

Revision of the manuscript: os-2018-111

Analysis of the effect of fish oil on wind waves and implications for air-water interaction studies

Alvise Benetazzo, Luigi Cavaleri, Hongyu Ma, Shumin Jiang,
Filippo Bergamasco, Wenzheng Jiang, Sheng Chen, and Fangli Qiao

Dear Sirs,

Please find enclosed a detailed list of replies to the Referee comments on the paper in Subject.

We would like to thank the Referee for her/his comments and suggestions, which have been useful to improve the manuscript.

Sincerely yours,

Alvise Benetazzo
Institute of Marine Sciences
National Research Council
Venice, ITALY

1.1 REFEREE #1

We would like to thank the Referee for the constructive and helpful comments. Our responses (in blue) to the comments are given below.

REFEREE: I think this is a very nice manuscript that presents refined measurements on complex problematics. I personally enjoyed reading the manuscript and I think that, while the subject has been studied previously in the literature, the experimental evidences presented here are numerous and of high enough quality to definitely improve the current state of the literature on the topic.

I have a couple of relatively minor comments. I think that they may help still improve the quality of the final paper as well as its potential reach and audience, while requiring relatively little work, so I would like the authors to consider including them in their final manuscript.

- 1: Regarding the reach and novelty of the paper, I think that it is already satisfactory as is, but that a bit more can be done. I am thinking more specifically about ‘cross-field’ applications of the measurements you perform. More specifically, there are a few more fields where applications of your findings could be relevant:

– a) The detection and tracking of oil spills. While you talk here about fish oils, and you mention that they present some differences compared with mineral oils, I think that in a modern context there is more interest in the effect of mineral oil leaks on the environment than fish oil. Could you discuss about this in the introduction, and put into context for example oil spill detections based on capillary waves damping? See for example:

- ‘Damping of gravity-capillary waves in the presence of oil slicks according to data from laboratory and numerical experiments’, Ermakov et. al. 2012.
- ‘Oil Spill Remote Sensing: A Review’, Fingas and Brown.
- ‘Drift and deformation of oil slicks due to surface waves’, Christensen and Terrile, 2009.

AUTHORS: We thank the Referee for this useful comment and for the suggested references. In this respect, we have mentioned in the “Introduction” the connection between our study and the “remote detection of oil spills”. The two relevant studies by Fingas and Brown (2017) and Christensen and Terrile (2009) have been cited accordingly.

– b) Another field receiving much attention recently is the interaction between waves and sea ice. This is obviously a ‘hot’ topic currently due to the current global climate trends. There also, elastic forces appear at the surface of the water masses, but this time due to the presence of ice. This field of research would be worth to mention in your introduction and / or conclusion, as it presents many analogies with your present study and making the waves in ice community aware of your findings will definitely be of interest. The parallels between those fields are visible in several works, for example:

- ‘Transient and steady drift currents in waves damped by surfactants’, Christensen 2005.
- ‘Measurements of wave damping by a grease ice slick in Svalbard using off-the-shelf sensors and open source electronics’, Rabault et. al. 2017.
- ‘The attenuation of monochromatic surface waves due to the presence of an inextensible cover’, Sutherland et. al., 2017.

We thank the referee for highlighting the parallel between those two relevant fields. In this respect, we have mentioned in the “Introduction” the similarity of the problem we investigated with the “wave attenuation under an ice cover”. The two studies by Weber (1987) and Christensen (2005) have been added to the reference lists.

- 2: p 5 l 21: can you give us an idea of which parameters you use in your Welch transformation, and why you chose them so? I ask about this because the choice of those parameters may participate in influencing the shape of your spectra later in the manuscript.

For the spectral analysis we have used the Welch method adopting eight segments with 50% overlap. Each segment was windowed with a Hamming window. We made sensitivity tests by changing the overlap and the window’s type, but we noted very minor differences in the spectrum shape. Following the referee’s suggestion, in the revised version of the manuscript we have specified the Welch method parameter: “eight segments of equal length, 50% overlap, Hamming window”.

- 3: p 14 Fig. 4: Are you sure that the W06-O signal is well resolved? In particular, you need a signal-to-noise ration high enough to trust the graph shown on the right panel. I ask about this because the red curve has a scale much collapsed compared with the blue one, and therefore I cannot visually check how well you can resolve it.

Consider adding a small sentence discussing the accuracy of your measurements in the methodology section, and discussing it in regards to your measurements here.

We thank the Referee for pointing out this important aspect. The calibrations we carried out before the Experiments showed a linear response of the gauges, whose accuracy was found to be not better than 0.3 mm. This provides a signal-to-noise ratio sufficient for all our analyses, being the standard deviation of the surface elevation during the test W06-O at least twice as large as the accuracy, and the maximum elevation about 2 mm. In the revised version of the manuscript (Section 2.1 “Experimental setup”) we have included the value of this accuracy as well as reported the linear-type response of the instrument.

- 4: p 15 Fig. 5: Why do you provide the ~ 4 and ~ 5 slopes? Please make it clearer in the text what you want to show with them. Also, if you still want to keep them, please add a sentence or two discussing how compelling evidence they provide. Your spectra display a power law behavior for ranges of frequency that span typically slightly less than a decade, which is arguably quite little.

We do agree with the referee that for the results presented in our study those slopes are not particularly meaningful. Following the Referee’s suggestion we have thus decided to remove those lines from Figures 5 and 8 in the revised version of the manuscript

- 5: p 17 Fig. 7: Please add error bars. For some help about error bars, you may consider reading for example: <https://www.ittc.info/media/8099/75-02-07-014.pdf>, ‘Confidence Intervals for Significant Wave Height and Modal Period’. Similarly, Sutherland et. al. previously cited also show some ways of obtaining error bars on this kind of statistical quantities.

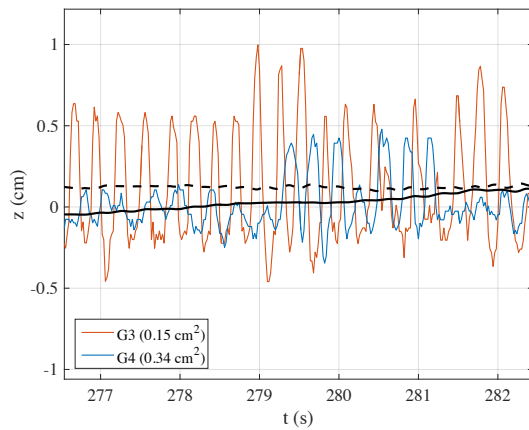
We thank for this suggestion that is helpful to improve the paper. As suggested by the Referee and following the example of Sutherland et al. (2017), we have evaluated the prediction intervals of the fit. They are displayed with black lines in the new Figure 7. We have additionally specified in the Figure’s caption the root-mean-square error for each fit.

- 6: p 17 l. 20: sec \rightarrow s

Thanks. Corrected

- 7: p 18 Fig. 8: Do the spikes in your figure correspond to noise or waves? Here also an estimate of the Signal To Noise Ratio would help.

The data displayed do represent waves, even though, we agree, they are not straightly detectable in the Figure. However, we have included in the revised version of the manuscript the expected accuracy for wave probes, hence it is straightforward to estimate the reliability of the plotted data (see surface elevations are in the order of few mm). For the sake of review, we provide below a zoom of the Figure.



- 8: p 23 Fig. 13: same comment about confidence intervals as for Fig. 7.

As for Figure 7, we have added in the new Figure 13 the confidence bounds for the fitted curves.

Analysis of the effect of fish oil on wind waves and implications for air-water interaction studies

~~Fish oil in a wave tank: a look at the air-water response~~

Alvise Benetazzo¹, Luigi Cavaleri¹, Hongyu Ma², Shumin Jiang², Filippo Bergamasco³, Wenzheng Jiang², Sheng Chen², Fangli Qiao²

¹ Istituto di Scienze Marine (ISMAR), Consiglio Nazionale delle Ricerche (CNR), Venice, Italy.

² First Institute of Oceanography (FIO), State Oceanic Administration (SOA), Qingdao, P. R. China.

³ DAIS – Università Ca' Foscari, Venice, Italy.

Correspondence to: A. Benetazzo (alvise.benetazzo@ve.ismar.cnr.it)

Abstract. Surfactant layers with viscoelastic properties floating on the water surface damp short gravity-capillary waves. ~~Inspired by~~ Taking advantage of the known virtue of fish oil to still angry seas, a laboratory study has been made ~~on~~ to analyze the ~~wind-wind~~-wave generation and ~~on~~ the interaction between wind-waves, paddle-waves and airflow. This was done in a tank containing a thin fish oil film uniformly spread on the water surface. ~~According to the Marangoni resonance-type damping mechanism, for oily surfaces the energy dissipation process is quite selective in wavenumbers, but its effects are not, since it spreads (although to a lesser extent) towards longer and shorter waves via nonlinear interactions and modification of the airflow profile.~~ The research was aimed, on the one hand, at quantifying for the first time the effectiveness of this surfactant in impeding the generation of wind waves, and, on the other, at using the derived conditions to disentangle relevant mechanisms involved in the air-sea interaction. In particular, our main interest concerned the processes acting on the wind stress and on the wave growth. ~~W~~With a thin layer of oil on the water surface, ~~it is rather peculiar~~ we have found that in the wind-only condition (no paddle waves) the wave field does not grow from the rest condition. This equilibrium ~~was~~ is altered by irregular paddle (longer) waves, the generation and evolution of short waves (in clean water and with oil) being modified by their interaction with the orbital velocity of the longer waves and their effect on the airflow. Paddle waves ~~did~~ do grow under the action of wind, how much being similar in clean and oily water conditions, a fact we ascribe to the similar distortion of the wind vertical profile in the two cases. We have also ~~found~~ verified that the wind-supported stress on the oily water surface ~~was~~ has been able to generate a surface current, whose magnitude turns out to be comparable to the one in clean water. ~~Our results expand previous~~

~~investigations on the same topic.~~ We stress the benefits of experiments with surfactants to explore in detail the physics at, and the exchanges across, the wavy and no-wavy air-water interface.

Keywords: Wind-wave growth; ~~Fish Oil~~; Surfactant; Fish Oil; Marangoni forces; Paddle waves; Air-sea interaction.

2 Introduction

It is well known that the addition of an almost mono-molecular film (thickness from 10^{-9} to 10^{-8} m) of surfactant (blend of *surface active agent*) to the water surface diminishes the energy of gravity-capillary waves by altering the surface tension at the water-air interface (Fiscella et al., 1985). For this reason, oily surfactants were used for centuries by seamen to smooth the ocean surface waves, so much that expressions as “to pour oil on troubled water” have acquired a more general meaning. Crucial in this respect is the type of oil, in particular its polarity. Mineral oils, often used for this purpose during the Second World War, are less effective because their molecules tend to group together. On the contrary the polar molecules of fish, and partly also vegetable, oils repel each other. Hence, once poured on water, they tend to distribute rapidly on the available surface reaching a quasi-monomolecular layer (see e.g. Cox et al., 2017).

Known since ancient time, this damping effect was first studied in the 19th century by the Italian physicist Carlo Marangoni (Marangoni, 1872), hence the official name of the process. In relatively recent times the first report of the resonance-type Marangoni damping of wave spectra (briefly sketched in Appendix A) comes from Cini et al. (1983) who had noted the effect in the polluted (although by mineral oils) water in the gulf of Genoa, Italy. However, clear evidence in the open sea of high damping of surface waves in the short-gravity-wave region by mono-molecular slicks was first verified by Ermakov et al. (1985, 1986) during field experiments in the Black Sea.

The Marangoni damping can be effective for surface waves in two possible conditions. The first one is in open ocean, in which an existing wind-forced wave field travels trough a surfactant patch, with the consequent possibility of recognition (lack of return signal by damped short waves) by microwave radars (Feindt, 1985). A direct application is, for instance, the remote detection of oil spills (Fingas and Brown, 2017), whose drift and deformation, and in turn the damping rate of waves, are affected by the properties of the slick (e.g. the elastic properties of the film) and of the entering wave field (Christensen and Terrile, 2009). Direct in situ observations of

1 the surfactant effects on wind waves have been however very limited because of the challenges to operate in
2 stormy conditions. According to the Marangoni mechanism, for oily surfaces the energy dissipation process is quite
3 selective in wavenumbers, but its effects are not, since it spreads (although to a lesser extent) towards longer and
4 shorter waves via nonlinear interactions and modification of the airflow profile. Hühnerfuss et al. (1983) in a slick
5 experiment carried out in the North Sea found that waves with wavelength up to 3 m are significantly decreased in
6 amplitude when they travel through a 1.5-km-long monomolecular surface film patch. The result is that the wave
7 growth is inhibited and the existing surface field is rapidly smoothed and progressively attenuated as it propagates
8 within a surfactant patch (Ermakov et al., 1986). This change in surface properties resembles the wave attenuation
9 under an ice cover (see e.g. (Weber, 1987), and (Christensen, 2005), for a parallel between the two fields), for
10 which however there are many other processes which also attenuate energy. The second condition, typical of
11 laboratory experiments (e.g. Hühnerfuss et al., 1981; Mitsuyasu and Honda, 1986), is where the wind blows over a
12 water surface homogeneously covered (since the rest condition) with a surfactant film. Compared with a clean
13 water environment, from the wind onset, the coupled air-water system is adjusted to a new state, characterized by a
14 large suppression of the generation of wind waves and a change of the wind stress corresponding to the reduction
15 of form drag of the wave field.

16 The suppression of wind-generated waves due to the oil slick alters heavily the air-sea interaction process
17 (Mitsuyasu and Honda, 1986), but the full mechanism remains poorly understood (Cox et al., 2017). In this respect,
18 with still different opinions on the reason why (see e.g. (Kawai, 1979; Phillips, 1957), we know that as soon as the
19 first wind blows, the sea surface is covered by tiny 2-3 cm long wavelets. That process is quickly overtaken as the
20 waves grow by the feedback caused by the wave-induced pressure oscillations in the air, as soon as the airflow
21 vertical profile is modified by the presence of waves. Miles (1957) proposed a wave growth mechanism that
22 accounts for this change. This theory was extended and later applied by Janssen (1991) to wave forecasting. Its
23 validity is questioned for very short waves whose phase speed is as slow as the air friction velocity (Miles, 1993).
24 According to the shear-flow model by Miles, waves with phase speed c grow when the curvature in the vertical
25 wind profile, at the height (called critical height) where the wind speeds equals c , is negative. As a result, the wind
26 profile changes because of the continuous transfer of energy to the waves (Janssen, 1982). The growth rate is
27 proportional to this curvature and it has an implicit dependence on the roughness on the wavy water surface

1 (Janssen, 1991). Hence it is expected that any modification of the vertical wind shear (for instance induced by the
2 oil film effect) modifies the momentum transfer from wind to waves.

3 In this study, we verify with experiments in a wave tank that the peculiarity of fish oil is indeed striking.
4 Previous researches suggested (e.g. Alpers and Hühnerfuss, 1989) a correlation between the intensity and
5 frequency-range of the wave damping and the chemical properties (namely the dilatational modulus) of the
6 surfactant. Therefore our study explores for the first time the effect of fish oil (a polar surfactant with high
7 dilatational modulus) by laboratory experiments in which the oil effects on the wind shear stress and the wave
8 growth are assessed in different conditions for short (wind-generated) and collinear long (paddle-generated) waves
9 The latter ones introduce the problem of the interaction between long and short waves, and between long waves
10 and the wind profile.

11 In the open ocean, the influence of swell on local wind-wave generation is a known fact, albeit a firm
12 explanation of the underlying mechanism has not been reached. Hwang et al. (2011) discuss how the Tehuano-
13 wind generated waves, on the Pacific coast of Mexico, are affected by the incoming oceanic opposing swell. With
14 some similarity, the cases of following or opposing swell seem to differ somehow in their physics. In the
15 laboratory, the “following swell” case was first studied by Mitsuyasu (1966) and later intensively by Donelan
16 (1987) who suggested that a swell (in practice paddle waves; also his experiments were done in a wind- and
17 paddle-wave tank at the University of Miami, USA) induces a detuning of the resonance conditions for non-linear
18 interactions among wind waves. Later, in the studies by Phillips and Banner (1974) and Donelan et al. (2010), the
19 suggested explanation was the enhanced wind wave breaking due to the wind and paddle waves interaction. Also,
20 the influence of paddle waves increases with their steepness. More recently, Chen and Belcher (2000) proposed the
21 idea that the long wave exerts a drag on the airflow, which reduces the turbulent stress in the airflow that is
22 available to generate wind waves.

23 Given these previous experiences, the present study is motivated, on the one hand, to quantify for the first
24 time the effect of fish oil on the generation of the gravity-capillary wind-wave field. We worked with waves
25 generated in a wind-flume using clean water and water with surfactant on the surface. Irregular paddle waves
26 coexisting with wind waves were also tested to investigate the mutual interaction between short waves, long waves,
27 and airflow. On the other hand, using the suppressed wind waves with surfactants, we aimed at using the
28 experiments to disentangle and analyze relevant mechanisms of the air-sea interaction; our interest was on the pure

1 frictional wind stress (which, in clean water, is not separable from the wave stress), the related water surface drift,
2 and the growth of irregular long waves under the action of the wind (by largely canceling the short-wave
3 roughness).

4 The paper is organized as follows. Section 3 makes a general description of the experimental set-up in the tank,
5 lists the general plan of experiments with wind and paddle waves in clean water and with oil, and describes the
6 water elevation and airflow data collected during the tests. The results of the experiments are examined in Section
7 4, where we show the response of the coupled air-water system to the presence of fish oil slick. The principal
8 results and implications for air-water interaction studies of the present investigation are discussed in Section 5.
9 Finally, the main findings of the study are summarized in Section 6. The manuscript is complemented with two
10 videos recorded during the experiments showing the effect on wind and paddle waves of the surface layer of fish
11 oil.

12 ~~Wind blowing over the water surface generates wind waves and drift currents. It is instructive that the physics of~~
13 ~~this evident truth is still a question of debate. One reason is that the implied physics spans a large range of scales,~~
14 ~~the various processes interacting among them, and possibly hiding the reasons of that behavior. Nature offers a full~~
15 ~~panorama of events at all the possible scales. However, it is mainly in the laboratory that we can explore, also with~~
16 ~~the desired repetitiveness, the details of some, albeit limited in scale, processes. Indeed this approach has provided~~
17 ~~in time enlightening findings to be then used in the daily operational activities. Already in the '70s and '80s~~
18 ~~Mitsuyasu, in a series of remarkable papers, provided basic hints into the generative and dissipative processes of~~
19 ~~wind waves (see, among others, Kusaba and Mitsuyasu, 1984; Mitsuyasu, 1966; Mitsuyasu and Honda, 1982,~~
20 ~~1986). Mark Donelan, using data first from a tower in lake Ontario and then in a laboratory wind wave tunnel in~~
21 ~~Miami, provided basic hints in several aspects of wind wave generation (see e.g. Donelan, 1990). In more recent~~
22 ~~times, following a very sophisticated and detailed series of experiments, Buckley and Veron (2016) have provided~~
23 ~~a detailed description of the air flow during wave generation. The specific problem of the trigger of the initial~~
24 ~~wavelets has been dealt with by Kawai (1979), van Gastel et al. (1985), and more recently by Liberzon and Shemer~~
25 ~~(2011) and Zavadsky and Shemer (2017).~~

26 ~~A problem that (in most of the cases) does not concern the open ocean is how air and sea interact when the~~
27 ~~water surface is covered by a thin layer of surface active agent. This physical aspect has been early dealt with~~
28 ~~experimentally in studies by Hühnerfuss et al. (1981) and Mitsuyasu and Honda (1986). The interest is not only on~~

1 the results of the experiments, but on the physics they reveal and the considerations they allow on the general
2 problem of wind wave generation. Following this logical link we have carried out a series of experiments aimed at,
3 if not solving the whole problem (a daunting task), at least shading new light on some of its aspects. Science
4 proceeds often by negations. New results may not only hint in one direction, but also exclude a solution, in so
5 doing helping focusing along the right path.

6 In the following we describe what has been done, for each experiment stressing the doubts and the
7 implications. Given that a large part of what was done deals with fish oil on the surface, following subsection 1.1
8 provides a compact, but sufficient for the purpose, description of the related physics. The general description of the
9 experimental set up is in section 2, where we also list the general plan of the experiments and the finally available
10 data. The actual technical description of the results of the experiments are in section 3, the whole then discussed in
11 section 4, and summarized and itemized in the final section 5.

2.1 A little physics on the interaction between oil slick and gravity capillary waves

12 It is well known that the addition of a thin film (from 10^{-9} to 10^{-8} m, almost mono-molecular) of surfactant (blend
13 of *surface active agent*) to the water surface has a intense effect on the energy of the gravity-capillary waves by
14 altering the surface tension at the water-air interface (Fiscella et al., 1985). Oil has been used for centuries to
15 smooth the sea surface, so much that expressions as “to pour oil on troubled water” have acquired a more general
16 meaning. See later in the paper the impressive example reported by Cox et al. (2017). Crucial in this respect is the
17 type of oil, in particular its polarity. Mineral oils, so often wrongly used during the Second World War, are not
18 effective because their molecules tend to group together in a heap. On the contrary the polar molecules of fish, and
19 partly also vegetable, oils repel each other. Hence, once poured on water, they tend to distribute rapidly on the
20 available surface acquiring a quasi-monomolecular level. Known since ancient time, this effect was first studied in
21 the 19th century by the Italian physicist Carlo Marangoni, hence the official name of the process (Marangoni,
22 1872). In relatively recent times the first report of Marangoni damping of wave spectra came from Cini et al.
23 (1983) who had noted the effect in the polluted (although by mineral oils) water in the gulf of Genoa, Italy.
24 However, clear evidence of Marangoni damping on slick-covered ocean waves was first presented by Ermakov et
25 al. (1985, 1986) during field experiment in the Black Sea.

26 This resonance-type Marangoni damping (to be soon described) can be effective for surface waves in two
27 possible conditions. The first one is in the open ocean, in which an existing wind-forced wave field travels trough a

1 surfactant patch, with the consequent possibility of detection (lack of return signal) by microwave radars (Feindt,
2 1985). The second one, typical of laboratory experiments, is where the wind blows over a water surface
3 homogeneously covered (since the rest condition) with a surfactant film. The latter is the one we dealt with in the
4 experiments described in this study.

5 The presence of an extremely thin (practically mono-molecular) layer of oil on the surface strongly affects
6 the air-sea interaction. In this respect, it is generally agreed that, in clean water, the growth of the first detectable
7 ripples on the water surface is rather well explained by the effect of air turbulence advected by the wind (Phillips,
8 1957). That process is quickly overtaken as the waves grow by the feedback caused by the wave-induced pressure
9 oscillations in the air, as soon as the airflow vertical profile is modified by waves. Miles (1957) proposed a wave
10 growth mechanism that accounts for this change. This theory was extended and later applied by Janssen (1991) to
11 wave forecasting. Its validity is questioned for very short waves whose phase speed is as slow as the air friction
12 velocity (Miles, 1993). According to the shear flow model by Miles, waves with phase speed c grow when the
13 curvature in the vertical wind profile, at the height (called critical height) where the wind speed equals c , is
14 negative. As a result, the wind profile changes because of the continuous transfer of energy to the waves (Janssen,
15 1982). The growth rate is proportional to this curvature and it has an implicit dependence on the roughness length
16 on the wavy water surface. Hence any modification of the vertical wind shear modifies the momentum transfer
17 from wind to waves. This equilibrium is altered for slick-covered surfaces.

18 The physics of the Marangoni effect is thought to be well understood, and it is generally agreed that the
19 gravity-capillary wave energy is damped by a surfactant by the following mechanism. Immediately after a wave
20 field enters a surfactant patch, the Marangoni effect due to the viscoelastic film on the water surface increases
21 viscous dissipation of short wave energy at specific frequencies. This is caused by an additional dissipation in the
22 surface boundary layer. Indeed a shear stress in the boundary layer is required to balance the stress due to the
23 surface tension gradients originated by the non-uniform concentration of the surface viscoelastic film (alternatively
24 contracted and expanded due to the passage of a wave). This gives rise to additional longitudinal waves in the
25 boundary layer superimposed on the existing surface waves that are thus damped by a resonance-type mechanism.
26 The dissipative spectral sink (the so-called Marangoni resonance region) is at frequencies between 3 Hz and 8 Hz,
27 the scale of the maximum damping depending on the dilatational modulus of the surfactant (Alpers and

Hühnerfuss, 1989; Fiscella et al., 1985). The resonant angular frequency ω_{res} for the Marangoni force wave damping is given by

$$\omega_{res} = \left\{ \frac{[\cos(\pi/8)]^4 g^4 (\eta \rho_w)}{\varepsilon^2} \right\}^{\frac{1}{5}} \text{ (rad/s)} \quad (1)$$

where g (m/s^2) is the gravity acceleration, ρ_w (kg/m^3) the clean water density, η (Ns/m^2) the clean water dynamic viscosity, and ε (N/m) denotes the dilatational modulus of the surface film. As stated by Eq. (1), the larger the modulus ε the longer the damped waves. The maximum damping of gravity-capillary waves is attained at a frequency lower than ω_{res} (the Marangoni wave is a strongly damped wave) and the width of the resonant damping is quite broad (the half power width is in the order from 1 to 2 Hz; Alpers and Hühnerfuss, 1989).

In a more formal approach, the description of water surface gravity waves follows generally a statistical approach by means of the development of the wave elevation variance spectrum $E = E(k, \theta, x, t)$ in the physical space x and time t (k is the wavenumber and θ the propagation direction), its evolution governed by the energy balance equation (Gelei et al., 1957). In deep waters, it reads

$$\frac{\partial N}{\partial t} + \frac{\partial N}{\partial x} \cdot (\dot{x}N) = S_{in} + S_{nl} + S_{di} \quad (2)$$

where $N = E / \omega$ is the wave action density spectrum with ω the intrinsic angular frequency. Furthermore, $\dot{x} = c_g + U$ with c_g the wave group velocity and U an appropriate current. The right hand side of Eq. (2) represents the net effect of sources and sinks for the spectrum (Komen et al., 1994): S_{in} is the rate of energy transferred from the wind to the wave field, S_{nl} is the rate of nonlinear energy transfer among wave components with different wavenumber, and $S_{di} = S_{di,b} + S_{di,v}$ is the rate of energy dissipation due to breaking ($S_{di,b}$) and viscous forces ($S_{di,v}$).

In our experiments the observations dealt with in this paper are the ones collected at steady state (we plan to deal with the transient in a different occasion), so that the spectrum at any fetch is determined by the upwind evolution of the source functions S_{in} , S_{nl} and S_{di} , that is

$$N = \int_0^x \left[(c_g + U)^{-1} (S_{in} + S_{nl} + S_{di}) \right] dx \quad (3)$$

1 where, with good approximation, we have neglected the cross-tank wave energy evolution. The velocities c_g and U
2 are also, but very weakly, fetch dependent. The balance in Eq. (3) indicates that any modification of the wave
3 energy may and must be caused by changes in the rate of wind input, dissipation, or/and nonlinear transfer.

4 In presence of oil, all three source functions in Eq. (2) undergo a change compared to the clean water
5 condition. Indeed, the rapid suppression of short waves by Marangoni forces reduces the water surface mean slope,
6 which leads to a change of the wind vertical profile and rapid decrease of the momentum flux from the wind to the
7 wave field (see, e.g., Mitsuyasu and Honda, 1986). Those two effects combined produce a change of the shape of
8 the wave spectrum in the equilibrium range, which leads, via nonlinear wave-wave interaction (Hasselmann, 1962),
9 to a slow leakage (but fast compared to the pure viscous one; Alpers and Hühnerfuss, 1989) at wavelengths longer
10 than those at which the Marangoni forces are effective (Hühnerfuss et al., 1983 found that waves with wavelength
11 around 3 m are significantly damped when they travel through a 1.5 km long monomolecular surface film patch).
12 The result is that the wave field is rapidly smoothed and progressively attenuated as it propagates within a
13 surfactant patch (Ermakov et al., 1986).

14 Given the possible variability of the surfactant density on the water surface, it is natural to wonder about the
15 related sensitivity of the effect on waves. Analyzing the wind-wave tank experiments with surfactants (sodium
16 lauryl sulfate) presented by Mitsuyasu and Honda (1986), we can distinguish two different regimes for wave
17 attenuation, which correspond to weak and strong wave damping, respectively. Firstly, for small surfactant
18 concentrations (i.e. weak damping), the peak frequency of the wind-wave spectrum in presence of films is shifted
19 to higher frequencies in reference to the peak frequency of clean water (in other words waves develop more
20 slowly). However, spectra preserve u_* similarity (u_* is the friction air velocity), and the new spectral shape was
21 ascribed mainly to the decrease of the wind stress: the surfactants smooth the surface and act reducing the wind
22 stress, therefore the waves grow less. We interpret this result assuming that for low surfactant concentrations the
23 effectiveness of the Marangoni damping is small (i.e. the water surface is not fully covered by an uniform film), but
24 with a partially reduced aerodynamic roughness. On the contrary, for the highest concentration (hence with a strong
25 damping) the similarity no longer holds, and most of the energy around the peak is lost (the maximum energy is at
26 a frequency smaller than the one in clean water; see also next Figure 5 and Figure 6).

27 A question about Marangoni forces concerns the maximum wind speed for which they are expected to keep
28 their damping efficiency. In early studies, the disappearance of the Marangoni damping was observed by Mitsuyasu

1 and Honda (1986) for wind speed larger than a critical value, that those authors found to be 12.5 m/s. A possible
2 explanation is provided in the study by Alpers and Hühnerfuss (1989), who argued that above a certain friction
3 velocity (around 0.5 m/s) the Marangoni dip is filled in owing to a large flux of wave energy into the Marangoni
4 resonance region by nonlinear wave-wave interactions. In addition, for stronger wind stresses the viscoelastic film
5 becomes more mixed with the underlying clean water bulk (the film is “washed down”), so that the Marangoni
6 damping is strongly attenuated (see also Feindt, 1985). However, these conclusions seem not to be fully consistent
7 with the recent analysis made by Cox et al. (2017) of the saving in 1883 of the crew of a sinking vessel by the ship
8 *Martha Cobb* under very severe stormy conditions (wind speed around 20 m/s). In that occasion 19 liters of fish oil
9 were dribbled into the sea and the log records report what, after a 20-minute delay, was defined as a “magic effect”,
10 i.e. that the water surface smoothed and breakers disappeared around the vessel, allowing the crew to be saved
11 using a small open deck dingy. Cox et al. (2017) estimated that after 20 minutes the surface covered by the oil film
12 was about 0.4 km^2 , hence, the average oil thickness was about $5 \times 10^{-8} \text{ m}$. In those conditions, therefore, the
13 thickness was comparable to that used in the experiments in the tank and, in spite of the high wind speed, the wave
14 damping (with practical cancelling of wave breaking) was still effective.

15 **3 Experimental facilities, experiments carried out, and data processing** Experiment

16 **3.1 The experimental setup**

17 The experiments described in this study were performed in a large wind- and paddle-wave facility allowing the
18 generation of winds at velocities comparable with those in open sea (but no extreme conditions). The
19 measurements were carried out in the flume of the First Institute of Oceanography ([FIO](#), Qingdao, P.R. China)
20 illustrated schematically in Figure 1. The tank dimensions are: length 32.5 m, wall-to-wall cross-section 1.0 m,
21 ceiling at 0.8 m above the mean water surface. The water depth is 1.2 m, satisfying the deep-water condition for the
22 wind-driven gravity-capillary, and practically also paddle, waves analyzed in this study. The smallest longitudinal
23 natural frequency of the tank is 0.052 Hz. Side walls are made of clear glass to enable visualization of the wave
field. A water pipe parallel to and below the flume allows the continuity between the two ends of the tank.

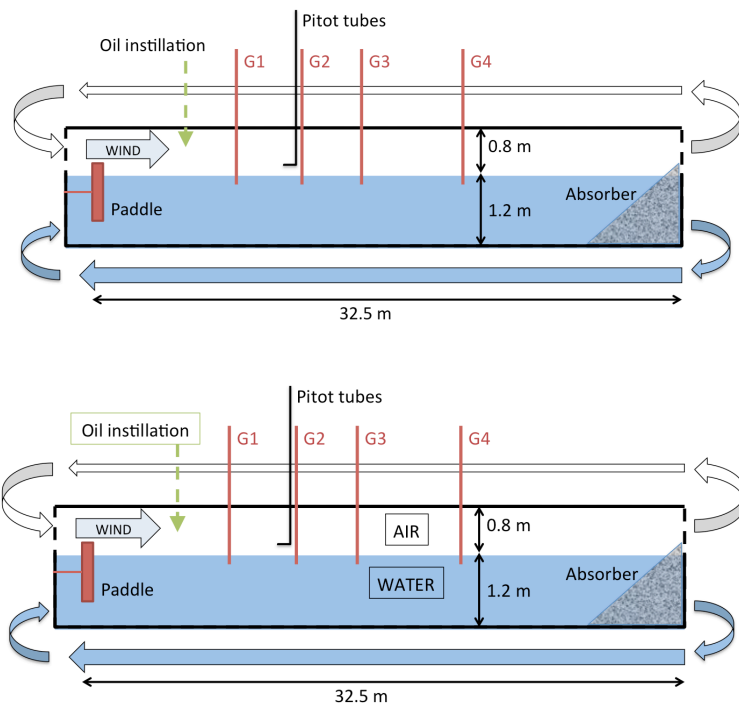


Figure 1: Schematic longitudinal diagram of the wave flume arrangement at the First Institute of Oceanography (FIO) flume (Qingdao, P.R. China). For the sake of clarity, horizontal and vertical scales are distorted. The arrows indicate the direction of the flow.

The wind tunnel is mounted atop the wave tank which is closed with side glass walls and ceiling. The airflow could be driven up to reference speed of 12 m/s. Mechanically-generated (paddle) waves coexisting with wind waves could be generated by a piston-type paddle in the range of periods from 0.5 s to 5.0 s (frequencies from 0.2 Hz to 2.0 Hz) and dissipated at the downwind end of the tank on a sloping beach of fibrous matter. Four calibrated (featuring a linear response and accuracy of 0.3 mm) capacitance-type wave gauges collecting synchronous water surface elevation data for 300 s at 50 Hz were distributed at fetches (along the tank main axis) $X = 8.0$ m (probe G1), 12.0 m (G2), 15.5 m (G3), and 20.5 m (G4). The fetch $X = 0.0$ m corresponds to the inlet for wind in the water tank. For the statistically steady part of the wave records the variance frequency-spectrum of water surface elevation $z(t)$ were was computed by using means of the Welch (1967) Welch's overlapped segment averaging estimator- (eight segments of equal length, 50% overlap, Hamming window) (Welch, 1967).

For characterization of the vertical profile of the along-channel component of the airflow velocity-vertical profile $U_a(h)$, five Pitot tubes sampling at 1/7 Hz have been located at $X = 11.5$ m in the center of the cross-section and distributed at different heights h above the still water surface, respectively (from tube 1 to 5) at $h = 8.3$ cm, 18.3 cm, 28.3 cm, 38.3 cm, and 48.3 cm. Estimates of the wind stress was were derived from air velocity average

profiles using fitting the Pitot tube observations fitted with a logarithmic profile law function of h . For an aerodynamically rough airflow, the mean value of the along-channel component of the wind velocity \bar{U} in the outer turbulent layer at height h above the boundary is expected to follow a self-similar Karman-Prandtl logarithmic law as a function of height

$$\bar{U}(h) = \frac{u_*}{\kappa} \log\left(\frac{h}{h_0}\right) \quad (1)$$

where the overbar indicates the temporal averaging process, u_* is the friction velocity along the same direction as \bar{U} , $\kappa = 0.41$ is the von Kármán's constant. The non-zero parameter h_0 has the meaning of the roughness height where \bar{U} appears to go to zero (namely h_0 is the virtual origin of the mean velocity profile). In presence of waves, the shape of the wind velocity profile $\bar{U}(h)$ is governed by both turbulent and wave-induced momentum flux, the latter being function of the wind input source term in Eq. (11). The transport of horizontal momentum due to molecular viscosity is considered negligible, except very near the surface where the vertical motion is suppressed. The total air-side shear stress τ_a at the boundary of the flow is then approximated as

$$\tau_a = \rho_a u_*^2 \quad (2)$$

with ρ_a the air density.

To account in Eq. (1) for the non-slip condition, the measured airflow velocity $U_a(h)$ has to be taken relative to along-wind components of the water surface velocity u_{w0} at $h = 0$, i.e. $U(h) = U_a(h) - u_{w0}$. It is thus assumed that the mean water surface drift velocity u_{w0} constitutes the boundary condition at $h = 0$ for the vertical profile of the airflow velocity. Wu (1975) found that at the air-water interface, the wind-induced current is proportional to the friction velocity of the wind, and it is associated to the wind shear, Stokes drift, and momentum injection during wave breaking events. For non-breaking wavy surfaces, the wind-induced surface current was determined to be around 50% of the airflow friction velocity (Phillips and Banner, 1974 and Wu, 1975). In a (clean water) wind-wave tank and at steady conditions, the value of u_{w0} can be related to the maximum value of $U_a(h)$. This is not achieved at the largest distances from the water due to the presence of the tank roof. A value u_{w0} around 3.3% of the free-stream maximum wind velocity seems to be a reasonable approximation (Liberzon and Shemer, 2011; Peirson, 1997; Wu, 1975) and was used in this study. The accuracy of the wind stress obtained from the profiles measured by Pitot tubes in a wave tank was examined by Liberzon and Shemer (2011) who found that the values of the wind stress obtained from the measurements by the Pitot tube and those calculated from the Reynolds stresses (using a X-hot-film thermo-anemometer) agree within about 10 % mean difference.

[A series of videos showing the water surface conditions in clean water and in water with oil complements the available data providing a plain perception of the fish oil effect on the surface waves.](#)

3.2 The experiments

Our experiments aimed at analyzing the different results, using the different combinations of reference wind speed U_r , paddle waves (changing the peak wave period T_p , and significant wave height H_s) and oily surface. The data of each experiment were later screened for correct data availability and consistency among the different instruments. This led to exclude several records considered not suitable (independently of the physical results) for the final analysis. This was based on the six experiments listed in Table 1. Two different blower reference speeds were analyzed, namely $U_r = 6$ m/s and 8 m/s, and one set of irregular paddle waves (JONSWAP spectrum with $T_p = 1.0$ s and $H_s = 6.2$ cm; steepness $H_s / L_p = 0.04$, with L_p the peak wavelength). Note that many of these experiments have been repeated up to four times. All experiments were initiated with no wind and undisturbed water surface.

Exp.	W06	W06-O	W06-O-NI	W08	W08-P	W08-P-O
Wind	6 m/s	6 m/s	6 m/s	8 m/s	8 m/s	8 m/s
Paddle	-	-	-	-	JONSWAP Spectrum ($T_p = 1.0$ s, $H_s = 6.2$ cm)	JONSWAP Spectrum ($T_p = 1.0$ s, $H_s = 6.2$ cm)
Oil	-	Instillation	No instillation	-	-	Instillation

Table 1: List of experiments performed in the wind- and paddle-wave tank, using clean water (ordinary tap water) and after instilling fish oil. The wind speed is the reference value U_r imposed at the blower. For paddle waves, T_p is the peak period and H_s the significant wave height. Blanks denote not applicable cases.

Three experiments (two with wind waves and one with wind and paddle waves) were made with the fish oil-covered water surface. The dilational modulus ε of this type of oil is roughly 0.03 N/m (Foda and Cox, 1980), hence its resonance frequency [given in Eq. \(10\)](#) is estimated to be $\omega_{res} = 23.7$ rad/s (i.e. linear frequency of 3.77 Hz and wavelength of about 11 cm). Moreover, the radial spreading speed of fish oil is around 0.14 m/s, sufficiently large to keep uniform the oil film that might be broken by the wave action (Cox et al., 2017). Before performing the experiments with the slick-covered surface, the oil was instilled from the ceiling at fetch $X = 4$ m, releasing 26 drops with the blower at rest. Estimating each drop of volume about 50×10^{-9} m³, the average oil thickness on the water surface was 4×10^{-8} m, namely [a few molecular layers](#). During the experiments W06-O and W08-P-O (see Table 1) the oil film was preserved (~~see later in section 3.1~~) by continuously instilling onto the water

1 | surface oil drops, while the dropping was interrupted (no instillation) at the onset of the wind start ~~of~~in the
2 | experiment W06-O-NI.

3 | A crucial point in wind wave tank measurements concerns the correct reference system for waves generated by
4 | wind. The wave data acquired by the probes in the tank are represented in a fixed (absolute) reference system,
5 | while the response of the wave field to the oil film is intrinsic in the wave dynamics. Therefore the sea surface
6 | elevation energy spectrum E must be mapped in a reference system moving with the wind-generated near-surface
7 | water current. To this end, the wave spectrum must therefore be transformed from absolute f_a to intrinsic
8 | frequencies f_i , i.e. those that would have been recorded by a probe moving with the current. Indeed, for waves
9 | propagating over a moving medium, the Doppler effect modifies the observed frequency of each elementary
10 | periodic wave that makes up the random wind field (Lindgren et al., 1999). This effect can be particularly large for
11 | short waves at sea (hence modifying the slope of the high-frequency spectrum tail; Benetazzo et al., 2018), and so
12 | in a wave tank where waves are generally short whilst the current speed can be a non-negligible fraction of the
13 | wave phase speed.

14 | For harmonic waves in the limit of small wave steepness and neglecting the modulation of short waves by long
15 | waves (Longuet-Higgins and Stewart, 1960), the relation between f_a and f_i is given by (Stewart and Joy, 1974):

$$f_a - f_i - [ku_w \cos(\theta - \theta_U)] / (2\pi) = 0 \quad (3)$$

16 | where u_w is an appropriate (Kirby and Chen, 1989; Stewart and Joy, 1974) water velocity vector (of direction θ_U),
17 | and θ the wave direction. At the leading order, it is assumed that the dispersion relationship of the gravity-capillary
18 | wave theory provides a unique relationship between the frequency f_i and the wavenumber k as follows:

$$2\pi f_i = \sqrt{gk + \frac{T}{\rho} k^3} \quad (4)$$

19 | with T the water surface tension, ρ the water density, and g is the gravity acceleration. In accordance to Eq. (3),
20 | the spectral representation in absolute frequencies experiences a shifting of the energy distribution (see Figure 5
21 | below). In our case, we ~~assume~~consider that short waves in the tank mostly feel the surface current drift ~~and~~but
22 | we neglect the Doppler shift associated with the orbital motion of long waves. That drift can be estimated by the
23 | wind speed ~~(see later)~~, and reasonably in the tank assumed aligned with the waves (namely, $\theta = \theta_U$). Hence, the
24 | frequency spectrum in intrinsic coordinates ~~may~~can be derived as

$$E(f_i) = E(f_a)J_{ai} \quad (5)$$

1 where $J_{ai} = |df_a / df_i|$ is the Jacobian of the transformation, which in the limit of deep water can be written explicitly
 2 as

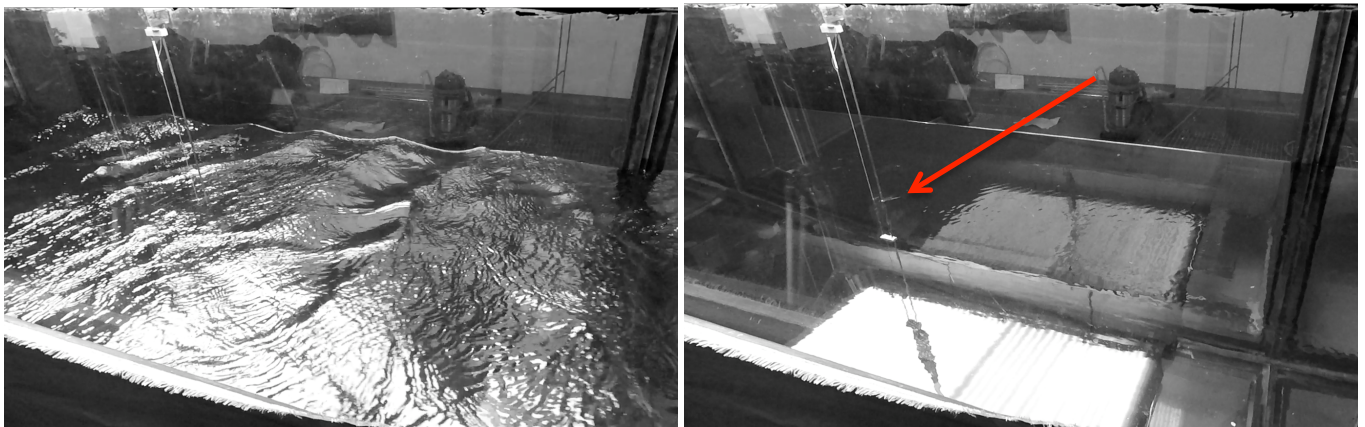
$$J_{ai} = |1 + 2u_w \sqrt{gk + \frac{T}{\rho} k^3} / (g + 3\frac{T}{\rho} k^2)| \quad (6)$$

3 ~~4 The basic results~~ Results

4 ~~We analyse and discuss in sequence the results of each set of experiments. We draw progressively our conclusions,~~
 5 ~~each one to be then possibly utilised for the analysis of the later sets.~~

6 **4.1 Wind waves without and with oil**

6 We begin the examination of the change of gravity-capillary wave properties caused by the fish oil film by
 7 analyzing the effects on the water elevation z and wind speed profile $U_a(h)$ during the experiments W06 ($U_r = 6$ m/s
 8 and clean water) and W06-O (the same as W06, but with oil slick). For the latter, the wind wave field attenuation
 9 due to the Marangoni forces is readily visible in Figure 2 that shows two pictures of the water surface (taken nearby
 10 the 20-m ~~fetch of 20-m~~) without (left panel) and with (right panel) ~~the~~ oil instillation. After the oil film is spread on
 11 the water, the surface is largely smooth, with only tiny elevation oscillations (1 mm at most; see Figure 4) and there
 12 appears to be no organized wave motion (see also the videos available as supplementary material SM1:
 13 <https://doi.org/10.5281/zenodo.1434262>). ~~The~~ It is obvious that the presence of an extremely thin (practically
 14 mono-molecular) layer of oil on the surface alters heavily the air-sea interface properties. ~~It is instructive to~~ We
 15 analyze the situation first from the air, then from the water, point of view.



16

1 **Figure 2: Two photographs showing the water surface condition at fetch of about 20 m taken without (left panel) and with oil**
 2 **instillation (right panel). On both cases the water surface was forced with a reference wind speed $U_r = 6$ m/s (blowing from left to**
 3 **right on the pictures). The wave probe G4 is visible on the left-hand side of both pictures. The red arrow in the right panel points to**
 4 **the oscillating flow (vortex shedding) past the probe. See also the video available as supplementary material SM1.**

5 **4.1.1 Airflow characterization**

6 We begin evaluating the air-side stress due to the wind drag on the water surface. ~~In this respect, the wind speed~~
 7 ~~vertical profile above the water surface was approximated using the Pitot tube records of the along-channel air~~
 8 ~~speed profile, namely $U_a(h)$. For an aerodynamically rough airflow, the along-channel component of the mean wind~~
 9 ~~speed \bar{U} in the outer turbulent layer at height h above the boundary is expected to follow a self-similar Karman-~~
 10 ~~Prandtl logarithmic law as a function of height~~

$$\bar{U}(h) = \frac{u_*}{\kappa} \log\left(\frac{h}{h_G}\right) \quad (8)$$

11 ~~where the overbar indicates the temporal averaging process, u_* is the friction velocity along the same direction as~~
 12 ~~\bar{U} , $\kappa = 0.41$ is the von Kármán's constant. The non-zero parameter h_G has the meaning of the roughness height~~
 13 ~~where \bar{U} appears to go to zero (namely h_G is the virtual origin of the mean velocity profile). In presence of waves,~~
 14 ~~the shape of the wind velocity profile $\bar{U}(h)$ is governed by both turbulent and wave induced momentum flux, the~~
 15 ~~latter being function of the source term S_{in} (the transport of horizontal momentum due to molecular viscosity is~~
 16 ~~considered negligible, except very near the surface where the vertical motion is suppressed). The total air-side~~
 17 ~~shear stress τ_a at the boundary of the flow is then approximated as~~

$$\tau_a = \rho_a u_*^2 \quad (9)$$

18 ~~with ρ_a the air density.~~

19 ~~To account in Eq. (8) for the non-slip condition, the measured airflow velocity $U_a(h)$ has to be taken relative to~~
 20 ~~along-wind components of the water velocity u_{w0} at $h = 0$, namely $U(h) = U_a(h) - u_{w0}$. It is thus assumed that the~~
 21 ~~mean water surface drift velocity u_{w0} constitutes the boundary condition at $h = 0$ for the vertical profile of the~~
 22 ~~airflow velocity. Wu (1975) found that at the air-water interface, the wind-induced current is proportional to the~~
 23 ~~friction velocity of the wind, and it results from the wind shear, Stokes drift, and momentum injection during wave~~
 24 ~~breaking events. For non-breaking wavy surfaces, the wind-induced surface current was determined to be around~~
 25 ~~50% of the airflow friction velocity (Phillips and Banner, 1974 and Wu, 1975). In a (clean water) wind-wave tank~~
 26 ~~and at steady conditions the value of u_{w0} can be related to the maximum value of $U_a(h)$ which is not achieved at the~~

largest distances from the water due to the presence of the tank roof. A value u_{w0} around 3.3% of the free stream maximum wind velocity seems to be a reasonable approximation (Liberzon and Shemer, 2011; Peirson, 1997; Wu, 1975) and was used in this study.

In the experiment W06 the maximum value of $\bar{U}_a(h)$ of 6.06 m/s was found, attained at the third Pitot tube, namely at $h = 28.3$ cm from the still water surface. Hence, accounting for a surface water speed $u_{w0} = 6.06 \times 0.033 \approx 0.2$ m/s, a logarithmic curve was fitted (the mean absolute error of the fitting is 0.01 m/s) to the average profile $\bar{U}(h) = \bar{U}_a(h) - u_{w0}$ shown in Figure 3 and the two parameters $u_* = 0.29$ m/s and $h_0 = 0.1$ mm were estimated accordingly. For the lowest Pitot tube ($h = 8.3$ cm), the dimensionless height $h_* = gh/u_*^2$ is 9.7, implying that ~~up~~ from there upward wind data were collected in a region where turbulent stresses are expected to dominate over wave-induced stresses (Janssen and Bidlot, 2018). The typical viscous sublayer thickness approximated as $11.6\nu/u_*$ measured ~~0.04–6~~ mm, ~~such that~~ and the atmospheric boundary layer ~~appears~~ may be characterized as aerodynamically smooth ~~to be aerodynamically rough~~. The wind shear stress τ_a based on the measurement in this layer equals 0.10 N/m². The equivalent wind speed at height $h = 10$ m, extrapolated from Eq. (1) ~~(8)~~, is $\bar{U}_{10} = 8.6$ m/s, which is in satisfactory agreement with the typical relation between u_* and \bar{U}_{10} found in a wind-wave tank filled with clean water (Liberzon and Shemer, 2011; Mitsuyasu and Honda, 1986). The neutral drag coefficient measured at ~~10–10~~-m height and defined as $C_D = (u_*/\bar{U}_{10})^2$ is 1.1×10^{-3} . The values of u_* and h_0 are in agreement with those obtained in the experimental results of Liberzon and Shemer (2011), and those estimated by the bulk parameterization of air–sea turbulent fluxes provided by the Coupled Ocean–Atmosphere Response Experiment (COARE) algorithm (Fairall et al., 2003) that gives $\tau_a = 0.11$ N/m², using as input the profile $\bar{U}(h)$ determined in our experiments.

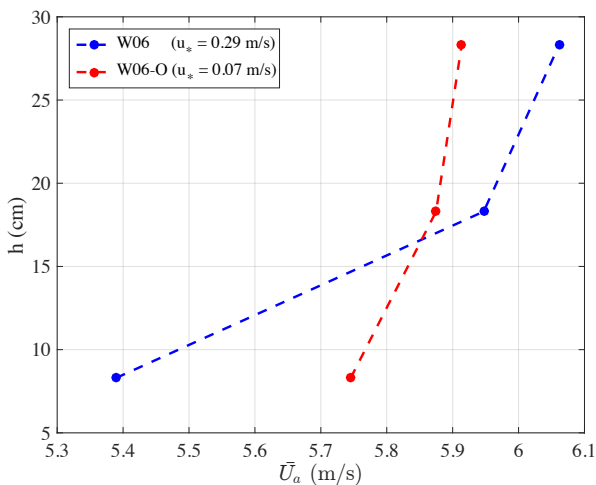


Figure 3: Vertical profile of ~~the mean horizontal wind speed~~ the wind velocity component \bar{U}_a measured over the water surface at fetch $X = 11.5$ m. Reference wind speed $U_r = 6$ m/s. Clean water conditions (blue) and oil-covered surface (red). In the legend, the value of the airflow friction velocity u_* is shown within brackets. Only the value recorded at the three lowest Pitot tubes are shown.

The smoothing of the water surface in presence of oil reflects on the airflow, which differs from that over clean water and has a smaller vertical gradient $d\bar{U}_a/dh$ of the wind speed (Figure 3). Because of the reduction of the resistance on the water surface, the wind speed strengthens over the film-covered surface, but the effect is limited to the lowest part of the turbulent airflow. Similar behavior was observed in the wind-wave tank experiments by Mitsuyasu and Honda (1986). For continuity reasons, i.e. for the (practically) constant airflow discharge in the tank (the difference of the discharges measured by the Pitot tubes is smaller than 1%), a less steep wind profile implies a lower velocity (with respect to the clean water case) in the central line of the flow (with oil the maximum value of $\bar{U}_a(h)$ was 5.91 m/s).

In the case of the oil film-covered surface, a problem arises, i.e. if the 3.3%-rule still holds to determine the surface current drift from the wind speed. The problem stems from the fact that for clean surfaces the momentum flux to the water column (i.e. for the generation of current) is the sum of the flux transferred across the air-sea interface not used to generate waves and the momentum flux transferred by wave breaking. In terms of spectral quantities the stress to the water column τ_w can be computed as

$$\tau_w = \tau_a - \rho_w g \int_0^{2\pi} \int_0^{k_{\max}} \frac{k}{\omega} (S_{\text{in}} + S_{\text{nl}} + S_{\text{di}}) dk d\theta \quad (7)$$

where we have omitted the direction of the flux that we assume aligned with the flume main axis. On the right side of Eq. (7), the S terms represent the net effect of sources and sinks for the wave energy spectrum (see Appendix A). In the high-frequency equilibrium range, the momentum coming from the wind and nonlinear interactions is dissipated, and is therefore directly transferred to the water column.

The balance in Eq. (7) is plainly altered for ~~the-an~~ oil-covered surface ~~analyzed in this study~~, as it is visible in the right panel of Figure 2, for which we assume $S_{\text{in}} + S_{\text{nl}} + S_{\text{di}} = 0$. In this case, the wave-induced transport ~~becomes negligible~~ is practically null, and ~~hence~~ the total current drift is supported only by the stress ~~exerted~~ τ_a exerted by ~~the~~ wind at the air-sea interface. In this respect, from visual inspection of the supporting movies acquired during the experiments (see the video available as supplementary material SM1), we did observe the presence of a water surface drift and a high-frequency oscillating flow (vortex shedding) downstream from the probes' beams (the shedding at G4 is pointed by the red arrow in the right panel of Figure 2). The latter implies the

1 presence of a near-surface drift impacting the probes. No adequate instrumentation (e.g. Particle Image
2 Velocimetry; see e.g. Adrian, 1991) had been designed in advance to obtain a representation of the fluid flow close
3 to the wavy air-water interface.

4 However, the availability of video-camera images allowed two independent estimates of near-surface water
5 drift. The first one was possible tracking the motion of tiny bubbles moving on the water surface along the tank and
6 clearly visible in the 1920x1080 pixel images captured at 60 Hz by a video-camera placed outside the tank, close to
7 the probe G4. A detailed description of the procedure is given in Appendix [A.B](#). The distribution of the so-defined
8 surface speed has [a](#) mean value of 26 cm/s and standard deviation of 11 cm/s. ~~Albeit~~ [Despite](#) the relatively large
9 variability, such observations clearly show that, even if the stress on the water surface is largely reduced by the oil
10 film, a surface current is still present whose order of magnitude is comparable with what one expects in clean
11 water. A possible objection to this approach is that the bubble motion could be due, partly at least, to the wind drag.
12 However, this estimate, albeit with some approximation, is supported by the second indirect estimate. On the right
13 panel of Figure 2 the wave probe across the surface is clearly visible, and there [is](#) a “wake” behind it. Indeed, as we
14 will soon discuss, the wave spectra show an isolated peak around 10 Hz that we interpret as due to the vortex
15 shedding caused by the surface current flowing around the probe support (diameter $d = 4$ mm). Use of the related
16 vortex shedding frequency $f \approx 0.21u_{w0,oil} / d$ (see later in subsection 4.1.2) suggests $u_{w0,oil} = 20$ cm/s that is close
17 (actually less than) the estimate using bubbles (which probably were partially also drifted by wind).

18 With this information, we have found that the wind stress for oil-covered smooth surface is $\tau_{a,oil} = 0.005$
19 N/m^2 , approximately 5% of τ_a , and the drag coefficient undergoes a decrease of one order of magnitude. The
20 extrapolated 10-m height wind speed $\bar{U}_{10,oil}$ is 6.3 m/s, smaller than \bar{U}_{10} , in contrast to the field observations of
21 Ermakov et al. (1986), most likely because our observations were collected in a tank with an upper roof. The
22 roughness height was determined to be ~~very close to zero~~ [\$h_0 < 10^{-6}\$ m](#), implying that the air boundary layer for the
23 oil-covered water shows properties of a hydrodynamically smooth flow. This ~~conclusion~~ [result complements those](#)
24 [of supports the idea presented in](#) Mitsuyasu and Honda (1986) and ~~discussed by~~ Mitsuyasu (2015), who ~~showed~~
25 [observed also](#) that for low wind speeds (few meters per second) [and short fetches](#) the water surface [aerodynamic](#)
26 properties are similar in clean water and in water with ~~oil~~ [surfactant](#). [Indeed, in those studies the surfactant only](#)
27 [partially suppressed the wind-wave field, while, on the contrary, the use of fish oil in our experiments cancels the](#)
28 [wind-wave generation process such that the water surface is felt as smooth by the airflow.](#)

4.1.2 Wave field characterization

In presence of the viscoelastic oily film, the gravity-capillary wave damping is quantified by analyzing the time records $z(t)$ of the sea surface elevation field at different fetches. In this respect, Figure 4 (left panel) gives a clear idea of the Marangoni damping effect, which can be quantified by noting that the standard deviation σ of $z(t)$ shrinks by one order of magnitude. However, ~~the process does not involve only a decrease~~ the process involves more than a decrease of the vertical oscillations, as it is the whole spatio-temporal distribution of the surface elevations that is abruptly changed (right panel of Figure 4). Indeed, whereas in clean water, in active wave generation, the histogram of z (high-pass filtered above 1 Hz; see discussion below) has a positive skewness coefficient (as it is expected for wind-waves; see Longuet-Higgins, 1963), in presence of oil the empirical histogram is quasi-symmetric around the mean (the skewness coefficient is -0.03, very close to zero). This implies that for slick-covered surfaces the generation and evolution of gravity-capillary waves are governed by different balance and process, which are dominated by the reduced wind input and the Marangoni energy sink, which lead to a quasi-Gaussian surface elevation field at all scales.

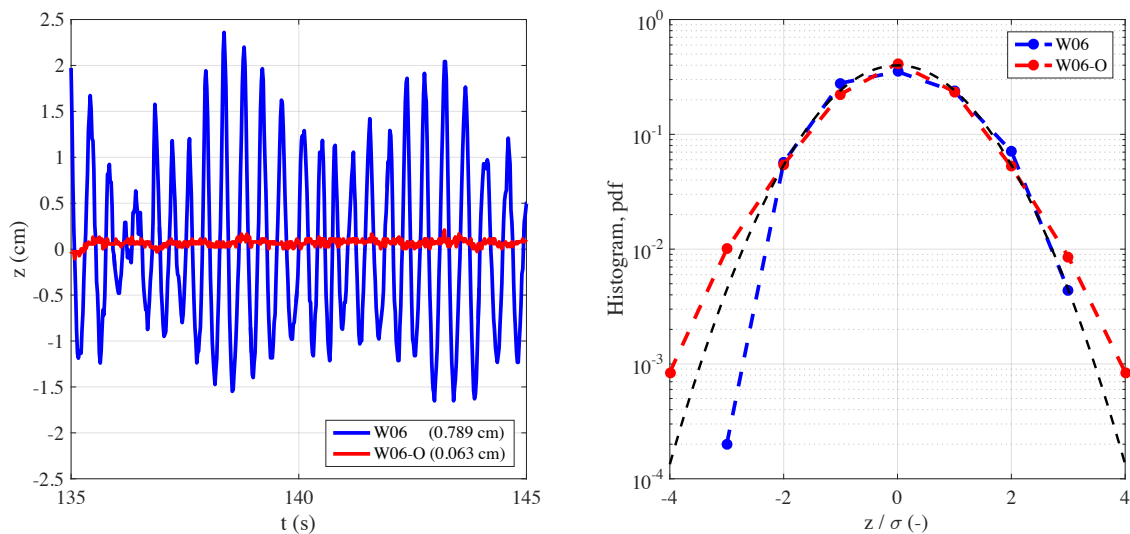
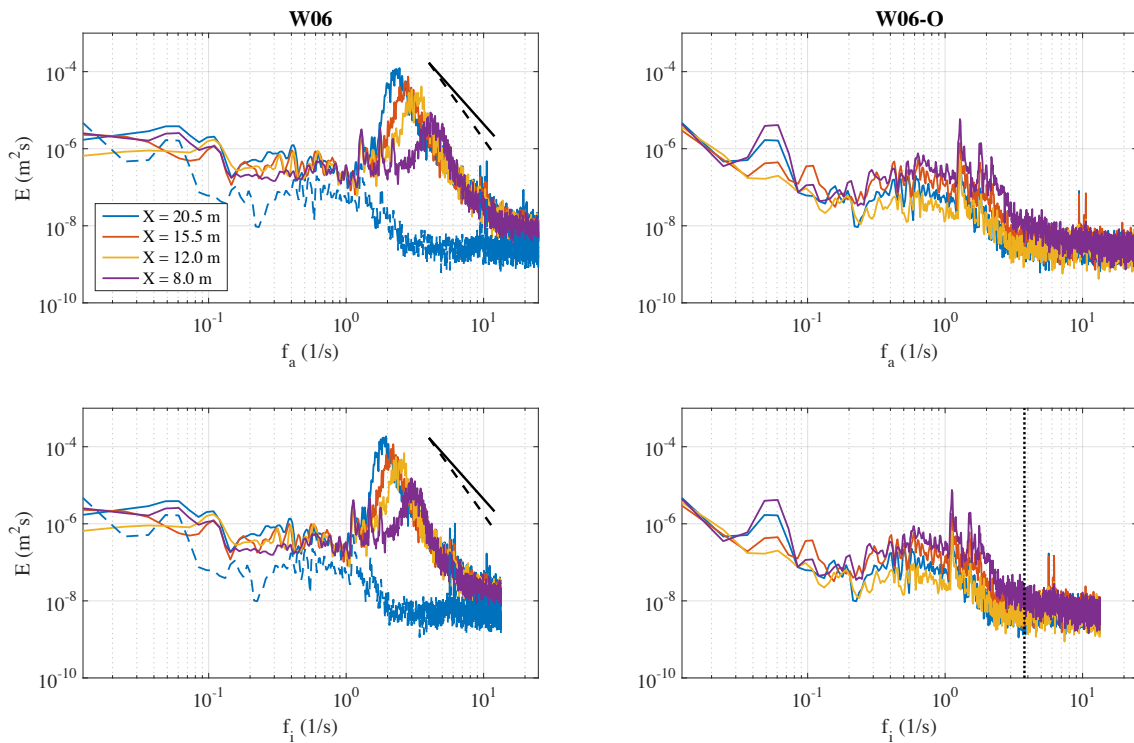


Figure 4: Sea surface elevation for clean (blue) and slick-covered (red) surface. (left) ~~Extract~~ Excerpt of the single-point record $z(t)$ at $X = 20.5$ m (probe G4) for the two conditions with clean water (experiment W06) and after the oil instillation (W06-O). In the legend, the value of the standard deviation σ of $z(t)$ is shown within brackets. (right) Histogram of the normalized elevations, high-pass filtered above 1 Hz (~~see discussion below~~). The black dashed line shows the Gaussian probability density function (pdf).

The most general and quantified view of the effect of oil is provided by the energy spectra $E(f_a)$ and $E(f_i)$ (respectively absolute and intrinsic frequency) of water elevations. These are shown in Figure 5, for experiments W06 (left panel) and W06-O (right panel). For a more direct comparison the G4 oil spectrum is reproduced in the

1 no-oil diagram (dashed blue line). The spectrum $E(f_i)$ was computed using the Jacobian transformation described in
 2 section 3.2 and assuming all ~~wavenumbers as shifted by the same current equal to that on the surface, namely~~
 3 wavenumbers are shifted by the surface current $u_{w0} = 0.2$ m/s. Note in the “intrinsic” spectrum the expected shift
 4 towards lower frequencies, more evident in the right side of the spectrum where higher frequencies move with a
 5 lower speed with respect to the current. ~~As physically sound, from now on all our considerations we only will deal~~
 6 with the intrinsic-frequency quantities. Starting with clean water conditions (left panels), the variation of the wave
 7 spectra with fetch is characterized by the expected downshift and overshoot of the peak of the spectrum. The total
 8 wave energy increases with fetch: the significant wave height H_s grows from 1.21 cm at the shortest fetch ($X = 8$
 9 m) ~~fetch~~ to 3.16 cm at $X = 20.5$ m. It is remarkable that for the slick-covered surface, there is no evidence of wave
 10 growth with fetch (right panels).



11

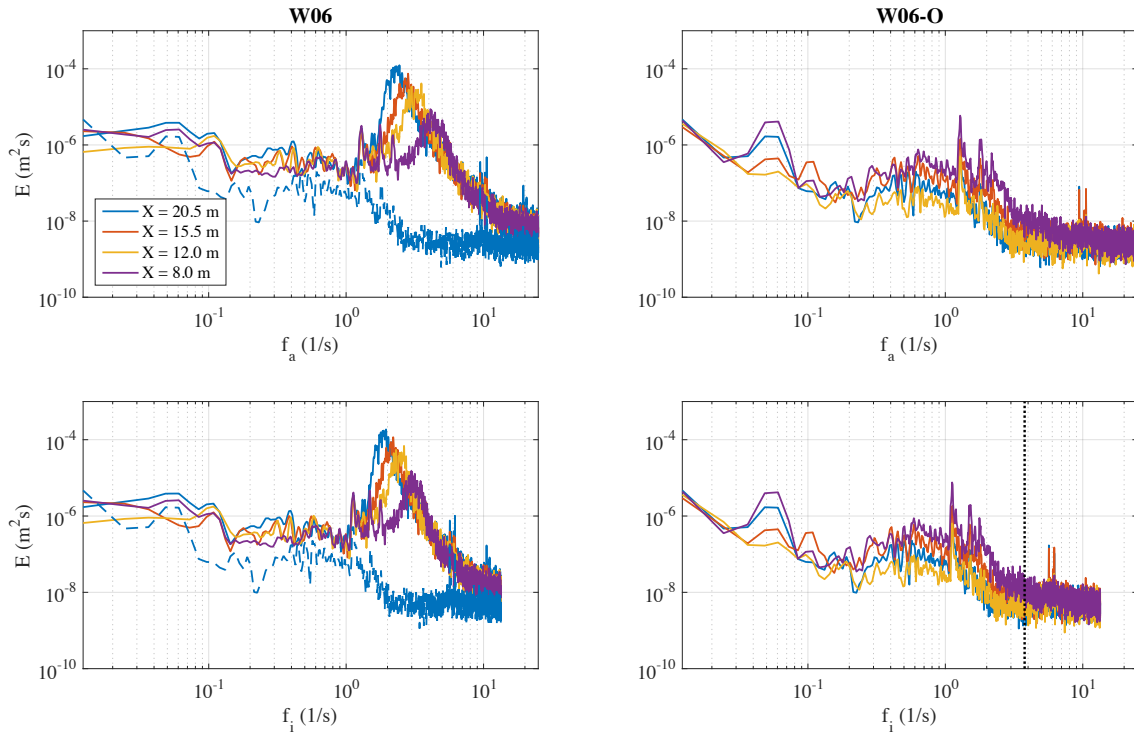
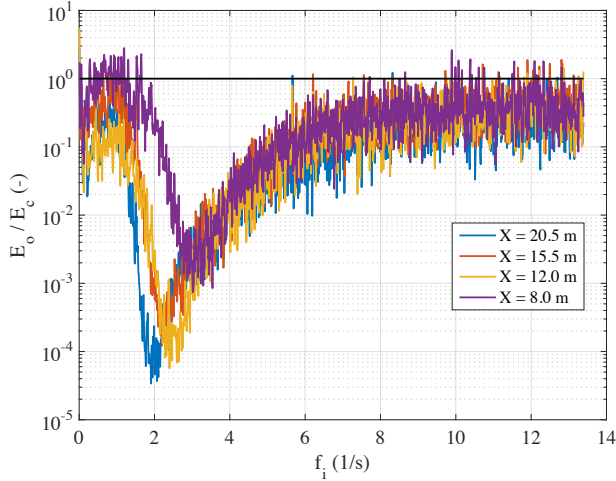


Figure 5: Wave energy spectra $E(f_a)$ and $E(f_i)$ of the water surface elevation $z(t)$ at different fetches. Reference wind speed $U_r = 6$ m/s. (left) Clean water experiment W06. (right) Water with oil experiment W06-O (the spectrum at the fetch $X = 20.5$ m is replicated with a dashed blue line on the left panels). The black solid and dashed lines are the reference spectral shape proportional to f^{-4} and f^{-5} , respectively. The vertical gray dotted line on the bottom-right panel shows the fish oil resonance frequency $f_{res} = \omega_{res}/(2\pi) = 3.77$ Hz.

Focusing for the time being on the comparison among the oil and no-oil cases, the differences are obviously macroscopic, but it is worthwhile to analyse them for different frequency ranges. For low frequencies, say below 1 Hz, there is clearly some energy also in the oily spectra. Note the peaks (around 0.05 Hz) at the G1 and G4 spectra, reduced at G2 and G3. Remembering (see Section-32) the longitudinal natural frequency of the tank, we interpret these as “seiches” of the wave tank, obviously more visible the further the gauges are from the center of the tank. In the clean water case more distributed oscillations exist, that we associate to a more active action of a possibly irregular wind flow. The most interesting range is of course between 1 Hz and 4 Hz (close to the fish oil resonance frequency). Here the effect of oil is macroscopic, with oil-case energy several orders of magnitude smaller than without oil. Finally, still for the oil spectra, no wave signal is visible above 3-4 Hz where we should expect the maximum damping of surface waves due to the oily surfactants (Alpers and Hühnerfuss, 1989).

A more direct comparison between the W06 and W06-O spectra is obtained showing in Figure 6 for each frequency the ratio of the respective spectral energies. If we represent the frequency/fetch-dependent damping

1 coefficient as the ratio $D(f_i, X) = E_o / E_c$ between the variance density spectrum of the water surface elevation with
 2 oil slick (E_o) and in clean water (E_c), we then find D values as small as 10^{-4} at the longer fetches. Of course the
 3 maximum differences are at the peak frequency of the no-oil spectra, the respective frequency and ratio decreasing
 4 with fetch while the no-oil energy increases.



5
 6 **Figure 6: Damping of the wave energy for oil-covered water surface. The damping coefficient is evaluated as the ratio $D = E_o / E_c$**
 7 **between the variance density spectrum of the water surface elevation with oil slick (E_o) and in clean water (E_c). The solid black thin**
 8 **line shows the level $E_o = E_c$.**

9 ~~For a non-trivial detail of how to~~To interpret the data from the experiments ~~it is instructive to plot~~
 10 ~~we~~ analyze how wave energy depends on fetch. In Figure 7 we show how the corresponding surface elevation (high-
 11 pass filtered above 1 Hz) variance $\sigma^2 = \langle (z(t) - \langle z(t) \rangle)^2 \rangle$ (the angle brackets $\langle \ \rangle$ denote the ensemble average)
 12 varies for the clean water and oil cases. Granted the different orders of magnitude, it is macroscopic that, while the
 13 ~~clean-water~~ wave energy in clean water grows with fetch, the opposite is true (or is suggested to be) with oil. To
 14 quantify better the fetch dependence we have fitted a power law

$$\sigma^2 = \alpha X^\beta \quad (8)$$

15 to the water surface variance σ^2 versus fetch X . The ~~values of best fit parameters~~ α and β , ~~respectively,~~ are
 16 tabulated, respectively, in the legend of Figure 7 (with σ^2 in cm^2 and X in m).

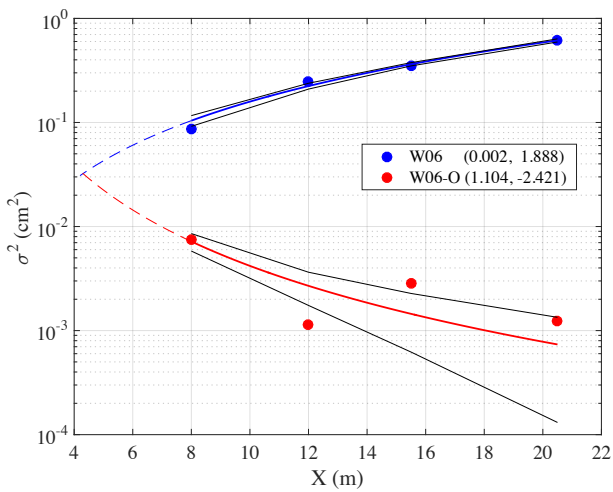
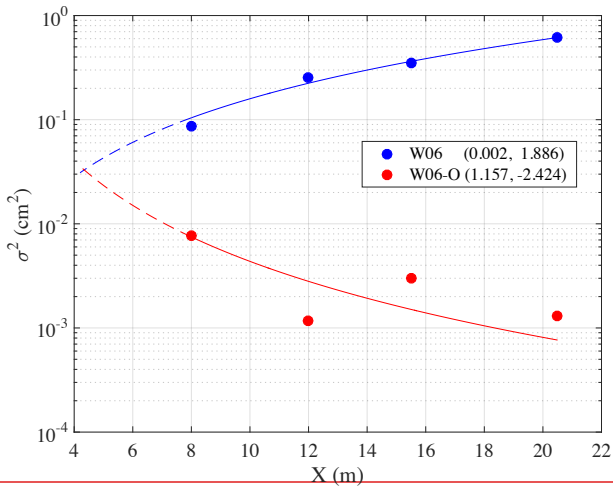
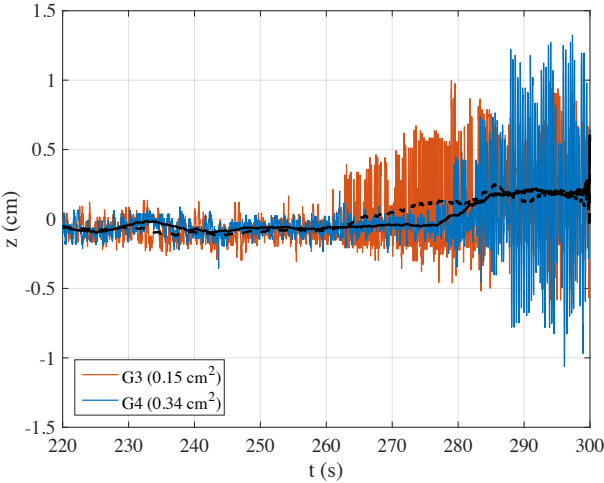


Figure 7: Spatial evolution of the water surface elevation variance σ^2 (filled markers) in clean water (W06) and with fish oil slick (W06-O). The solid blue and red lines are the power law-type function $\sigma^2 = \alpha X^\beta$ fitting the observations (in the legend, the coefficient α and β , respectively, are tabulated), while the dashed lines show the law extended outside the observed data interval. The root-mean-square error for the fitted function is 0.027 cm^2 and 0.002 cm^2 for W06 and W06-O, respectively. The black lines show the prediction bounds (confidence level of 50%) for the fitted curves.

Prolonged in the figure backwards out of the experimental range in the figure, the two fitted laws intersect each other around $X = 4 \text{ m}$. This suggests an explanation. This is the fetch at which oil was introduced into the tank. Note that in the W06-O experiment oil was continuously instilled during the experiment. This was because the wind, acting on the surface oil and creating, as we have seen, a current, tends to push it along the tank faster than the oil tends to distribute uniformly on the surface (with radial speed around 14 cm/s). Indeed this was is smaller than the surface speed of the oily water surface we have discussed and derived in the previous sub-section discussing the airflow characterization for the oil-case. While the continuous, although very limited, instillation of oil during W06-O ensured the presence of oil film from the instillation point onwards, the wind, acting from fetch

1 $X = 0$ m, was pushing the oil away from the first four-metre zone where therefore waves could be generated, hence
 2 equal, in both the oil and the no-oil cases. Therefore the “oil” energy we see in Figure 7 at eight-metre fetch is the
 3 remnant of the one previously generated and already partially dissipated (between the 4 and 8 m fetches) due to the
 4 acting Marangoni forces. ~~Incidentally, this explains one point we had deliberately avoided while discussing the~~
 5 ~~spectra in Figure 5, i.e.~~ why the highest energy in the oily spectra (right panel) is in the first spectrum, i.e. the
 6 shortest fetch.

7 The shift along the tank of the surface oil film due to the wind drag is also well illustrated by the results of
 8 the experiment W06-O-NI, i.e. when, starting with a layer of oil well distributed on the water surface in the tank,
 9 we did not further instillate oil during the action of the wind (reference wind speed $U_r = 6$ m/s). The resulting
 10 records at $X = 15.5$ m (G3) and 20.5 m (G4) are shown in Figure 8. It is obvious that around 262 ~~see~~s the effect of
 11 oil is beginning to vanish at G3, followed 15-20 s later by a similar result at G4. Note that this does not mean the
 12 whole oil was pushed past G3 at 262 ~~see~~s. Were this the case we should see in the record the already (up to G3
 13 position) generated waves. Rather, the oil edge is getting close enough to let G3 feel the consequences, which are
 14 different from those at G4: in the range [290 s, 300 s] H_s grows from 1.56 cm (G3) to 2.34 cm (G4), conveying the
 15 fact that a longer fetch was progressively made clean by the near-surface water drift. The progressively increasing
 16 space free of oil is also manifest in the record of each probe, where the basic wave period tends to increase with
 17 time.



18
 19 **Figure 8: Sea surface elevation at probes G3 ($X = 15.5$ m) and G4 ($X = 20.5$ m) for an initially slick-covered surface without oil**
 20 **instillation (experiment W06-O-NI). The dashed and solid black lines show the smoothed elevations (moving average of size 5 s) at**
 21 **G3 and G4, respectively. In the legend, the variance of $z(t)$ within the range of $290 \text{ s} \leq t \leq 300 \text{ s}$ is reported.**

1 In the experiment W06, spectra at the longer fetches (probes G3 and G4, see Figure 5) show two highly
2 energetic and very close peaks around the frequency $f_a \approx 10$ Hz. As mentioned in section 4.1.1, our interpretation is
3 that they are originated by the vortex-induced vibrations at the cylindrical holding beams of the probes. Indeed, the
4 frequency f_v at which vortex shedding takes place is related to the Strouhal number by the following equation:

$$St = \frac{f_v d}{u} \quad (9)$$

5 where St is the dimensionless Strouhal number, f_v is the vortex shedding frequency, d is the diameter of the body,
6 and u is the flow velocity. The Strouhal number depends on the Reynolds number, but a value of 0.21 is commonly
7 adopted (Steinman, 1946). Adopting $d = 0.4$ cm (the diameter of the probe's holding beam) and $u = 20$ cm/s, the
8 vortex frequency is $f_v = 10.5$ Hz, consistent with the experimental evidence. Elaborating this point further, it is
9 worth noting that similar spectral peaks (as energy and frequency) have been found also during the W06-O
10 experiment. In our interpretation, this evidence supports the fact that the water surface drift was generated by the
11 wind friction also in presence of oil, and that its magnitude is consistent with the one expected in clean water
12 conditions.

4.2 Wind and paddle waves without and with oil

13 The second series of experiments was done adding mechanically-generated paddle waves to the wind-generated
14 ones, both in clean water and in water with fish oil. ~~Within the general purpose of a better understanding of the~~
15 ~~related air-sea interactions, w~~We had two specific purposes. The first one was to explore the influence of pre-
16 existing relatively long waves (the paddle generated ones) on the local generation of wind waves. The second
17 purpose was how this interference was modified by the presence of fish oil. ~~This~~ese second set of experiments
18 (namely W08-P and W08-P-O) was done with 8 m/s ~~nominal-reference~~ wind speed. ~~Of course a~~ 6 m/s ~~value~~
19 ~~reference speed~~ would have allowed a more direct comparison with the results obtained without paddle waves
20 (previous section). At the same time, a higher wind speed was useful to better highlight the interaction with the
21 paddle waves. ~~Originally we had planned two full sets of parallel experiments. However, as mentioned in section 2,~~
22 ~~the strict condition of analyzing only good quality data left us with what is listed in Table 1. As we have seen and~~
23 ~~will see, the available data suffice for providing a number of remarkable results.~~

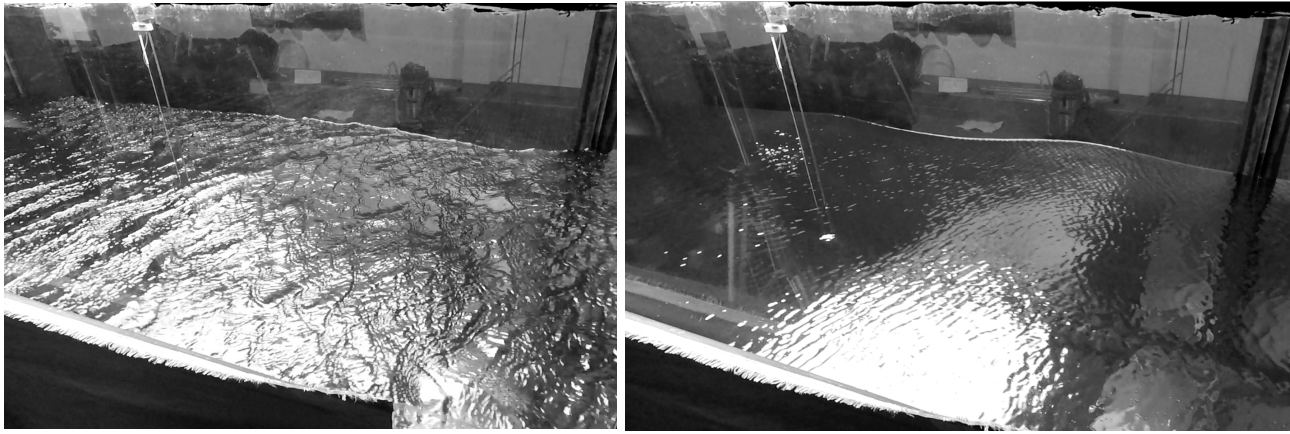
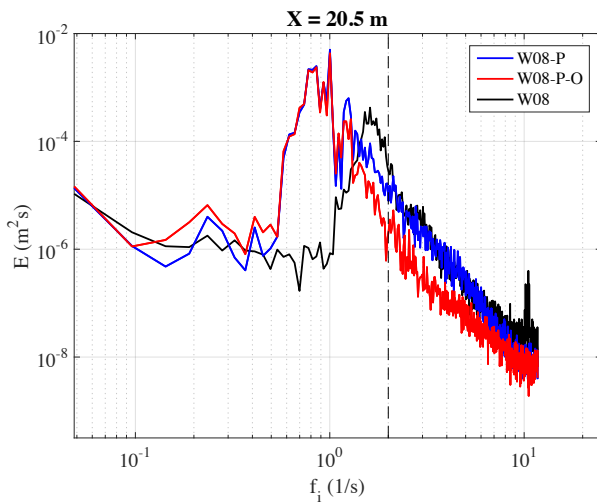


Figure 9: Two photographs of the water surface condition at fetch of about 20 m taken without (left panel, experiment W08-P) and with oil instillation (right panel, experiment W08-P-O) onto wind-waves (wind blowing from left to right of the pictures at the reference wind speed $U_r = 8$ m/s) and irregular paddle-waves. See also the videos available as supplementary material SM2.

In the tank paddle waves were ~~nominally~~ generated as a JONSWAP-like spectrum with nominal 6.2-2-cm significant wave height and 1.0-0-see peak period. On top of this wind waves were generated (~~within limits~~) by a the wind ~~reference 8 m/s wind (experiment W08-P)~~. The resulting ~~situation~~ surface wave field is shown in (Figure 9; (left panel), the picture being taken, as Figure 2, close to fetch $X = 20.5$ m. Starting with a qualitative perception from the image (see also the videos available as supplementary material SM2; <https://doi.org/10.5281/zenodo.1434272>), we derive, as expected from what is reported in the literature, that wind waves grow substantially less than expected in a pure wind sea (Wu, 1977). ~~Incidentally, f~~For a full comparison we also ran the W08 experiment, -with wind blowing at ($U_r = 8$ m/s without paddle waves and in clean water). ~~We will soon show also this result.~~ The comparison between Figure 2 and Figure 9 is even more striking considering the larger wind speed in Figure 9. Clearly the presence of the paddle waves has an effect. This is a matter of practical relevance for the cases when in the ocean fresh new waves are generated superimposed on a pre-existing swell (in this case propagating along the same direction). A more quantified comparison of W08-P versus W08 (i.e. with versus without paddle, respectively) is provided by the wave spectra shown in Figure 10. ~~Ignoring for the time being the oily results (experiment W08-P-O), w~~We see that the introduction of the irregular paddle waves (~~with a JONSWAP spectrum~~) cancels the wind wave peak of W08 at about 1.6 Hz. However, the tails of the two spectra somehow converge above 2.2 Hz. As we will soon see, with paddle waves the conditions did not allow the visual measurement of current.

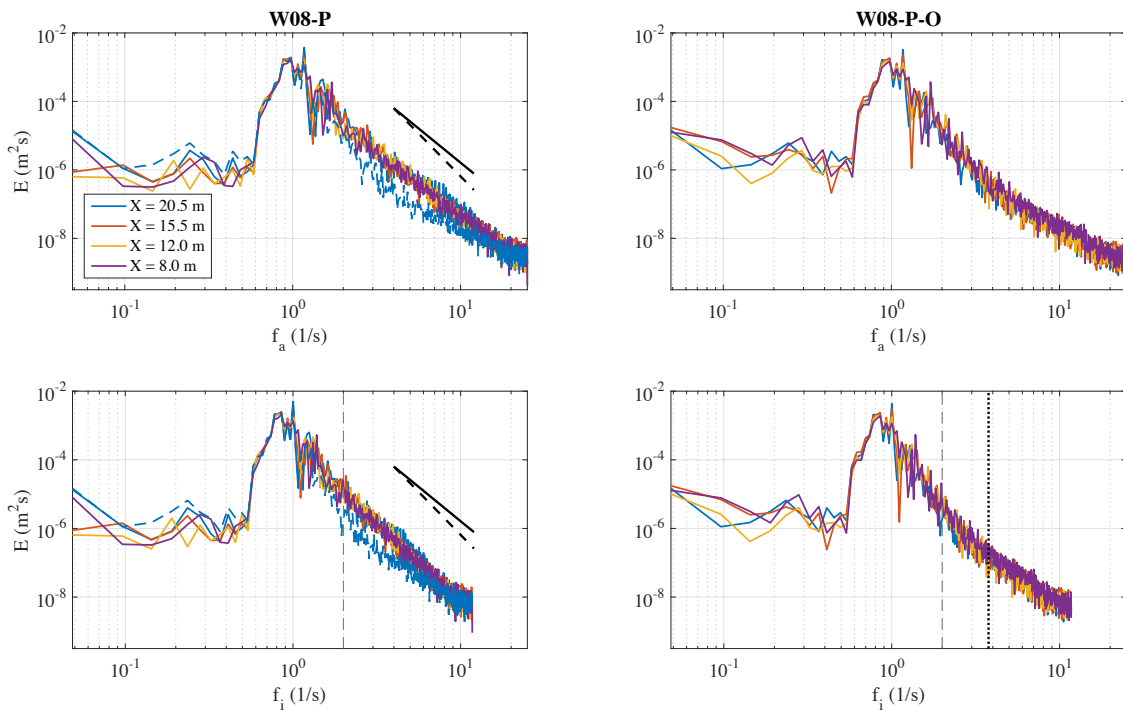


1
2 **Figure 10: Variance density spectrum $E(f_i)$ of the water surface elevation $z(t)$ at fetch $X = 20.5$ m (wave probe G4) in presence of co-**
3 **existing wind and paddle waves in clean water (W08-P), wind and paddle waves in water with oil (W08-P-O), and wind waves only in**
4 **clean water (W08). The dashed gray vertical line shows the maximum frequency (2 Hz) produced by the paddle.**

5 ~~In the open ocean, the influence of swell on local wind wave generation is a known fact. Hwang et al.~~
6 ~~(2011) discuss how the Tehuano wind generated waves, on the Pacific coast of Mexico, are affected by the~~
7 ~~incoming oceanic opposing swell. With some similarity, the cases of following or opposing swell seem to differ~~
8 ~~somehow in their physics. The “following swell” case was first studied by Mitsuyasu (1966) and later intensively~~
9 ~~by Donelan (1987) who suggested that a swell (in practice paddle waves; also his experiments were done in a wind-~~
10 ~~and paddle wave tank at the University of Miami, USA) induces a detuning of the resonance conditions for non-~~
11 ~~linear interactions among wind waves. Later, in the studies by Phillips and Banner (1974) and Donelan et al. (2010)~~
12 ~~the suggested explanation was the enhanced wind wave breaking due to the wind and paddle waves interactions.~~
13 ~~Also, the influence of paddle waves increases with their steepness. More recently, Chen and Belcher (2000)~~
14 ~~proposed the idea that the long wave exerts a drag on the airflow, which reduces the turbulent stress in the airflow~~
15 ~~that is available to generate wind waves.~~

16 ~~It is instructive to see~~ [We analyze](#) how the overall effect (both without and with oil) varies with fetch. The
17 related spectra are in depicted in Figure 11. Contrarily to the pure windy cases (experiments W06 and W08), there
18 appear to be no evident dependence on fetch of the wave energy. Our interpretation is the following. On the one
19 hand the disappearance of the wind sea energy peak in presence of long waves implies that [the](#) wind wave peak
20 does not develop with fetch. On the other hand, in water with oil, at higher frequencies the balance is between non-
21 linear interactions and Marangoni dissipation, which is only slightly depending on fetch. Note that, as clearly

1 represented in Figure 12, the attenuation is maximum around 3 Hz (smaller than the resonance frequency) and the
 2 maximum damping (D) of wind wave energy (see for comparison Figure 6) ~~is such that the level of damping (D) is~~
 3 ~~is two and-or~~ three orders of magnitude smaller than with only wind waves (experiments W06). This is the
 4 consequence of two parallel facts: less wind wave energy in presence of paddle waves, and a decreased efficiency
 5 of damping by oil film (as evident comparing the right panels of Figure 2 and Figure 9). ~~One explanation for this~~
 6 ~~latter effect is that the stretching, due to swell, of the thin (almost) mono-molecular layer of oil breaks its~~
 7 ~~continuity, hence decreasing its damping efficiency. Moreover, paddle-wave orbital motions de-phase Marangoni~~
 8 ~~and gravity-capillary waves making the resonance-type damping due to the oil film less effective.~~ These effects
 9 have impact also on the short wind waves, as the damping effect appears to cease at frequencies higher than 9 Hz
 10 (Figure 12)



11

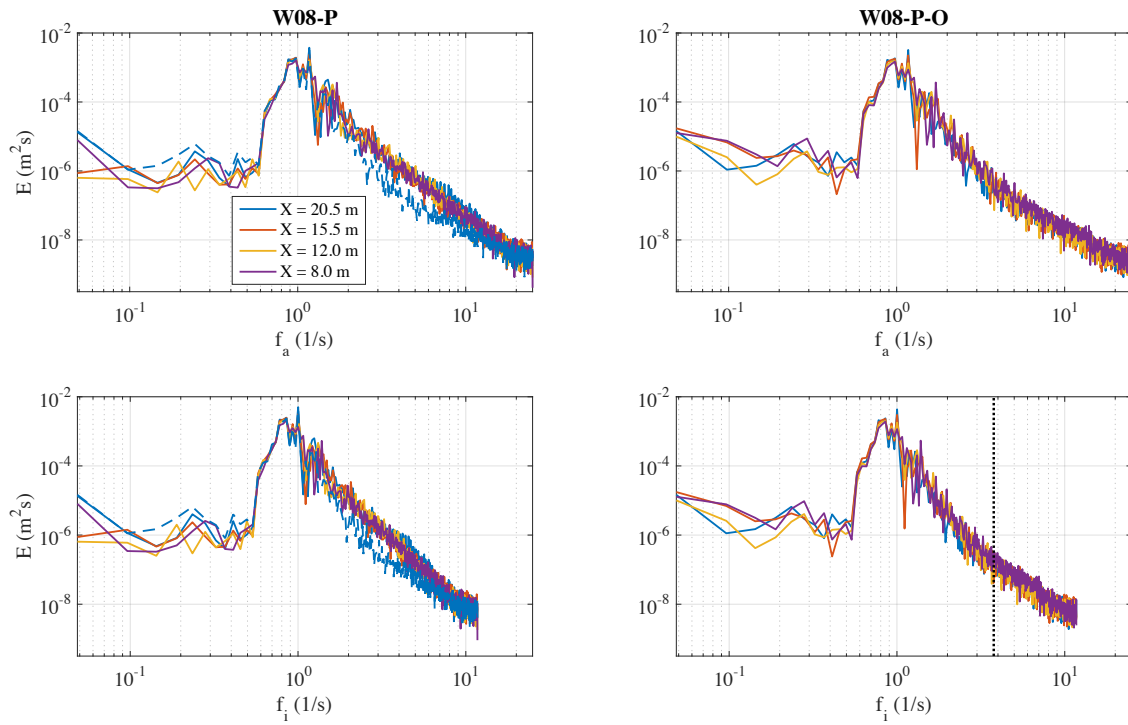


Figure 11: Wave energy spectra $E(f_a)$ and $E(f_i)$ of the water surface elevation $z(t)$ at different fetches for the reference wind speed of 8 m/s and irregular paddle waves. (left) Clean water experiment W08-P. (right) Water with oil experiment W08-P-O (the spectrum at the fetch $X = 20.5$ m is replicated with a blue-dashed blue line on the left panel). On left panels, the black-solid and dashed lines are the reference spectral shape proportional to f^{-4} and f^{-5} , respectively. On bottom panels the dashed gray vertical line shows the maximum frequency (2 Hz) produced by the paddle, and the vertical dotted black line on the bottom-right panel shows the fish oil resonance frequency $f_{res} = \omega_{res}/(2\pi) = 3.77$ Hz.

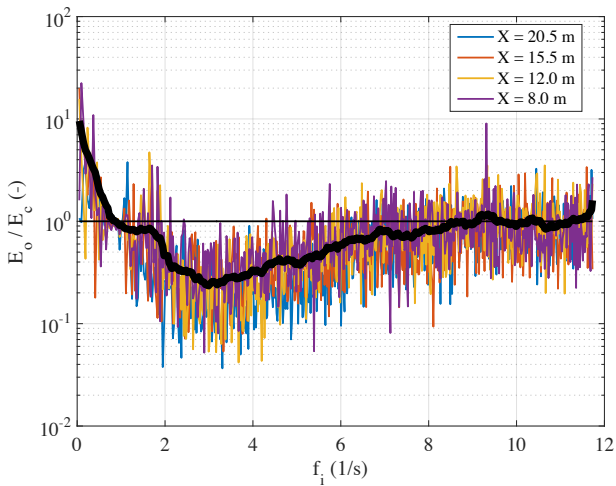
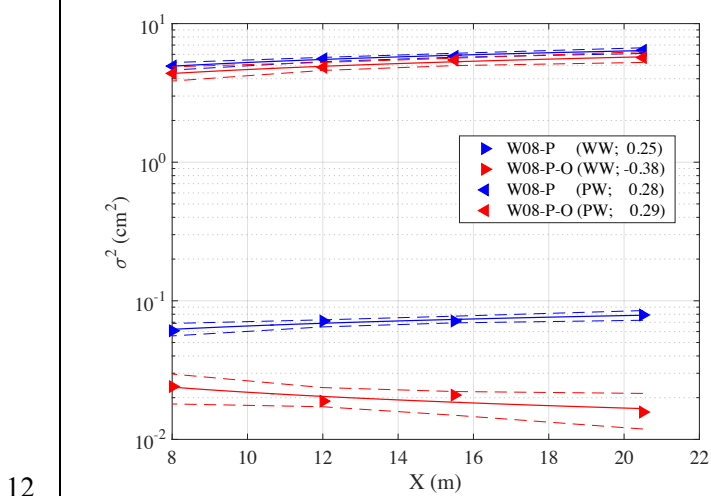
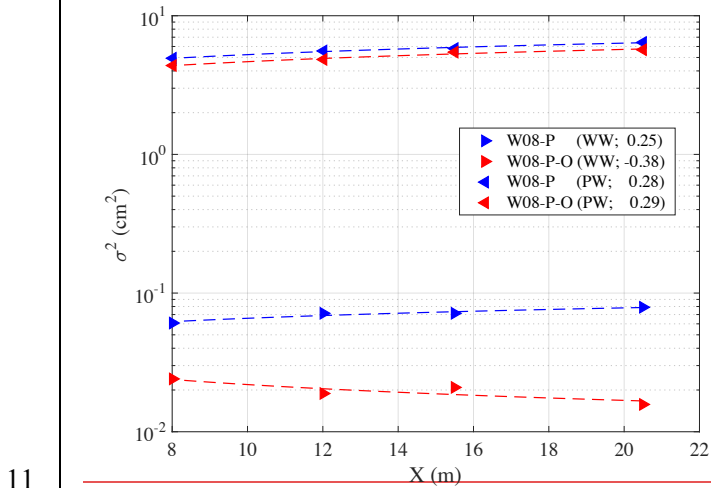


Figure 12: Damping of the wave energy for oil-covered water surface. The damping coefficient is evaluated as the ratio $D = E_o / E_c$ between the variance density spectrum of the water surface elevation with oil slick (E_o ; experiment W08-P-O) and in clean water (E_c ; experiment W08-P). The black-solid black thick line is the average shape of the damping coefficient (for the sake of clarity the series is smoothed with a moving average procedure). The solid black thin line shows the level $E_o = E_c$.

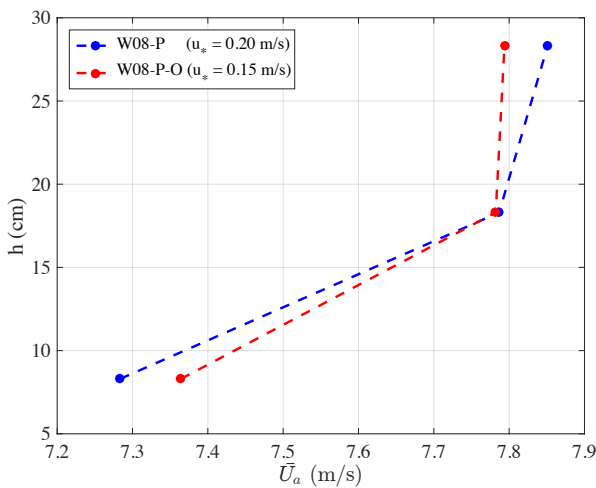
1 Similarly to what was done for the only wind-wave case (Figure 7), ~~it is instructive to~~ we check the small
 2 difference of energy (~~in practice wave height~~) with fetch of the two basic components (paddle and wind waves) of
 3 the spectra in clean water and in water with oil. The differences are ~~tiny~~small, and ~~barely are~~ visible in Figure 13.
 4 Because of the partial superposition of the two (paddle and wind) frequency ranges, we have computed, for the
 5 intrinsic spectra, the surface elevation variance below 1.3 Hz (PW in Figure 13, dominated by paddle waves) and
 6 above 2 Hz (WW in Figure 13, dominated by wind waves). For the high-frequency part of the wind wave spectrum,
 7 in clean water, waves grow slightly with fetch, gaining 30% energy passing from $X = 8$ m fetch to $X = 20.5$ m. The
 8 growth is obviously much smaller than in absence of swell, ~~but still there is a bit~~. The presence of oil (red marker)
 9 makes the waves progressively decreasing with fetch (the coefficient $\beta < 0$), consistently with, and with the same
 10 explanation for, the results obtained without paddle waves.



13 **Figure 13: Spatial evolution of the water surface elevation variance σ^2 of co-existing wind (WW) and paddle (PW) waves in clean**
 14 **water (W08-P) and with oil slick (W08-P-O). The solid ~~lines and dashed lines~~ show the power law-type functions fitting the**

1 experimental data. In the legend the coefficient β of the fitted power law is shown. The dashed lines show the prediction bounds
2 (confidence level of 90%) for the fitted curves.

3 The growth of paddle waves under the wind forcing ~~-(swell) is particularly interesting because it~~ appears to
4 be marginally affected by the presence of oil (PW markers in Figure 13), ~~similar to the result found by~~ generalizing
5 to a more realistic wave field the results of Mitsuyasu and Honda (1986) ~~using obtained for~~ monochromatic paddle
6 waves. We interpret this ~~saying-arguing~~ that the reduction of surface roughness between ~~the two panels in Figure 9~~
7 W08-P and W08-P-O is not sufficient to change substantially the vertical profile of the turbulent airflow, hence the
8 generation process acting on ~~swell~~ long waves. This is confirmed by Figure 14 ~~that shows~~ showing the wind profile
9 with and without oil. There is only a small difference between the two cases, ~~(however the friction velocity is, as~~
10 ~~expected, larger in clean water)~~. This implies that the minor disturbances we see in the right panel of Figure 9
11 suffice for making the wind feel the surface as rough. Indeed we are here at the limit because the further, almost
12 complete, wave reduction we see in Figure 2 for the experiment W06-O changes dramatically the wind profile, as
13 already seen in Figure 3.



16
17 **Figure 14:** Vertical profile of the wind velocity component ~~Vertical profile of the measured mean horizontal wind speed \bar{U}_a measured~~
18 ~~over the water surface at fetch $X = 11.5$ m for co-existing wind- and paddle-generated waves in clean water condition (blue) and~~ for
19 oil-covered surface ~~after the oil instillation~~ (red). In the legend, the value of the friction velocity is shown within brackets. Only the
20 value recorded at the three lowest Pitot tubes are shown.

5 Discussion

Our previous description of the general methodology and results has been focused much on the implications of having the water surface covered by a very thin ($\sim 10^{-8}$ m) layer of fish oil. However interesting in itself, it is clear that the main virtue of these experiments has been the opening of ~~a different~~new perspectives on the physics of air-sea interactions. We discuss here the main suggestions and ideas derived from our results.

– The different wind profile and wave growth without and with oil clearly show that the stress felt by the atmosphere is, as anticipated by Janssen (1991), the sum of the friction stress and the input to waves. Lacking the latter, the atmospheric stress reduces to the purely frictional one. This has implications also for circulation modeling where quite often the wave intermediate role (wind input to waves followed by wave input to current via breaking) is by-passed by an artificially inflated surface friction to current. ~~Janssen (1991) added wave growth to the stress felt by the atmosphere. In this respect,~~ McWilliams and Restrepo (1999) showed how the general global circulation could be obtained also driving it only with breaking wave momentum injections. ~~Our experiments have shown what τ_a reduces to if waves do not appear. We can argue about a possibly increased friction drag in presence of a rough surface, but the general principle remains.~~

– Especially with young, hence relatively slow, waves it is essential to consider generation with respect to the surface current. In our case, lacking any instrument to measure current, and in particular its vertical profile, we have used two independent methods based on video documentation to get an estimate of the surface current drift. The two approaches provided similar results, consistent with ~~that~~the one derived from the wind speed and similar conditions in the literature. Lacking any data on the current vertical profile, and supported also by the recirculation characteristics of the wave tank, we made the blunt assumption of a vertically uniform current. This is a first order approximation, that we consider acceptable in our case because the related discussion concerns only very short waves. In any case, ~~stated in the final summary,~~ more complete experiments are planned for the near future.

– We have found it ~~fascinating~~interesting to look at how the water surface reacts and evolves under the action of an impulsive wind forcing. ~~As with oil, there is a lot to learn from these first stages of evolution of a wave field.~~ For this first analysis of the obtained data, we have limited ourselves to the steady, fetch-limited conditions ~~where we already found plenty of material for arguing and discussion. Our next step will be in the~~

~~transient area. However, f~~ This subject takes us to a very short discussion on the generation mechanism(s) of the earliest waves. In this respect, the spectral approach to wind wave modeling began with the study by Pierson et al. (1955), followed by the two parallel and independent, but complementary, papers by Phillips (1957) and Miles (1957), and the definition of the energy balance equation by Gelci et al. (1957). While the Miles' mechanism, refined by Janssen (1991), provides the bulk of the input to waves, we still need to trigger the first wavelets on which Miles, and non-linear interactions, can then act. Two processes compete for this first stage: the just mentioned one by Phillips, associated to assumed pressure oscillations moving with the wind, supported also by the recent paper by Zavadsky and Shemer (2017), and a sort of Kelvin-Helmoltz instability (Kawai, 1979) due to the strong vertical shear in the surface water layer following the initial action by wind. The matter is not relevant for practical purposes because these initial stages are usually parameterized or bypassed in wave modeling in a pragmatic way. We know these wavelets appear and their exact dimensions are irrelevant for the following evolution of the actual field. ~~However~~ In this regard, our experiments provide a small piece of information. The Phillips' mechanism is supposed to act on any wavelength, independently of the other ones. We argue that in the oily experiment, granted the dissipation at the wavelet scale due to the Marangoni effect, nothing would impede the Phillips' mechanism to act on the longer waves. However, we found no evidence of energy in the corresponding wave components.

- With short wind and ~~swell~~ long paddle waves, the presence of oil still reduces wind-wave generation, but there is more wind-wave energy than with only wind. Therefore ~~we can say that~~ the presence of a swell reduces the effectiveness of the oil in impeding local generation. We hypothesize this ~~is~~ as mainly due to the long wave orbital motion that detunes the resonance conditions between Marangoni waves and gravity-capillary waves. ~~Moreover, to the very thin, almost mono-molecular, layer of oil we used and to the swell orbital stretching~~ this motion continuously ~~disrupt~~ disrupts the continuity of the oil layer, hence the effectiveness of the Marangoni forces.

6 Conclusions and summary

With the help of an experimental facility, we have studied the influence of a very thin layer of fish oil (~~acting as surfactant~~) on wind and paddle waves as well as on the parameters of the lowest airflow layer. Measurements of sea surface elevation at different fetches and of wind speed were carried out in both clean water (~~acting as reference~~

1 ~~condition~~) and in water with fish oil (~~producing a viscoelastic film on the surface~~). The damping of short gravity-
2 capillary waves by surfactants appears a convenient condition to study, to a large ~~scale~~extent, the processes of
3 interaction between the water body and the atmosphere. The aim of the present study is thus to evaluate the
4 influence of the fish oil film on the ~~frequency spectrum and~~ growth of wind and paddle waves and on ~~some~~
5 ~~parameters of the interaction of the water body with the atmosphere~~the air-water interaction process. Taking this
6 viewpoint, the principal conclusions of our study can be summarized as follows:

- 7 – Marangoni forces, associated to the presence of the fish oil, quickly dissipate and impede the formation of the
8 first wavelets, hence, in a laboratory, the growth of any wind sea. As it is generally agreed, this dissipation at
9 short wavelengths leads to an intensified energy transfer via non-linear interactions from the bulk of the
10 spectrum, in so doing not only smoothing, but also partly calming the sea. In the fish-oil covered wave tank,
11 the powerful suppression of the first wavelets leaves the airflow vertical profile unaffected by the wave field,
12 so that the Miles-Janssen wave growth mechanism is not triggered.
- 13 – Our results show the efficacy of the fish oil in suppressing the wave generation by wind. Indeed, in the
14 experiments in a wind-wave tank contaminated by non-animal surfactants, Hühnerfuss et al. (1981) found that
15 the peak of the spectra is shifted towards higher frequency ~~in reference to~~when compared with the peak
16 ~~frequency in~~ clean water conditions. However, a wind-wave spectrum was still present in their tests, whilst we
17 have found that, using fish oil in the wind-only condition (reference wind speed of 6 m/s), the wave field does
18 not grow from the rest condition, leading to a strong modification of the airflow vertical profile.
- 19 – The experiment with wind-wave only in water with fish oil (experiment W06-O) gave us the unique
20 opportunity to investigate (albeit preliminarily) the interactions at the air-water interface in absence of surface
21 waves. Clearly, the stress exerted in that case by the airflow is smaller than the one in clean water (when the
22 wave field regularly develops) and the water current is determined by the wind shear only, so that $\tau_w \approx \tau_a$.
23 This condition is expected to be different from the one obtained for fully developed waves (in clean water),
24 when one should find that in Eq. (7) the momentum flux into the water column τ_w should become the
25 atmospheric stress τ_a as the wave field reaches equilibrium (see ECMWF, 2017). For instance, the water
26 current vertical profile below the surface is expected to be different in clean water and in water with oil. In this
27 respect, new experiments are already planned that will investigate also the drift current distribution beneath the
28 water surface for an oil-covered water surface.

~~The strong wave damping by oil in pure wind sea conditions is less so in presence of swell. We ascribe this to the continuous stretching of the surface due to swell and the consequent decrease of the effectiveness of the Marangoni forces.~~

The growth of paddle-generated (relatively) long waves seems to be little affected by the roughness of short waves. Provided a minimal background of very short waves (in practice surface roughness) is present, the growth of paddle waves under the action of wind is largely independent on the background level, a fact we ascribe to the similar distortion of the wind profile in the two cases.

~~As mentioned in the text, we have barely (and literally) touched the surface of the subject. W~~With our study we have shown that wave generation and dissipation, and more general atmosphere and sea dynamic interaction, are still to be fully explored. The approach we followed, experiments in a wind wave tank without and with oil on the surface, offers new possibilities for explaining studying into this old, but still fruitful, field.

Appendix A: The Marangoni wave damping effect

The physics of the Marangoni effect is well understood, and it is generally agreed that the gravity-capillary wave energy is damped by a surfactant by the following mechanism. Immediately after a wave field enters a surfactant patch, the Marangoni effect due to the viscoelastic film on the water surface increases viscous dissipation of short wave energy at specific frequencies. This is caused by an additional dissipation in the surface boundary layer. Indeed a shear stress in the boundary layer is required to balance the stress due to the surface tension gradients originated by the non uniform concentration of the surface viscoelastic film (alternatively contracted and expanded due to the passage of a wave). This gives rise to additional longitudinal waves in the boundary layer superimposed on the existing surface waves that are thus damped by a resonance-type mechanism. The dissipative spectral sink (the so-called Marangoni resonance region) is at frequencies between 3 Hz and 8 Hz, the scale of the maximum damping depending on the dilatational modulus of the surfactant (Alpers and Hühnerfuss, 1989; Fiscella et al., 1985). The resonant angular frequency ω_{res} for the Marangoni-force wave damping is given by

$$\omega_{res} = \left\{ \frac{[\cos(\pi/8)]^4 g^4 (\eta \rho_w)}{\varepsilon^2} \right\}^{\frac{1}{5}} \text{ (rad/s)} \quad (10)$$

where g (m/s^2) is the gravity acceleration, ρ_w (kg/m^3) the clean water density, η (Ns/m^2) the clean water dynamic viscosity, and ε (N/m) denotes the dilatational modulus of the surface film. As stated by Eq. (10), the larger the

modulus ε the longer the damped waves. The maximum damping of gravity-capillary waves is attained at a frequency lower than ω_{res} (the Marangoni wave is a strongly damped wave) and the width of the resonant damping is quite broad (the half-power width is in the order from 1 to 2 Hz; Alpers and Hühnerfuss, 1989).

In a more formal approach, the description of water surface gravity waves follows generally a statistical approach by means of the development of the wave elevation variance spectrum $E = E(k, \theta, \mathbf{x}, t)$ in the physical space \mathbf{x} and time t (k is the wavenumber and θ the propagation direction), its evolution governed by the energy balance equation (Gelci et al., 1957). In deep waters, it reads

$$\frac{\partial N}{\partial t} + \frac{\partial N}{\partial \mathbf{x}} \cdot (\dot{\mathbf{x}}N) = S_{\text{in}} + S_{\text{nl}} + S_{\text{di}} \quad (11)$$

where $N = E / \omega$ is the wave action density spectrum with ω the intrinsic angular frequency. Furthermore, $\dot{\mathbf{x}} = \mathbf{c}_g + \mathbf{U}$ with \mathbf{c}_g the wave group velocity and \mathbf{U} an appropriate current. The right hand side of Eq. (11) represents the net effect of sources and sinks for the spectrum (Komen et al., 1994): S_{in} is the rate of energy transferred from the wind to the wave field, S_{nl} is the rate of nonlinear energy transfer among wave components with different wavenumber, and $S_{\text{di}} = S_{\text{di,b}} + S_{\text{di,v}}$ is the rate of energy dissipation due to breaking ($S_{\text{di,b}}$) and viscous forces ($S_{\text{di,v}}$).

In our experiments the observations dealt with in this paper are the ones collected at steady state, so that the spectrum at any fetch is determined by the upwind evolution of the source functions S_{in} , S_{nl} and S_{di} , that is

$$N = \int_0^x \left[(\mathbf{c}_g + \mathbf{U})^{-1} (S_{\text{in}} + S_{\text{nl}} + S_{\text{di}}) \right] dx \quad (12)$$

where, with good approximation, we have neglected the cross-tank wave energy evolution. The velocities \mathbf{c}_g and \mathbf{U} are also, but very weakly, fetch dependent. The balance in Eq. (12) indicates that any modification of the wave energy may and must be caused by changes in the rate of wind input, dissipation, or/and nonlinear transfer.

In presence of oil, all three source functions undergo a change compared to the clean water condition. Indeed, the rapid suppression of short waves by Marangoni forces reduces the water surface mean slope, which leads to a change of the wind vertical profile and rapid decrease of the momentum flux from the wind to the wave field (see, e.g., Mitsuyasu and Honda, 1986). Those two effects combined produce a change of the shape of the wave spectrum in the equilibrium range, which leads, via nonlinear wave-wave interaction (Hasselmann, 1962), to a slow

1 [leakage \(but fast compared to the pure viscous one; Alpers and Hühnerfuss, 1989\) at wavelengths longer than those](#)
2 [at which the Marangoni forces are effective](#)

3 [Given the possible variability of the surfactant density on the water surface, it is natural to wonder about the](#)
4 [related sensitivity of the effect on waves. Analyzing the wind-wave tank experiments with surfactants \(sodium](#)
5 [lauryl sulfate\) presented by Mitsuyasu and Honda \(1986\), we can distinguish two different regimes for wave](#)
6 [attenuation, which correspond to weak and strong wave damping, respectively. Firstly, for small surfactant](#)
7 [concentrations \(i.e. weak damping\), the peak frequency of the wind-wave spectrum in presence of films is shifted](#)
8 [to higher frequencies in reference to the peak frequency of clean water \(in other words waves develop more](#)
9 [slowly\). However, spectra preserve \$u_*\$ -similarity, and the new spectral shape was ascribed mainly to the decrease](#)
10 [of the wind stress: the surfactants smooth the surface and act reducing the wind stress, therefore the waves grow](#)
11 [less. We interpret this result assuming that for low surfactant concentrations the effectiveness of the Marangoni](#)
12 [damping is small \(i.e. the water surface is not fully covered by an uniform film\), but with a partially reduced](#)
13 [aerodynamic roughness. On the contrary, for the highest concentration \(hence with a strong damping\) the similarity](#)
14 [no longer holds, and most of the energy around the peak is lost \(the maximum energy is at a frequency smaller than](#)
15 [the one in clean water; see also \[Figure 5\]\(#\) and \[Figure 6\]\(#\)\).](#)

16 [A question about Marangoni forces concerns the maximum wind speed for which they are expected to keep](#)
17 [their damping efficiency. In early studies, the disappearance of the Marangoni damping was observed by Mitsuyasu](#)
18 [and Honda \(1986\) for wind speed larger than a critical value, that those authors found to be 12.5 m/s. A possible](#)
19 [explanation is provided in the study by Alpers and Hühnerfuss \(1989\), who argued that above a certain friction](#)
20 [velocity \(around 0.5 m/s\) the Marangoni dip is filled in owing to a large flux of wave energy into the Marangoni](#)
21 [resonance region by nonlinear wave-wave interactions. In addition, for stronger wind stresses the viscoelastic film](#)
22 [becomes more mixed with the underlying clean water bulk \(the film is “washed down”\), so that the Marangoni](#)
23 [damping is strongly attenuated \(see also Feindt, 1985\). However, these conclusions seem not to be fully consistent](#)
24 [with the recent analysis made by Cox et al. \(2017\) of the saving in 1883 of the crew of a sinking vessel by the ship](#)
25 [Martha Cobb under very severe stormy conditions \(wind speed around 20 m/s\). In that occasion 19 liters of fish oil](#)
26 [were dribbled into the sea and the log records report what, after a 20-minute delay, was defined as a “magic effect”,](#)
27 [i.e. that the water surface smoothed and breakers disappeared around the vessel, allowing the crew to be saved](#)
28 [using a small open deck dingy. Cox et al. \(2017\) estimated that after 20 minutes the surface covered by the oil film](#)

1 | [was about 0.4 km², hence, the average oil thickness was about 5x10⁻⁸ m. In those conditions, therefore, the](#)
2 | [thickness was comparable to that used in our experiments in the tank and, in spite of the high wind speed, the wave](#)
3 | [damping \(with practical cancelling of wave breaking\) was still effective.](#)

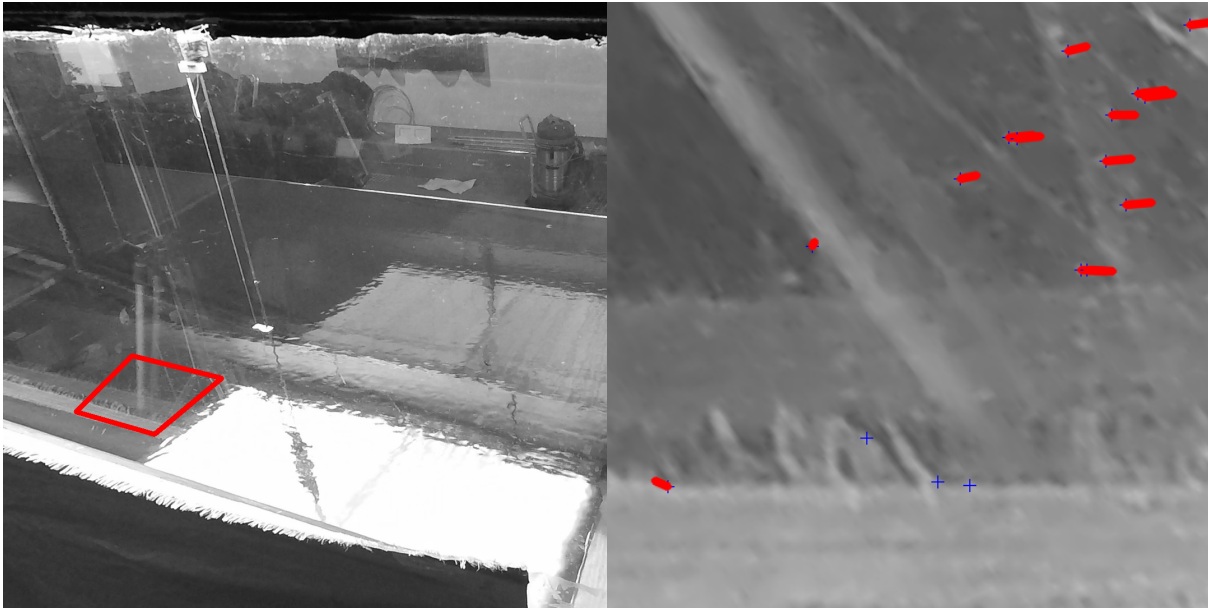
4 | **Appendix AB: Surface current drift estimate using optical flow**

5 | As it is specified in Section 4.1.1, tiny bubbles moving on the surface along the tank, and visible in the 1920x1080
6 | pixel images captured at 60 Hz by a video-camera placed outside the tank close to prove G4, made it possible to
7 | have an estimate of the [water](#) surface current. The probe's two vertical wires, whose measures have been accurately
8 | determined, were used to map visual features from the image space (in pixels) to the tank surface space (in meters).
9 | To ease the computation, we manually defined a quadrilateral area in the image and computed the homographic
10 | transformation between the quadrilateral space to a normalized rectangular space of size 512x512 pixels. To
11 | account for the possible uneven illumination along the sequence, each image was normalized so that the intensity
12 | values have zero mean and unitary standard deviation. Due to the optical characteristics of the water, bubbles are
13 | not the only visual features present in the frames. Indeed, visual clutter mostly due to reflections makes it more
14 | complex to reliably track the bubbles during the whole sequence. Since the cameras were firmly placed on a tripod
15 | during the acquisition, and light conditions were mostly controlled, the clutter appearance remains quite stable
16 | among the frames, with slight fluctuations due to the small waves and the automatic exposure adjustments of the
17 | camera.

18 | Therefore, we performed a simple background subtraction by computing the squared difference between
19 | each frame and the frame obtained by averaging the intensity values of the previous 3 frames. To remove the high-
20 | frequency noise and artifacts caused by video compression, we blurred the background-subtracted image with a
21 | 3x3 Gaussian kernel and applied a threshold of 1.8 to obtain binary images. From the binary image of each frame,
22 | we extracted the location of each particle by using the function *goodFeaturesToTrack()* provided by the OpenCV
23 | Computer Vision Library (Bradski and Kaehler, 2008). We specified 2000 max corners, a quality level of 0.08, a
24 | minimum distance between features of 3 pixels and a block size of 9x9 pixels. Then, we computed the sparse
25 | optical flow with respect to the subsequent frame at the location of each particle using the iterative Lucas-Kanade
26 | method with pyramids provided by OpenCV. We used a 15x15 pixels window for the matching and a pyramid
27 | depth of 5 levels. The computed optical flow gives the amount of movement performed by each tracked particle
28 | between each frame (Figure 15). By knowing the mapping between pixels and tank metric space, and the camera

1 frame rate, we could estimate the speed (in m/s) of each particle. So, we transformed particle locations and
2 movement vectors back to the original image space by inverting the homography.

3



4

5 **Figure 15:** Estimate of surface current speed by optical flow during experiment W06-O. (left) Bounded by a red polygon, the surface
6 area used for the determination of the flow. (right) Example of detected particles with their corresponding movement vector. ~~The~~
7 ~~wind was blowing from the left side to the right side of the images~~ (wind blowing from left to right of the pictures).

8 **Supplementary Material (Videos)**

- 9 1. Supplementary material SM1 available at <https://doi.org/10.5281/zenodo.1434262>.
- 10 2. Supplementary material SM2 available at <https://doi.org/10.5281/zenodo.1434272>.

11 **Author contributions.** All authors have contributed to the writing of the paper. Experiments were planned
12 by LC, ~~and~~ FQ, ~~and~~ AB, and executed by all authors. Data analysis and interpretation were performed by AB with
13 the help of LC, FB, and SJ.

14 **Competing interests.** The authors declare that they have no conflict of interest.

15 **Acknowledgements**

16 Authors gratefully acknowledge the funding from the Flagship Project RITMARE - The Italian Research for the
17 Sea - coordinated by the Italian National Research Council and funded by the Italian Ministry of Education,
18 University and Research within the National Research Program 2011-2015. ~~The authors are pleased to~~

~~acknowledge useful discussions with P.A.E.M. Janssen, Norden Huang, Jean-Raymond Bidlot, and Francesco Barbariol.~~ Luigi Cavaleri has been partially supported by the EU contract 730030 call H2020-EO-20116 ‘CEASELESS’. [Fanqli Qiao was supported by the international cooperation project on the China-Australia Research Center for Maritime Engineering of Ministry of Science and Technology, China under grant 2016YFE0101400, and the international cooperation project of Indo-Pacific ocean environment variation and air-sea interaction under Grant GASI-IPOVAI-05. The authors are pleased to acknowledge useful discussions with P.A.E.M. Janssen, Norden Huang, Jean-Raymond Bidlot, and Francesco Barbariol. We are grateful for the efforts of the editor and reviewers whose insights greatly improved this paper.](#)

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