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Olivier Bousquet, David Barbary, Soline Bielli, Sélim Kébir, Laure Raynaud, et al.. An evaluation of tropical cyclone forecast in the Southwest Indian Ocean basin with AROME-Indian Ocean convection-permitting numerical weather predicting system. *Atmospheric Science Letters*, 2020, 21 (3), pp.e950. 10.1002/asl.950 . hal-02516736

HAL Id: hal-02516736

<https://hal.science/hal-02516736>

Submitted on 24 Mar 2020

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RESEARCH ARTICLE

An evaluation of tropical cyclone forecast in the Southwest Indian Ocean basin with AROME-Indian Ocean convection-permitting numerical weather predicting system

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Funding information

INTERREG-V Ocean Indien 2014-2020 "ReNovRisk-Cyclones and Climate Change."; French National Research Agency, Grant/Award Number: ANR - 14 - CE03 - 0013 "Spicy"

Abstract

In order to contribute to ongoing efforts on tropical cyclone (TC) forecasting, a new, convection-permitting, limited-area coupled model called AROME-Indian Ocean (AROME-IO) was deployed in the Southwest Indian Ocean basin (SWIO) in April 2016. The skill of this numerical weather predicting system for TC prediction is evaluated against its coupling model (European Center for Medium Range Weather Forecasting-Integrated Forecasting System [ECMWF-IFS]) using 120-hr reforecasts of 11 major storms that developed in this area over TC seasons 2017–2018 and 2018–2019. Results show that AROME-IO generally provides significantly better performance than IFS for intensity (maximum wind) and structure (wind extensions, radius of maximum wind) forecasts at all lead times, with similar performance in terms of trajectories. The performance of a prototype, 12-member ensemble prediction system (EPS), of AROME-IO is also evaluated on the case of TC Fakir (April 2018), a storm characterized by an extremely low predictability in global deterministic and ensemble models. AROME-IO EPS is shown to significantly improve the predictability of the system with two scenarios being produced: a most probable one (~66%), which follows the prediction of AROME-IO, and a second one (~33%) that closely matches reality.

KEYWORDS

ensemble forecasting, mesoscale modeling, ocean-atmosphere coupling, tropical cyclones, Southwest Indian Ocean

1 | INTRODUCTION

Socioeconomic losses resulting from landfalling tropical cyclones (TC) have increased sharply worldwide over the last decades (Pielke Jr. *et al.*, 2008; Zhang *et al.*, 2009) due to the ever-increasing population and expanding social development (Pielke Jr. and Landsea, 1998). This is particularly true

in tropical islands where space is limited, and where it is often difficult to rapidly evacuate populations from threatened areas. Because damages suffered by these territories are generally strongly correlated to the intensity of landfalling TCs, accurate intensity and structure forecasts are needed to quickly identify potentially impacted areas and efficiently alert communities of incoming danger.

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Although the resolution of TC forecast models has increased sharply in recent years, intensity and structure forecast still face serious deficiencies (Sampson and Knaff, 2014). These weaknesses stem from several factors such as the limitations of current numerical weather predicting (NWP) systems, the lack of available observations over tropical oceans as well as the incomplete understanding of physical processes that govern the life cycle of tropical disturbances. While sources of progress are numerous, it is nevertheless commonly accepted that the most effective means for improving TC forecasting consist in coupling atmospheric models with ocean models, improving model physical parameterizations (convection, microphysics, and surface processes) and increasing the resolution of atmospheric models.

With its numerous Overseas Territories, France is present in three (North Atlantic, South Pacific and Southwest Indian Ocean) of the seven cyclonic basins and is thus particularly concerned by TC hazards. With this regard, the French Weather Service, Météo-France, has deployed in 2016 five new overseas configurations of its operational, high-resolution, mesoscale cloud resolving model “Application of Research to Operations at the Mesoscale” (AROME, Seity *et al.*, 2011) over these 3 basins (Faure *et al.*, 2019, submitted). Among these five NWP systems, the Southwest Indian Ocean (SWIO) configuration, called AROME Indian Ocean (AROME-IO), is considered as the flagship of all AROME overseas models and has been used since 2012 to test, and evaluate, new developments aiming at improving TC prediction (Bousquet *et al.*, 2014), in close collaboration with the Tropical Cyclone Regional Specialized Meteorological Center (RSMC) La Reunion.

In the SWIO basin (0–40°S, 30–90°E), the TC season extends from mid-November to mid-April with an average number of 10 storms per season (Leroux *et al.*, 2018). While TC activity in this part of the world is generally weaker compared to that of several other basins (Northwest and Northeast Pacific, North Atlantic), major storms regularly cause considerable social and economic losses in vulnerable African countries such as Mozambique and Madagascar. Hence, over the last 19 years TCs have caused at least 20 fatalities every season in the SWIO area with more than 100 fatalities in eight seasons¹—the two deadliest (and costliest) seasons occurred in 2016–2017 (more than 350 fatalities and economic losses of ~200 M€ in Mozambique and Madagascar following the landfall of TCs Dineo and Enawo), and 2018–2019 (where TC Idai alone caused ~1,000 fatalities in Mozambique in March 2019).

The present study aims to evaluate the performance of AROME-IO for TC prediction using extended (re)forecasts of 11 major events that occurred in the SWIO in

summer seasons 2017–2018 and 2018–2019. The paper is organized as follows: A brief description of AROME-IO specifications is given in Section 2. The evaluation of the model skill for track, intensity, and structure forecast is discussed in Section 3 while further potential improvements of the model are discussed in Section 4, with emphasis on ensemble prediction system (EPS).

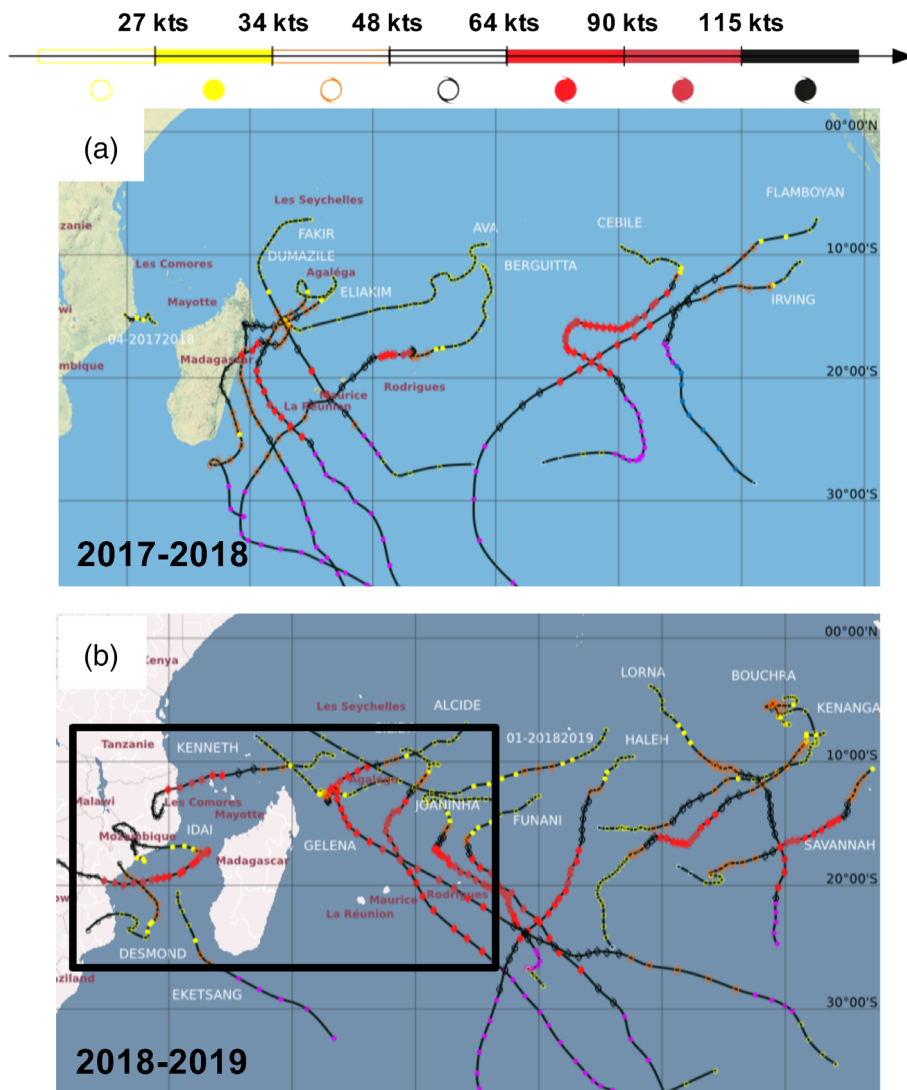
2 | AROME-IO SPECIFICATIONS

AROME-IO was put into operations in April 2016 (Faure *et al.*, 2019, submitted) after several years of development. The specifications of AROME-IO are very similar to those of the model AROME-France (AROME-F), which is run routinely over France since 2008, except for: (a) its horizontal resolution (2.5 km vs. 1.3 km in AROME-F), (b) its initialization scheme (IAU—see hereafter—vs. 3D-Var in AROME-F), (c) its coupling model (European Center for Medium Range Weather Forecasting [ECMWF]’s global Integrated Forecasting System [IFS] vs. action de recherche petite echelle grande echelle (ARPEGE) in AROME-F), and (d) AROME-IO is coupled to a one-dimensional (1D) ocean mixed layer (OML) model while AROME-F is not.

AROME-IO covers an area of ~3,000 km × 1,400 km encompassing most inhabited islands of the SWIO exposed to TC hazards such as the Mascarene Archipelago, Madagascar, Mayotte, and Comoros (Figure 1b). It uses 90 vertical levels at a fixed horizontal resolution of 2.5 km with a time step of 60′. The lowest grid level is 5 m (with 34 levels within the first 2 km) and the height of the model lid is fixed to 31 km. As mentioned previously, AROME-IO is coupled every 300′ to a 1D OML model in order to better take into account atmospheric–oceanic interactions in cyclonic conditions. This OML model, based on Lebeau-pin-Brossier *et al.* (2009), is part of the externalized surface model SurFex (Masson *et al.*, 2013) that is common to all numerical models used by the French Weather Service. Ocean parameters (currents, salinity and temperatures fields) are initialized from Mercator Ocean global model PSY4 (Lellouche *et al.*, 2018) 0000 UTC forecasts.

In its operational configuration, AROME-IO is initialized from ECMWF’s IFS NWP system, which also provides lateral boundary conditions. In order to better represent small-scale features and reduce the model spin up at initiation time T_0 , the Analysis Incremental Update (IAU) scheme proposed by Bloom *et al.* (1996) is used to combine ECMWF large-scale atmospheric fields (temperature, wind, humidity, and surface pressure) valid at T_0 with a 6-hr AROME-IO forecast initialized at T_0 —6 hr. It runs four times per day at 0000, 0006, 1200, and 1800

FIGURE 1 Trajectories and intensities (colors, see caption at top) of all storms tracked by Regional Specialized Meteorological Center La Reunion in the Southwest Indian Ocean basin during (a) 2017–2018 and (b) 2018–2019 (bottom) tropical cyclone seasons. The black rectangle in (b) shows the footprint of the AROME-Indian Ocean model



UTC over periods of 42 and, on demand, 76 hr. In the present study, this operational configuration is relied upon to achieve 120-hr model reforecasts of major tropical storms that developed in the SWIO in the last two cyclonic seasons.

3 | OVERVIEW OF AROME-IO PERFORMANCE FOR TC PREDICTION

3.1 | Datasets

In order to assess the overall performance of AROME-IO for TC prediction, a statistical analysis of intensity, track, and structure errors was performed for 11 major storms that occurred in the simulation domain during TC seasons 2017–2018 and 2018–2019 (see Table 1 and Figure 1). Analyzed storms include six intensity stages

ranging from tropical depression to intense TC. 120-hr AROME-IO reforecasts are generated at 0000 and 1200 UTC analysis time for all storms, and compared against AROME-IO's coupling model (IFS) past operational forecasts over the same period of time. This 2-year sample includes 115 individual forecasts (Table 1), among which 90 (85%), 76 (66%), 60 (52%), 44 (38%), and 29 (25%) verify at 24, 48, 72, 96, and 120 hr lead time, respectively— Note that the decrease in the number of samples over time is due to either the dissipation of TCs or to their exit from the computation domain.

In the following all AROME-IO and IFS forecasts are verified against RSMC La Reunion best-track (BT) database, which consists in a postseason reanalysis of TC track, intensity, and structure data accounting for observations unavailable in real time. To avoid potential tracking issues, the statistical analysis is restricted to systems located within the model domain at initiation time, and limited to the periods during which they evolve over the ocean.

TABLE 1 Name, intensity, and number of forecasts for the 11 tropical storms considered in the study

Name	Category	Maximum intensity (ms^{-1})	No. of forecasts
AVA (01/2018)	TC	43.0	17
DUMAZILE (03/2018)	ITC	45.8	9
ELIAKIM (03/2018)	STS	30.5	11
FAKIR (04/2018)	TC	36.1	4
ALCIDE (11/2018)	ITC	45.8	12
CILIDA (12/2018)	ITC	60	12
DESMOND (01/2019)	MTS	26.4	7
FUNANI (02/2019)	ITC	54.1	6
GELENA (02/2019)	ITC	57	11
IDAI (03/2019)	ITC	48.6	14
JOANINHA (03/2019)	ITC	51.4	12
			115

3.2 | Track forecast

Figure 2a presents AROME-IO and IFS absolute track error (bias) in 6-hr time steps up to forecast a lead time of 120 hr. Overall, one can note that absolute track errors for AROME-IO and its coupling model are comparable at all lead times. Knowing that simulated TC trajectories are principally driven by large-scale circulation, this result is not surprising. Overall track error increases linearly with time to reach 70, 130, and 200 km at 24, 72, and 120 hr lead time, which is significantly better than track forecast skill estimated from main NWP systems in the Southern Hemisphere basins (~75, 210, and 416 km for the same lead times, respectively—Heming and Prates, 2018), and comparable to RSMC La Reunion official track forecasts (not shown). The spread of AROME-IO track forecast errors (not shown), which is a good proxy of the temporal consistency of the model, also increases linearly with time and ranges from 30 km (analysis time) to 120 km (120 hr lead time). Overall, the mean bias of absolute track errors for AROME-IO (resp. IFS) averages at $129 \text{ km} \pm 78 \text{ km}$ (resp. $127 \text{ km} \pm 82 \text{ km}$) over the 120-hr period of verification.

3.3 | Intensity and structure forecast

The skill of AROME-IO for intensity and structure forecast is shown in Figure 2b–d. Intensity (bias) errors (Figure 2b) are estimated from RSMC La Reunion maximum wind speed (WMAX) averaged over a period of 10 min (recommendation of the World Meteorological

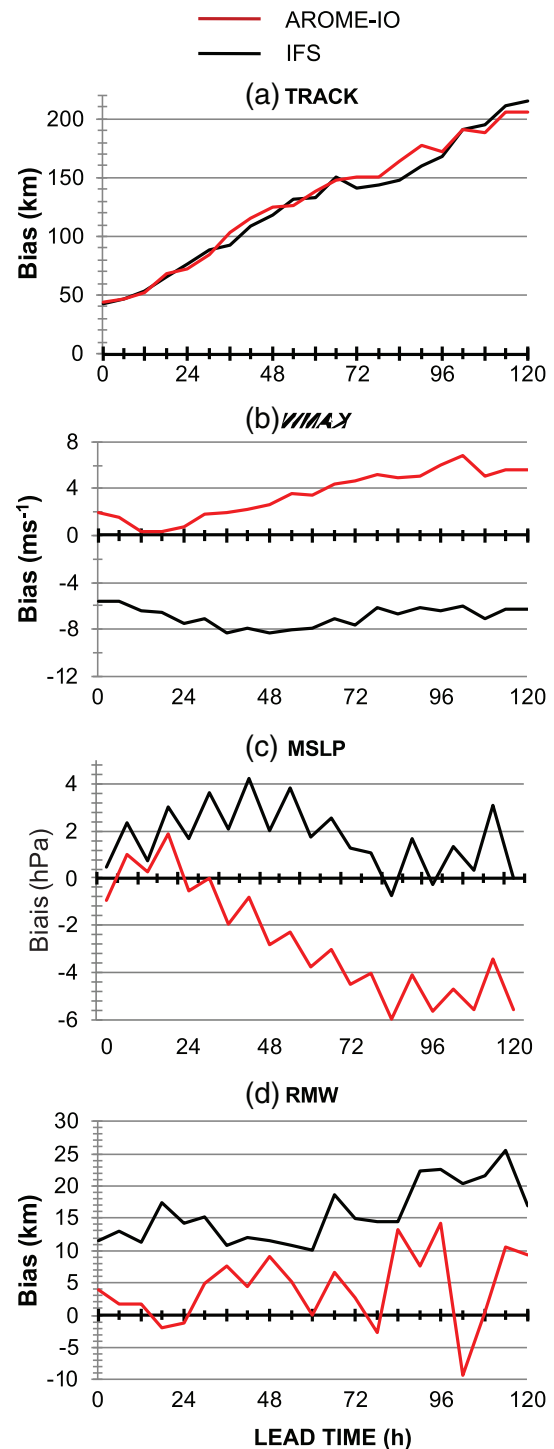


FIGURE 2 Bias errors on (a) location (TRACK), (b) maximum wind (WMAX), (c) central mean sea level pressure and (d) structure (radius of maximum wind) forecasts as a function of lead-time for AROME-Indian Ocean (AROME-IO) (red) and Integrated Forecasting System (black). Statistics are deduced from the analysis of (115) 120-hr reforecasts of 11 major storms occurring in AROME-IO domain from 2017 to 2019 (Table 1)

Organization, Figure 2b) and central mean sea level pressure (MSLP, Figure 2c). While AROME-IO almost systematically overestimates TC intensity, errors on WMAX

(resp. MSLP) remain generally small at all lead times with WMAX (resp. MSLP) bias ranging from $\sim 1 \text{ ms}^{-1}$ at analysis time (00) and $+5 \text{ ms}^{-1}$ after 120 hr of simulation (resp. -1 to -5 hPa). Error on WMAX is significantly reduced with respect to IFS, which tends to underestimate TC intensity at all lead times (bias error comprised between -6 ms^{-1} and -8 ms^{-1}) although error spread is slightly higher in AROME-IO than IFS (not shown). Errors on MSLP (Figure 2c) are also reduced with respect to IFS by up to 60% during the first 60 hr of forecast before stabilizing at approximately -5 hPa afterward (vs. approximately $+1.5 \text{ hPa}$ for IFS). Overall, the mean error on WMAX (resp. MSLP) is equal to $+3.51 \text{ ms}^{-1} \pm 9.6 \text{ ms}^{-1}$ (resp. $-2.5 \text{ hPa} \pm 12 \text{ hPa}$) for AROME-IO and $-7 \text{ ms}^{-1} \pm 7.8 \text{ ms}^{-1}$ (resp. $1.7 \text{ hPa} \pm 10.5 \text{ hPa}$) over the 120-hr period of verification.

As shown in Figure 2d, which presents the error on the radius of maximum wind (RMW, distance between the center of the storm and the position of the strongest winds in the eye wall area), the other major improvement brought by AROME-IO with respect to IFS is related to TC structure forecast. Although both models tend to produce TC cores that are too compact with respect to BT data (positive bias), the skill of AROME-IO is significantly higher than that of IFS at all lead times. Thus, the bias on RMW averages around 4 km ($\pm 39 \text{ km}$) in AROME-IO versus $\sim 16 \text{ km}$ ($\pm 36 \text{ km}$) in its coupling model over the whole verification period.

Another way to evaluate TC structure forecast is to assess errors on surface wind structures (a.k.a wind extensions) associated with the three operational thresholds commonly used by TC forecasters (Tallapragada *et al.*, 2014; Sampson *et al.*, 2018) to estimate TC structure: Gale ($>33 \text{ kts}$), Storm ($>47 \text{ kts}$), and Hurricane ($>63 \text{ kts}$) wind force (Figure 3). Again AROME-IO significantly outperforms its coupling model for all wind extensions. For storm (Figure 3b) and Hurricane (Figure 3c) force winds, AROME-IO bias error is, in particular, quite uniform over the 120-hr verification period and averages near 14 km ($\pm 30 \text{ km}$) versus 50 km ($\pm 37 \text{ km}$) for IFS. Overall, these results show that storm sizes produced by AROME-IO are generally realistic, although slightly over estimated (negative bias), meaning that this model is particularly skilled to estimate where the most severe wind damage may occur.

4 | AROME-IO-BASED ENSEMBLE FORECASTS

EPS schemes based on individual (e.g., Zhang and Yu, 2017) or multiple (e.g., TIGGE; Bougeault *et al.*, 2010) global models are being used for many years to improve

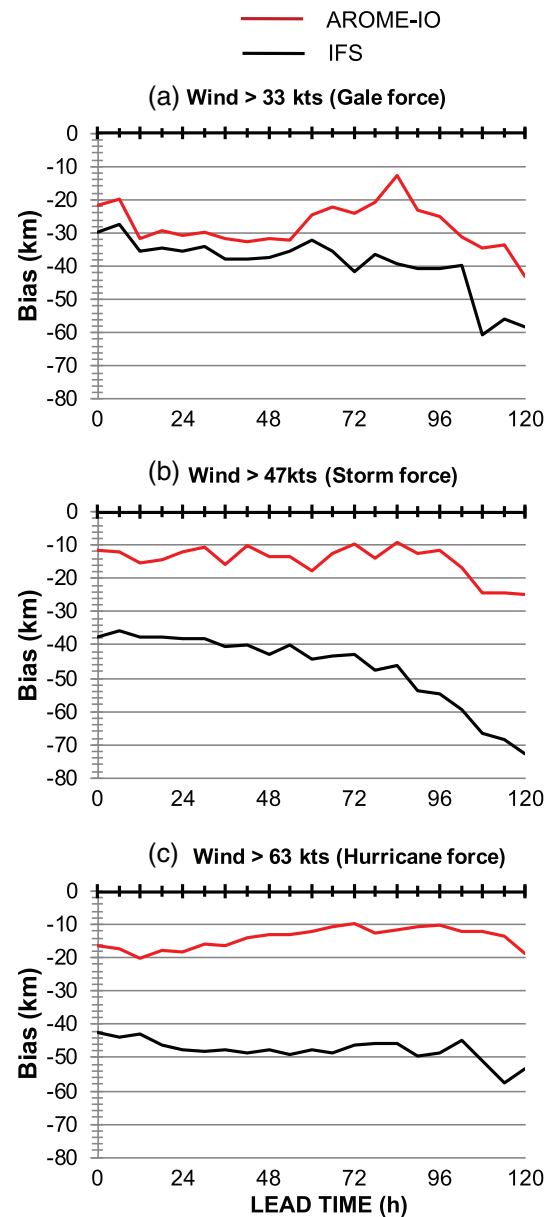


FIGURE 3 As in Figure 2, but for (a) Gale, (b) storm, and (c) Hurricane wind force extensions. Negative values indicate underestimated extensions

TC prediction, but are usually limited to track forecasting due to their limited spatial resolution. The benefit of high-resolution ensemble forecast systems for TC track and intensity prediction was recently evaluated over the Atlantic basin in the frame of the Hurricane Forecast Improvement Program (HFIP, Gall *et al.*, 2013), with promising results (Zhang *et al.*, 2014). In the following we present preliminary results of a similar study based on the use of an experimental EPS configuration of AROME-IO.

In order to evaluate the benefit of high-resolution probabilistic TC prediction over the SWIO basin, the EPS

configuration of AROME-France (Bouttier *et al.*, 2016; Raynaud and Bouttier, 2017), which operationally runs 12 perturbed members at 2.5-km horizontal resolution, was implemented in AROME-IO and run, a-posteriori, on TC cases characterized by poor predictability in deterministic models. An illustration of AROME-IO EPS performance is illustrated in Figure 4 for TC Fakir, which passed nearby Reunion Island on April 24, 2018. This storm that formed northeast of Madagascar in the Farquhar Island Archipelago (Figure 1) was misforecasted by global operational models, which all predicted a rapid decay of the storm due to strong vertical wind shear in its area of evolution. In particular, global ensemble models such as ECMWF-EPS (not shown) and deterministic models such as IFS (red line) and ARPEGE (the French operational global model, Yessad and Wedi, 2011, blue line) did not anticipate the rapid motion of the system (12 ms^{-1}) that counteracted the effect of the wind shear and led to a rapid strengthening of the TC. Hence, in the April 23 runs of 0000 UTC (Figure 4a) and 1200 UTC (Figure 4b), that is ~ 24 and ~ 12 hr before Fakir closest point approach to Reunion Island at TC intensity stage, none of the global deterministic models were able to forecast its rapid intensification. Note that the deterministic, operational, version of AROME-IO (green line) was nevertheless able to produce a deepening of the system in the 1200 UTC run (Figure 4b) although intensity was not strong enough and timing was 6 hr late. Due to the low predictability of this TC, forecasters were only able to trigger warnings a few hours before Fakir closest point approach to Reunion, which obviously caused significant organizational issues.

In its EPS experimental configuration, AROME-IO is initialized from AROME-IO operational analysis and coupled to ECMWF-EPS members, which provides boundary and surface conditions (ECMWF-EPS is coupled to the ocean model Nucleus for European Modeling of the Ocean [NEMO] since 2011). Twelve AROME-IO perturbed members are generated following the three-step approach used in AROME-France EPS: (a) initial surface perturbations and boundary conditions are determined from 12 ECMWF-EPS coupling members, which are selected with the clustering technique described in Nuissier *et al.* (2012), (b) model errors are accounted for with the stochastically perturbed physics tendencies (SPPT) approach (Bouttier *et al.*, 2012), which simulates the effect of random errors associated with AROME-IO physical parameterizations, and (c) random perturbations are added to the SST and OML following Bouttier *et al.* (2016).

The temporal evolution of the minimum pressure exceedance threshold deduced from the April 23, 0000 and 1200 UTC AROME-IO EPS runs is shown in

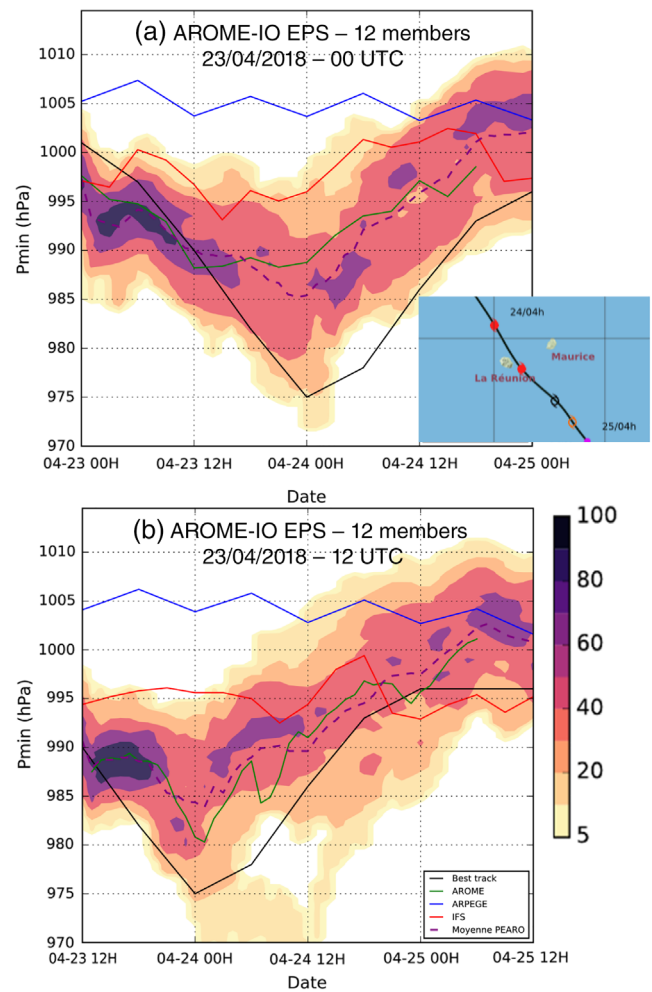
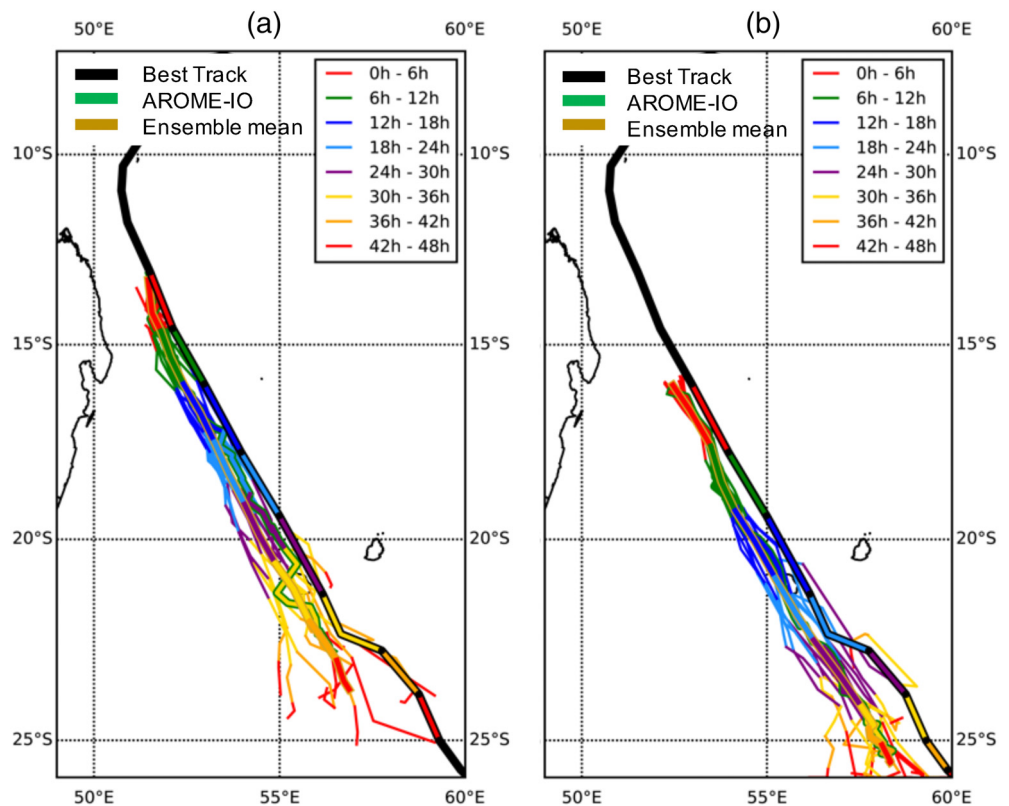


FIGURE 4 Temporal evolution of the minimum pressure probability (color) based on forecasts initiated on April 23, 2018 at (a) 0000 UTC and (b) 1200 UTC. Black (resp. purple) plain (resp. dashed) line show Regional Specialized Meteorological Center (RSMC) La Reunion best-track data (resp. model ensemble mean). Blue, red, and green lines show pressure forecasts from the deterministic models ARPEGE, Integrated Forecasting System, and AROME-Indian Ocean, respectively. Insert in (a) show the official RSMC track forecast in the vicinity of Reunion Island

Figure 4. In both runs MSLP ensemble mean (purple line) closely matches AROME-IO deterministic forecast (green line), but one can note that several members of the EPS forecast produced scenarios for which both timing and intensity are in good agreement with BT data (black line). Hence, one third of AROME-IO EPS members show a significant deepening of the system up to 975 hPa, such as observed in BT data on April 24 at 0000UTC, while half of them indicate a deepening up to 980 hPa.

AROME-EPS forecasted trajectories (Figure 5) are more or less distributed on both sides of AROME-IO forecasted track. The mean EPS track thus shows strong similarities with AROME-IO and is shifted westward by

FIGURE 5 Forty eight-hr simulation of tropical cyclone Fakir trajectories initialized on April 23, 2018 at (a) 0000 UTC and (b) 1200 UTC. Thin lines show the tracks of the 12 AROME-EPS members. Large black-, green-, and brown-contoured line show best-track, AROME-Indian Ocean and AROME-EPS ensemble mean, respectively. The colors indicate the time elapsed since the beginning of the forecast in 6-hr steps (color code at upper right)



~30 km with respect to BT data. In the 0000 UTC run (Figure 5a), all AROME-IO EPS members are also slightly late (~3 hr) with respect to BT data, but this delay is almost made up in the 1200 UTC run (Figure 5b). In the latter run, two third of the members also show improvement compared to AROME-IO forecasted track in the vicinity of Reunion island, with four of them closely matching the BT. Overall, knowledge of this alternative scenario would have been extremely valuable for RSMC La Reunion TC forecasters who would have then been able to better anticipate the behavior of this system and to trigger first warnings at least 24 hr before Fakir closest point approach to Reunion Island (S. Langlade, personal communication).

The benefit of AROME-IO EPS for intensity forecast was also noted for several other studied cases (e.g., Joanhia, Idai). Following these promising results, work is currently ongoing to optimize this EPS system through choosing the perturbations the most suited to TC forecasting, with the goal to put this configuration into operations as soon as possible.

5 | CONCLUSIONS AND FUTURE WORK

A coupled, Overseas version, of the mesoscale NWP system AROME, used in mainland France since 2009, was

recently deployed over the SWIO basin to improve weather forecasting in this region particularly prone to weather hazards. This high-resolution (2.5 km) model, called AROME-IO, was notably put into operations to provide guidance information to the 15 member States of the SWIO Regional Tropical Cyclone Committee.

The performance of AROME-IO for TC forecasting was evaluated from 120-hr reforecasts of 11 storms that developed in this basin during TC seasons 2017–2018 and 2018–2019. The skill of the model for track, intensity, and structure forecasts was compared against the performance of its coupling model IFS (~9-km resolution) using RSMC La Reunion BT data as ground-truth. Results show that AROME-IO performance for track forecasts is similar to that of IFS with average track errors of 70, 130, and 200 km at 24, 72, and 120 hr lead time, which is not surprising as track forecasts are mostly driven by large-scale circulations. AROME-IO intensity and structure forecasts are, however, much improved with respect to its coupling model at all lead times. Hence, AROME-IO bias errors on TC maximum wind are comprised between 1 ms^{-1} at analysis time and $+5 \text{ ms}^{-1}$ after 120 hr, while errors on the RMW average near 4 km over the whole verification period. Another significant improvement brought by AROME-IO appears related to surface wind structure forecast away from the storm center. The analysis of bias errors for principal wind extensions (Gale, Storm, and Hurricane wind force) shows that these errors were

reduced by 30 to 70% with respect to IFS, to average around 14 km (storm and Hurricane wind force) over the 120-hr period of verification. Overall, these results clearly demonstrate the superior performance of convection-permitting NWP systems for representing the temporal evolution of TC structure and intensity.

In parallel, additional developments aiming at improving TC forecasting are also investigated using a research configuration of the model, used since 2012 to test and evaluate improvements to be potentially implemented in operations—several studies based on this research configuration have already been achieved within the last few years (e.g., Pianezze *et al.*, 2018; Colomb *et al.*, 2019). In this study, the potential of a high-resolution EPS based on an experimental configuration of AROME-IO was demonstrated on a case of low-predictability TC, which passed over Reunion Island in April 2018. Given the encouraging results obtained with this EPS configuration, this approach will be further explored on a large set of TC events with the goal to put it into operations as soon as possible.

In addition to ensemble forecasting, a three-dimensional (3D)Var assimilation scheme, allowing assimilating all types of observations (rawinsondes, buoys, GNSS, infrared, and microwave satellite radiances, weather radar data...) currently assimilated in AROME-France (Gustafsson *et al.*, 2018), has also been implemented in AROME-IO research configuration. Future research work will, in particular, focus on the assimilation of synthetic aperture radar (SAR) data to better constrain TC structure in the model analysis. Following the implementation of a new surface scheme allowing for 3D ocean coupling (Voldoire *et al.*, 2017), the research version of AROME-IO was also recently coupled with a limited area configuration of the 3D ocean model NEMO, Gurvan *et al.*, 2017) to evaluate the benefits of 3D ocean coupling for TC forecasting. Indeed, as OML models are not able to reproduce the outward horizontal transport of warm waters located near the TC core (and thus transient upwelling in or around the center of the storm), the storm-core sea surface cooling can be significantly underestimated, especially in the case of slow moving systems (Yablonsky and Ginis, 2009). Ongoing research on recent TC cases will allow determining whether the transition to 3D ocean coupling (Bielli *et al.*, 2019, submitted) can improve TC forecasts.

ACKNOWLEDGEMENT

This work was supported by the French National Research Agency (grant ANR – 14 – CE03 – 0013 “Spicy”) and the research program INTERREG-V Ocean Indien 2014-2020 “ReNovRisk-Cyclones and Climate Change.”

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ENDNOTE

¹ European commission Join Research Center Emergency Reporting #23 (<http://www.gdacs.org/Public/download.aspx?type=DC&id=161>).

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How to cite this article: Bousquet O, Barbary D, Bielli S, *et al.* An evaluation of tropical cyclone forecast in the Southwest Indian Ocean basin with AROME-Indian Ocean convection-permitting numerical weather predicting system. *Atmos Sci Lett.* 2020;21:e950. <https://doi.org/10.1002/asl.950>