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Operational Implementation of Ensemble-Based "dynamical" Uncertainty Circles around Tropical Cyclone Track Forecasts

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1. Introduction

Although tropical cyclone (TC) track forecasts have been steadily improving for several decades (Avila et al. 2006), some uncertainty still remains. A part of this uncertainty is due to an inherent predictability bound (Fraedrich and Leslie 1989; Plu 2011) that future improvements in numerical models and in forecasting techniques will not allow to overcome. End-users of TC forecasts, such as risk managers and public agencies, will ever have to deal with forecast uncertainty. As a consequence, they do not only need the most possible reliable track forecasts, but also some estimation of the forecast uncertainty. In the South-West Indian Ocean (SWIO), the Regional Specialized Meteorological Centre of La Réunion (Meteo-France) issues TC forecasts and warnings towards the countries of this area, up to 5-day lead time. RSMC La Réunion has been developing a new technique to measure and to display the uncertainty of its official track forecast, whose presentation and verification are the main purposes of the present abstract.

Most RSMCs (Miami, Tokyo and Hawai) and Tropical Cyclone Warning Centers (around Australia) currently display uncertainty cones around their official track forecasts, using a climatological method attached to their basin of responsability. At each forecast lead time, is built an uncertainty circle whose radius is taken as a fixed quantile (67% for Miami, 70% for Tokyo) of the distribution of direct position error (DPE) computed over several previous seasons. The Joint Typhoon Warning Center (JTWC) in Hawai superposes to the climatological average DPE the forecasted 34 kts-wind radius of the storm, which introduces some dependency on the meteorological situation.

However this dependency is expected to be largely insufficient since TC motion is driven by complex processes involving numerous factors. Cyclone motion depends on its intensity, its structure and its environment.

The purpose of the present study (Dupont et al. 2011) is to demonstrate the skill of uncertainty circles built around the official RSMC La Réunion TC track forecast. These circles are computed from the Ensemble Prediction System (EPS) of the European Centre for Medium-Range Weather Forecasts (ECMWF). The area swept out by the circles at successive forecast terms forms an uncertainty cone. The main reason why the EPS of ECMWF has been chosen is that it is recognized as one of the best among global ensemble systems (Buizza et al. 2005; Bourke et al. 2005). Besides, some specifities are dedicated to TC forecasts: the

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initial perturbations are computed using singular vectors that are targeted on TC (Puri et al. 2001) and that are computed along a tangent-linear model using diabatic physics (Barkmeijer et al. 2001).

The probabilistic verification method will aim at testing whether these uncertainty circles describe better the distribution of the RSMC forecast than the climatological circles.

2. Probabilistic forecast of TC positions

a. Data

The data sample is composed of the tracks of TCs of all intensities over the South-West Indian Ocean (between the Equator and 40 ˚ S, from the African coast to 90 ˚ E), during the seasons 2007-2008 and 2008-2009. 225 forecast tracks are available until the 3-day term. The observed TC positions are from the official RSMC BestTrack. The RSMC forecast tracks result from an humanly-expertised forecasting process of the official RSMC track forecast. The TC positions forecasted by the EPS members are directly received from ECMWF which runs its own tracking algorithm (described by van der Grijn 2002). The distribution of DPE, sometimes called the distribution of climatological error hereafter, is fed in by the distance between the RSMC forecast and the RSMC BestTrack.

b. Definition of a probability distribution of forecast position

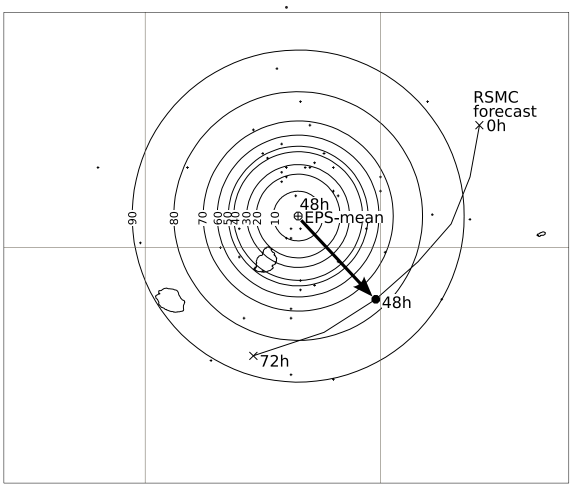

FIG. 1. Example of construction of the distribution of probability of forecast position at a given term (here 48 h).

An ensemble forecast gives the successive positions of the TC for each of the members that predict this TC. A simple probability distribution may be described by concentric circles of different radii around the mean position. Since the RSMC position forecast is the most probable one, it is relevant to have the probability distribution centered on it (Fig.1). This is particularly important since the skill of the ensemble forecasts highly depends on the error of the center position of the circles (Majumdar and Finocchio 2010).

c. Reliability and calibration of the probabilistic forecasts

One of the first property that is expected from a probabilistic forecast is that the forecast probability equals the observed probability, this property is measured by the reliability of the forecast.

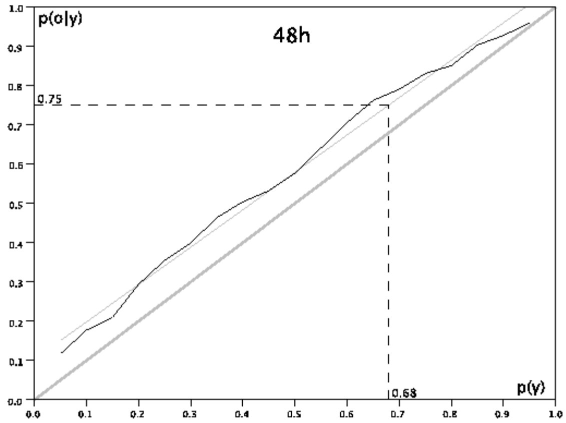

FIG. 2. Reliability diagrams from term 48 h lead time showing the relationship between the verifying analysis is inside the circle $p(o|y)$ and the associated circle of probability $p(y)$ (black curve), the linear regression used for calibration (grey thin line) and the diagonal calibrated curve (grey thick line).

The reliability diagrams are in general quite close to the diagonal lines. For the 24 hours term and after, the forecast probability is always lower than the observed probability. Overall, the curves are quite close to the diagonal lines, which suggests that the EPS dispersion is linked to the RSMC error distribution.If the reliability of the forecast is not perfect, then a calibration should be applied. Since the reliability diagram follows approximately a line (Fig.2), a simple two-steps calibration method may be applied to them. Each curve on the reliability diagrams is approximated by a linear regression function (Fig. 2) and this function is used for calibrating the probability.

The operational implementation of such a calibration is straightforward. For instance, for 48 h forecasts, a circle associated with the probability

75 % should be the smallest circle containing 68% of the EPS members (Fig. 2).

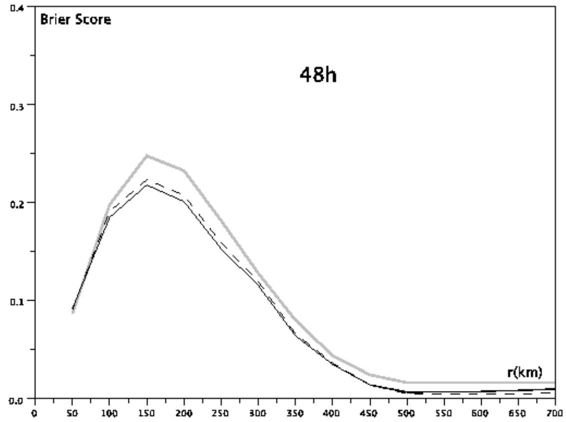

FIG. 3. Brier scores from term 48 h lead time for the climatological forecast (thick grey curve), the uncalibrated EPS forecast (black dashed curve) and the calibrated EPS forecast (black solid curve).

The Brier score encompasses some information about the reliability and its resolution (Wilks 2006). The calibrated probabilistic forecast is better (e.g. lower Brier scores) than the climatology at almost every radii and at every range (Fig. 3). This simple calibration method that is used is therefore relevant.

3. Construction and validation of uncertainty circles

In order to represent graphically the uncertainty of the forecast position, the probability will be set to a fixed value, similarly to the existing climatological methods used by operational centers. An uncertainty circle is then given by a single predicted radius (PR), associated with this calibrated probability, centered at the RSMC forecast position. The probability value 75 % has been chosen among other possibilities (50% 67%, for instance). One of the reasons for choosing this 75 % value is that the EPS seems to be rather well calibrated at this point. Since the purpose is to measure the uncertainty, the relevant information is the size of the circle rather than the probability value, provided it is fixed. The validation of the uncertainty circles and of the PR should employ a different method from the hereabove probabilistic verification. By definition, what is expected from uncertainty circles is to give a measure of the uncertainty, that is to say, when the PR is high (resp. small), the error should be large (resp. small). Like previous studies (Yamaguchi et al. 2009; Majumdar and Finocchio 2010), the link between the DPE and the PR will be assessed on a statistical basis to more precisely measure the skill at detecting large and small forecast errors.

a. Spread/skill relationship

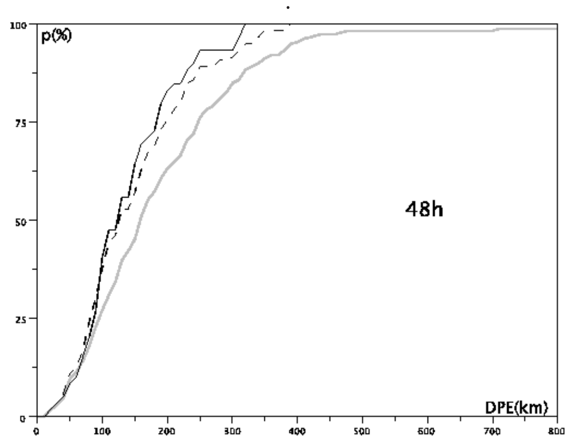

FIG. 4. Cumulated frequency of DPE for 48-h lead time conditionally to the predicted radius.For small radii ($PR < Q_{PR}(0.5)$, black dashed line) , very small ones ($PR < Q_{PR}(0.25)$, black solid line) and unconditional ones (grey thick line).

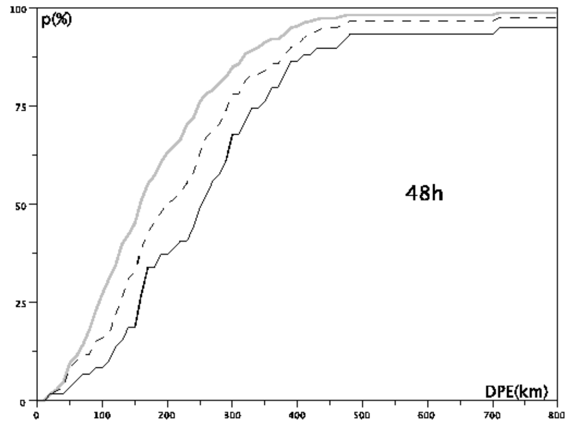

FIG. 5. Same legend as Fig. 4 for the conditions $PR > Q_{PR}(0.75)$ (black solid line) and $PR > Q_{PR}(0.5)$ (black dashed line) and unconditional ones (grey thick line).

A informative diagnostic is to determine whether predicting a large (resp. small) radius has an impact on the distribution on the forecast error. A measure for this is the probability distribution of DPE conditionally to PR lower or higher than a fixed value. Such conditional distributions is compared to the unconditional DPE distributions. At every forecast lead time, the conditional distributions (Small and Very Small Radii) appear to the left of the unconditional ones (Fig. 4) and the conditional distributions (Large and Very Large Radii) appear to the right of the unconditional ones (Fig. 5). In addition, large radii versus very large radii seem to be more effectively discriminated than small versus very small radii: the curves between the conditional distributions tend to be more separated for large radii than for small radii.

These results confirm that the spread of the EPS has some skill at detecting the forecast uncertainty of the RSMC forecast. Majumdar and Finocchio (2010) suggested that the EPS spread could be useful to discriminate between large and small forecast errors of the ensemble mean. The present results prove that the spread of the EPS is also skillful at detecting small and large errors of the RSMC forecast.

b. Detection rate of the amplitude of DPE

The skill of the present method at detecting large and small errors may be quantitatively estimated. The following decision rule is applied to the size of the uncertainty circles: if the PR is lower than a given quantile, then it is decided that the forecast DPE will be lower than the corresponding quantile. The decision rule and the associated contingency tables are defined for three cases:

- detection of very small error :

36-h lead time	$PR < Q_{PR}(0.25)$	$PR \geqslant Q_{PR}(0.25)$
$DPE < Q_{DPE}(0.25)$	13%	12%
$DPE \geqslant Q_{DPE}(0.25)$	12%	63%

- detection of small error : (symetric conditions for detection of large error)

36-h lead time	$PR < Q_{PR}(0.5)$	$PR \geqslant Q_{PR}(0.5)$
$DPE < Q_{DPE}(0.5)$	34%	16%
$DPE \geqslant Q_{DPE}(0.5)$	16%	34%

- detection of very large error :

36-h lead time	$PR > Q_{PR}(0.75)$	$PR \leqslant Q_{PR}(0.75)$
$DPE > Q_{DPE}(0.75)$	12%	13%
$DPE \leqslant Q_{DPE}(0.75)$	13%	62%

These tables lead to input data for computing some probability scores: probability of detection (POD) and false alarm rate (FAR) associated with the detection of large and small error values. Since the climatological circles are case-independent, they do not give any information about the detection of the size of the DPE. Therefore, the forecast skill is obtained by comparison with a random forecast, obtained by picking up a PR value among the climatological DPE distribution. The POD and FAR values for the events $< Q_{DPE}$ and $> Q_{DPE}$ of such a random forecast may be easily computed. A skillful forecast should have a higher POD and a lower FAR than this random forecast.

The scores are always better for the ensemble method than for the random forecast, but they are sometimes very close.

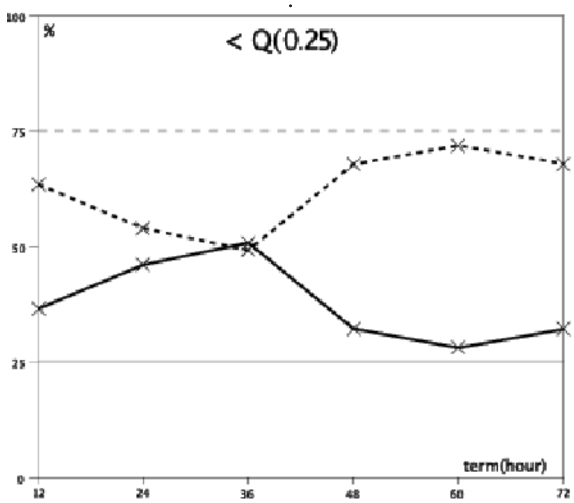

Fig. 6. Probability of detection (POD, solid lines) and false-alarm rate (FAR, dashed lines) as a function of the forecast term, for the EPS forecast (black lines) and a random forecast (grey lines) with no skill, for the events $< Q(0.25)$.

The discrimination of DPE apart its median value $Q(0.5)$ by the PR is valuable at all terms, but it is close to the random value at 72 hours (Fig. 7). The POD and FAR associated with the detection of very large DPE ($> Q(0.75)$) are always better

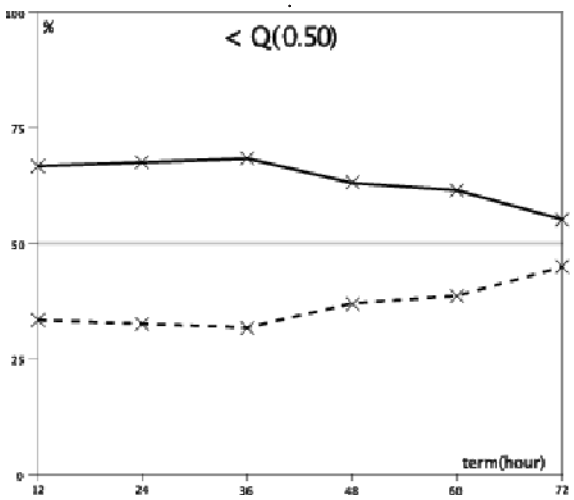

FIG. 7. Same legend as Fig. 6 for the events $< Q(0.5)$.

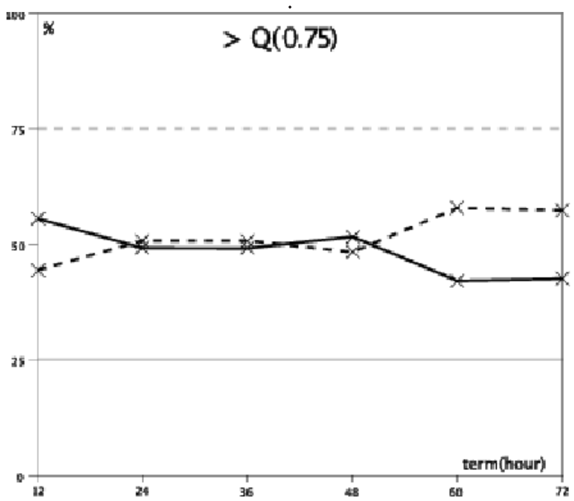

FIG. 8. Same legend as Fig. 6 for the events $> Q(0.75)$.

than the random forecast.(Fig. 8)
The scores for the detection of very small DPE are better than the random forecast until 36-hours lead time, but then it jumps to values close to the random forecast(Fig. 6).
Therefore, the uncertainty circles are valuable to detect a large error at least until the 72-h lead time, and they are able to detect small uncertainty until the term 48 h.

c. Operational Issues

The positive results from the initial study have led to the operational implementation of the uncertainty circles based on the ECMWF EPS by RSMC La Réunion since the beginning of the current 2011/2012 cyclone season needing new calibration to take into account the delay in operational availability of EPS forecasts. Uncertainty cones have also been extended until the 5-days lead time of track forecasts.The case of TC Giovanna's forecast showed large differences between the Ensemble-Based and the Climatological uncertainty cones (Fig. 9). The future area of likely landfall over Madagascar was better targeted 60-h prior to landfall by the EPS-based uncertainty cone than by the climatological-based one (both with same probability). As the final expertise and decision depends on him, the duty forecaster selected (in real-time) the Ensemble-Based uncertainty cone as the official one rather than the climatological one. Final graphical products (Fig. 10) display only one official uncertainty cone (the human selected one) around the RSMC forecast Track.

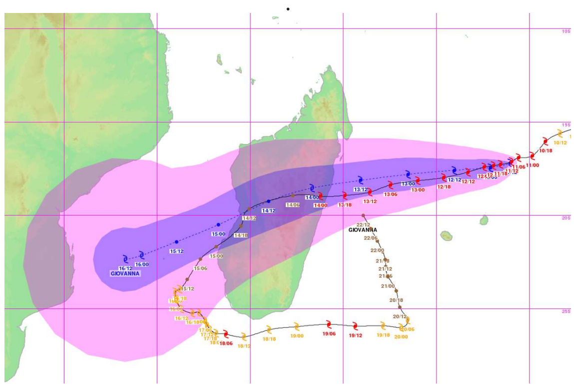

FIG. 9. TC GIOVANNA, 1200Z RSMC La Réunion official forecast with associated uncertainty cones overlaying the Best-Track (Ensemble-Based cone in purple, Climatological one in pink.

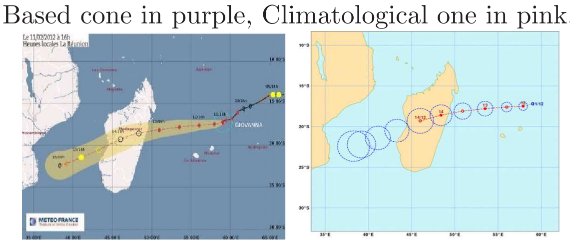

FIG. 10. Final Graphical Products on the Public Website of RSMC La Réunion (left panel) and on the Southern Africa SWFDP (Severe Weather Forecasting Demonstration Project) Extranet Website (right panel)

d. *Conclusion*

A method of construction of uncertainty circles around official TC track forecasts, using the EPS of ECMWF, has been described and assessed (Dupont et al. 2011). The circles are calibrated using a simple scheme. A validation in two steps is performed, firstly by the computation of scores on the probability distribution of forecast position and secondly by measuring the skill of the predicted radius (PR) at detecting large and small DPE.

The operational implementation of the Ensemble-based dynamical uncertainty circles by RSMC La Réunion, has provided valuable new information for final-users in several critical cases this season. In addition to the afore-described well-targeted area for the landfall of Intense Tropical Cyclone Giovanna over the eastern Malagasy coastline, one can mention the case of Intense Tropical Cyclone Funso, for which the Ensemble-Based Uncertainty cone also strongly reduced the potential threat area in the Mozambique Channel.

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