

# Probabilistic Forecast of Coastal Waves for Flood Warning Applications at Reunion Island (Indian Ocean)

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## ABSTRACT

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La Reunion being a small isolated island, the coastal impacts of tropical cyclones transiting nearby are tightly related to the relative position of the track, wind intensity and size. Thus, the forecast of cyclone-induced waves should be conducted in a probabilistic manner.

Using ensemble track and intensity forecasts of Bonnardot and Quetelard (2016), the approach presented here relies on two steps: (1) Considering that the use of parametric models leads to an underestimation of wave heights distant from the cyclone eye, the forecasted vortex is bogused into the large-scale wind field provided by ECMWF's IFS model for each track and time step. A short simulation is conducted with Meso-NH model at 8 km resolution so that it can create realistic wind and pressure fields well balanced with the large-scale conditions (2) A combination of a two-way nested Wavewatch 3 modelling framework enables to compute the waves associated to each track from 10 km to 300 m resolution at the coast.

Results extracted at 50 m depth are presented as exceedance values and probabilities of exceedance of wave heights for different coastal segments and thresholds. The comparison with measurements and simulations performed with Best-Track data show that probabilistic wave forecasts performed with the ensemble sets of Bonnardot and Quetelard (2016) upgrade the precision and the level of information provided compared to the deterministic method. Nevertheless, the study also points out that the size and shape parameters of the cyclones should be considered in the ensemble generation method to produce more accurate wave forecast.

**ADDITIONAL INDEX WORDS:** *cyclone, waves, ensemble forecast, probability, Reunion Island, modelling*

## INTRODUCTION

Within the French Overseas Territories, Reunion Island is one of the most exposed to cyclone-induced hazards. The Southwest Indian Ocean cyclonic season is officially from November to April. Cyclone tracks often follow a southwestward trajectory. Thus, cyclonic waves mainly affect the northern and eastern parts of the island. In the past decade, seven cyclones passed within 200 km of Reunion Island. For the two last strong cyclones, Dumile and Bejisa (resp. in Jan. 2013 and Jan. 2014), the red alert level of the French emergency plan was triggered.

The configuration of the coast, with steep slopes and no continental shelf, limits the impact of the atmospheric surge, which is mainly due to inverse barometer effect with a very low contribution of wind. On the contrary, waves may generate high wave set-up, in particular along the fringing reef areas, and cause considerable overtopping leading to substantial floods on coastal roads and districts.

As of today, cyclonic wave forecasts at Reunion Island come from global or regional wave models forced by the ECMWF Numerical Weather Prediction System. Overall, this approach presents several limitations: (1) wave forecasts are not necessarily consistent with the official Regional Specialized Meteorological Center (hereafter RSMC La Reunion) advisories (2) wind and wave models resolutions are not always sufficient to properly describe the cyclone structure and simulate coastal processes (3) wave forecasts are mostly deterministic and do not account for uncertainties.

Nowadays, ongoing efforts at international level tend to generalize the use of probabilistic storm surge, waves and inundation forecasts in cyclonic-prone areas. Numerous examples exist for the United-States such as the NOAA P-surge Forecasting System (Taylor and Glahn, 2008) or the CH3D-SSMS Forecasting System (Davis *et al.*, 2010). However, these systems focus on storm surge forecasts, as it is the most important factor of marine submersion of US low-lying coasts.

RSMC La Reunion recently developed an original method to build alternative scenarios around the official deterministic forecasted track based on both historical forecast errors and the ECMWF Ensemble Prediction System (EPS) scattering

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information (Bonnardot and Quetelard, 2016). The method results in ensemble forecasts of track and intensity with 15-25 members (thanks to a preliminary clustering of similar members), each of them being associated with a probability of occurrence. Thus, the limited number of members constituting the ensemble set enables to consider the use of this tool to infer probabilistic coastal waves forecast at Reunion Island. Based on cyclones Bejisa and Dumile cases, the objectives of this paper are to evaluate and identify:

- The relevance of the method of Bonnardot and Quetelard (2016) to infer probabilistic waves forecast at Reunion Island;
- The benefit of this approach compared to a classical deterministic forecast based on RSMC official advisories;
- Further required efforts to upgrade cyclone-induced waves forecast and estimation of impacts at Reunion Island.

## METHODS

Using ensemble tracks and intensity forecasts of Bonnardot and Quetelard (2016), the method comprises the following steps:

### Wind and pressure modeling

Considering that the use of parametric wind models like Holland (1980) may lead to an underestimation of simulated wave heights, an alternative method is used. For each member and time step (every hour):

(1) The cyclone vortex is removed from global ECMWF IFS forecasted wind field following the method proposed by Kurihara *et al.* (1993, 1995).

(2) The forecasted vortex is then bogused into the research model Meso-NH (Lafore *et al.*, 1999) initialized and coupled with the large-scale wind field provided by IFS model. The characteristics of the desired vortex are controlled by imposing the position of the vortex and the maximum wind intensity ( $V_m$ ), but also the radius of maximum wind ( $R_m$ ) and a shape parameter ( $B_0$ ) that controls the rate of decrease of wind intensity beyond  $R_m$ . Basically, an increasing  $R_m$  tends to enlarge the cyclonic wind field, while an increasing  $B_0$  rather tends to contract the wind field around the eye (see Holland, 1980). As the tool of Bonnardot and Quetelard (2016) does not give any indication on  $R_m$  and  $B_0$  for the ensemble members, strong hypothesis are necessary. If  $R_m$  is known at the forecast time considered (based on satellite imagery), an assumption of persistence is made. Otherwise, statistical values corresponding to cyclone categories are applied:  $R_m = 48$  km if  $V_m < 48$  kt (tropical storm),  $R_m = 41$  km if  $48 \text{ kt} < V_m < 64$  kt (strong tropical storm) and  $R_m = 34$  km for  $V_m > 64$  kt (cyclone). For  $B_0$ , a mean value of 1.65 is systematically applied because the actual real-time analysis and forecast method of RSMC La Reunion does not provide the shape parameter.

(3) A short simulation of 400 s (5 time steps) is then conducted with Meso-NH at 8 km resolution (on a small grid centered on the vortex) so that it can create realistic wind fields well balanced with the large-scale conditions.

(4) Meso-NH cyclonic wind field is finally merged into the ECMWF IFS large-scale model interpolated at 8 km.

### Coastal waves modeling

The wave model (see Figure 1) is a combination of a two-way nested Wavewatch III modelling framework (Tolman 2014; hereinafter denoted WW3) forced by Meso-NH wind fields enabling the offshore waves generation and propagation to Reunion Island coastlines. The version 4.18 of WW3 is used

with the source term package described by Ardhuin *et al.* (2010). The first grid (R1) covers a large part of the South Indian Ocean with a regular resolution of  $0.1^\circ$  while (R2), centered on Reunion island, is composed of finite elements whose resolution reach about 300 m at the coast. The bathymetric data used come from ETOPO1 with a spatial resolution of 1 minute (Amante and Eakins, 2009) as well as the bathymetric measurements from the French Naval Hydrographic and Oceanographic Service near the island. The time series of significant wave heights (hereafter  $H_s$ ) are extracted from grid R2 at regular intervals at 50 m depth with 10-minute-frequency.

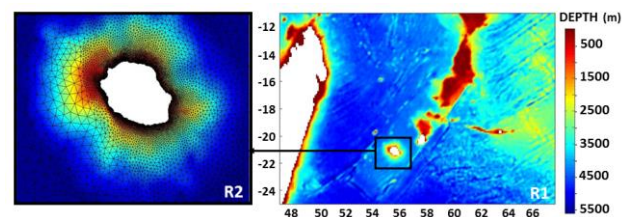


Figure 1. WW3 regular grid R1 (Indian Ocean, geographic coordinates) and R2 (Reunion Island, unstructured grid) with bathymetric depths.

## RESULTS

We apply this method to the two last cyclones passing within 200 km from Reunion Island: Dumile and Bejisa (see Figure 2). The characteristics of the two cyclones are quite similar with a southward track passing west of the island. Although, Bejisa was more intense and passed closer from the Island with a southeastward track (see Table 1).

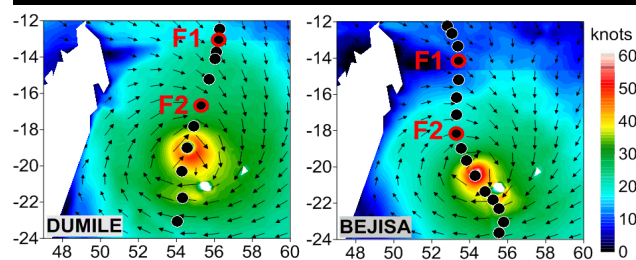


Figure 2. Dumile and Bejisa Best-Tracks and wind intensity (kt)

Table 1. Best-Track parameters of Dumile and Bejisa near Reunion

Cyclone	Distance from Reunion	$V_m$	$R_m$	$B_0$
BEJISA	50 km	80 kt	33 km	1.4
DUMILE	100 km	70 kt	56 km	1.6

The modelling chain using Meso-NH and WW3 models is validated with simulations performed with Best-Track data, *i.e.* with re-analyzed cyclone's parameters (position,  $R_m$ ,  $V_m$  and  $B_0$ ). The comparison between simulations and observations at buoy RN4 (AWAC 600 kHz at 40 m depth on the northern coast near Saint-Denis) are very satisfactory, with a good representation of wave height peak and timing, although a slight underestimation of  $H_s$  for Bejisa (see Figure 3). Maximum simulated  $H_s$  (extracted at 50 m depth) are averaged on eight homogeneous coastal sectors in terms of wave exposure. For both cyclones, the northern coast is the most affected by waves with  $H_s$  exceeding 6 m. However, Bejisa generated higher

waves on the eastern and western sides of the island with maximum  $H_s$  values exceeding 4m when Dumile's waves exceeded 4 m only on the eastern side.

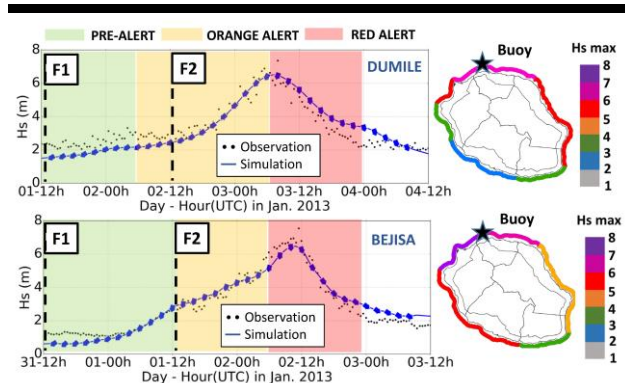


Figure 3. Left: Comparison of  $H_s$  measurements at buoy RN4 (black dots) with simulations (blue line) performed with Best-Track data. Right: Mean of maximum  $H_s$  simulated on the eight coastal sectors.

In the following, we focus on two forecast times with 24 hours' time interval (see F1 and F2 on Figure 2 and Figure 3). Actually, they have a particular interest for the Civil Security:

- F1: About 48 h before the cyclone landfall, during the pre-alert state. This forecast time enables to anticipate and adjust the transition in orange alert, which is the time for operation organization and potential evacuations.
- F2: About 24 h before the cyclone landfall, at the very beginning of the orange-alert state. It enables to anticipate the potential marine submersion impacts before the red alert level, which is a period of confinement preventing any action.

While Dumile's track and intensity forecasts are particularly good for both F1 and F2, forecast errors are higher for Bejisa. The forecasted track is 150 km too close from Reunion Island for F1 and  $V_m$  is overestimated of 10 kt for F2 (Table 2).

Table 2. Forecast errors near La Reunion for Bejisa and Dumile2

Cyclone	F1 (landfall -48h)		F2 (landfall -24h)	
	Track	$V_m$	Track	$V_m$
BEJISA	<b>150 km</b>	0 kt	30 km	<b>+10 kt</b>
DUMILE	50 km	+8 kt	50 km	-3 kt

For both cyclones,  $R_m$  was not available at the forecast times considered. Thus, following the method described above, statistical values of  $R_m$  and  $B_0$  should be applied to force Meso-NH in operational conditions. Nevertheless, as a first step, we consider wave forecasts performed with Best-Track  $R_m$  and  $B_0$  in order to evaluate how the ensemble set can balance with deterministic track and intensity forecast errors regardless other sources of uncertainty. Figure 4 and 5 present for both cases:

- The Best-Track (considered as observation) plotted together with deterministic and ensemble forecasted tracks;
- The comparison at buoy RN4 between observations, deterministic forecast and ensemble forecast described as exceedance values of  $H_s$ . The confidence interval (termed as envelope hereafter) is defined by the 10% and 90% percentiles.
- The probability of exceedance for two thresholds,  $H_s=4m$  (vigilance threshold) and  $H_s = 6 m$  (strengthened vigilance threshold), on the eight homogeneous coastal sectors.

Concerning Dumile, track and intensity deterministic forecasts being very reliable for F1 and F2 (cf. table 2), the related deterministic wave forecasts obtained are very close to observations, with an appropriate representation of wave peak values and timing (see Figure 4). The confidence intervals of the ensemble sets are quite reduced because the great majority of the members passes west from La Reunion and the tracks' scattering near the island remains moderate. Thus, the probabilistic forecast tends to comfort the deterministic one, which lies in the middle of the ensemble envelope close to the value exceeded at 50%. The probabilities of exceedance for  $H_s = 4 m$  and  $H_s = 6 m$  thresholds on coastal sectors gives an interesting outlook of wave exposition hierarchy on the different sides of the island. The sectors exposed to wave heights greater than 4m are well identified for both forecast times (compared to the maximum  $H_s$  simulated with Best-Track data on Figure 3) with probabilities above or close to 50%. The exceedance of the 6m threshold is more difficult to predict with substantial probabilities because it is very close to the highest waves simulated with the Best-Track. However, the ensemble forecasts point out non-negligible probabilities for  $H_s$  to exceed 6 m on the northern coast and succeed in detecting that this sector is the most exposed.

For Bejisa, that presents larger forecast errors of track (F1) and intensity (F2), the deterministic wave forecast clearly overestimates wave heights on RN4 buoy up to 2 m. The confidence interval of the ensemble forecast is quite large for F1 mainly because of the tracks dispersion near Reunion Island. It reveals a high uncertainty for both wave heights peak value and timing that enables to put the deterministic forecast into perspective and show that the deterministic peak value corresponds to the worst possible cases above the percentile 90%. Here, the probabilistic forecast gives valuable information compared to the deterministic one. Actually, for both F1 and F2, the envelope of the ensemble forecast enables to surround the  $H_s$  measurements at buoy RN4 and gives a better outlook of observations than the deterministic version. Again, the probability for  $H_s$  to exceed 4m on the great majority of the sectors is well identified with high probabilities above 50% for both forecast times. Contrary to Dumile, the exposure of the coast to waves higher than 6m is a bit overestimated on the eastern and western sides of the island due to the initial intensity and track deterministic forecast errors. Anyhow, for F1 and F2, the relative exposure of coastal segments enables to highlights the northwestern sectors as the most exposed.

Let us now consider the wave forecast at F2 simulated with operational conditions, that is, with statistical values of  $R_m$  and  $B_0$ . Table 1 shows that near La Reunion, the  $R_m$  of Dumile was 26 km greater and the  $B_0$  of Bejisa was lower than the mean values (resp. 30km and 1.65). Thus, the wind extent and the wave heights obtained with statistical parameters should be in theory lower than values obtained with Best-Track  $R_m$  and  $B_0$ . Actually, this time,  $H_s$  deterministic forecast of Dumile clearly underestimates waves and the confidence interval given by the ensemble forecast is shifted 2 meters under the previous version (Figure 6). The wave height peak observed at the buoy is even out of the confidence interval. The case of Bejisa is particular as the new forecast obtained with statistical  $R_m$  and  $B_0$  is actually closer to observations. Here, there is a compensation between the intensity forecast error that tends to overestimate waves and the wind shape error that tends to underestimate waves.



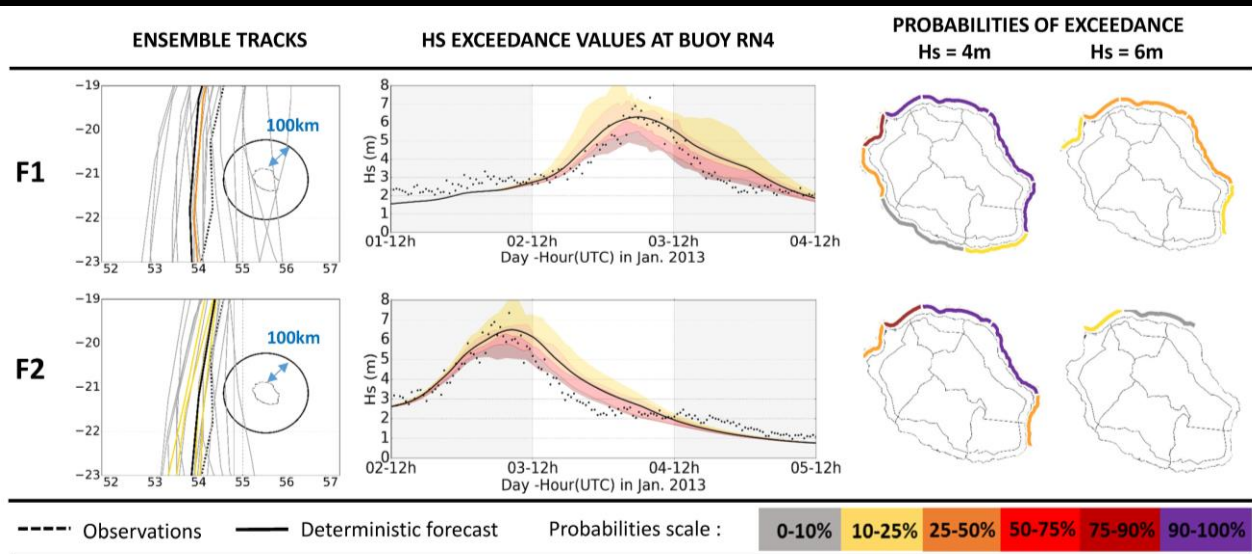


Figure 4. Dumile case performed with Best-Track  $R_m$  and  $B_0$ : (1) Ensemble tracks and probabilities near La Reunion (2)  $H_s$  deterministic forecast at buoy RN4 (black line) compared to observations (black dots) and ensemble forecast exceedance values delimited by percentiles 10% and 90% (3) Ensemble forecast probabilities of exceedance for the two thresholds,  $H_s=4m$  and  $H_s=6m$ , for the eight coastal segments.

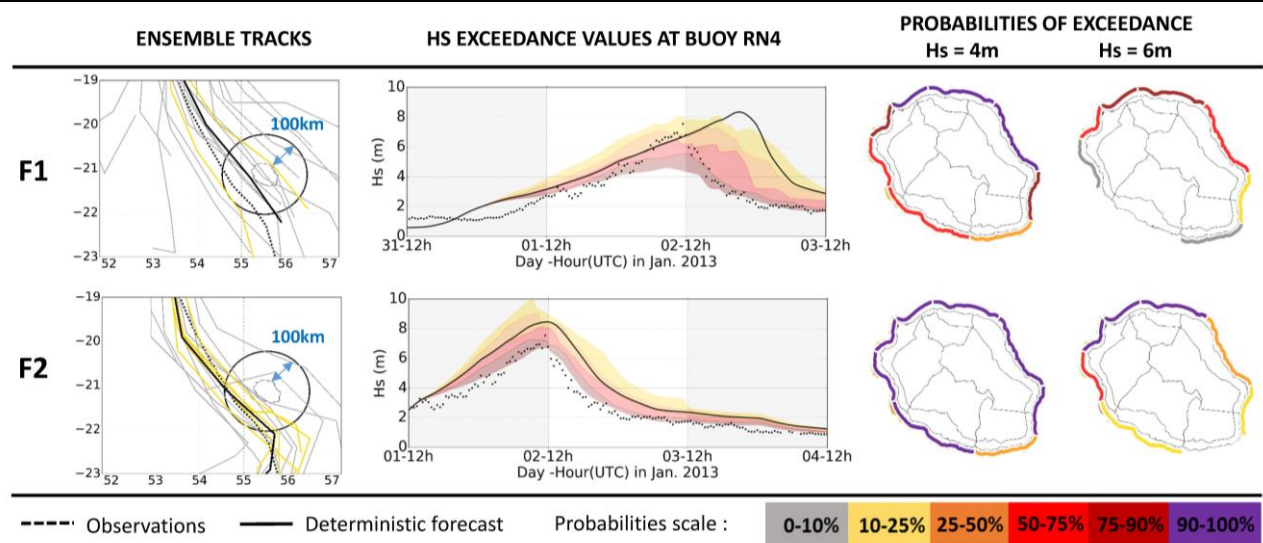


Figure 5. Same as Figure 4 for cyclone Bejisa.

### DISCUSSION

The ensemble forecast tool based on track and intensity variations proposed by Bonnardot and Quetelard (2016) is a good starting point to make ensemble cyclone-induced wave forecast at Reunion Island. Putting aside the problem of cyclone size and shape forecast, the information provided by associated coastal waves forecast are valuable in terms of coastal sectors relative exposure and estimation of uncertainty. When the deterministic forecast is already accurate, it enables to comfort

the deterministic predictions. In the case of higher deterministic forecast errors, it enables to consider over possibilities.

The ensemble sets provided by the method of Bonnardot and Quetelard (2016) is limited to 20-25 members thanks to a preliminary clustering. This number seems sufficient to give an overview of the range of possible wave heights with relevant confidence intervals. However, the results are also more dependent from the few members with important probabilities (generally close to the deterministic tracks). Thus, analyzing the optimal number of members and the proper repartition of

probabilities to find the good compromise between computing time and level of confidence would certainly be of interest.

The main limit of the approach remains the decisive role of cyclone size and shape representation to simulate and thereby forecast proper induced waves. It corroborates the sensitivity analysis performed by Rohmer *et al.* (2017) that already pointed out  $R_m$  as one of the most important parameters conditioning wave heights with wind intensity and track position. Dumile's case shows that ensemble forecasts considering only track and intensity variations cannot counterbalance major size or structure errors, whatever the quality of the deterministic forecast and the number of tracks used.

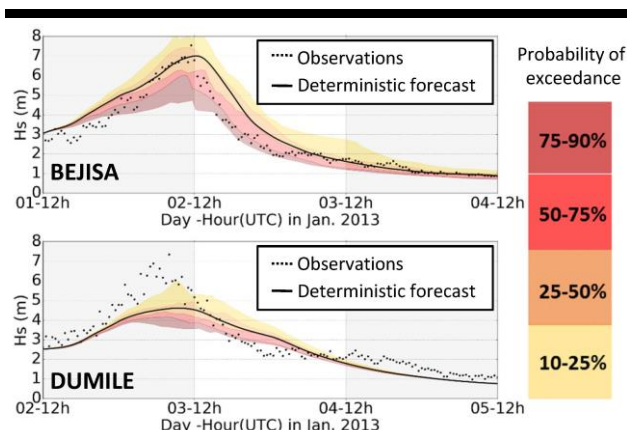


Figure 6.  $H_s$  deterministic forecast at buoy RN4 (black line),  $H_s$  observations (black dots) and ensemble forecast exceedance values delimited by quantiles 10% and 90% for F2 performed with statistical values of  $R_m$  and  $B_0$ .

As marine submersion is due to overtopping only at Reunion Island, the use of ensemble wave forecasts for flood warning applications seems necessary. Actually, slight  $H_s$  forecast errors may lead to important misestimating of the impacts. Now, computing times to simulate waves overtopping become a key issue in operational conditions, especially when considering ensemble sets. Existing probabilistic inundation models such as ADCIRC Surge Guidance System (ASGS; Dietrich *et al.*, 2013) are generally based on generalized overflowing, whose computing time is not as problematic. Thus, for Reunion Island case, future work will explore different alternatives to manage this issue using either atlas based on pre-computed scenarios or real-time simulations based on meta-modelling technics.

### CONCLUSIONS

This paper investigates the use of the new ensemble cyclone track and intensity forecast tool developed by Bonnardot and Quetelard (2016) to infer probabilistic coastal wave forecast at Reunion Island. The specificity of the approach rests upon the choice to work with a limited number of tracks associated with probabilities in order to put the computing efforts on the generation of realistic wind fields with Meso-NH (instead of parametric method) notably to take into account the island relief.

The comparison with measurements and simulations performed with Best-Track data enable to conclude that (1) the

wind generation method is relevant to obtain realistic wind and waves (2) the number of tracks considered seems appropriate to estimate uncertainties (3) the wave forecast for cyclones with classical sizes is valuable during the orange and pre-alert states.

Nevertheless, the study also points out that ensemble track and intensity forecasts cannot counterbalance major size and shape errors for cyclones wind atypical sizes. Thus, future research efforts at RSMC La Reunion should now focus on  $R_m$  and wind extension forecasts.

### ACKNOWLEDGMENTS

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