SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	**The different effects of heavy rain on the development of ocean waves.**
Computer Project Account:	SPITWM
Start Year - End Year :	2017 - 2019
Principal Investigator(s)	Luciana Bertotti
Affiliation/Address:	ISMAR, Institute of Marine Sciences, CNR Arsenale – Tesa 104, Castello 2737/F 30122 Venice, Italy
Other Researchers (Name/Affiliation):	Luigi Cavaleri ISMAR - CNR

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The aim of the present project, as clearly indicated in the title, is to investigate the influence of rain on the process of growing and developing of ocean waves, analysing all the processes that concur to their development. Last year we had focused on, although not the most relevant, probably the most difficult one, i.e. the attenuation of wind waves by rain while they propagate on the sea. We are presently finalising the work in this direction. At the same time we have explored the sensitivity of the model results for hurricanes to some of the source functions.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

Technically no particular problem has been encountered. As the previous year, a practical aspect is that, because of the heavy access to the archive, the large volume of storage of the intermediate data, and the required interaction with local staff, large part of our work needs to be conveniently done at ECMWF.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

All in all we have not find any particular problem neither in the application procedure nor in the submission of progress reports or special requests as, for example, the request for additional computing resources.

Summary of results

1- Framing the problem

During these last few years we have tackled the problem of the influence of rain on the generation and dissipation of ocean waves. This problem is complicated, involving not only wind waves, but also meteorological modelling. Rain is presently an “output” of the meteorological model, without any mechanical feed back into the system. However, rain may affect the sea surface at a substantial level in so doing affecting the air-sea exchange processes at the interface. There are both dynamical and thermodynamical aspects involved. We are tacking these aspects one by one. Our first step has been to clarify and quantify the attenuation of waves by rain.

Wave modeling and the related operational forecasts have reached a satisfactory level. This implies that further progress requires considering what, at least for the quantification of the energy involved, can be defined as second order processes.
Starting from the theoretical approach by Le Mehaute’ and Khangaonkar (1990) we made use of the meteorological and wave model results produced by the Centre during a conveniently long period between 2011 and 2016. Using the meteo and wave results we derived an estimate of the wave attenuation with rain.
The first step has been to compare wave height model results with altimeter measurements. The result shows an evident overestimate of the wave model with increasing rain rate. Hence, see the figure below, we have plotted the H_{mod}/H_{sat} values versus the amount of rain encountered by the local wave systems during their approach to the measurement location. We then have traced a best-fit line to the data with an obvious positive slope with increasing rain. This means that the model over-estimates the wave height for larger rain rates. In so doing we see that the wave model neglects the the attenuation by rain.

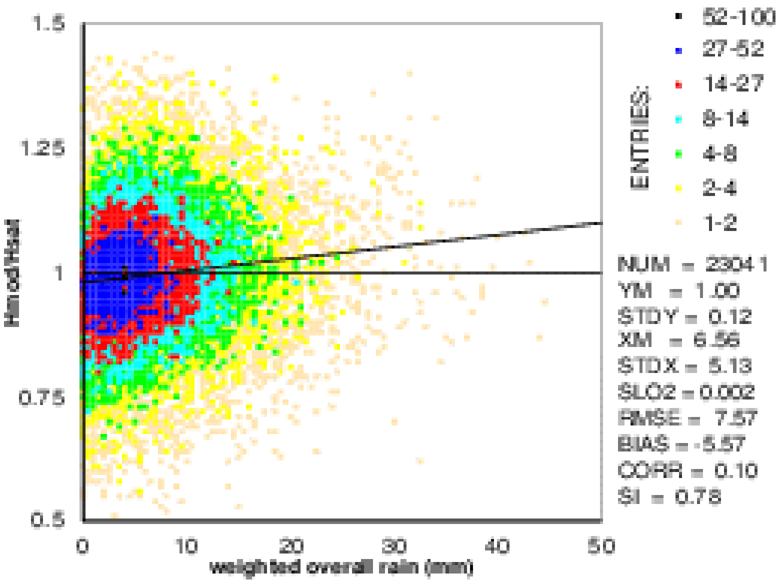

Figure 1 - Distribution of ratio (model Vs satellite) wave data according to weighted overall rain.

Because the influence of rain on waves is much smaller than other more dominant processes, we need to consider cases where the dominant energy non-conservative processes (wind input and white-capping) are not at work. We therefore have focused our attention on the tropical zone, from 30ºS to 30ºN, basically out of the storm belts, where the frequency of convective precipitation and the presence of swell provide more favorable conditions. The basic idea is to compare with altimeter data the wave model results, taking into account how much rain the waves have passed through before reaching the measurement point.

We have used the 12 to 24 hour forecast fields of the ECMWF coupled model system, from December 2011 to February 2016. This corresponds to the use of the T1279 spectral resolution of the meteorological model. During this period we have selected data at 0.5° resolution, retaining significant wave height H_s, the full 2D spectra, wind speed and direction, and rain rate. Working with forecast fields has avoided the objectivity problems consequent to data assimilation and allowed the availability of fields at one hour interval.

Starting from the basic equation by Le Mehaute' and Khangaonkar

$$E_{sat} = E_0 \exp(-\alpha R/T^2)$$

we have splitted the total energy E_o into different , more specifically four, wave systems from different directions, each one with its own history. Therefore at our generic point P we have

$$E_{sat} = \sum_1^4 [E_i^{''}(1-\alpha \frac{R_i}{T_i^2} + \frac{\alpha^2}{2}\frac{R_i^2}{T_i^4})]$$

that can be solved providing the specific value for α. The above procedure has applied to each single altimeter, hence model, value providing different estimates of the α attenuation coefficient.

2 – The quantification of this effect.

The rain effect, although statistically obvious (see the Figure 2), is small compared to the usually found differences between model and measured data. This implies a wide range of possible results about the actual attenuation with rain that again must be interpreted in statistical terms. This is shown, and evident, in Figure 2 where we show the statistical distribution of the derived α attenuation coefficient as a function of the rain rate. While, as expected, the distribution is very wide for low rain rates, the distribution progressively shrinks and converges with increasing rain rates. The final formula, suitable for direct applications, is given by

$$\exp(-0.036\ R/T^2) \qquad (1)$$

with R the overall amount of rain (mm) and T the wave period (sec). The noteworthy fact in (1) is that the attenuation does not depend on the rain rate, but, with very good approximation, it is a function of only the overall rain amount.

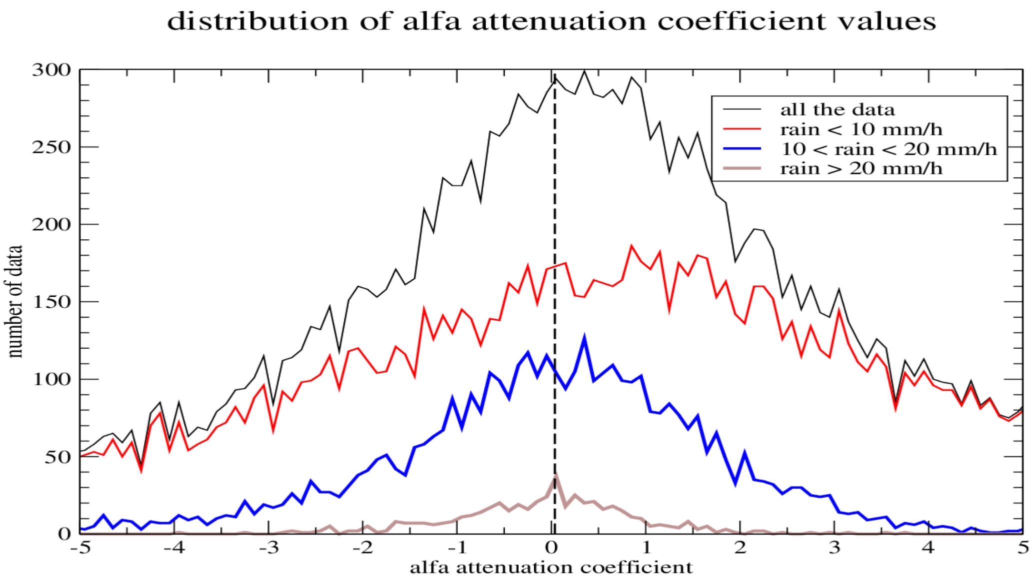

Figure 2 - Distribution of the estimated value of the α attenuation coefficient as a function of the rain encountered by the wave system. The vertical dashed line indicates the mean value of the distribution (0.036), not distinguishable at this scale (after Cavaleri and Bertotti, 2017).

The implications are made clear in Figure 3 where we plot the actual overall attenuation for different periods of ocean waves. It is evident that, negligible for small rain amounts and more so for large wave periods, the attenuation becomes appreciable for large rain rates (hence amounts) and lower wave periods.

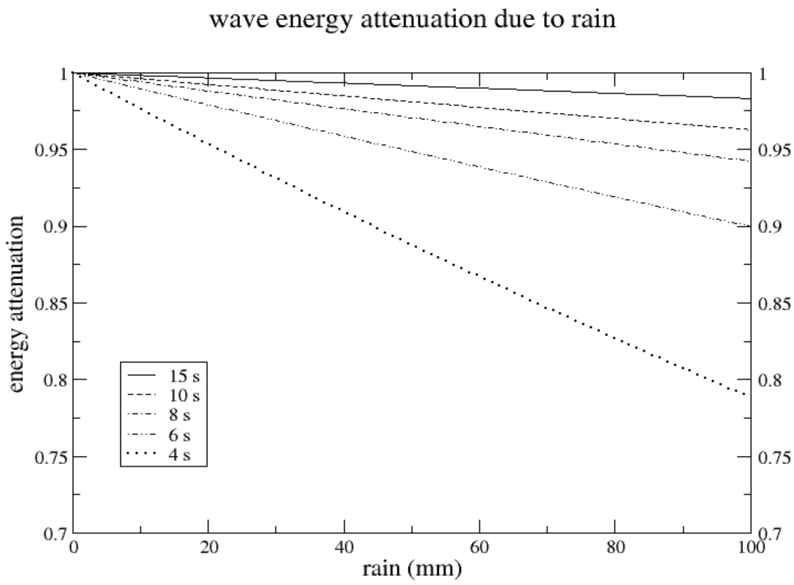

Figure 3 – Attenuation, according to formula (1), of the energy of waves with different period (4, 6, 8, 10 and 15 s) as a function of the encountered rain (after Cavaleri and Bertotti, 2017).

The results have been published in the cited reference.

3 – The effect of rain on generation and dissipation

Following the logical course of actions of the first two years of the project, we then tackled the problem of the effects of rain on the physics of the atmosphere-ocean interface. From the perspective of wave modelling, the immediate problem is the influence of rain on the generation and dissipation of ocean waves. This problem is complicated, involving not only wind waves, but also meteorological modelling. Rain is presently an "output" of the meteorological model, withoutany mechanical feed back into the system. However, rain may affect the sea surface at a substantial level in so doing affecting the air-sea exchange processes at the interface. There are both dynamical and thermodynamic aspects involved. We have tackled these aspects one by one.

Our approach has been rather unconventional. After highlighting the basic physics and the data available that lead to the problem we were tackling, we have taken for granted the present models, more specifically one of them, and run a reference test. We have assume this to be correct. Then we introduced some substantial modifications suggested by the evidence we had available and we showed how, notwithstanding these changes, we could reproduce with good approximation the original results. The logical principle behind this is to stress that good results are a necessary, but not sufficient, condition to state that the model, hence the embedded physics, we use are correct.

The modifications we have used are not meant to be the solution. They are potential, physically sound possibilities showing the directions along which in our opinion it is necessary to work. Granted the present accuracy of wave forecast (see the statistics at http://www.ecmwf.int/en/forecasts/charts/obstat/?facets=Parameter,Wave%20Height), we must acknowledge that problems often exist and appear, especially in rapidly changing or rather extreme situations. The repeated simulations of the worst typhoons and hurricanes looking for a good fit are a classical example.

Our initial activity in this Special Project (as reported in the first two yearly reports) was focused on a passive reaction by waves to the falling rain. Waves are duly attenuated, but no attention was given to the dynamics of the system, in practice generation by wind. Indeed, to be able to derive from the ECMWF wave model results the attenuation of swell by rain, we had to work on areas with no rain at all. Following our previous experiments with Jean Bidlot (Cavaleri et al., 2015) and a remarkable event with one of us (L.C.) on the ISMAR oceanographic tower during a mild storm (see Cavaleri et al., 2018), it became clear that rain does have a direct effect on the interaction between wind and waves. The smoothing of the surface (i.e. the canceling of the spectral tail) in strong rainy conditions implies that both input and white-capping (a direct evidence) are strongly reduced.

Following the direct experience on the oceanographic tower of our institute, our arguing was as follows. By direct evidence, large white-caps disappear during a downpour (only to reappear as soon as the rain is over). This is practically instantaneous (matter of seconds). So the energy drain by white-capping is no longer present. The fact that the wave height did not grow rapidly strongly suggests that also the input by wind was strongly reduced. Were this not the case, given the wind speed, a direct estimate of the overall energy balance showed that the significant wave height H_s would have grown about 15 %. We have also considered different possible attenuation sources, as the previously cited mechanical attenuation by rain or the sink of energy in the tail of the spectrum where energy is transferred by non-linear interactions. Direct estimates exclude also these possibilities. Using the previous results of this project Cavaleri and Bertotti (2017), given the local conditions, the former attenuation was estimated at less than 0.5 % (wave height). For the non-linear possibility, a full (EXACT-NL) calculation using the Zakharov approach indicated an initial exponential decay with about one hour time constant. This implied that the related energy change in the three minutes (or less) of the downpour was less than 5 %. Therefore we could confidently assume that wind input was (almost) absent during the downpour.

In this situation we set-up and ran a few numerical experiments to show, at a possibly naive but quantitatively instructive level, how much the sea would grow if the wind input were still present when white-capping disappears or is strongly reduced. More in general, the action of rain on the two processes, generation by wind and dissipation by breaking, was modulated by the rain rate and the wind speed (soon to be detailed). We tested different modulations although, as we discuss later, we physically favoured the solution of similar, not necessarily identical, modulations of the two processes. Being the test comparative with respect to the present operational formulation, in our tests we did not introduce any further process not considered in the present ECMWF set-up.

4 – The experiments and their results

To summarize the situation: 1) we considered that a sufficiently strong rain would strongly reduce the loss by white-capping $S_{w\text{-}c}$ and input by wind S_{in}; 2) at the same time, guided also by the very enlightening paper by Holthuijsen et al. (2012), we assumed that a sufficiently strong wind (typically in a typhoon or a hurricane) will, partly at least, counteract the effects of rain. Given this basic idea, on purely intuitive and experimental ground we parametrized $S_{w\text{-}c}$ and S_{in} as follows:

$$S_{w\text{-}c} = S^*_{w\text{-}c}\,[1\text{-rain}/r1\,(1\text{-}U_{10}/U1)] \qquad (1)$$

$$S_{in} = S^*_{in}\,[1\text{-rain}/r2\,(1\text{-}U_{10}/U2)] \qquad (2)$$

where $S^*_{w\text{-}c}$, S^*_{in} are the standard source functions used in the ECMWF wave model, 'rain', r1, r2 are in mmh^{-1} and wind speeds U_{10}, U1, U2 are ms^{-1}. 'rain' and U_{10} are the actual conditions, r1, r2, U1, U2 are the modulating parameters. In actual coding suitable checks have been used to avoid unrealistic results for 'rain'>r1, r2 and U_{10}>U1 or U2. (1) and (2) imply that $S_{w\text{-}c}$ and S_{in} are nullified for 'rain' >=r1 and r2 respectively, but this rain effect decreases with increasing wind speed and is in turn nullified if U10>=U1 and U2.

We have carried out six experiments with different modulation by rain of the wind input and loss by white-capping with respect to a standard run with the standard source functions. The period considered is 13-23 October 2016, that includes hurricane Nicole and typhoons Sarika and Haima. Figure 4 shows their respective tracks (the one of the maximum significant wave height H_s) at each hourly step. All the three tropical storms were up to category 4 or 5.

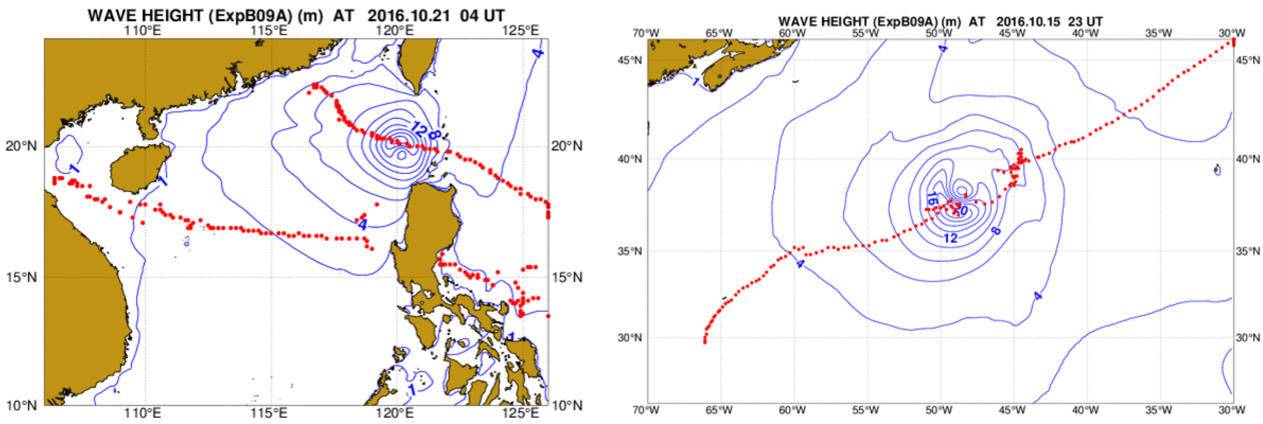

Figure 4 – Left panel: tracks of typhoons Sarika (left) and Haima (right, acting in the panel). Right panel: as left panel, but for hurricane Nicole. The respective areas are the ones considered for their analysis.

Looking at the paper (Cavaleri and Bertotti, 2018) and at the details of the overall results, the key point we want to stress here for the purpose of this project is that a full modulation with rain of the inout by wind and loss by white-capping leads in practice to the same results (as significant wave height is concerned) as the standard, operational model formulation.

5 – Main conclusions

We itemize as follows our main conclusions:

1- rain attenuates swell and we have provided a related expression derived from an extended comparison between ECMWF wave results and corresponding measured data.
2 - on a more active role of rain with the dynamical interaction between wind and waves, there is experimental evidence that rain, more in general, or together with, a high frequency smoothing of the surface, affects (strongly decreases) white-capping and input by wind,
3 - the consequences can be large, especially in very rainy conditions, that however we have assumed (on pure physical, albeit intuitive, ground, but based on documented literature) wind can counteract if strong enough,
4 - a purely "order of magnitude" guess of the related quantification, as implemented in the tests, provides results practically in full agreement with the "regular" ones,
5 - on more general terms, as dealt more in detail in the cited paper, all these results and experience cast some doubts on the physics that is presently at the base of our wave modeling.

List of publications/reports from the project with complete references

Cavaleri, L., L.Bertotti, and J.-R.Bidlot, 2015. Waving in the rain, J. Geophys. Res., 13pp, doi:10.1002/2014JCO10348.

Biao Zhao, Fangli Qiao, Luigi Cavaleri, Guansuo Wang, Luciana Bertotti, Li Liu, 2017 . Sensitivity of typhoon modeling to surface waves and rainfall , *Journal of Geophysical Research*, DOI: 10.1002/2016JC012262

Cavaleri, L., and L.Bertotti, 2017. The attenuation of swell waves by rain, *Geoph. Res. Letters*, 44, 1-7, https://doi.org/10.1002/2017GL075458.

Cavaleri, L., and L Bertotti, 2018. Rain on generative seas, Geoph. Res. Let., 45,8pp, https://doi.org/10.1029/2018GL078006.

Cavaleri, L., T.Baldock, L.Bertotti, S.Langodan, M.Olfateh, and P.Pezzutto, 2018. What a sudden downpour reveals about wind wave generation, IUTAM Symposium on Wind Waves, 4-8 September 2017, London, U.K., Elsevier, Science Direct.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Following the course of our research we have applied for another Special Project : “Underestimate of modelled offshore blowing winds” that started on 01/01/2020