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EVOLUTION OF SHORT WIND WAVES OVER UNIFORM SURFACE CURRENTS

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Abstract. Experiments were conducted in the large IMST Facility to better specify the effect of uniform surface current on the evolution of the short wind waves, mostly involved in microwave backscattering. An adverse current induces a decrease of the dominant wave frequency, a large increase of the significant wave height, a broadening of wave angular dispersion, a lengthening of the dominant wavelength, and an increase of the effective fetch length. A following current has the opposite effects. Moreover, an adverse current acts as a low-pass frequency filter inducing a blockage of the short wind waves and generating explosive sub-harmonic instabilities. Finally, scatterometer radar returns are found to be affected by the currents, more particularly at low wind speed.

1 Introduction

How surface waves interact with water currents is of great interest for many applications. But in spite of extensive research, the interactions between wind waves and surface currents are still not well understood. As far as short waves and surface current are considered, wind-wave tanks may be used to simulate the interactions. In the past, Francis and Dudgeon (1967), Plate and Trawle (1970) and Kato and Tsuruya (1978) have shown experimentally that uniform currents have a strong influence on short wind-wave development. To extend their investigations, we conducted experiments in the large IMST wind wave facility, looking more particularly at the modification of the temporal and spatial characteristics of the wind waves by the current. Moreover, changes in the scatterometer radar return due to wave-current interaction were investigated. The experimental arrangement and data processing are described in section 2. Results and conclusions are addressed in section 3 and section 4.

2 Experimental arrangement

The IMST facility was recently equipped with a new water circulating device capable of producing uniform current either in or against the wind direction. To obtain sufficient current velocity, a smaller tank was installed in the facility as shown in Figure 1. Over the test area, the current was quasi-uniform with very thin boundary layers at the bottom and side walls. The measurements corresponded to a fetch value of approximately 7 m.

We measured the current velocity, the wind speed and the water elevation using respectively a micro-currentmeter, a Pitot tube and a capacitance probe. The along-wind component of the wave-slope was inferred from an optical device with a video recording and image processing system. This technique, based on light refraction by the surface slope, is similar to the method described by Jähne and Riemer (1990). The actual size of the digitized images was $32 \times 23 \text{ cm}^2$

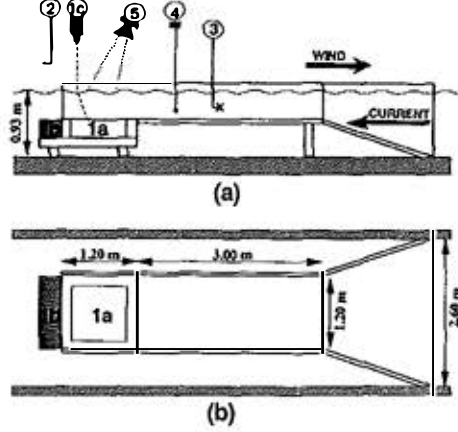


Fig. 1. Schematic side (a) and top (b) views of the experimental arrangement for adverse current. (1) the ensemble of the wave slope measuring devices : (1a) aqueous suspension box, (1b) lighting device, (1c) video camera. (2) Pitot tube. (3) current meter. (4) capacitance wave gauge. (5) radar device.

with a resolution of 256×128 pixels. If I_0 and I are the recorded images of, respectively, the calm surface and the wavy surface, then the along-wind component of the wave slope is determined by : $H_x = \alpha S$, where S is the relative slope defined by: $S = (I - I_0)/I_0$, and α is a constant depending on the experimental arrangement.

Finally we operated a Ku-band (2.2 cm wavelength) scatterometer, vertically polarized, looking up-wind with a 30° incidence angle. This radar system was similar to the system described by Bliven *et al.* (1993).

Temporal characteristics of the wave field were estimated with an FFT applied to the water elevation time series with a frequency resolution of 0.06 Hz. Spatial characteristics of the wave field were inferred from a two-dimensional FFT applied to the numerical images of the along-wind component of the wave slope. The wavenumber resolution was respectively 20 rad/m and 27 rad/m in the along-wind and cross-wind directions.

3 Results

Although large series of experiments were performed with following as well as adverse current, this short paper will be limited to the second situation which led to striking modification of the wind-wave fields.

Current effects on the wave field are illustrated by the time series and frequency spectra displayed in Figure 2. The following four points are most noticeable : i) the wave field dominant frequency decreases rapidly when the (adverse) current velocity increases; ii) the significant wave height increases hugely when the current velocity increases; iii) at a given current velocity, the dominant frequency is not influenced by the wind speed; iv) the high frequency range exhibits a quasi-saturation state affected only slightly by the current and/or the wind

U (m/s)	6.0			6.9			7.8			8.7		
U_c (cm/s)	0	-11	-26	0	-11	-26	0	-11	-26	0	-11	-26
SWH (cm)	0.1	0.7	2.2	0.2	0.8	2.5	0.3	0.9	2.6	0.5	1.1	3.1
n (Hz)	8.3	3.9	1.5	8.1	3.3	1.5	7.3	3.6	1.5	6.6	3.7	1.5
L (cm)	4.0	9.6	n.m.	4.0	10.4	n.m.	5.6	11.2	n.m.	6.3	11.2	n.m.

TABLE I

Measured significant wave height, apparent frequency and wavelength of the dominant waves as functions of wind velocity U and surface current velocity U_c ; n.m. : not measured.

speed.

Points i) and ii) are quantified in Table I : for example, at a wind speed of $U = 6$ m/s, an adverse current of velocity $U_c = -26$ cm/s induces a 2200 % increase of the significant wave height and a 550 % decrease of the dominant frequency.

Point iii) is probably due to a frequency blockage induced by the combined current and wind actions. Basovich and Talanov (1977) have shown analytically than an adverse current acts as a low-pass frequency filter, all the waves with a frequency higher than the critical value $n_{cr} = g/(-8\pi U_c)$ being either blocked or reflected by the current. At $U_c = -11$ cm/s, n_{cr} is 3.5 Hz, and at $U_c = -26$ cm/s, n_{cr} is 1.5 Hz. The measured frequencies, shown in Table 1, fit almost exactly these theoretical values, thus leading us to conclude that the large frequency downshifting observed on Figure 2 results from a wave-blocking effect by the current. Because of the continuous input of energy by the wind and possibly nonlinearity in the wave field, blocked waves acquire more and more energy, so they become higher and longer, with a lower frequency and a higher intrinsic celerity. This transformation stops when the group velocity is large enough to pass over the current, i.e. when the frequency is low enough (lower than n_{cr}) in order not to be filtered by the current.

These results are in good agreement with the decrease of the dominant wavenumber (increase of the wavelength) shown in Figure 3. At $U = 8.7$ m/s, the dominant wavelength increased from 4 cm with zero current to more than 32 cm with a current of -26 cm/s (the spectra cannot be fully resolved because the dominant waves were longer than the window size). It should be pointed out that this is opposite to what it is commonly observed when long wave or paddle generated waves interact with an adverse current (Jonsson (1990)). Figure 3 illustrates also the increase of the angular distribution by the adverse current.

The similarity of the spectrum evolution as a function of the current velocity (Figures 2a and 3) with the commonly observed evolution as a function of fetch is remarkable. A simple Doppler effect is not sufficient to explain these explosive subharmonic instabilities. As a matter of fact, an increase of the current velocity seems to be roughly equivalent to an increase of the apparent fetch. At short fetch, the theoretical exponential growth in time of the wave height (Miles 1957) can be expressed in terms of a growth in fetch (Gaster, 1962):

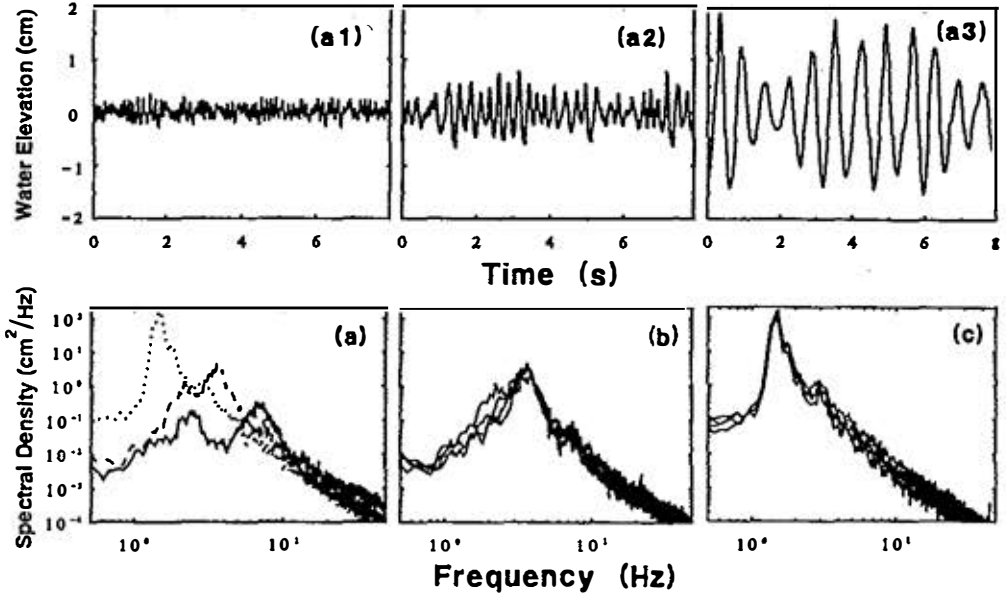


Fig. 2. Water surface deflection level. (a1), (a2), (a3) : Time series for wind velocity $U = 8.7$ m/s and current velocity respectively $U_c = 0$ cm/s, -11 cm/s and -26 cm/s. (a): Spectra for $U = 8.7$ m/s and $U_c = 0$ cm/s (—), -11 cm/s (---), -26 cm/s (.....), (b), (c): Spectra at $U_c = -11$ cm/s and -26 cm/s respectively, U ranging from 6.0 to 8.7 m/s.

$$H \approx a \exp(\beta t) \approx a \exp((\beta/C_g)X) \quad (1)$$

where C_g is the group velocity. With a surface current of velocity U_c , formula (1) becomes:

$$H \approx a \exp((\beta/(U_c + C_g))X) \quad (2)$$

which can be written in a form similar to formula (1):

$$H \approx a \exp((\beta/C_g)\chi) \quad \text{with} \quad \chi = X/(1 + (U_c/C_g)) \quad (3)$$

χ is the *effective fetch length*.

This suggests that the higher the adverse current and/or the lower the group velocity (i.e. lower wind speed) the higher the effective fetch length. This is in accordance with our observations: wave field modification by the surface current is more significant at high current velocity and low wind speed.

Figure 4 displays dispersion relations of short waves in the presence of a following current, an adverse current, and without any current, in a reference system moving with the celerity U_c . All the data lie just above the theoretical dispersion relation from linear theory. The positive offset in frequency is probably mainly due to the wind drift that acts as a supplementary positive surface current.

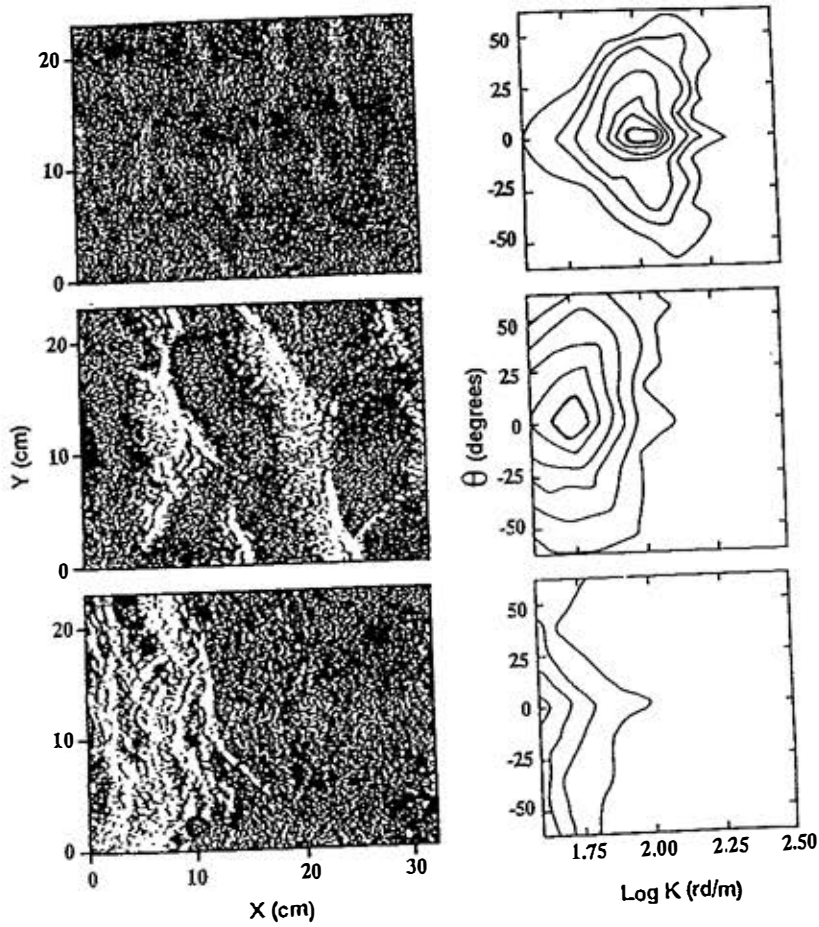


Fig. 3. Images (left) and wavenumber spectra (right) of the along wind short waves slope at wind velocity $U = 8.7$ m/s and current velocity $U_c = 0$ cm/s (top), -11 cm/s (middle) and -26 cm/s (bottom). Contours correspond to arbitrary relative slope values.

A direct consequence of these interactions, is the modification of the scatterometer returns by the current: Ku-band radar backscattering at medium incidence angle is highly correlated with the energy of small wind-waves. Because the group velocity of such waves is small, these waves are highly affected by surface current. So radar returns are expected to change with the current velocity, more particularly at low sea state. Figure 5 displays the measured radar cross section as a function of wind speed, with and without an adverse current. At low wind speed, the radar backscatter significantly increased, thus leading to an over-estimation of the wind speed by the usual scatterometer algorithms. At higher wind speed, differences are less noticeable, probably because the relaxation time of small waves is very short in time when the wind is high.

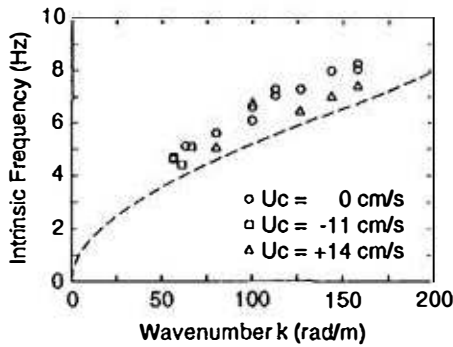


Fig. 4. Dispersion relation of the short wind waves in a reference system moving with the current at various wind speeds (U ranging from 4.3 to 8.7 m/s); experiments with adverse, following and zero current velocity; - - - Theoretical linear relation.

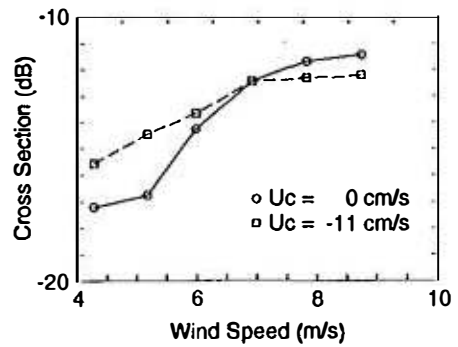


Fig. 5. Scatterometer cross section as a function of wind speed with and without adverse current.

4 Conclusions

Uniform currents have a very strong influence on the development of short wind waves. Adverse surface currents induce remarkable transformations of the wave field with wave blockage, subharmonic transitions in the frequency and the wavenumber domains, and an apparent increase of the effective fetch length. The physical mechanisms involved require further investigation. They need to be considered in the context of microwave backscattering, and also to improve the modelling of short wave evolution for ocean-wave prediction.

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