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Rain and the dynamics of wind waves

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Abstract

Sea mariners have reported for a long time the calming of wind waves when oil was put on the sea surface. A similar effect appears under an intense rain on an otherwise very actively generated sea. We numerically analyze the processes involved concluding, according to present theories, that waves should grow higher under rainy conditions. However, this is denied by the open sea measured data. This has prompted a keen analysis of the overall process, leading to the conclusion that a) oil and rain calm the sea only as far as breakers disappear, b) this is associated to an almost lack of generation mechanism, c) this suggests that generation by wind and white-capping are two tightly related processes, certainly much more than till now assumed.

1 – Oil (and rain) calm the sea-surface

At least this is what universally reported by the ancient sailors. When in troubling conditions, the crew of typically the whaler ships resorted to pour into the sea a certain volume of animal oil. If done in the proper way and conditions this had indeed the effect of smoothing the surface, the most conspicuous feature being the almost complete absence of breakers. There are very well documented episodes, perhaps the most cited one being that of the saving of the crews of a sinking vessel by the ship Martha Cobb in 1883.

Interestingly the procedure was followed also during the second world war when trying to recover men at sea. However, although partly successful, these actions appeared much less effective that what reported in the old tradition.

The explanation stems from the different characteristics of the molecules in animal and vegetation oils versus the mineral ones (civilian and war ships tended to use the on board readily available oil for the purpose). The former ones have a non-polar molecule while the latter ones are polar. Being non-polar implies that, instead of making long chains, the molecules tend to distribute as a single layer, while the polar characteristics lead to thick layers of oil on the surface. In practice the animal and vegetation oils tend to distribute, for the same volume of oil, on a much wider surface, till the (realistic) limit of a single mono-molecular layer. Interestingly the problem was recognized and studied by Benjamin Franklin who experimented on a pond in England how a single spoon of oil was capable of fully smoothing the surface of a large pond previously choppy under a brisky wind. Even more interestingly, although these results were distributed and widely known, no one realized that this offered a mean for estimating the molecular dimension something like two centuries before then done with well different means.

Another saying is common among also present mariners, i.e. that, similarly to oil, also “rain calms the sea”. The effect of rain falling on sea waves atrtacted the attention of several scientists, starting with Reynolds (1875, 1900) till the valuable paper by Le Mehaute and Khangaonkar (1990). The attention of these scholars was focused on the direct mechanical action of the rain drops on the existing sea waves without much attention to the implications on the physical processes at the interface (these processes attracted the attention much later). Besides, because the rain action is significant on a large scale and in due time, all the laboratory experiments had to be done with very short waves (easily paddle generated and more rapidly attenuated) and unrealistic rain rates.

What is coming out of the previously available knowledge is that rain indeed, if intense enough, tends to smooth waves in the high frequency range of the spectrum, the effect decreasing very rapidly when moving to longer waves. Within this perspective the effect of rain is similar to that of oil. Our purpose is to dig into the problem and to analyze, physically, numerically and with comparison with available data, what is going on on the sea under rainy conditions, particularly on an actively generated sea.

2 – What the present theories suggest

The basic theory for wind wave generation, as the most widely accepted and used for more than half a century, was proposed by Miles (1957). In its essence, given a logarithmic vertical profile of the driving wind, a sinusoidal sea wave causes a deformation of the profile along the wave cycle with a resulting net input of energy and momentum. Together with the Pierson and Marks (1952) idea of a wave spectrum and the energy balance equation by Gelci et al. (1957), this provided an apparently solid background for the development of wave models. The Miles theory was then improved by Janssen (1989, 1991) who pointed out that the energy and momentum flow from wind to waves must imply a slow down of the wind speed. This turned out to be indeed the case and good results followed accordingly (Janssen 2008). This, the presently commonly accepted point of view, is the starting point for the first stage of our analysis.

The flow of momentum from wind to waves increases very rapidly with the wave frequency, the spectral tail turning out as the related critical area. It follows that, if rain smooths the sea surface, there will be much less flow of momentum, with a consequent minor decrese of the wind speed. In other words, if rain falls on the sea, the wind speed has a tendency to increase with respect to the case of no rain. Because the growth of the single longer wave components, where most of the wave energy is located, depends on the wind speed, we derive that, according to present theory, waves should grow higher. This does not exclude that, as reported by sailors and described above, there will be less breakers, in so doing having ”a calmer sea”. To verify if this is indeed the case, we carried out both numerical experiments and extensive comparison with measured data. This is the subject of the next section.

3 – What models and measurements say

The numerical experiment was set up using the operational model of the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, U.K.). We point out that the experiment requires a fully two-way coupled atmospheric and wave model system. After choosing a suitable area and period characterized by storms and rainy conditions (North-Atlantic, December 2009), we ran the models with the regular set up in sequential 24 hour forecast mode, but adding the condition, before evaluating the source functions, of zero-ing the spectral tail from a frequency upward, this frequency decreasing with the intensity of the local rain (see Cavaleri et al., 2015, for all the related details). In no case waves shorter than 0.40 m were zeroed. Obviously this was a relatively crude approach, but it fit the purpose.

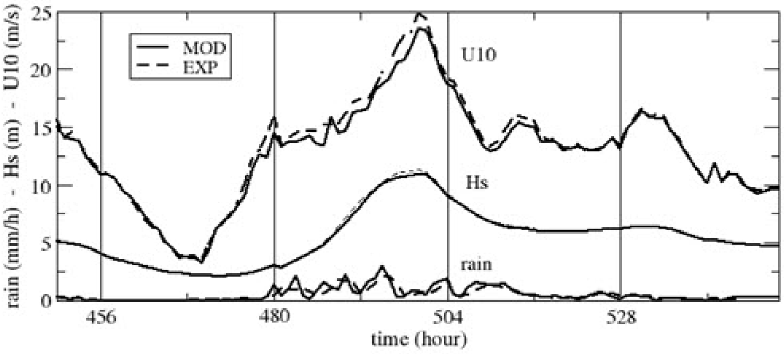

Figure 1 – Four day time series of model wind speeds, significant wave heights and rain rates at a position in the North Atlantic Ocean during December 2009. Continuous lines show the regular model results, the dash ones taking the reduced surface roughness under rain into account (after Cavaleri et al., 2015)

The results are shown in Figure 1 where, following the time series of significant wave height H_s, wind speed U10 and rain rate, we see that the model does indeed suggest that, when a substantial rain appears, wind gets stronger and waves get higher. This fits with the general considerations outlined in the previous section.

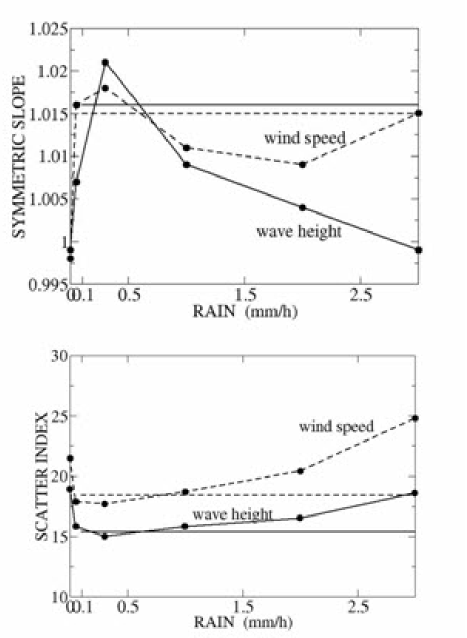

Figure 2 – Intercomparison between ECMWF operational model results and buoy recorded data. Both wind speeds and significant waves heights are considered. The considered area is North-Atlantic. The period is 2009-2013. Upper panel for the symmetric slope, lower panel for the scatter index SI .The discrete values on the horizontal scales separate the various ranges of rain rate considered. The corresponding slope and SI results are plotted at the center of each range. The 0. point corresponds to the “no rain” cases. The upper RAIN point is for all the cases the rain rate is greater than 2.5 mmh^{-1}. The horizontal lines summarize all the results for rain rate > 0.1 mmh^{-1} (after Cavaleri et al., 2015).

However, the comparison with measured data suggests otherwise. We could not verify the wind speed at large using scatterometer, and even altimeter, data because these are based on the interactions with capillary waves, the very waves cancelled by rain. We used altimeter wave heights and buoy measured wind speed and H_s. (see Figure 2). The results were unequivocal. With 99% certainty the data show that a) indeed there is a higher wind speed in rainy areas, but b) correspondingly there are lower wave heights. Not much, but enough to exclude the enhanced growth.

This showed that something was wrong in our approach and in our starting hypotheses. This prompted a new phase of research to get new light on the overall process.

4 – A new view of the overall process

We jump back to 1962 when Lighthill published a very nice paper where, avoiding the mathematics, he provided a detailed physical interpretation of the Miles process. One of the crucial detail of Miles generation is the idea of critical height h_{cr}, i.e. the one where, starting from 0 at the surface, the wind achieves the same speed of the sinusoidal wave it is acting on (it follows that the critical height varies with frequency). The actual input to waves is extremely sensitive to the value of h_{cr} via a negative exponential. On the other hand the value of h_{cr} depends critically on the vertical wind profile close to the surface. In using in our tests the approach by Janssen with an increased wind speed due to the reduced surface drag in rainy conditions, we implicitly had assumed that the wind profile remains the same (but with an increased speed value). However, if, as it is indeed the case, the surface drag conditions are different, also the wind profile will change, certainly so close to the surface where the critical interaction takes place. A reduced surface drag will lead to a, so to say, 'relaxation' of the profile with a consequent increase of the critical height. But we have seen that the input to waves is critically depending on the value of h_{cr}, a minor increase leading to a drastic decrease of the action of wind on the driven waves. Therefore a reduced surface drag does lead to an increased wind speed, but at the same time to a much reduced input by the Miles-Janssen process.

There is more to argue on the overall process of evolution of a wind wave field under rainy conditions. In absence of rain the wave growth is due to a minor difference between two, positive and negative, processes. Of course we refer to wind generation and white-capping respectively. Last December one of us (L.C.) had an enlightening experience during a wave measuring campaign from the ISMAR oceanographic tower in the Northern Adriatic Sea (see Cavaleri, 2000, for a description of the structure and related measurements and results). There was a mild bora storm, wind speed 14 ms^{-1} and 1.4 m H_s, and no rain. White-caps were frequent and uniformly distributed on the surface. Suddenly a downpour took place (a rare event if so isolated in time). The aspect of the sea surface changed instantaneously, in a matter of seconds (we have video evidence of both the situations; some hints can be gained from the two pictures in Figure 3). White-caps virtually disappeared, reduced to less than 10% of the no-rain number (counted from the videos), the waves continued waving, but with a smooth surface, no short or capillary waves, wind continued blowing, but at no avail.

This suggests some thinking. The almost total absence of white-caps on the surface implies the practical absence, or so, of white-cap dissipation. Instruments were at work and we have a full record of the event. Although the detailed analysis is still on the way, preliminary results show clearly that the wave height was not growing (the downpour lasted about ten minutes). Given that (see above) a tiny difference between white-caps and generation energy balance would lead to a rapid change of the wave height, the evidence strongly suggests that during the downpour the wind speed, probably increased, certainly not decreased, was not inputting energy to waves (almost at least). This is coherent with the explanation we have given above for the lack of, or reduced, generation in rainy conditions.

Figure 3 – Sea surface and white-capping distribution during (left) and just before (right) a violent and sudden downpour (32 mmh^{-1}). The two pictures have been taken at less than three minute distance. Significant wave height 1.4 m, wind speed 14 ms^{-1}. Oceanographic tower of ISMAR, 16 m depth, 15 km offshore Venice, Italy (after Cavaleri et al., 2015).

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There is something to say also about white-capping. In the present conceptual approach the energy lost by white-capping depends only, or basically, on the spectral shape, in particular on the bulk of the spectrum. Some consideration of the local wind has been discussed, but not widely applied. However, in our case on the tower the spectrum did not change across the rainy event, certainly not the bulk of the energetic spectrum. Therefore, still according to this approach, the white-capping should have continued (also wind was the same, if not higher). But this was not the case. The white-caps did disappear. This leads to a number of possible logical explanations.

1) there is less drag on the surface, hence the wind is not pushing the single already elevated and steep waves beyond the breaking condition. Note that this would implies that wind does have a role in white-capping,

2) white-capping depends on the presence of energy on the high frequency part of the spectrum,

3) there is a strong physical relationship between input by wind and contemporary dissipation by white-capping, so that, once the former disappears, also the latter is strongly decreased.

Experience teaches that the likely explanation is a mixture of processes, so there is no, so to say, single culprit. However, we favour the last explanation. There is a long history of field or laboratory measurements showing how (see in particular Banner and Melville, 1976) the input by wind is not 'uniformly' distributed along the wave profile, but often associated in enhanced single bursts to the surface breakers. We suggest that the two processes at the heart of any wave model, generation by wind and dissipation by white-capping, are not two separate almost independent processes, but they are part of a more general one in the transfer of momentum and energy from the atmosphere to the ocean. We do not have a theory at hand, and probably an enlightened thinking will be necessary, if we are right, to frame the new physics and related mathematical description. But this will make sense. To have a system evolving following a minor difference between two large scale processes does not make sense also from the engineering point of view, a minor error in one of the two leading to a much larger error of the difference. A single approach is, we believe, the way to go for the future.

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