a fundamental problem concerning the spectral model of wind waves. Important properties of the nonlinear effect were clarified and we now have a clear understanding of the nonlinear effects in the dispersion relation of wind waves. In ocean waves, however, this problem will not be very serious, because the nonlinearity of ocean waves is relatively weak except for the extreme waves such as the waves in a strong storm area.

5) The study in the section 7, the wind-induced growth of the water waves exactly corresponds to the study of the source function $S_{in}$ in the energy balance equation. The most interesting result of the study is the finding of the $U^*$-similarity in the wind-induced growth of water waves. That is, the growth of the water waves by the wind is essentially controlled by the friction velocity of the wind even when the water surface roughness and the stratification in the air-sea boundary change.

6) The study in the section 8, the momentum transfer from wind to waves, is a rough sketch of the momentum balance at the air-sea boundary. In order to confirm the sketch we need to clarify the various complicated processes, among others the energy dissipation due to wave breaking and the effect of the current system in the water which is generated by the wind and wind waves.

7) The study in the section 9, the effects of surfactant on air-sea interaction, is not directly concerned with the wind waves. However, the results of the study cast a light on the effects of wind waves in the air-sea boundary process. Re-evaluation of the critical wind speed by using the accurately measured data is required.
In recent years many important new advances in the study of wind waves have been made. The current numerical wave models, supported by many fundamental studies, enable us to compute ocean surface waves on a global scale with sufficient accuracy for practical purposes. We can obtain wind and wave data in wide areas of the ocean by using a technique of satellite remote sensing. This situation gives an impression that there are few important problems in the study on wind waves. However, the physical process controlling the energy balance of wind waves is still not completely understood and we still depend on empirical knowledge in practical problems such as the numerical wave model. Many of the studies discussed in the present review are, as it were, classic studies but I have tried to show and to draw attention to the unsolved problems relating to the phenomena discussed in each study.

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Profile

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