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What a Sudden Downpour Reveals About Wind Wave Generation

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Abstract

We use our previous numerical and measuring experience and the evidence from a rather unique episode at sea to summarise our doubts on the present physical approach in wave modelling. The evidence strongly suggests that generation by wind and dissipation by white-capping have a different physics than presently considered. Most of all they should be viewed as part of a single physical process.

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Keywords: air-sea interactions; wind wave generation; white-capping; surface processes; wave modelling

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1 – The present situation and the first puzzling questions

It is widely accepted that the present situation of wind wave modelling, especially for what practical results are concerned, is very good. It is enough to explore the statistics (of model results versus measured data) of the National Center for Environmental Prediction (NCEP, at http://polar.ncep.noaa.gov/waves/validation) and of the European Centre for Medium-Range Weather Forecasts (ECMWF, at http://www.ecmwf.int/en/forecasts/charts/obstat/?facets=Parameter,Wave%20Height) to be convinced that, at least in terms of overall statistics, it is difficult to expect further significant improvements. Little touches, sometime concerning physics, sometime numerical, are done here and there, but the related improvements are now of the order of a fraction of a percent. To be honest, accuracy drops in the case of the most extreme storms, especially typhoons and hurricanes, but still with very useful results.

Of course the high quality of the present situation is not due only to "perfect" wave modelling. A key factor, that was also the main reason of the past errors, is a drastic improvement of the driving wind fields. The present 9 km resolution of the global fully coupled (meteo-wave-ocean) ECMWF model provides accurate wind fields till a few days in advance, at least in the open oceans. In the inner seas, where coastline and orography play a relevant rôle, the accuracy drops (the wind speeds are often underestimated, see e.g. Cavaleri and Bertotti [1]), but this is a purely meteorological aspect independent of our present interest. In this paper, using some recent findings, we make a keen discussion on the present physics of the so-called advanced third generation wave models. The widely known and used, open source ones are the classical WAM, WaveWatch3 and SWAN. The respective master references are (WAM) Komen et al. [2] and Janssen [3], (WaveWatch3) Tolman [4] and http://polar.ncep.noaa.gov/waves/wavewatch.shtml, (SWAN) Booij et al. [5] and Ris et al. [6], plus various later refinements.

The backbone of these models is the spectral approach suggested by Pierson and Marks [7] that Miles [8] soon exploited providing a theory and the practical formula for the growth of the single spectral components under the action of wind. His theory was later improved by Janssen [9] to take into account the feed-back of waves on the surface wind field. A dissipation term for white-capping (henceforth w-c) was provided by Hasselmann [10], later modified to take into account the different breaking conditions for swell and wind sea (see the work of Bidlot et al. [11]). This overall approach was completed with the definition of the non-linear interactions, a conservative energy exchange among the various spectral components. See in this respect [12], [13] and [2]. Various other tweakings took place or were proposed, but, by and large and certainly so for the following discussion, this is a fair picture of the situation. A key point to remember is that, while wind input (henceforth w-i) and non-linear interactions are in principle theoretically well defined, w-c has more approximate and empirical expressions. Indeed w-c has always been, and still is, the tuning knob of the system.

So far so good. However, if we try to detach from our enthusiasm for the present results and consider the truth of a storm, we may be a bit puzzled. For whoever has been at sea during a raging storm, the idea that a furious, irregularly breaking surface can be decomposed into simple and neat one-dimensional sinusoidal waves over which the wind flows with a regularly oscillating pattern (Miles' process) sounds far fetched. Especially one of us (L.C.) has spent many months measuring stormy waves from an open sea oceanographic tower (see the description by Cavaleri [14]) witnessing the dynamical behaviour of the sea, the vortex shedding of wind behind a sharp or breaking crest, the non-linear mixing of crossing waves. Banner and Melville [15] showed more than forty years ago that most of the momentum from wind to waves happens behind (ahead of) a breaking crest.

Another direct experience at sea, especially from the comfortable position of an oceanographic tower, is to witness how w-c depends on wind. In a gusty wind field, where the local speed can change up to ±30 % within one minute or so, the white-caps adapt instantaneously to the situation, while the general spectrum has hardly any time for a substantial change.

The first theory for wave growth under the action of wind was due to Jeffreys ([16], [17]). He estimated the actual push by wind on the backside of a wave conceived as an obstacle. Jeffreys' consequent estimate fell short of the existing evidence, and it was then forgotten. However, recently Donelan et al. [18] started from this theory to frame a different wave model that, once tuned to reproduce an extended series of measured data in the North Sea and on the Norwegian coast, is reported to work pretty well.

To summarize the situation, we acknowledge we are presently quite successful in terms of results (we do run daily wave forecasts), but at the same time we feel a little uneasy in the general applauding community. We recall a sentence by George Bernard Shaw : "Science becomes dangerous when it imagines that it has reached its goal". In these conditions and wondering where to start from, one needs a good hint of the way to go. This substantial evidence was given by a particular episode on the cited oceanographic tower, episode that we describe in the next section.

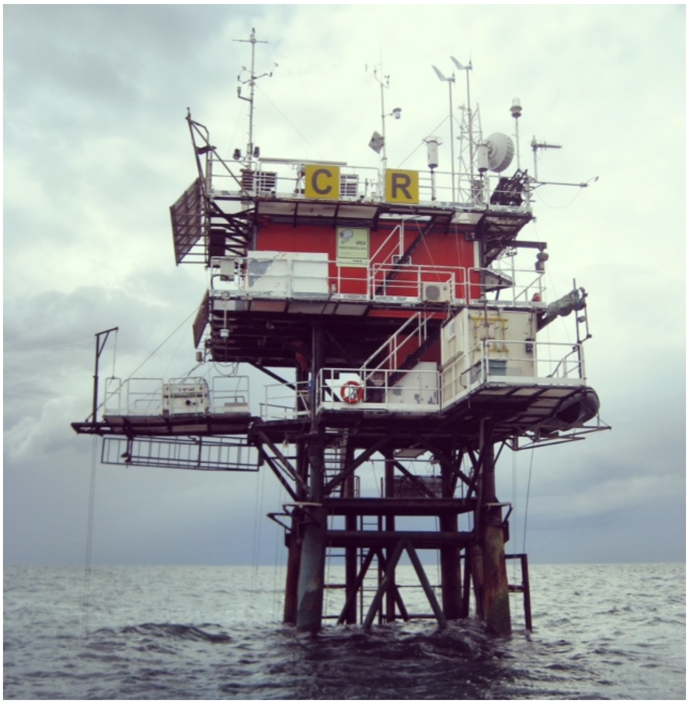

Figure 1 – The ISMAR oceanographic tower, 15 km offshore the coast of the Venice lagoon, in the northern Adriatic Sea, East of Italy (see Figure 2). The upper structure has now been replaced by a new, two metre higher, one.

2 – The experience on the tower

In November 2014 a rather complete wind and wave measuring system (whose purpose is irrelevant for the present discussion) had been set up on the cited ISMAR oceanographic tower (see Figure 1). For atmosphere the considered parameters were wind speed and direction, temperature and rain. For the sea the system included a resistance wave gauge, two two-dimensional current metres, three pressure transducers at cross-angle, temperature. The experiment and the instrumental setting required people on board. To our later dismay (and we will soon see why) the wave gauge did not work.

In November 12 we were measuring a classical mild bora storm. The general situation is shown in Figure 2. Wind from East was blowing at about 10 ms^{-1}, associated to an active generative sea of about 1.4 m significant wave height H_s. Weather was cloudy but dry. Perfect visibility till the horizon. As expected from the situation, frequent white-caps were distributed throughout the surface.

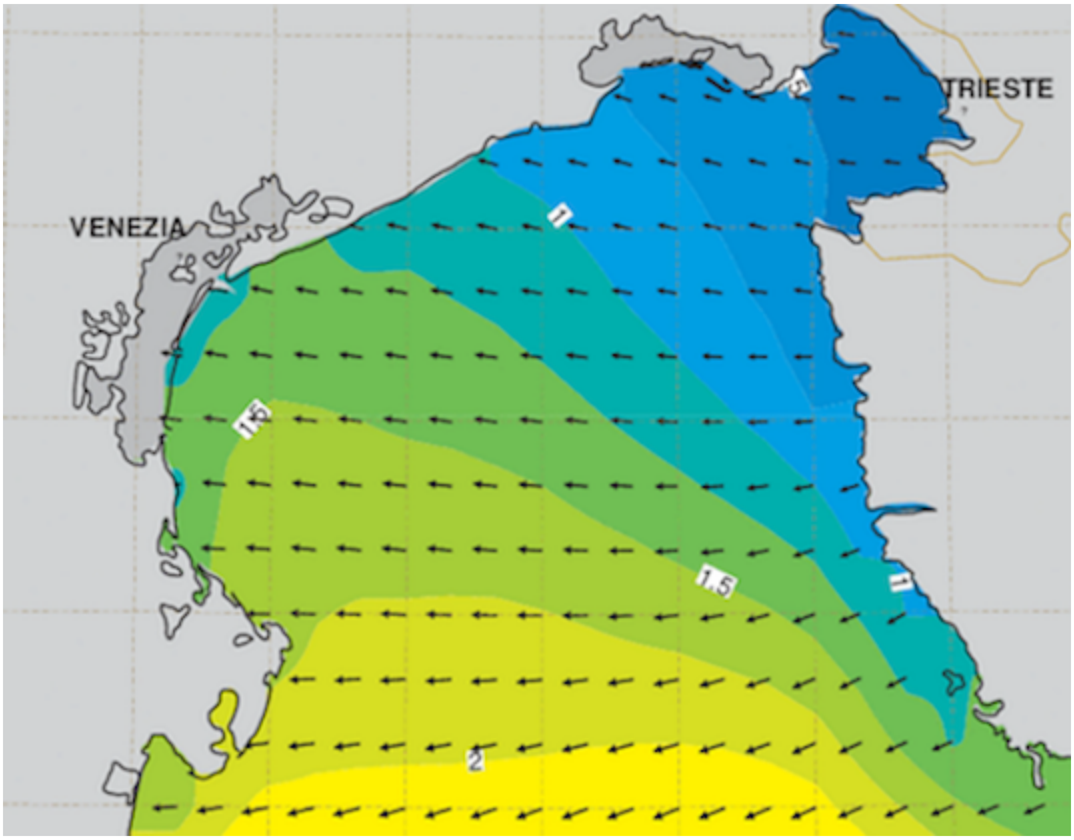

Figure 2 – Wave conditions in the northern Adriatic Sea, east of Italy. The dot shows the position of the ISMAR oceanographic tower (see Figure 1). Arrows, proportional to the local significant wave height, show the local mean wave direction.

All of a sudden there was a tremendous downpour that later we checked (rain gauge) close to 80 mmh^{-1}. For our present interests the relevant point is that at once the appearance of the surface changed completely. White-caps almost disappeared, the sea surface, granted the large drops splashing, was much smoother, waves appeared more relaxed as when during a gusty storm wind speed suddenly decreases. We have photo (see Cavaleri et al., 2015) and video documentation of the two situations (with and without rain). For the videos see http://www.ismar.cnr.it/divulgazione/Video/video/waves_and_rain. Figure 3 shows the situation before (panel a) and during (panel b) the downpour (images extracted from the videos). In the two 20 second videos a quick counting indicates ~140 (before downpour) and ~20 (during it) white-caps. Figure 4 shows the wind speed (panel a) and pressure (panel b) records, the latter at 3.20 m depth. Wind was recorded at 10 Hz, waves at 25 Hz. The latter, unnecessarily high for a pressure transducer, was dictated by the resistance wave gauge out of which we meant to measure also the high frequency tail of the spectrum. This information would have been extremely important to quantify the surface differences between the two conditions (rain and no rain), but the wave gauge did not work properly.

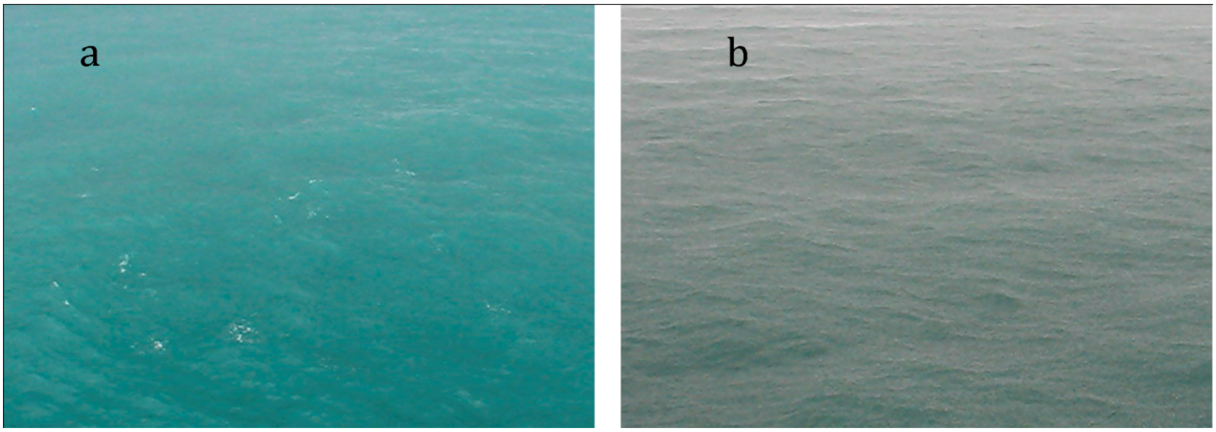

Figure 3 – The sea surface situation before (a) and during (b) the downpour. Note the smoother surface during the rain and the much reduced number of white-caps, strongly indicative of a reduced input by wind. See the videos at http://www.ismar.cnr.it/divulgazione/Video/video/waves_and_rain

One last detail concerning the rain. During the recording periods we were going in and out of the tower cabin. Until two minutes before the downpour there was no rain in the horizon. Soon after it stopped we checked again and there was no visible trace of any rain till the far horizon (as in Figure 3a). So the phenomenon was sudden and local, although we have no way to estimate its actual spatial extent.

This is the detailed account of the event, of the meteorological and wave conditions, and of the measured data we have. What to deduce from this is the subject of the next section.

3 – The implications

We start from the visual evidence about w-c. As soon as rain (very intense) started falling, white-caps virtually disappeared. Our documented estimate for them is close to about 10 % of their original number, but this order of approximation is irrelevant for our considerations.

A wind sea is a dynamical equilibrium expressed with the energy balance equation (see [2] and [19]). In practice an active wind keeps inputting energy (and momentum) into the wave field, most of which (energy and momentum) are counterbalanced by an intense w-c that characterizes an active generation (the lost energy and momentum go into turbulence and current). By and large (and again the exact figure is not relevant) only a net 10 % of the input goes into wave growth, w-c corresponding to about 90 % of the input by wind (see [2]). Should the input be active during the rain, this would have resulted in a rapid growth of wave height. A first hand estimate has been done considering the exchange of energy involved in a time limited growth (see again [2] and the very good book by Holthuijsen [19]).

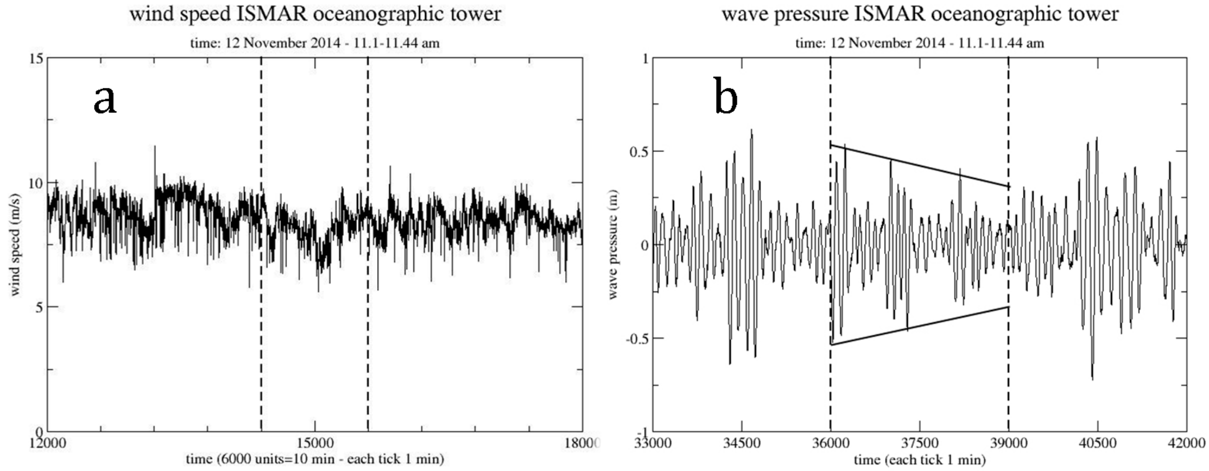

Figure 4 – a) Wind speed history before, during and after the downpour. Sampling at 10 Hz. b) Pressure record at 3.2. m depth. Sampling at 25 Hz. In both the panels the downpour is (approximately) limited by the two dashed vertical lines. Horizontal scales in sampling units. Note the decrease of the maximum wave height in each group during the rain period.

In both the panels the period of the downpour is limited (with some approximation) by the two dashed vertical lines. In panel 4b we have also traced two lines showing how during the downpour the maximum wave height in each group is decreasing, with both decreasing crests and rising troughs. Taking into account the cited approximation, the two lines could also be extended to the groups just before and after the marked interval. This decrease is confirmed by the progressive values of the significant wave height. In the original plan each record would last for more than half an hour. However, the rapidly changing conditions with and during the downpour forced us to estimate five minute spectra. Three sequential pressure spectra around the rain period are shown in Figure 5, the 11.36 being the one across the rain period. The spectra are substantially different, due to the changing conditions and to the large confidence limits (that we have purposely not drawn not to confound the essential information). The overall significant wave height history is in Figure 6. Note the drastic decrease during the downpour and the tendency to grow again when the rain is over. The records stop at minute 32 in the figure as planned in the original purpose of the experiment.

Starting from the conditions before the downpour (Hs~1.5 m, see Figure 6), using U_{10}~10 ms^{-1}, and excluding w-c, in the two minutes of the downpour energy would have grown of about 30 %, with H_s growing to more than 1.7 m. Tests with 8 ms^{-1} wind provide slightly smaller, but similar, figures. Because this did not happen, on the contrary H_s dropped substantially, we conclude that wind input was not active during the rain. Indeed (see Figure 3 and the cited videos) when rain started, the sea immediately "relaxed", crests were no longer sharp and so higher than troughs, as when in a storm wind suddenly ceases or drops to low values. However, in our case wind was actively blowing, but without apparent effect on the waves. The question is which are the possible explanations. Before proceeding further, we point out that this evidence is not supported by present modelling that, also ignoring the disappearance of the white-caps, would indicate a further growth of the wave field. See in this respect Figure 4 of Cavaleri et al. [20].

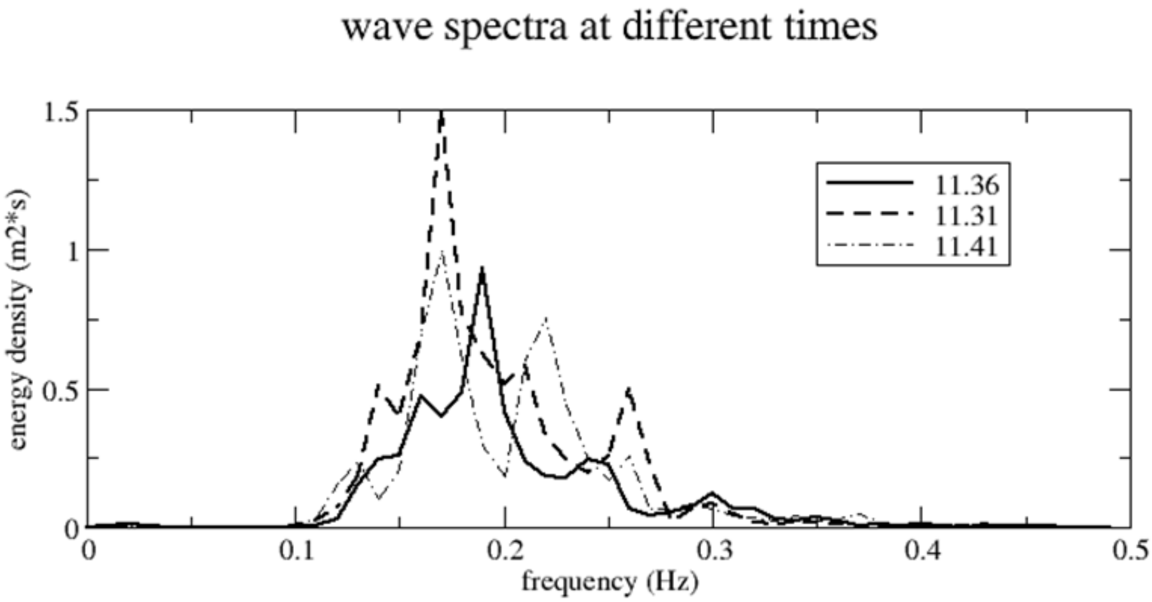

Figure 5 – Three five minute spectra taken across the downpour period. 11.36 marks the time of the shower. We have purposely not drawn the large confidence limits not to confound the essential information.

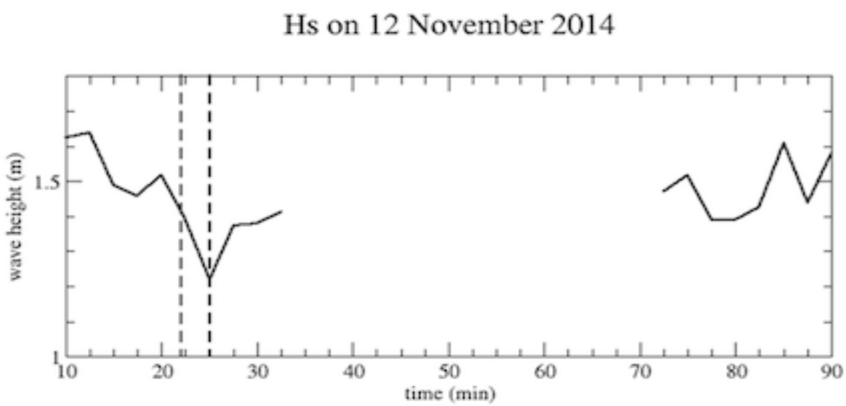

Figure 6 – Variation of the significant wave height across the downpour period, marked by the two dashed vertical lines. Note the substantial decrease during the rain.

Let us consider first the theoretical background of input by wind. Almost all the operational wave models (the exception is Donelan that we discuss later on) are based on the theory by Miles [8] complemented by Janssen [9] with the wave feed-back to the atmosphere. We argue on this basis. Within the wind speed logarithmic vertical profile of the surface boundary layer Miles focused his attention on the so-called "critical layer", i.e. the height at which the wind speed equals the phase one of the specific spectral wave component we are considering. The relevant information is the curvature of the profile at this height. The profile itself depends on, and is due to, the surface roughness. This depends mostly on the shortest waves (till the capillary level), i.e. on the tail of the spectrum. These are the ones cancelled by rain, so in these conditions the vertical profile changes substantially. In practice higher wind speeds are present till much closer to the surface. This changes completely the efficiency of the Miles-Janssen process so that in the downpour conditions hardly any energy was transferred from wind to sea. This is a possible interpretation according to this theory.

W-c is in itself an interesting story. For a long while the number of breakers on the sea was considered a function of only the wind speed. See in this respect the proceedings of the Galway conference edited by Monahan and Macv Niocaill [21]. At the same time the wave modeller community was looking for an expression of the energy lost by w-c, suitable for use in wave modelling. A first solution was provided by Hasselmann [10] as a function of only the wave spectrum, hence, explicitly at least, independent of wind. Improvements were then introduced, see in this respect [3], [22] and [23], and the extensive review by Babanin [24]. The present situation can be summarized saying that modelled energy loss by w-c is still fundamentally a function of the energy in the spectrum. Considered as the least known element of the energy balance equation, it is conveniently used as the tuning knob of the model system to get, on average, very good results. However, direct experience on the sea teaches otherwise. One of the classical storms in the Adriatic Sea (see Figures 1 and 2|) is "clear bora", i.e. clear sky, cold dry strong gusty wind from the East (mutatis mutandis as in Figure 2). The gustiness (see the approach by Abdalla and Cavaleri [25]) can be up to 30 %. Witnessing from the tower, it is immediate to see how, within the order of one minute or so, hence (following present theories) with little time for the wave spectrum to change, the amount of w-c increases drastically with increasing wind speed (and vice versa). In the episode under discussion the wind was more or less the same, and we had a mild reduction of the significant wave height. Direct inspection of the source functions suggest that, still according to present modelling, the spectral changes were not enough to justify the practical disappearance of w-c during the rain.

All this pushes towards a more integrated, although not yet clear, view of the w-i and w-c processes. Different possibilities exist. On one hand we could argue that w-c disappeared because w-i was strongly reduced. At the same time we could follow Banner and Melville [15] and derive that w-i disappeared because w-c was strongly reduced. In our opinion the most likely solution is that, contrarily to the present approach, the two processes are strongly connected and should be viewed as a single one, dependent both on the wave spectrum and the local wind.

If this is the case, which is the role of rain or, in other words, the spectral tail? A first obvious result seems to be that reduced energy in the tail, i.e. a smoother sea surface, implies less input by wind, hence less w-c. However, other opinions exist on the role of short waves destabilizing the single crests. The wind drag on a crest is likely to increase when short waves are present, possibly making the crest breaking more likely.

Where did the wave height decrease during the downpour come from? Direct inspection of mechanical attenuation of waves by rain (see the recent approach by Cavaleri and Bertotti [26]) excludes this as the main culprit. There was the obvious visual relaxation of the wave field that could suggest that certain aspects of the spectrum might change more rapidly than presently supposed. Longuet-Higgins [27] and more recently Cox et al. [28] pointed out the rôle of the non-linear interactions. What Cox [29] and Cox et al defined as a spectral hole, in practice no energy in the tail of the spectrum, could enhance the transfer towards this area, hence the continuous indirect dissipation, of energy from the bulk of the spectrum, leading also to a relatively rapid decrease of the most energetic part.

Obviously the situation is very confused and different possibilities for the right path and solution exist. A general framing of the situation and what to do next is the subject of the final section.

4 – The road ahead

As we pointed out at the beginning, the present results of the operational, or purposely run, wave models are generally good. Granted the necessary good quality of the driving wind fields, by and large the wave results are mostly satisfactory. This is possibly less the case when we go into the details of the results, e.g. of the two-dimensional wave spectrum, or we model extreme situations as typhoons and hurricanes. In all this apparently pleased environment, a keen analysis in specific situations, as when wind and waves are associated to a strong rain, casts some doubts on the present theoretical background. We should not forget a principle of logical deduction: to get correct results is a necessary, but not sufficient, condition to state our model is correct. On the contrary one single wrong result (granted all the other boundary conditions) may suggest that "something" is wrong. This is the case with rain, this was the case at the tower, and this is where we are. The results by Cavaleri et al. [20] and the evidence from the downpour at the tower strongly suggest something needs to be changed. The question is what, how and how much. We do not have the reply now. Definitely more and new research is required involving laboratory, numerical and field experiments.

As a general idea, our opinion is that a more comprehensive and realistic view of the processes at work is required. The almost idealistic view of decomposing a rough raging sea surface into linear one-dimensional sinusoids on which wind is smoothly acting is at odd with the evidence at sea. There must be truth in this approach; the results are too good to be ignored. At the same time the Jeffreys ([16], [17]) approach of wind pushing on the back of the waves, notwithstanding its underestimate of the resulting wave growth, appears too intuitive to be ignored. A possibility is that both the processes, Jeffreys and Miles, are at work, and that their effect should be estimated when acting on the single waves rather than on the sinusoidal spectral components. Indeed, concerning Jeffreys, starting from this theory for the input by wind and using alternative expressions for the other source functions, Donelan et al. [18] obtained good results, including hurricane Ike (2008). The fact that fully different approaches provide good results should make us wonder, especially when the key source function, the wind input, is based on completely different theories.

How do we proceed from here ? There are different levels of approach. The simplest one (but not really simple) is to adapt a theory, e.g. Miles-Janssen, to the new evidence. Here we refer to the smooth sea (when under rain), and the consequent reduction of the surface roughness and drastic change of the wind vertical profile. In the present operational set-ups, as the fully coupled system at ECMWF (see https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model/ifs-documentation), the apparent roughness felt by the atmosphere, i.e. the momentum transfer to the ocean, involves also the growth of the wave field. However, granted a change of the Charnock parameter and of the driving wind, this does not imply a drastic change of its vertical profile. This is why, contrarily to the measured evidence, in our 2015 numerical experiment waves kept growing also under the rain. Should this be the correct approach, the solution would involve the meteorologists for the need to model with high vertical resolution the wind profile according to wave conditions, something on the contrary done as a relatively simple post-processing starting from the lowest σ-level of the meteorological model, typically at 10 or 20 m height.

We have mentioned the possibility of estimating the w-i not on the single sinusoidal components, but the single real waves, i.e. the ones we see looking at a stormy sea. Without entering into the numerical implications for combining this with a spectral approach, we point out here a permanent substantial difference between a real sea and its spectral representation. A real sea is highly skewed, with higher and peaked crests and lower (closer to mean sea level) and rounded troughs. This is quite different from the up-down symmetrical representation we derive from the straightforward Fourier anti-transform of a spectrum. More sophisticated methods can be used to highlight the non-linearities. However, the basic point is that, while the recorded spectrum of a skewed wind sea shows the so-called 'locked hyper-frequencies' (the clearest evidence of skewness), these do not exist in the spectra of the third generation spectral models. Remaining in the real world of the affordable numerical approaches to wave modelling, it is our feeling that we will not succeed in representing the real generation, and also w-c, processes till when we will not devise a way to act on the sharp crests, also modelling w-i and w-c as a single process. How to do this must be part of the research in the future. However, our first step should be how to verify and improve our recently accepted theories (and approaches) also for the cases where we know they do not work properly. Of course in the while we have to carry on with our present models and generally good results, better if aware of the possible approximations in certain conditions. At the same time and on a parallel course, we need to venture into these (partly) new ideas to build our future on a more solid ground.

Acknowledgements

The rain experience fell on a fertile, although doubtful, ground derived from our previous experience. While we take full responsibility of what we state and suggest, we acknowledge the long discussions with many of our colleagues of the wave and atmosphere modelling community. Luigi Cavaleri, Luciana Bertotti and Paolo Pezzutto have been partly supported by the EU contract 730030 call H2020-EO-2016 'CEASELESS'.

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