Spectral downshift of Three-wave system and Bichromatic waves under “sea ice”

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In the Arctic region, where ice cover is decreasing, there are growing expectations for the Arctic Shipping Route as an alternative to the route through the Suez Canal. For safe navigation in the Arctic Sea, accurate prediction of waves becomes important, as the waves intensify due to the loss of sea ice. It is necessary to clarify the dynamic processes of wave propagation under sea ice, such as in the marginal ice zone (MIZ) of the Arctic Sea.

The MIZ is the boundary between the ice-covered sea and the open water. Compared to the ice-covered sea where waves are completely attenuated by thick and dense ice, the dynamic interaction between waves and sea ice, i.e., the wave-ice interaction, is active in the MIZ. There are two main aspects of the wave-ice interaction: the process that waves create and destroy the sea ice, and the process that the sea ice modulates the physical properties of propagating waves. Although both processes are important, this study focuses on the latter, the dynamic process of wave transmission in the presence of sea ice.

The important feature of the wind wave spectrum is the presence of a high-frequency tail and a low-frequency peak. Wind waves grow under the action of the wind and at the same time the wavelength increases due to the energy evolution of the low-frequency peak. The continuous reduction of the spectral peak frequency of the growing windsea is called the “Spectral downshift”. It is also known that wind waves propagating into the ice-covered sea undergo spectral downshift. Recent experimental work showed that this spectral downshift under the ice can be attributed to an increased attenuation rate of wave energy at high frequencies (Passerotti et al., 2020); the attenuation coefficient α ($a/a_0 = \exp(-\alpha x)$) increases with frequency (e.g. $\alpha \propto f^{3.5}$, Weber (1987)). However, observation by Waseda et al. (2022) in the Okhotsk Sea cannot be explained by attenuation alone because low-frequency wave energy grew at the expense of high-frequency components. We present here an experimental case that shows a possible dissipation-driven nonlinear spectral downshift.

It is known that a monochromatic wave at frequency f with sufficiently large wave steepness is unstable to sideband waves with slightly different frequencies $f \pm \Delta f$ (Benjamin & Feir, 1967), a.k.a. “modulational instability”. To investigate wave-ice interactions under ice, we produced “sea ice” in a fresh-water ice-wave tank and generated two types of wave trains. First, a modulated wave train, which is a system of three waves, a carrier wave, and two sidebands. Second, a bichromatic wave train, which is a system of two waves of different frequencies but with the same energy. In the bichromatic case, the energy of two waves is not small compared to a 3-wave system, so we expect more intense nonlinear energy transfer compared to a 3-wave system. We confirmed spectral downshift in both cases, but their rates are much faster than the evolution of the same unstable wave train without ice. We found that the $f - 2\Delta f$ component grew, which is not generated by the wave maker. The results indicate that the nonlinear energy transfer is enhanced due to a strong energy attenuation by the “sea ice”.

Table 1. The condition of frequency and amplitude of 3-wave system and Bichromatic waves

	Frequency			Amplitude		
	carrier	lower sideband	upper sideband	carrier	lower sideband	upper sideband
3-wave system	1.15	1.03	1.27	0.74	0.26	0.2
Bichromatic	1.15	1.03		1.22	(a) 1.38	

$$2k_c = k_+ + k_- + \Delta k,\ \ 2\omega_c = \omega_+ + \omega_-,\ \ \omega_\pm = \omega_c \pm \delta\omega,\ \ a_0^2 = a_c^2 + a_-^2 + a_+^2$$
$$(a_0\text{: } amplitude\ of\ monochro\ wave\ which\ ak\ is\ 0.15,$$
$$c, +, -\ denotes\ carrier, lower, upper\ respectively.)$$

In this symposium, we will focus on the ice we have created in the tank for the experiments. In the marginal ice zone, there are several types of ice, such as "pancake ice", "ice sheet", "frazil ice", etc. In this experiment, we are studying the wave-ice interaction between ice particles and nonlinear waves, so we had to create ice in our wave tank. The tank we used is 8m long, 1.5m wide, and is in a freezing room where the room temperature can be lowered to a minimum of -20°C. One of the most significant differences between our tank and the real sea is the salinity. In the ocean, while the sea ice forms, the salt is released into the surrounding water. Ionic crystalline solutes such as salt or antifreeze such as polypropylene glycol can be added to reproduce brine rejection, but for experimental simplicity we used previous method by Fujiwara et al. (2021) to reproduce “sea ice” in fresh water. We generate waves as we lower the temperature of the water. We call this process "model-ice generation by waves". We generated waves with $ak = 0.08, f = 0.9[Hz]$, and initial temperature of air and water is around $2°C$, and set the room temperature as -10$°C$ for 24 hours. The air temperature dropped to -10$°C$ in 1 hour and the water temperature dropped to -0.1$°C$ in 8 hours. We could create ice particles as shown in Fig.1. The size of the "sea ice" we created is $O(1)[cm]$ and the shape is flat and close to a rectangle. The surface of the tank is completely covered with a layer of a mixture of water and these particles, and the amount of ice (mass per $1m^2$) in a layer of $O(10)[cm]$ thickness.

We have done analysis on the attenuation of propagating wave energy by sea ice for the waves we created in the experiment, as shown in Fig.3. This figure represents the experiments which we created 3-wave system with $ak = 0.15, f_c = 1.15[Hz]$ (f_c represents the carrier wave frequency) for two minutes, repeated ten times and take average of these. After each experiment, the drifted sea ice is artificially returned to the beach side and the experiment is repeated. One of the most important and difficult problems in our experiment is the drifting of the ice in the tank. We are dealing with nonlinear waves, so the wave steepness is inevitably quite high. Therefore, the Stokes Drift of the waves and the radiation stress on the ice is very strong, so that the distribution of ice through the tank is not equivalent, because ice accumulates on the beach side (the beach is on the wall opposite the wavemaker to absorb wave energy and suppress wave reflections). Wave height gauges were placed at distances ranging from 2[m] to 5[m] from the plunger at 1[m] intervals. Previous research indicates the exponential decay of amplitude of propagating waves, but from Fig.3 the damping of waves in this experiment is rapidly changing between the wave height gauge at 2[m] and the one at 3[m]. Increasing amount of ice on the beach side explains why the rate of wave attenuation is not linear with distance travelled. Also, the scale of waves and ice in this tank and the scale of the real ocean are different. Hence, conducting experiments that directly downscale the real ocean phenomena to tank experiments is difficult.

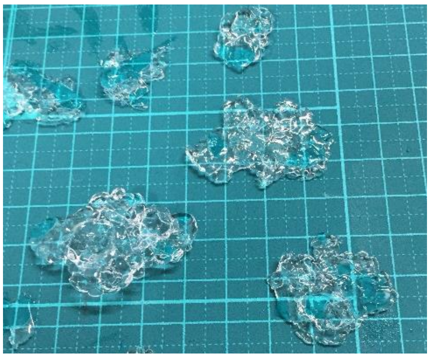

Fig.1 Ice particles we created in the tank.

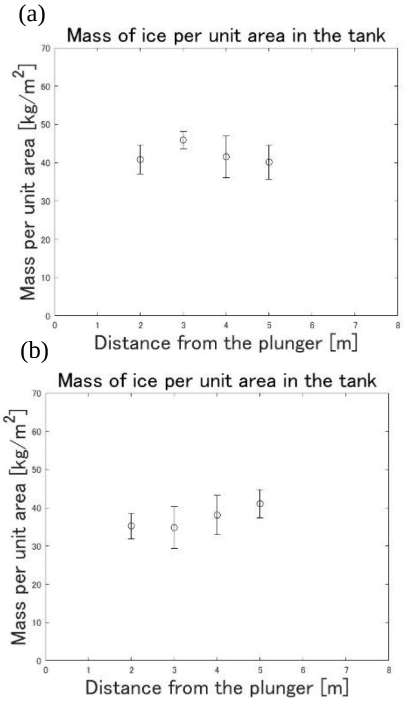

Fig.2 Mass of ice per unit area (a) in 3-wave and (b) in bichromatic case with standard deviations in four measurement points

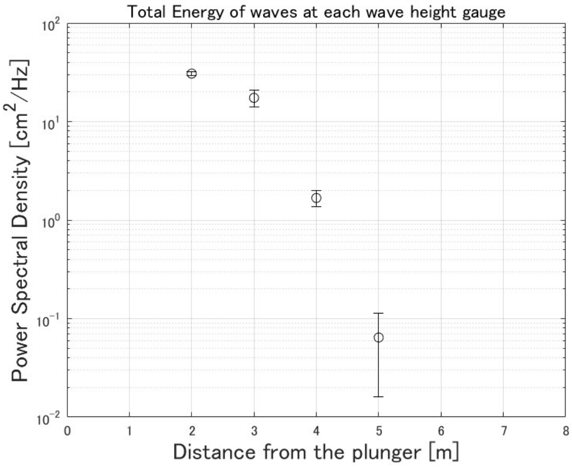

Fig.3 Change of total energy of propagating waves at each wave height gauges, which is located 2,3,4,5m from the plunger with standard deviations.

Acknowledgements

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