La mer 54 : 43-53, 2016
Société franco-japonaise d'océanographie, Tokyo

Field measurements of drag force on *Sargassum horneri* (Turner) C. Agardh towed by a boat and estimation of drag coefficient

Min XU[1), 2)] and Teruhisa KOMATSU[1)]

Abstract: *Sargassum horneri* is one of the most important *Sargassum* species forming floating seaweed rafts. Drag force is the most important factor involved in detaching seaweeds from substrates. We conducted field experiments on drag force on *S. horneri* thalli > 40 cm by towing them with a boat at steady speeds of 0.5-4.0 m s^{-1} in Nabeta Cove, Japan, from in April 2014 and February 2015. The holdfast of thallus was attached to the end of a non-stretching fishing line; the other end was attached to a spring scale running through a steel pipe attached to the side of the boat and on low-friction pulleys fixed at both ends of the pipe. The lower end of the pipe was projected into the sea at a depth of approximately 1 m to keep the thallus submerged. The thallus was towed while force was measured on the spring scale. The relative speed of the boat towing the thallus versus seawater was continuously recorded by a flow meter attached to the end of the steel pipe. The results showed that drag force on the thallus was increased with thallus length and current speed; the drag force was roughly proportional to flow $speed^{3/2}$; the drag coefficient, *Cd*, of *S. horneri* was expressed with the following equation: $Cd = 18.295Re^{-0.571}$ in a range of Reynolds number (*Re*) between 10^4 and 10^6.

Keywords: *Sargassum horneri*, drag force, drag coefficient, towing experiment

1. Introduction

Brown algae such as *Sargassum* species form submerged forests in shallow rocky coastal areas of tropical, boreal and temperate regions. *Sargassum* species grow luxuriantly in spring but scantly in summer in Japan (KOMATSU *et al.*, 1982). Their thalli attain heights in the order of several meters due to the buoyancy provided by their many gas-filled vesicles. Thus, *Sargassum* forests have a strong influence on marine environmental conditions, such as water temperature (KOMATSU *et al.*, 1982, 1990, 1994; KOMATSU, 1985), downward illumination (KOMATSU *et al.*, 1990), and water flow (KOMATSU and MURAKAMI, 1994), due to their

1) Atmosphere and Ocean Research Institute, the University of Tokyo
Address: 5-1-5, Kashiwanoha, Kashiwa, Chiba 277-8564, Japan
Tel: 04-7136-6222
2) present: Key Laboratory of Marine Ecology & Environmental Sciences
Institute of Oceanology, Chinese Academy of Sciences
Address: Qingdao 266071, P. R. China, Postal code: 266071
Tel/Fax: + 86-532-8289-8645
＊Corresponding author: Min XU
E-mail: xuminwzy@aliyun.com

physical structure, pH (KOMATSU and KAWAI, 1986), and dissolved oxygen concentrations (KOMATSU, 1989), which are a product of photosynthesis and respiration. Commercially important fish, such as flying fish (e.g., *Hirundichthys oxycephalus*), and Japanese halfbeak (*Hyporhamphus sajori*) (IKEHARA and SANO, 1986), spawn in *Sargassum* forests in spring, whereas abalone and turban shells use forest habitats as feeding and reproductive grounds. Larvae and juveniles, such as *Sebastes inermis*, use *Sargassum* forests as nursery grounds (FUSE, 1962). Therefore, *Sargassum* forests play very important ecological roles in nearshore coastal waters.

Some *Sargassum* species are detached from substrates by strong waves when they become large in spring (YOSHIDA, 1963). *Sargassum* species, which are detached from the substrate and float due to the buoyancy effect produced by their vesicles, are called *Nagare-mo* in Japanese which means drifting (*Nagare*) seaweed (*mo*) (YOSHIDA, 1963). Although some become stranded on the beach, others are transported offshore by surface currents. Floating seaweeds are hosts for flora and fauna (CHO *et al*., 2001; THIEL and GUTOW, 2005; ABé *et al*., 2012) and serve as spawning and nursery grounds for many marine fish (SENTA, 1986; THIEL and GUTOW, 2005), including flying fish and Pacific saury (*Cololabis saira*). Japanese halfbeak spawn eggs with filaments in floating seaweed (KOMATSU *et al*., 2009), and yellowtail (*Seriola quinqueradiata*) and Japanese horse mackerel (*Trachurus japonicus*) juveniles accompany floating seaweed rafts (SENTA, 1986).

Sargassum horneri (Turner) C. Agardh is a very important contributor to floating seaweed rafts in waters off the coast of northeastern Asia, in particular the East China Sea, where the rafts consist only of *S. horneri* thalli (KOMATSU *et al*., 2007; KOMATSU *et al*., 2008, 2014b; Mizuno *et al*., 2014). This species is widely distributed from Hokkaido Island in the boreal zone, to the northern part of Kyushu Island facing the East China Sea, and the center of Honshu Island facing the Pacific Ocean, and along Chinese continental coast facing the East China Sea in the temperate zone (UMEZAKI, 1987; KOMATSU *et al*., 2014a). These plants grow several meters long, have high biomass and play important ecological roles in coastal waters as mentioned above. Moreover, *S. horneri* is one of the most important edible seaweeds in Japan (IKEHARA, 1987) and Korea (AJISAKA, personal communication).

In this study, we focused on *S. horneri*, which is a very important species in seaweed beds and floating seaweed rafts, from a fisheries and biodiversity perspective. Dislodgment of *S. horneri* is key to understanding the generation of floating *S. horneri*. SUGAWARA *et al*. (1998) revealed that, on kelp, the drag force is much more important than the added mass force in a recirculating tank system that generated an oscillating current flow under long wave conditions, similar to the swell produced by a typhoon. As the latter force is negligible, only the former force dislodges kelp under long wave conditions. The drag force, *Fd*, exerted on an organism by water flow under long wave conditions can be expressed by the following equation (*e.g.,* KOEHL, 1977):

$$Fd = 1/2\ \rho\ A\ Cd\ U^2, \qquad (1)$$

where ρ, A, Cd and U are the mass density of the fluid, area of an organism vertically projected to flow direction, drag coefficient (depending on the shape of the organism), and fluid speed relative to the speed of organism, respectively. Drag force is proportional to fluid speed squared. Cd can be estimated from A, U and Fd. Fd can be estimated at different flow speeds under long wave

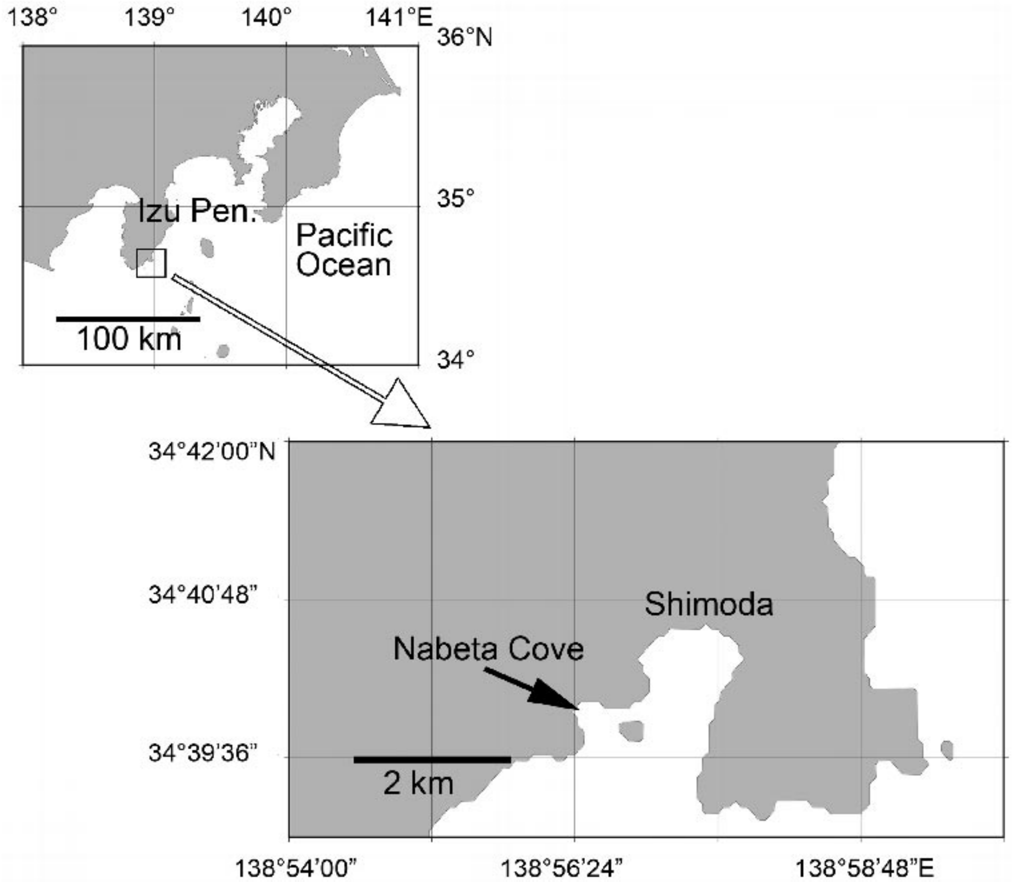

Fig. 1. Map showing Izu Peninsula (a) and the field experiment site in Nabeta Cove near Shimoda (b).

conditions if *Cd* is given.

Hydrodynamic force is important during the life history of an annual species, such as *S. horneri*, particularly for large-sized individuals (because of the large value of *A*). It is difficult to measure drag force on a large *S. horneri* thallus in an experimental tank. Thus, the present study measured drag force on *S. horneri* thalli > 40 cm to obtain their drag coefficients by field experiments.

2. Materials and Methods

(1) Study site and field experiment

The study site was located in Nabeta Cove near Shimoda in the southernmost part of Izu Peninsula, Japan (Fig. 1). Nabeta Cove is located near the Shimoda Marine Research Center of Tsukuba University, and consists of rocky beds sheltered from waves.

Scuba divers randomly collected 13 *S. horneri* individuals with thalli > 100 cm long on 16 April 2014, and 32 individuals with 40–200 cm long thalli on 24 February 2015 (Table 1). After collecting the samples, these thalli were maintained in an outdoor tank with running filtered seawater and covered with sheets of black cloth for about 24 h. Field experiments to measure the drag force on 25 samples in total under steady flow conditions were conducted near Nabeta Cove on 17 April 2014 and 25–26 February 2015. The method used

Table. 1. Number of samples belonging to thallus length groups of 40–50, 50–100, 100–150, 150–200 and > 200 cm collected on 16 April 2014 and 24 February 2015.

Thallus length group (cm)	16 Aprl 2014	25 February 2015
40–50	0	2
50–100	1	19
100–150	4	5
150–200	2	6
> 200	6	0
Total	13	32

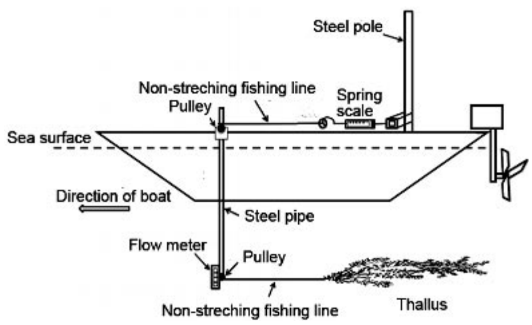

Fig. 2. Schematic diagram showing the system used to measure drag force on a *Sargassum horneri* thallus towed at a constant speed by a boat.

to measure drag force on seaweeds was based on UTTER and DENNY (1996), who measured drag force on *Macrocystis pyrifera* (Linnaeus) C. Agardh. A thallus was attached to the end of a non-stretching fishing line; the other end was attached to a spring scale running on low-friction pulleys through a vertical steel pipe attached to the side of the boat (Fig. 2). A steel pipe was projected into the sea at a depth of approximately 1 m to keep the sample thallus submerged at a position out of the wake of the boat. The thallus was towed behind the boat at a constant speed, and the drag force was read from the spring scale and recorded in a notebook. Drag force of only the line without thallus was also measured at each speed as offset force, which was subtracted from drag force with a thallus. The relative speed of the boat towing the thallus versus seawater was recorded by a flow meter (PD3GT; Little Leonard) attached to the end of the steel pipe. The spring scale used for the *in situ* experiments was calibrated with known weights before each experiment. Each thallus was towed at three or four constant speeds, and four spring scale readings were taken at each speed.

The slowest thallus towing speed was 0.5 m s^{-1}, because the thallus was parallel to the displacement direction of the boat. HASEGAWA (1999) also reported that the surface area of *Sargassum* species vertically projected to flow direction tends to constant at a speed > 0.5 m s^{-1}. BETTIGNIES *et al.* (2013) reported that seaweeds experienced water flow of 2–4 m s^{-1} during a storm in Marmion Lagoon, 20 km north of Perth, Western Australia. Therefore, we set 4.0 m s^{-1} as the maximum speed. Each thallus was towed at three or four constant speeds, including the minimum and maximum speeds.

After the field experiment, all samples were immediately transported to the laboratory, where they were frozen until the morphological measurements were taken. After thawing, thallus length was defined as the distance from the bottom of the holdfast to the top of the longest lateral branch (±1 cm) using a 30-cm ruler. The wet weight of the thallus was measured with a balance (±2 g) (CR-5000WP; Custom) after removing seawater with a paper towel. The one-sided surface area of thallus was measured in units of 0.01 cm^2 using ImageJ software (ver. 6.4; National Institutes of Health, Bethesda, MD, USA) that can calculate area from a digital image. We estimated the one-sided surface area of each thallus used in the experiments by applying the

ImageJ software to a digital image of a thallus taken with a digital camera (DMC TX-1; Panasonic, Tokyo, Japan) set above the thallus. An area of each image was scaled with an edge of 5 cm of square paper pictured with the sample. The area of a given thallus was based on the mean data of five images of that thallus.

Thallus length may be related to one-sided surface area and/or wet weight. Thus, the relationship between thallus length and one-sided surface area, and between thallus length and wet weight, were examined. The *S. horneri* samples were divided into length groups at 50-cm intervals from 50 to 200 cm. Samples with thallus lengths of 40-50 cm and > 200 cm were classified into two different groups, respectively.

Drag force was given by equation (1). As the salinity in Nabeta Cove was about 30, the mass density of seawater, ρ, at 20℃ on 17 April 2014, and at 15℃ on 25-26 February 2015, was 1.021 and 1.022 g cm^{-3}, respectively. The one-sided surface area of each thallus was used as A in equation (1).

The Reynolds number, Re, is defined as follows:

$$Re=\frac{UL}{\upsilon}, \qquad (2)$$

where L and ν are the characteristic length of a thallus and kinematic viscosity of a fluid, respectively. We used the square root of one-sided surface area of each thallus as the characteristic length for each thallus to calculate its Re at different U. Seawater temperatures on 17 April 2014 and 26 February 2015 were 20 and 15℃, respectively, and the kinematic viscosities of the seawater at 20 and 15℃ were 0.01054 and 0.01188 cm^2 s^{-1}, respectively (International Towing Tank Conference, 2011).

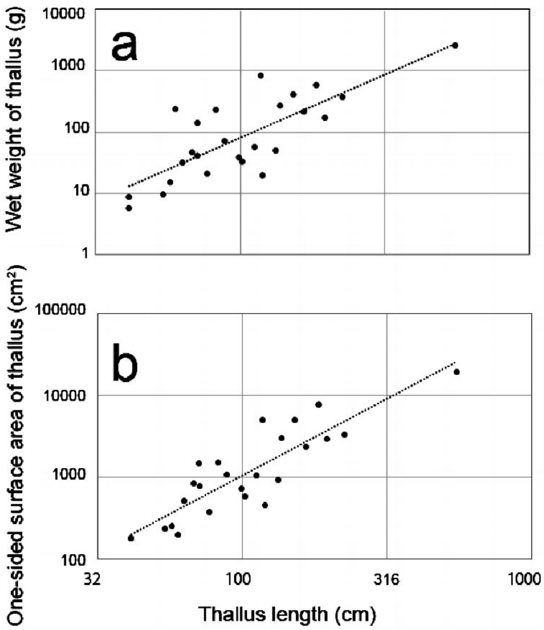

Fig. 3. Wet weight (W) (a) and one-sided surface area (A) (b) according to a thallus length (L) > 40 cm of *Sargassum horneri* on logarithmic axes. Dotted lines are regression lines: $W = 0.00206L^{2.27}$ for (a) and $A = 0.196L^{1.87}$ for (b).

3. Results

(1) One-sided surface area of the thallus and weight by thallus length

The one-sided surface areas and wet weights of *S. horneri* used in the field experiments were compared according to thallus length. Log plots of thallus length versus one-sided surface area and wet weight showed that the log transformed one-sided surface area and wet weight of the thallus were exponentially proportional to the log-transformed thallus length (Fig. 3), as expressed by the following equations:

$$A = 0.196L^{1.87}\ ; \qquad (3)$$

$$W = 0.00206L^{2.27}. \qquad (4)$$

The R^2 values of equations (3) and (4) were 0.765 and 0.698, respectively. These equations

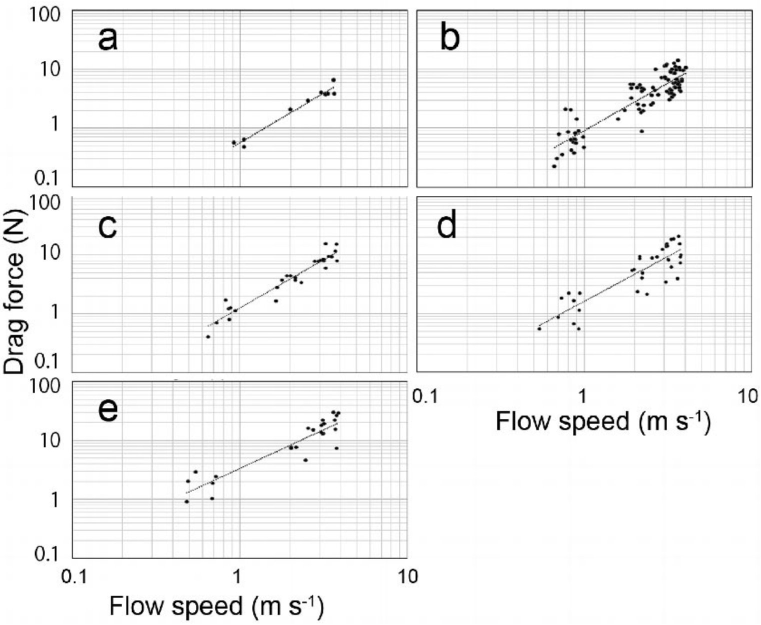

Fig. 4. Drag force (Fd) versus unidirectional flow speed for thallus lengths of *Sargassum horneri* of 40–50 cm (a), 50–100 cm (b), 100–150 cm (c), 150–200 cm (d), and 200 and 550 cm (e) on logarithmic axes. Dotted lines are regression lines: $Fd = 0.567U^{1.69}$ for (a), $Fd = 0.917U^{1.62}$ for (b), $Fd = 1.252U^{1.64}$ for (c), $Fd = 1.623U^{1.54}$ for (d), and $Fd = 3.352U^{1.31}$ for (e).

indicate that the one-sided surface area and wet weight of the thallus were roughly proportional to the square of thallus length suggesting *S. horneri* is relatively flat rather than cubic.

(2) Drag force exerted on *S. horneri* classified by thallus length group

Drag force increased with thallus length (Fig. 4), particularly at the higher speed of 3–4 m s^{-1}. The drag forces on samples were in the range of 0.2 and 15 N at flow speeds of 0.5–3 m s^{-1}. The drag force of samples with 40–50 cm long thalli were usually < 5 N, except for a few samples at flow speeds > 3 m s^{-1}. The drag forces on samples with 50–100 cm long thalli were < 15 N, whereas most in the long thallus group > 100 cm were < 20 N at maximum flow speeds. The drag forces on all samples were < 5 N at low flow speeds, and those during intermediate flow speeds were < 15 N. The drag forces on a few samples were > 30 N during the maximum flow speed (Fig. 4). Log plots of U and Fd produced exponential approximations depending on thallus length, as follows:

$$Fd = 0.567U^{1.69}, \quad (5)$$

for thalli with lengths of 40–50 cm (n = 10; R^2 = 0.966);

$$Fd = 0.917U^{1.62}, \quad (6)$$

for thalli with lengths of 50–100 cm (n = 85; R^2 = 0.783);

$$Fd = 1.252U^{1.64}, \quad (7)$$

for thalli with lengths of 100–150 cm (n = 31; R^2 = 0.924);

$$Fd = 1.623U^{1.54}, \quad (8)$$

for thalli with lengths of 150–200 cm (n = 36; R^2 = 0.752);

$$Fd = 3.352U^{1.31}, \quad (9)$$

for thalli with lengths > 200 cm (n = 24; R^2 = 0.846). Equations (5–9) show that drag force was roughly proportional to the flow speed$^{3/2}$.

(3) Drag coefficient by Reynolds number

The drag coefficient decreased from 0.1 at a Reynolds number of 10^4 to 0.01 at a Reynolds number of 10^6 (Fig. 5). The drag coefficient of thalli > 40 cm under Reynolds numbers of 10^4–10^6

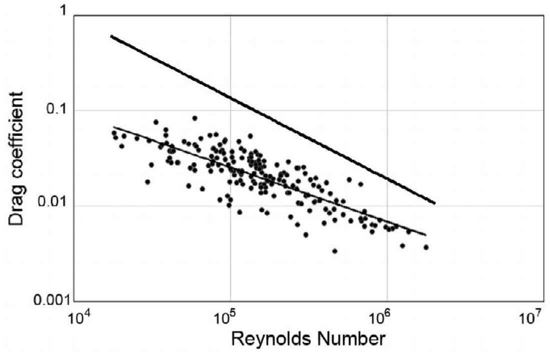

Fig. 5. Drag coefficient (*Cd*) versus Reynolds number for all *Sargassum horneri* thalli used in the experiments. Thin and thick lines are the regression lines determined in this study, expressed as $Cd = 18.295\ Re^{-0.571}$ and those of Sugawara *et al.* (2003), who studied the relationship between *Cd* and the Reynolds number of the brown seaweeds *Ecklonia cava* Kjellman in Kjellman et Petersen and *Eisenia bicyclis* (Kjellman) Setchell, expressed as $Cd = 2358\ Re^{-0.85}$.

was expressed as follows:

$$Cd = 18.295\ Re^{-0.571}. \tag{10}$$

Equation (10) ($R^2 = 0.651$; n = 186) indicates that *Cd* is roughly proportional to $Re^{-1/2}$.

4. Discussion

The drag force exerted on a fixed organism under steady flow conditions consists of skin friction drag between the fluid and surface of the organism, and pressure drag, which is generated by the difference in pressure on the upstream versus downstream side of the organism (KOEHL, 1977). CHARTERS *et al.* (1969) calculated the relative effects of skin friction and pressure drag on brown seaweed, *Eisenia arborea* Areschoug, and reported that the overwhelming proportion of drag on the seaweed was due to pressure drag. Pressure drag force is a bulk force that dislodges the thallus from the substrate under a high Reynolds number (e.g. CARRINGTON, 1990; DUDGEON and JOHNSON, 1992). Thus, the drag force on *S. horneri* with a thallus > 40 cm under a steady flow speed of 0.5–4 m s^{-1} is mainly pressure drag force.

High flexibility is typical of seaweeds several meters in length, which protects them in strong wave environments (GAYLORD and DENNY, 1997). If the seaweed is sufficiently long and flexible, it can move with the flow as the wave passes. As *S. horneri* is long and flexible, it employs this strategy for protection against strong, high speed waves that exert a high drag force. The drag coefficient, *Cd*, is also decreased as flow speeds increase, for the same reason (BOLLER and CARRINGTON, 2007; MARTONE *et al.*, 2012). This indicates that *Cd* is decreased as the Reynolds number increases due to water flow.

The drag coefficients of marine organisms are decreased gradually when the Reynolds number increases in the range 10^4–10^6 during steady flow (VOGEL, 1981). The present study also showed that the *Cd* of *S. horneri* was decreased with as the Reynolds number increased within this range. Previous studies reported that the drag coefficients of several small kelps, at a Reynolds number of 10^6 and under high flow speed conditions, were 0.01–0.05, such as a *Cd* of 0.02 for *Egregia menziesii* (Turner) Areschoug (FRIEDLAND and DENNY, 1995), 0.02 and 0.04 for *E. isenia arborea* and *Pterogophora californica* Ruprecht (CARRINGTON, 1990), and 0.05 and 0.04 for *Pelvetia fastigiata* (J. Agardh) De Toni. On the other hand, the *Cd* of *M. pyrifera*, which has long stipes, was 0.001 (GAYLORD and DENNY, 1997). SUGAWARA *et al.* (1998) measured the *Cd* of *Ecklonia cava* Kjellman in Kjellman et Petersen and *Eisenia bicyclis* (Kjellman) Setchell, and determined the relationship between *Cd* and Reynolds number (Fig. 5). These seaweeds have solid stipes and hard fronds. Thus, the *Cd* of *Ec. cava* is greater than that of *S. horneri*. Therefore, it is reasonable that the *Cd* of *S. horneri* was decreased to 0.002 at a higher Reynolds number of 10^6. Regressing the *Cd* with Reynolds number was expressed with equation (10), where the *Cd* is roughly proportional to $Re^{-1/2}$.

Thallus length is important to determine the drag force on a seaweed, because the length of seaweeds is related to surface area (e.g. BETTIGNIES *et al.*, 2013; DEMES *et al.*, 2013). As the thallus length of seaweeds increases, so does their surface area, which eventually influences the drag force (DEMES *et al.*, 2013). Therefore, *S. horneri* thalli length is an important drag force parameter because the surface areas of *S. horneri* thalli are proportional to the thallus length squared.

NEUSHUL *et al.* (1967) measured the pull exerted by currents on *Macrocystis* plants, after severing the plants from the bottom, by attaching one end of a spring scale to the basal dichotomy of the plant and the other end to the bottom. When one individual of *M. pyrifera* with 38 stipes moved by the wave surges, the spring scale showed a tension force of ~90 N at a water flow speed of ~0.1 m s^{-1} under conditions of moderate wave surge. On the other hand, *S. horneri* with a thallus > 2 m pulled with around 30 N by a high water flow speed of 4 m s^{-1}. *S. horneri* have flexible laterals, so they can change the shape and angle between the thallus and the water flow direction under high flow speed conditions to avoid breakage of a stipe or lateral, and dislodgement of the holdfast.

Drag force was roughly proportional to flow speed$^{3/2}$, although equation (1) shows that drag force is proportional to flow speed^2. This is explained by the dependence of *Cd* on flow speed. *Cd* was roughly proportional to the flow speed$^{-1/2}$ as indicated in equation (10).

$$Cd \propto Re^{-1/2}. \qquad (11)$$

Substituting *U* for *Re* based on equation (2), equation (11) is transformed as follows:

$$Cd \propto U^{-1/2}. \qquad (12)$$

When equation (12) is substituted for *Cd*, equation (1) is transformed as follows:

$$Fd \propto u^{3/2}. \qquad (13)$$

Equation (13) roughly corresponds to equations (5–9). It demonstrates the validity of Morison's equation in this experiment.

The *Cd* of *S. horneri* obtained in the present study can be used to estimate drag force in a storm. If the maximum water flow speed due to a storm wave is known, the drag force on *S. horneri* can be estimated using water flow speed. If the attachment strength of the *S. horneri* holdfast is known, the estimated forces can be compared according to attachment strength to verify whether the holdfast is detached by the drag force.

Acknowledgements

The authors thank to Mr. Yasutaka TSUCHIYA, Hideo SHINAGAWA and Toshihiko SATO of Shimoda Marine Research Center of Tsukuba University for their helps to field experiments. The first author thanks to Ministry of Education, Culture, Science and Sports of Japan (MEXT) for giving him Japanese Government (Monbukagakusho) Scholarship. This study was supported by Grant-in-Aid for Scientific Research (A), No. 22255010 from Japan Society for the Promotion of Science and Japanese Association of Marine Biology (JAMBIO) of Shimoda Marine Research Center, Tsukuba University. The authors appreciate two anonymous reviewers' constructive comments to ameliorate this article. Finally, the authors thank to Drs. Shuji SASA, Masayasu HAMANA, Shuhei SAWAYAMA and Takayoshi OHTAKI, and Mr. Hideki MURATA of Laboratory of Behavior, Ecology and Observation Systems, Atmosphere and Ocean Research Institute, The University of Tokyo, who helped the field experiments and encouraged the authors throughout the study.

References

ABé, H., T. KOMATSU, Y. KOKUBU, N. MOHAMMAD, E. A. ROTHäUSLER, H. SHISHIDO, S. YOSHIZAWA and T. AJISAKA (2013): Invertebrate fauna associated with floating *Sargassum horneri* (Fucales: Sargassaceae) in the East China Sea. *Species Diversity, 18,* 75–85.

BETTIGNIES, T. and T. WERNBERG (2013): Size, not morphology, determines hydrodynamic performance of a kelp during peak flow. Marine Biology, **160**, 843–851.

BOLLER, M. L. and E. CARRINGTON (2007): Interspecific comparison of hydrodynamic performance and structural properties among intertidal macroalgae. Journal of Experimental Biology., **210**, 1874–1884.

CARRINGTON, E. (1990): Drag and dislodgment of an intertidal macroalga: consequences of morphological variation in *Mastocarpus papillatus* Kutzing. Journal of Experimental Marine Biology and Ecology, **139**, 185–200.

CHARTERS, A. C., M. NEUSHUL and C. Barilotti (1969): The functional morphology of *Eisenia arborea.* Proceedings of the International Seaweed Symposium, **6**, 89–105.

CHO, S. H., J. G. MYOUNG, J. M. KIM and J. H. LEE (2001): Fish fauna associated with drifting seaweed in the coastal area of Tongyeong. Korea. Transactions of the American Fisheries Society, **130**, 1190–1202.

DEMES, K. W., C. D. G. HARLEY, L. M. ANDERSON and E. CARRINGTON (2013): Shifts in morphological and mechanical traits compensate for performance costs of reproduction in a wave-swept seaweed. Journal of Ecology., **101**, 963–970.

DUDGEON, S. R. and S. A. JOHNSON (1992): Thick vs thin: thallus morphology and tissue mechanics influence differential drag and dislodgement of two co-dominant seaweeds. Journal of Experimental Biology, **165**, 23–43.

FRIEDLAND, M. T. and M. W. DENNY (1995): Surviving hydrodynamic forces in a wave-swept environment: consequences of morphology in the feather boa kelp, *Egregia menziesii* (Turner). Journal of Experimental Marine Biology and Ecology, **190**, 109–133.

FUSE, S. (1962): The animal community in the *Sargassum* belt. Physiology and Ecology, **11**, 23–45. (in Japanese with English abstract).

GAYLORD, B. and M. W. DENNY (1997): Flow and flexibility - I. Effects of size, shape and stiffness in determining wave forces on the stipitate kelps *Eisenia arborea* and *Pterygophora californica.* Journal of Experimental Biology, **200**, 3141–3164.

HASEGAWA, H. (1999): Wave force through seaweeds on cover layer materials of artificial seaweed bed. Doboku Gakkai Ronbunshu, **1999** (621), 153–165. (in Japanese)

IKEHARA, K. (1987): *Sargassum* (*Sargassum fulvellum* and *S. horneri*) as a food in the coast of Japan Sea. Japanese Journal of Phycology, **35**, 233–234.

IKEHARA, K. and O. SANO (1986): Distribution and species composition of floating seaweeds collected in the Sado Straights of the Japan Sea. Bulletin of Japan Sea Regional Fisheries Research Laboratory, **36**, 59–75. (in Japanese with English abstract).

INTERNATIONAL TOWING TANK CONFERENCE (2011): Recommended procedures: fresh water and seawater properties. Laboratório de Tecnologia Oceânica, Rio de Janeiro, 45pp. http://www.laboceano.coppe.ufrj.br/ ittc2011/ documents/ 2011/pdf%20Procedures%202011/7.5-02-01-03.pdf

KOEHL, M. A. R. (1977): Effects of sea anemones on the flow gorces they encounter. Journal of Experimental Biology, **69**, 87–105.

KOMATSU T. (1985): Temporal fluctuations of water temperature in a *Sargassum* forest. Journal of Oceanographical Scoiety of Japan, **41**, 235–243.

KOMATSU T. (1989): Day-night reversion in the horizontal distributions of dissolved oxygen content and pH in a *Sargassum* forest. Journal of Oceanographical Society of Japan, **45**, 106–115

Komatsu, T. and H. Kawai (1986): Diurnal changes of pH distributions and the cascading of shore water in a *Sargassum* forest. Journal of Oceanographical Society of Japan, **42**, 447–458.

Komatsu, T. and S. Murakami (1994): Influence of a *Sargassum* forest on the spatial distribution of water flow. Fisheries Oceanography, **3**, 256–266.

Komatsu T., H. Ariyama, H. Nakahara and W. Sakamoto (1982): Spatial and temporal distributions of water temperature in a *Sargassum* forest. Journal of the Oceanographical Society of Japan, **38**, 63–72.

Komatsu, T., M. Fukuda, A. Mikami, S. Mizuno, A. Kantachumpoo, H. Tanoue and M. Kawamiya (2014a): Possible change in distribution of seaweed, *Sargassum horneri*, in northeast Asia under A2 scenario of global warming and consequent effect on some fish. Marine Pollution Bulletin, **85**, 317–324.

Komatsu, T., H. Kawai and W. Sakamoto (1990): Influences of *Sargassum* forests on marine environments. Bulletin on Coastal Oceanography, **27**, 115–126. (in Japanese with English abstract)

Komatsu, T., A. Mikami, T. Ajisaka, S. Uwai, M. Aoki, K. Tanaka, M. Fukuda, Y. Kokubu, K. Tanaka, Y. Michida and T. Sugimoto (2009): Ecological characteristics of drifting seaweed rafts composed of *Sargassum* Species. Bulletin on Coastal Oceanography, **46**, 127–136. (in Japanese with English abstract)

Komatsu, T., S. Mizuno, N. Alabsi, A. Kantachumpoo, K. Tanaka, A. Morimoto, S-T. Hsiao, E. A. Rothäusler, H. Shishidou, M. Aoki and T. Ajisaka (2014b): Unusual distribution of floating seaweeds in the East China Sea in the early spring of 2012. Journal of Applied Phycology, **26** (2), 1169–1179.

Komatsu, T., S. Murakami and H. Kawai (1994): Some features of jump of water temperature in a *Sargassum* forest. Journal of Oceanography, **52**, 109–124.

Komatsu, T., K. Tatsukawa, J. B. Filippi., T. Sagawa, D. Matsunaga, A. Mikami, K. Ishida, T. Ajisaka, K. Tanaka, M. Aoki, W. D. Wang, F. I. , Liu, S. Y. Zhang, M. D. Zhou and T. Sugimoto (2007): Distribution of drifting seaweeds in eastern East China Sea. Journal of Marine Systems, **67** (3–4), 245–252.

Martone, P. T., L. Kost and M. Boller (2012): Drag reduction in wave-swept macroalgae: alternative strategies and new predictions. American Journal of Botany, **99**, 806–815.

Mizuno, S., T. Ajisaka, S. Lahbib, Y. Kokubu, M. N. Alabsi and T. Komatsu (2014): Spatial distributions of floating seaweeds in the East China Sea from late winter to early spring. Journal of Applied Phycology, **26**, 1159–1167.

Neushul, M., W. D. Clarke and D. W. Brown (1967): Subtidal plant and animal communities of the southern California islands. *In* Proceedings of the Symposium on the Biology of California Islands. R. N. Philbrick (ed.), Santa Barbara Botanic Garden, Santa Barbara, California. p. 37–55.

Senta T. (1986): Mechanism that juvenile fishes accompany drifting seaweeds. Kaiyo Monthly, **18**, 712–718. (in Japanese)

Sugawara, A., M. Seto and T. Komatsu (1998): Study on the Zonation of Macro Algae: vertical distribution and current environments in *Eisenia bicyclis* Setchell and *Ecklonia cava* Kjellman. Proceedings of Civil Engineering in the Ocean. **14**, 29–34. (in Japanese with English abstract)

Thiel, M. and Gutow L. (2005): The ecology of rafting in the marine environment - I - The floating substrata. Oceanography and Marine Biolology: Annual Review, **42**, 181–263.

Utter, B. and M. denny (1996): Wave-induced forces on the giant kelp *Macrocystis pyrifera* (Agardh): field test of a computational model. Journal of Experimental Biology, **199**, 2645–2654.

Umezaki, I. (1984): Distributions of genus *Sargassum* (subgenus *Bactrophycus*) along the coasts of Japan, Otsuchi Marine Research Center, Ocean Research Institute, The University of Tokyo, **10**, 70–76. (in Japanese)

Vogel, S. (1981): Life in moving fluids: the physical biology of flow. Princeton University Press,

Princeton, 467pp.
YOSHIDA T. (1963): Studies on the distribution and drift of the floating seaweed. Bulletin of Tohoku Regional Fisheries Research Laboratory, **23**, 141–186. (in Japanese with English abstract).

Received: December 18, 2015
Accepted: January 25, 2016