SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Effect of heavy rain on the development of tropical cyclones
Computer Project Account:	spitwm
Start Year - End Year :	2014 - 2016
Principal Investigator(s)	Luciana Bertotti
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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 strong storms and tropical cyclones, analysing all the processes that concur to their development. The problem is complicated, in the sense that the interaction of rain with the sea surface has many implications presently ignored in both meteorological and wave, hence also ocean, modelling. We have now a fairly good idea of the qualitative aspects of the problems. These concerns both the direct mechanical action of rain on waves, and, most of all, the influence of rain on the characteristics of the sea surface, in so doing affecting all the air-sea transfers at the sea surface. Focusing progressively on different aspects of the problem, we have analysed the consequences of rain on strong extra-tropical storms. Besides 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. 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. However, we are cooperating with other institutions on the problem of the hurricanes, and we describe some of the results in this respect, also connected to rain.

Experience with the Special Project framework

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

No particular problems have been encountered. If any question arose about application procedure and/or reports forms we got all the needed help from user support which provided the correct link to the neede form.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

The basic problem and the influence of rain in extra-tropical storms

The basic problem

A basic problem that has emerged in the last few years is that the operational model systems do not take into account the effect of rain on wind and waves. This reflects several parallel processes whose relevance is progressively emerging. The subtle point is that it is not the direct effect of the rain of waves that is important, but rain does affect, and changes the way they develop, the processes that dominate the evolution of a wave fields. The key point is that the evolution of a wave field is a dynamical equilibrium between generation (input by wind) and dissipation (white-capping). Our previous results show that an intense rain cancels completely the white-capping, hence the drain of energy from the wave system, and reduces at a substantial level the input by wind. The reasons for the latter is not yet completely clear. A basic point is likely to be the reduced smoothness of the sea surface, and the consequent ‘sliding’ of the wind on the wave profile with a substantially reduced or cancelling of the Miles-Janssen process of wind input to waves. Possibly only the process devised by Jeffreys in the first half of the last century is still active, with a correspondingly reduced input to waves.

It is a common experience among seafarers, both of the past and today, that “rain calms the sea”. Figure 1 shows such a situation. The irregular surface clearly indicates that we are not dealing with swell. At the same time, for whoever had the chance to witness a stormy sea, the lack of short wave features and breakers is macroscopically evident.

The related processes have attracted scholar attention since long time ago. The first report we managed to trace back is by *Reynolds* [1875] who experimented with artificial drops falling on calm water. He reported that, if sufficiently large and energetic, each drop has a tendency to create a vortex ring and, more in general, to increase turbulence in the upper layer. He concluded saying that this had the potential of attenuating water waves. Reynolds came back to the subject in 1900 with more details, but basically the same idea.

Figure 1 – Wind sea in rainy conditions (courtesy of Ginni Callahan). Environmental conditions (on-board estimate): wind speed 15 ms^{-1}, significant wave height > 1 m, mainly wind sea, very heavy rain.

With few exceptions, as *Manton* [1973], the subject laid basically dormant, at least according to our information, for a long while. Wave modeling, entering the digital era in the ‘70s, was too busy with more fundamental and quantitatively relevant processes to pay attention to rain. The matter came into focus again in the late ‘80s, early ‘90s, in connection with the use of remote sensing instruments, scatterometer and Synthetic Aperture Radar (SAR) in particular. Relying for signal detection on the interaction of the emitted radar signal with the centimetric waves at the sea surface, the efficiency of the instruments was obviously depending on rain. This led to a number of studies and reported results. *Tsimplis and Thorpe* [1989], *Tsimplis* [1992], *Beya et al.* [2010] and *Peirson et al.* [2013] studied the effect of artificial rain on mechanically generated waves in a wave flume. *Poon et al.* [1992], as also *Braun et al.* [2002], went a step further using wind generated waves in a flume with rain falling on a limited section of it. With some differences among the various reported results, the emerging general picture is the following. Rain, if intense enough as usually the case in laboratory experiments, leads to a small scale turbulence in the first few centimeters below the water surface. It also increases the surface roughness at the centimetric scale (order of frequency 10 Hz). Witnessing a downpour on a lake or a small pond will provide immediate evidence of the little messy surface. The consequent surface motion is very low, incoherent and, with the exception of an oblique rain component, isotropic. In practical terms it does not contribute directly to wind wave generation.

Longer waves, from a few centimeters upwards, are attenuated. Corresponding evidence for the shorter waves, i.e. the high tail of the spectrum, is given in the various laboratory experiments quoted above. A quantification for the longer waves, not achievable in laboratory conditions, has been provided by *Le Méhauté and Khangaonkar* [1990, henceforth referred to as LMK] who made a keen analysis of the effect of falling rain drops on an underlying wave field, taking into consideration also the possible wind effect, i.e. of rain falling at a marked angle with respect to the vertical. For a 50 mmh^{-1} precipitation rate (soon to be commented about) they derived a 38, 5, 0.5 % hourly wave height decay for 1, 10, 100 meter long waves respectively.

The practical implications for scatterometer and SAR instruments have been well defined, among others, by *Weissman et al.* [2012] and *ESA* [2013]. The Ku band signal (~14 GHz, 2.1 cm) is strongly affected, as it was the case for QuikSCAT. C band (~5.3 GHz, 5.6 cm) seems to fare better, and it has been the preferred choice for ASCAT. *Chen et al.* [1998] used this difference, together with radiometer data, to estimate the rain distribution on the oceans. However, according to ESA the problem is not so well defined because the transition zone between increased and decreased wave heights, certainly in the 5 to 10 cm range, depends on the rain rate, the drop size distribution, the wind speed, and the time history of the rain event.

From the point of view of wave modeling, our present main interest, the seemingly accepted fact is that, when rain is present, for waves from a few centimeters upwards there is a marked attenuation, rain rate dependent and rapidly decreasing with the wave length.

Our temporary results are summarized in the Figure 2 where we see the different performance of the Ecmwf model with respect to the altimeter wave height data according to the different rain rate. The information is not provided by the single plots, with a slight underestimate of the model versus the measured data. Rather, the relevant finding is given by the comparison among the four plots. It is clear that the underestimate by the model decreases with the increase of the rain rate. Because the model does not consider the effect of rain, this must correspond to a different, on average, measured wave height in the different conditions. In practice we have found that, granted all the other conditions, the measured wave heights decrease with increasing rain rate.

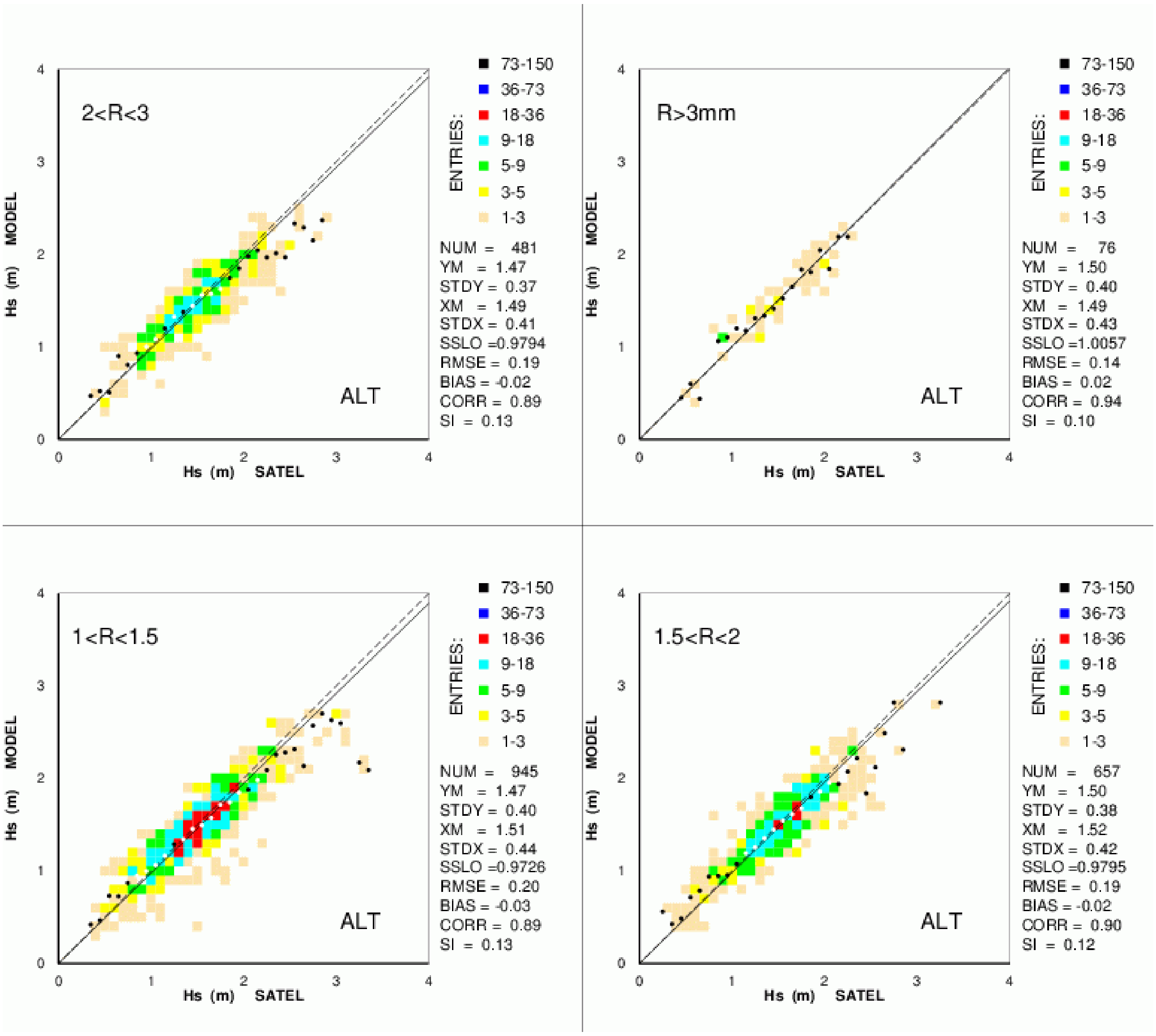

Figure 2 – Comparison between Ecmwf modelled wave heights and corresponding altimeter measured data. The underestimate decrease with increasing rain rate.

Modelling set-up

To verify our hypothesis, we have used the coupled modeling system operational at ECMWF till November 2013. The system implies a full two-way coupling between the meteorological and WAM wave models (see respectively, *Simmons and Gibson* [2000], and *Komen et al.* [1994], *Janssen* [2008]).

We have used the T1279 version of the system, i.e. 16 and 28 km spatial resolution respectively for the meteorological and wave global models. The wave model was run with 36 frequency (f_1 = 0.0345 Hz) with 1.1 geometric progression, and 36 directions starting at 5 degree clockwise with respect to North. Focused on a period to be soon specified, we have first done a reference run with the standard set-up. The run was then repeated introducing a zero-ing of the wave spectrum, beyond a frequency f_c depending on the rain rate, in the calculation of the high frequency contribution to the surface stress. The rule we adopted was f_c*rain=54, with rain (rate) given as mmh^{-1}. Whichever the rain rate, the minimum zero-ed frequency was 0.5 Hz. As previously specified, the incoherent centimeter scale surface turbulence due to rain is ignored, also because it becomes appreciable only in heavy rain conditions, when the rain attenuated spectral tail range is larger. Overall this was clearly a rather crude and arbitrary approach. For instance, it is natural to think of a progressive smoothing of the zero-ing with frequency. However, lacking any more precise indication, especially for limited rain rates, our purpose was only to verify the physical principle, leaving, if the results were positive, to a second stage the task to better quantify the details. As the results will show, this was a convenient move.

To verify our hypothesis, obviously we need windy and stormy areas. This excluded the equatorial zone for lack of sustained winds. We also excluded hurricanes and typhoons as isolated and extreme events, not suitable for a first approach. We focused our attention on the North Atlantic Ocean, especially in the 35°-70 ° latitude range. Here we have frequent storms and plenty of measured data, both from buoys and satellites.

Searching for a suitable period, we have explored the wind and rain maps from January 2006 till December 2010. Our choice for a full month period was for December 2009. In this month, the ECMWF system was still running with T799 resolution (about 25 km). The archived results are regularly available at 6-hour interval for analysis, 3-hour for forecast. However, rain events can be shorter and spatially localized and measured data are available in the intermediate hours. Therefore we were interested in higher time and space resolution. Hence in this phase we ignored the archived data and we repeated the simulation for the full December 2009 with the already specified T1279 resolution, saving the results at one hour interval. As said above, this was first done with the standard set-up, and then repeated with the zero-ed spectral tail according to rain. Standard meteorological and wave integrated parameters and full 2D spectra were saved at each grid point. Each run was done as a sequence of 24 hour forecasts at 12 hour interval. For each forecast, the 13-24 hour section was retained. This provided a full month simulation suitable for the subsequent analysis.

Measured data were from moored buoy and satellite measurements. A large portion of the buoy data comes from the archive of in-situ data routinely obtained from the global telecommunication system with the rest supplemented as part of the data exchanged under the JCOMM project of model performance inter-comparison [*Bidlot et al.*, 2007]. Both wind and wave data were used. For the satellites we excluded the scatterometer data because of their doubtful use in rainy areas. C band data, e.g. ASCAT, are less affected by rain and regularly used for operational purposes. However, as we will see, we deal with limited differences that would be comparable with the, albeit limited, error of the scatterometer in rainy areas. For similar, although less doubtful, reasons we excluded also the use of altimeter wind data. Altimeter wave height data seem a much more solid information. We used these data from both ENVISAT and Jason-2 satellites. The data were extracted from the RADS database [*Naeije et al.*, 2008]; see http://rads.tudelft.nl/rads/literature.shtml for details. The model results were linearly interpolated in space and time to the buoy and altimeter data.

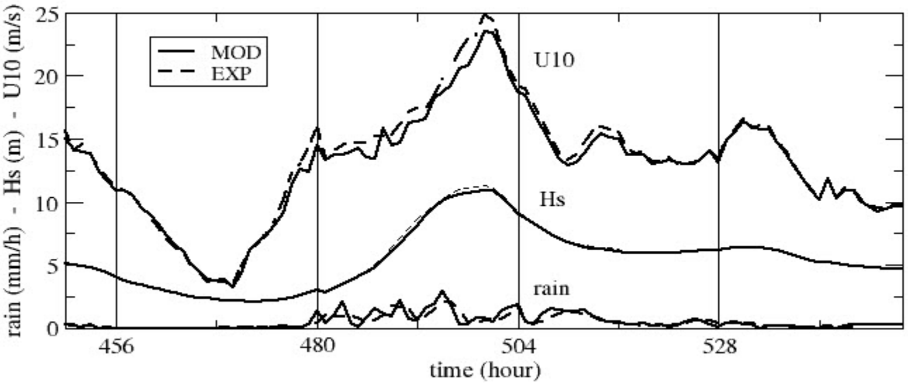

Figure 3 – Four day time series of model wind speeds, significant wave heights and rain rates at a position in the North Atlantic Ocean during December 2009. Continuous lines show the regular model results, the dash ones taking the reduced surface roughness under rain into account.

Results

A typical result of our modelling exercise is shown in Figure 3. We see that in correspondence to the rainy event both the wind and the wave height increase. However interesting this result seems to be, once carefully analysed it is opposite to what we should have expected. If Figure 3 represents the truth with rain, we should expect a growing underestimate of Hs by the model with increasing rain. On the contrary the analysed data in Figure 2 suggest the opposite. Hence we were forced to look for a different explanation. This was further supported by the comparison in Figure 4.

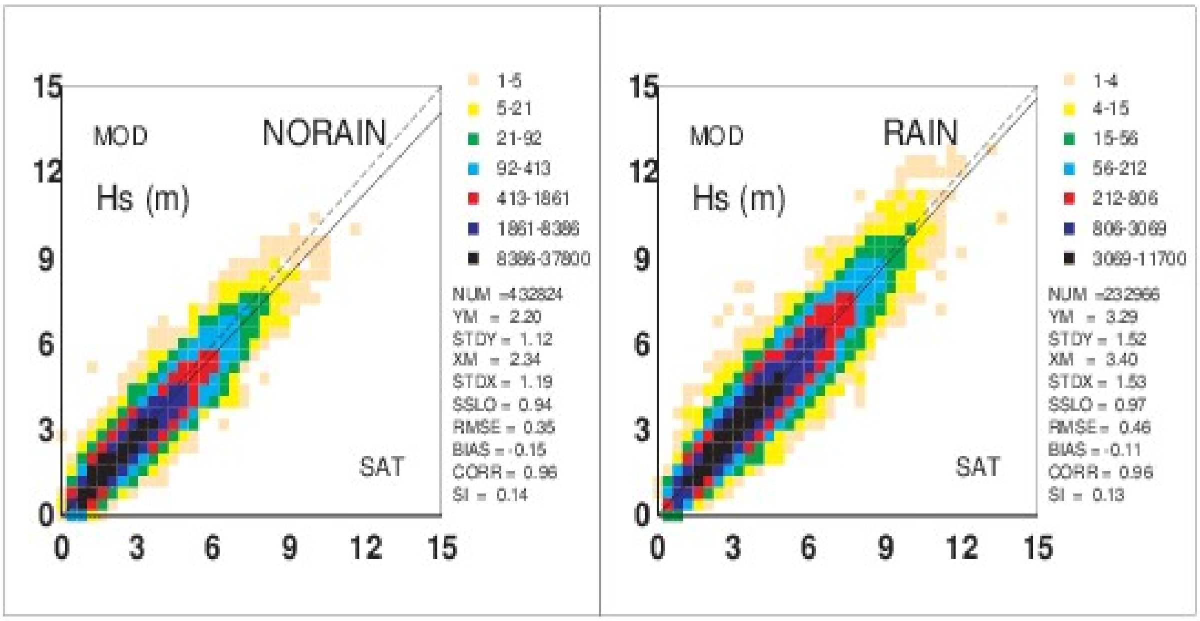

Figure 4 – Four day time series of model wind speeds, significant wave heights and rain rates at a position in the North Atlantic Ocean during December 2009. Continuous lines show the regular model results, the dash ones taking the reduced surface roughness under rain into account.

The search for an explanation

Given that our results contradict the experimental evidence, clearly we need to look for the missing physics in our approach. We stress again that all our reported statistics, exemplified in the intercomparisons in Figures 2 and 4, are very robust. We double-checked their significance using both the boot-strap and the jack-knife approaches [see, e.g., *Edgington*, 1995]. All the results turned out significant at better than 99%.

We also cannot neglect the perception that after a sustained rain we perceive (measurements are scarce in these conditions) that the wave heights are somehow lower. However, the key point we need to stress is that the disappearance, or decreasing number, of whitecaps under a strong rain is practically an instantaneous process (matter of seconds). The steep waves in Figure 1 are suggestive in this respect. The picture was taken in the Tahiti area during a squall. Being a localized event, model data, referred to a wider area, do not represent the specific conditions. The people onboard reported wind speed larger than 15 ms^{-1} and significant wave height higher than 1 m. As also evident from the picture because of wave steepness, dominant waves were locally generated. Rain was reported as “very heavy”. One of us (L.C.) has recently witnessed such an event during a wave measuring campaign on the ISMAR oceanographic tower (Northern Adriatic Sea, 16 meter depth, 15 km offshore the Venice coast).

A stronger effect turns out to concern the key element of any sea storm, i.e. the wind input to waves. The basic theory was formulated by Miles [1957, plus a later sequence of papers], then refined by Janssen [1989, 1991] to consider the feed-back of waves on the driving wind field. The theory stands on three basic concepts, those of roughness length z_0 (i.e. the height close to the surface where the wind speed is null), of a logarithmic vertical profile of the wind speed, and of critical height z_c as the one where wind speed equals the phase speed of the wave component we consider acting upon. The major drag of the wind profile, hence a large momentum flux from wind to waves, is given by the tail of the spectrum with its low but steep waves, hence the low values of z_0. If these waves are flattened by rain z_0 increases (now related to longer and higher waves), and the logarithmic profile, so to say, relaxes, with a less steep increase of the wind speed close to the surface. In turn this implies a substantial increase of the critical height z_c. This has a dramatic effect on the input by wind to the considered component, because the momentum transfer to waves is roughly proportional to $\exp(-2kz_c)$ with k the wave number [see the discussion by Lighthill, 1999]. Indeed the Miles-Janssen mechanism is effective only for low values of the critical height with respect to the wavelength. This makes the input to the bulk of the spectrum extremely sensitive to the condition of the tail. Following the above argument a heavy rain, via its effect on the tail, indirectly affects the whole generation process. Because during generation most of energy input by wind (>90%) is immediately lost as white-capping, cancelling the tail leads also to an immediate decrease, in the extreme the disappearance, of white-capping.

So the tail of the spectrum acts on surface breaking in two ways: via the direct influence of the tail on the breaking process, and via the possible drastic decrease of input by wind. In this second aspect it is worth mentioning that there is a feed-back process at work. In 1976 Banner and Melville pointed out that much, if not most, of the momentum input by wind to waves does not take place as a smooth continuous process. Rather, it happens in bursts, mostly in connection with the breakers, or white-caps, that characterize the crests of a sea under the vigorous action of wind.

Two things need to be pointed out about the effect of rain or torn drops on waves. The nice machine we have assembled in a numerical wave model assumes a clean well defined separation surface between air and water. However, when we go to very high wind speeds, the obvious examples being hurricanes, the separation surface begins to lose its meaning, substituted by a layer of “foaming material”, troughs full of foam, and so on. The physics of this interface, still a subject of valuable studies [see, e.g., Soloviev and Lukas, 2010], is different, and it is amazing that our wave models still manage to produce valuable results also in these conditions. This takes us to the second part of our research in this project.

The influence of rain on the tropical cyclones

We considered introducing the process of the smoothness of the sea surface in the modelling of a hurricane. However, the correct physical representation of what is going on the surface of the sea under wind of the order of 50 m/s or more is not obvious at all. It is well known that, while the surface drag coefficient increase with wind speed till 30 m/s or so, at higher speeds there is a levelling of the coefficient, with also a possible reduction. This is thought to be due to a) the physical cut of the wave crests by the wind, b) the filling of the wave troughs by foam so that wind slides horizontally on the sea surface cancelling or strongly reducing the effect of the Miles-Janssen generation process. While the level of rain in a hurricane can be extremely high, the mechanics of the surface is not clear, i.e. if, for what roughness is concerned, how the opposite effects of rain and wind combine to determine the level of roughness. The difficulty stems from the fact that there is a lot of parameterization in modelling an extreme process as a hurricane. Therefore it is much simpler to study the sensitivity of the results to changing a process rather than determining if a certain process improves the final results.

It is obviously of interest to model hurricanes, cyclones and typhoons with satisfactory accuracy. With this we imply not only accurate results, but also a more and more detailed description of the processes at work. Typhoons are probably the most powerful phenomenon due to strong air-sea interaction, capable of tremendous destruction, and also relevant for their climatic implications. Note that for simplicity we will use this word throughout this report, also because most of the tests we worked on were done on typhoon Haiyan, one of the most powerful and deadly events of this kind.

A typhoon can be thought of as a heat transfer machine. The heat and moisture fluxes that fuel it at the air-sea interface play an important role in intensifying a typhoon [*Chen et al.*, 2007], with the ensuing transformation of potential energy into kinetic one (wind), with consequent generation of potentially very large waves. In turn these are important because, being one of the main features of the sea surface, they modulate to a large extent the critical exchanges between atmosphere and ocean [*Cavaleri et al.*, 2012; *Fan et al,* 2010]. The progress in typhoon modeling is basically associated with an improved description of the physical processes involved. This may happen because of an increased spatial resolution (a typhoon center is characterized by very strong spatial gradients) or using a better or novel description of how they work.

Over the past several decades, the track forecasts of typhoon have statistically been improved, while the validation results of intensity forecast have shown little improvement [*Rappaport et al*., 2012]. An operational model tends to overestimate the intensity of weak typhoons, while underestimate the strong ones [*Bender and Ginis*, 2000]. The lack of skill of intensity forecasts may be due to insufficient consideration of the physical processes at the air-sea interface, and of those involving thermal exchanges in particular [*Chen et al.*, 2007]. For example, surface wave breaking induced spray will enhance air-sea heat flux [*Andreas et al*., 2015], while non-breaking surface waves may enhance the vertical mixing rate of the upper ocean [*Qiao et al*, 2004, 2016]. Rainfall could induce cooling of sea surface waters. All these physical processes have the capability of affecting the developing of a typhoon. To better understand the interaction mechanisms between typhoon and these physical processes, in this project we have explored the sensitivity of typhoon model results to the the presence of rain on the sea surface. This has been done by hindcasting a strong typhoon, Haiyan, with a fully coupled atmosphere-ocean-wave system and checking how the results, with and without this process, vary and compare with the available measured data.

The physical processes to be considered

The extreme conditions reached in typhoons stretch to the limit the physics regularly used in, e.g, the third generation wave models to transfer energy and momentum from the atmosphere to the ocean. Indeed in these conditions one can wonder about the physical meaning of the sea surface. Rather than the neat curved surface that for wave modeling purposes we decompose into spectral components, the separation between air and water is better represented by a thick layer whose characteristics vary progressively, in a simplified way, from air filled with foam to bubbles filled water. One can reasonably argue how comes that, notwithstanding these conditions and the other ones that a typhoon implies close to the surface, the operational models, in particular the wave ones, produce good quality results [see, among others, *Magnusson et al.*, 2014]. More in general, there are many parallel and interacting processes at work in a typhoon, and we usually represent only part of them, obviously the ones we consider as the most important ones.

Rainfall

Heavy rain is a characteristic of a typhoon system. Falling from the upper layers of atmosphere, rain is cooler than the lower layers it moves through. However, it rapidly reaches a dynamical equilibrium between the layer temperature and the intensive cooling derived from the progressive evaporation of drops. *Kinzer and Gunn* [1951] carried out very careful and well thought experiments on this topic. They found that, due to the wet bulb effect, a 0.27 mm falling drop is up to 14ºC cooler than the surrounding air. Using the TOGA-COARE data, *Gosnell et al.* [1995] reported even larger differences (cooler rain), with a negative heat flux to the sea surface of up to 200 Wm^{-2}. *Schlüssel et al.* [1997] confirmed these results.

In summary the falling rain in a typhoon can be much colder than that of the sea surface water. This is usually the case considering that typhoons appear mostly in areas where the sea surface temperature is typically above 27°C. The basic information to start from is that rain is much cooler than the water it falls on at the sea surface.

Our present purpose is to explore the implications for the development of a typhoon when the sea surface temperature cools because of heavy rain events. We did not succeed in collecting much information on the subject (this does not seem to receive much attention at present). Therefore, in the pure spirit of exploring the sensitivity of a typhoon to a change of the sea surface temperature associated to rain, we have made the following assumptions:

1 – the maximum cooling of the sea surface is $\Delta T_0 = 4°C$, for rainfall rates greater than or equal to 40 mmh^{-1}. Based on the cited literature, a higher value could be chosen, but we prefer to be conservative to be sure of the obtained results.

2 – this figure is linearly decreased with the rain rate “rain”. In practice $\Delta T = \Delta T_0 * (rain/40)\,°C$

3 –however, waves, and especially breaking waves, obviously play a role in that they tend to mix the surface layers. Hence we also assume $\Delta T = 0°C$ for significant wave heights H_s higher than 10 m. For lower values two further possibilities have been considered: swell and wind sea (plus intermediate situations), the latter being more active in surface mixing because of white-capping and crest tearing by waves (see spray effects in sub-section 2.1 above). For swell, i.e. when the phase speed of the spectral peak frequency C_P is larger than the 10 m wind speed U_{10}, the cooling reduction was assumed to be

$$\Delta T = \Delta T_0 * \min\left[\left(rain/40\right), 1\right] * \max\left[\left(1 - \left(H_s/10\right)^2\right), 0\right] \tag{7}$$

For wind sea, i.e. when $C_p/U_{10} < 1$, a further reduction of ΔT has been assumed as

$$\Delta T = \Delta T_0 * \min\left[\left(rain/40\right), 1\right] * \max\left[\left(1 - \left(H_s/10\right)^2\right), 0\right] * \min\left[\left(0.5 + 0.5 * \left(C_p/U_{10}\right)^{0.5}\right), 1\right] \tag{8}$$

Note that (8) converges to (7) when C_P approaches U_{10}. We stress that the described procedure does not imply any tuning of the ocean model. The ΔT in (7) and (8) is calculated in the atmospheric model (taking waves into account). This information is passed to the ocean model, which is then used to estimate the actual sensible heat flux. This is evaluated as

$$H_{Sen} = \rho_a c_p C_T u_* \left[T_a - \left(T_s - \Delta T\right)\right] \tag{9}$$

where, ρ_a is the density of air, c_{pa} represents the air specific heat, C_T the Stanton number, T_a the surface air temperature, T_s the sea surface temperature, H_{Sen} the sensible heat flux.

This process has been introduced in the coupled model system we have used for the purpose, in particular for the estimate of the heat transfer between the ocean and the atmosphere during the development of the typhoon.

Preliminary results

While the full results are still under strict scrutiny, some preliminary conclusion can be drafted with implicative indications for the process under consideration (note that more extensive results canbe found in Zhao et al., [2017]). Of the various tests there reported, the best results concerning the typhoon Haiyan have been obtained wgen considering the described effect of rain in colling the sea surface. There is a number of processes going on that affect the heat transfer from the sea to the typhoon. Although not the dominant process (this role is up to the sea spray), considering the effect of rain in cooling the sea surface is crucial in a detailed and accurate modelling of the typhoon. Obviously the parameterization described above is a first attempt, but physically sound. Data are crucially missing in this respect. However, the positive results we have obtained suggest we are on the right track.

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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 what done in the past project we plan to explore the influence of rain on the wave development in different cases with different intensities of event. We want to study all this with devoted experiments. Changing the various boundary conditions will provide the possibility to explore the sensitivity of the coupled model results to the parametrization of the various mentioned processes.
We have already applied for a continuaton of our research, presently we started a new Special Project with title: “The different effects of heavy rain on the development of ocean waves”
The project will continue for the period 2017-2019