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## RESEARCH ARTICLE

# The orographic effect of Reunion Island on tropical cyclone track and intensity

David Barbary<sup>1,2</sup>  | Marie-Dominique Leroux<sup>2</sup> | Olivier Bousquet<sup>1</sup>

<sup>1</sup>Equipe cyclone, Laboratoire de l'Atmosphère et des Cyclones (UMR 8105, Météo-France, CNRS, Reunion University), Saint-Denis de La Réunion, France

<sup>2</sup>PCA, Météo-France, Direction Interrégionale pour l'Océan Indien (DIROI), Saint-Denis de La Réunion, France

**Correspondence**

David Barbary, DIROI/PCA, 50 Boulevard du Chaudron, 97490 Saint-Denis de La Réunion, France.

Email: david.barbary@meteo.fr

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Like Taiwan, the orography of Reunion Island may impact tropical cyclone (TC) track and intensity. A Mann–Whitney test is applied on best-track data from the Regional Specialized Meteorological Center (RSMC) La Reunion to demonstrate that this effect is detectable at less than 250 km from the island. A set of idealized experiments is carried out to investigate this effect with the French non-hydrostatic mesoscale numerical model Meso-NH at 12 and 4-km horizontal grid spacing. Results show that the island influences TC track and intensity within two radii of maximum winds, defining a distance of influence. The impact is similar to an aspiration of the vortex by the island, accompanied by vortex weakening. An asymmetry is found between TCs passing north or south of the island and can be explained by the presence of the island in the flow.

**KEYWORDS**

topographic effects, tropical cyclones, mesoscale modelling

## 1 | INTRODUCTION

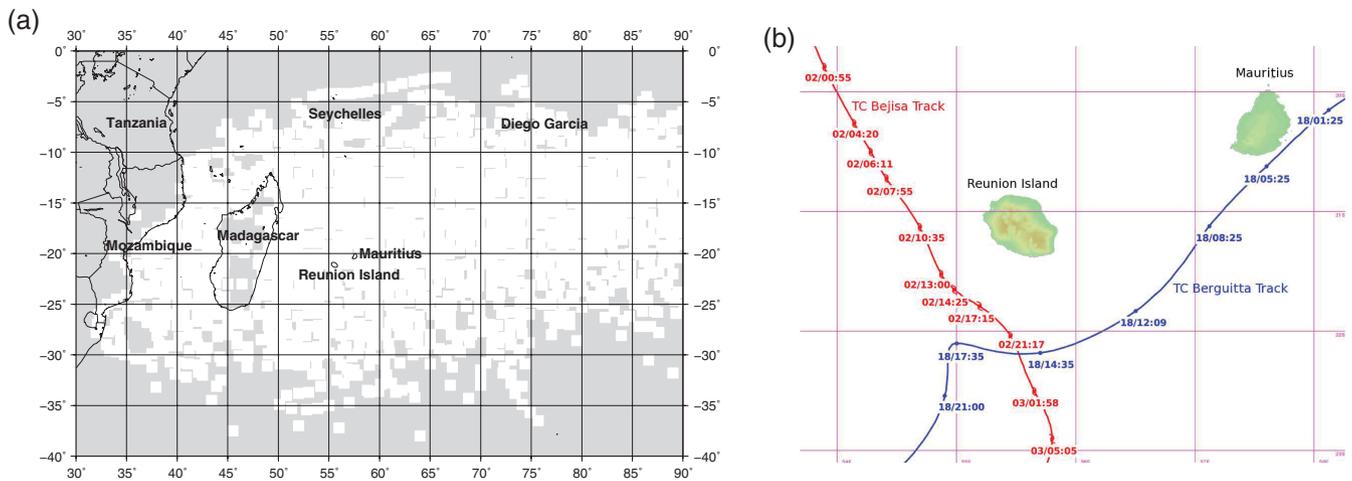
Reunion Island (55.5°E/21.1°S) is a small tropical mountainous island located in the southwest Indian Ocean (SWIO, Figure 1a). The island emerges from the sea as two volcanic summits originating from the same hot spot, resulting in a roughly circular shape of 60 km mean diameter with a peak altitude of 3,000 m. The steep orography of this island, combined with the frequent passage of tropical cyclones (TC) in this area, can generate huge amounts of precipitation over both short and long periods of time. Hence, La Reunion is famous for holding most of the rainfall world records for time periods extending from 9 hr to 15 days (see [http://www.nws.noaa.gov/oh/hdsc/record\\_precip/record\\_precip\\_world.html](http://www.nws.noaa.gov/oh/hdsc/record_precip/record_precip_world.html) for all worldwide rainfall records). On such a small island the spatial extent of precipitation associated with a tropical cyclone can nevertheless induce large variations of rainfall amounts (the all or nothing effect). It is therefore crucial to accurately predict the track and structure of tropical cyclones passing nearby La Reunion to properly forecast the associated cyclonic precipitation. A climatology

of TC activity in this basin has been proposed by Leroux *et al.* (2018).

Many studies have shown that the orography could influence TC track and intensity. Due to its large size, steep terrain, and position with respect to North Pacific TC routes, the island of Taiwan case has been particularly studied over the last decade (e.g., Lin *et al.*, 2005; Wu *et al.*, 2015). In the case of Taiwan, whether observed or simulated, studies about track deflection were limited to landfalling cyclones. In their results, Huang *et al.* (2011) did not mention a distance of influence without landfall, although this effect should exist. Smaller islands such as Hawaii's Big Island (Chambers and Li, 2011) were also found to possibly influence TC track. Without doing a statistical study of the Hawaiian Islands, Chambers and Li (2011) investigated the effect of Big Island on the trajectory and intensity of three representative central Pacific TCs, before making a numerical study with Advanced Research Weather Research and Forecasting (ARW-WRF) model version 2.2 at the finest resolution of 3 km. The authors found that Big Island could influence TCs hundreds of kilometers away from the island.

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**FIGURE 1** (a) Southwest Indian Ocean (SWIO) basin and TC location area with at least one individual in a square of  $1^\circ$  side, in the database (class ALL, see Table 1). The grey-shaded area represents the absence of data. (b) Tracks of TC Bejisa (between January 2–3, 2014) in red and TC Berguitta (January 18, 2018) in blue. Format of the date is day/hours:minutes

Very recently, observations (Figure 1b) and numerical simulations of TC Berguitta (January 2018) also showed an intriguing change of track when the storm moved close to Reunion Island, which surprised the TC operational forecasters. A similar behavior was also observed during TC Bejisa (Pianezze *et al.*, 2018; December 2013–January 2014, Figure 1b) and TC Dina in January 2002 (Roux *et al.*, 2004; Jolivet *et al.*, 2013), as they passed nearby La Reunion.

The aim of this study is to further investigate the potential effect of a small island such as La Reunion on TC behavior as well as to quantify its distance of influence. To achieve this objective, the large observational database of the Regional Specialized Meteorological Center (RSMC) La Reunion is first relied upon to search for the possible signature of TC track and intensity changes in the vicinity of La Reunion. A set of idealized experiments is then carried out to complement and refine this observation-based statistical analysis.

## 2 | OBSERVATIONS

### 2.1 | Database and definitions

The database used in this study is the best-track of RSMC La Reunion. In order to ensure good data quality, the dataset spans from August 1981 to July 2015 and covers the entire SWIO basin, which extends from the eastern African coast to  $90^\circ\text{E}$  and from the equator to  $40^\circ\text{S}$  (Figure 1a).

In the following, TC track changes are quantified by the absolute difference of storm heading and storm speed  $\Delta V$  at successive times, hereafter labeled, respectively,  $|\Delta D|$  and  $|\Delta V|$ . Using absolute values allows to better show the statistical effect of the relief by taking into account compensation resulting from acceleration and deflection of the systems. Using current intensity (CI) to estimate the intensity of

tropical systems following the approach of Dvorak (1975), the temporal evolution of CI is used to diagnose TC intensity changes (intensification if  $\Delta\text{CI} > 0$ ). As a reminder, CI is a quantity resulting from a subjective analysis of the cloud configuration using visible or Infra-Red satellite data and used to define the intensity of a cyclonic vortex. This is a discrete value ranging from 1 to 8 in steps of 0.5. The larger the CI, the more intense the vortex is, so stronger winds and lower central pressure. For the intensity, the predominance of the population  $\Delta\text{CI} = 0$  or  $|\Delta\text{CI}| = 0$  being true, no signal is gained by using the absolute values. This allows us to keep information on intensification or weakening, using  $\Delta\text{CI}$ .

The database statistics are reported in Table 1. Overall, it is found that all parameters (deviation or speed) are associated with large standard deviation. The higher the intensity is, the lower the standard deviation is. For intensity change, Table 1 also shows the predominance of the class  $\Delta\text{CI} = 0$ , that is, no intensity change.

### 2.2 | Area of significant influence of Reunion Island and maximum distance of influence

Assuming that La Reunion topography may significantly influence TC intensity and track (direction or speed), mean values of  $|\Delta D|$ ,  $|\Delta V|$  and  $\Delta\text{CI}$  should be significantly different over the area surrounding the island with respect to the rest of the basin. Let us define  $\mu_0^R$  as the average value of the variable *var* for the population over the entire basin except for a disk centered on Reunion Island with a radius  $R$ . Similarly, we define  $\mu_1^R$  as the average value of *var* for the population over the disk centered on Reunion Island. The hypothesis  $H_0(R)$  of equal averages is that  $\mu_0^R = \mu_1^R$  and the alternative hypothesis  $H_1(R)$  is that  $\mu_0^R \neq \mu_1^R$ . Without any assumption on the distribution, if  $H_0(R)$  is true then the statistical test of Mann and Whitney (1947), hereafter

**TABLE 1** Different populations used (ALL, moderate tropical storm [MTS], severe tropical storm [STS], tropical cyclone [TC]) with the criterion of selection of CI (Dvorak), number of individuals, mean and standard deviation for  $|\Delta D|$  (degrees),  $|\Delta V|$  (m/s) and frequency (%) of  $\Delta CI$  classes and distance of significant influence (km) for each parameter, stratified by storm intensity

Class of intensity	ALL	MTS	STS	TC
CI range	All CI	[2.5;3]	[3.5;4]	$\geq 4.5$
Number of individuals	9150	3048	1812	1825
$ \Delta D  \pm \sigma_{ \Delta D }$	$18.81 \pm 24.55$	$18.81 \pm 24.55$	$18.45 \pm 24.30$	$14.44 \pm 18.98$
$ \Delta V  \pm \sigma_{ \Delta V }$	$3.77 \pm 3.70$	$3.97 \pm 3.90$	$3.80 \pm 3.53$	$3.29 \pm 2.91$
Frequency (%) of $\Delta CI < 0$	14.5	12.5	17.3	16.2
Frequency (%) of $\Delta CI = 0$	66.1	68.5	57.4	56.8
Frequency (%) of $\Delta CI > 0$	19.4	19	25.3	27
$Dist_{\Delta CI}$	Undefined	280	340	340
$Dist_{ \Delta D }$	380	340	280	None
$Dist_{ \Delta V }$	380	370	None	None

referenced MW test, follows a normal distribution, provided that there are more than 20 individuals in both populations. This hypothesis  $H_0(R)$  was examined for all storms located within 100–1,800 km radius of the island's center using the MW test. The area of significant influence of the island is defined by the threshold value of the radius for which the statistical test becomes rejected with a threshold of  $\alpha = 5\%$ . This provides a value of the distance of significant influence for each parameter:  $Dist_{\Delta CI}$ ,  $Dist_{|\Delta D|}$  and  $Dist_{|\Delta V|}$ .

Results in Table 1 show that La Reunion affects TC tracks, either in direction or speed, even if the sign of these changes is not defined. The statistical analysis also shows that the distance of influence of Reunion Island depends on storm intensity. This distance never exceeds 380 km by all metrics whatever the parameter and class of intensity. If the threshold value of 20 individuals is not reached for the validity of the MW test, the notation “none” is written in Table 1.

A more restrictive limit, or maximum distance of influence, can be determined subjectively on class ALL from Figure 2a–c, where the shaded area defines the significant limit of influence of the island, following the MW test. By considering the distance from the island, one can estimate the dispersion of the population. This is shown in Figure 2 where all the data are indicated by crosses. In Figure 2 the bars provide a representation of the deviation from the average of the entire population (the value of which is given in Table 1) per 50 km block. Thus, a bar close to zero means a track deflection close to the average value over the entire population. A positive and significant value means a greater deflection at the distance  $R$  from the island compared to the entire population: the track will be more impacted at this distance  $R$  from the island than it is for the entire population. Conversely, for a negative value, the track will be less

impacted. A similar analysis can be made for speed changes in Figure 2b: positive and important values indicate a more pronounced speed change at distance  $R$  than for the entire population. Direction changes (Figure 2a) are significantly more important (positive values) when the vortex center is located within 200 km of the island compared to the rest of the population (i.e., farther away from the island). This is even more noticeable when the vortex center is located within 50 km of the island. Outside of this radius, tracks are close enough to average (values near zero).

During the approach phase (negative distances), speed changes (without being able to operate if there is an acceleration or a deceleration) start increasing from  $-250$  km (Figure 2b). The evolution of the speed variation (Figure 2b) is more variable during the away phase (positive distances) than during the approach phase. Regarding intensity changes (Figure 2c), it clearly appears that vortices moving away from the island within 250 km or less tend to weaken, no matter their intensity (no positive data is notable between 0 and  $+250$  km in Figure 2c). A slight weakening tendency also exists during the approach phase. One can also note the discrete nature of the variable  $\Delta CI$  and the predominance of the population  $\Delta CI = 0$  in Figure 2c,f,i,l.

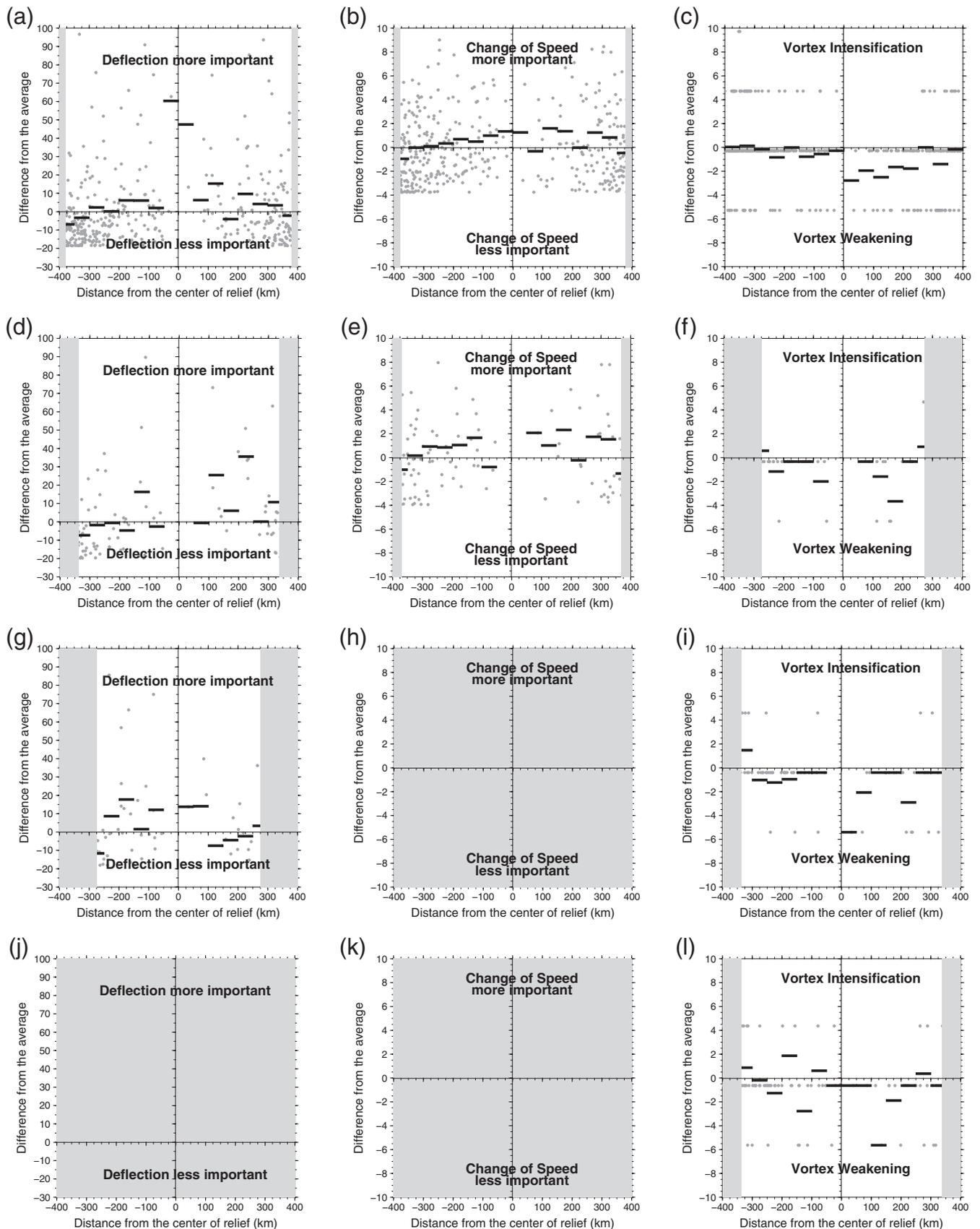
A similar analysis can be performed for other classes of intensity (Figure 2d–l). The values can be different from the class ALL, but for track deflections and change of speed (Figure 2d,e,g) the important point is the classification of the vortex intensity due to the effects of topography: the lower the intensity of the vortex, the more noticeable the effect of the topography. For more intense vortices, the difference is then insignificant according to the MW test (Figure 2h,g,k). Regarding intensity changes (Figure 2f,i,h), the values are close to the average (which is close to zero but negative, meaning a tendency to weaken over the entire population) with a slight tendency to weaken. Orography thus appears to have a weak but systematic effect on the weakening according to the statistics.

In order to further qualify and quantify the potential impact of topography on TC track and intensity changes, idealized experiments are performed with the high-resolution mesoscale model Meso-NH (Lafore *et al.*, 1998).

### 3 | NUMERICAL SIMULATIONS

#### 3.1 | Model description and experimental setup

The non-hydrostatic mesoscale model Meso-NH was chosen to achieve numerical simulations of TC tracks and intensities. This research model is designed to simulate atmospheric motions from the meso- $\alpha$  to the small scale. It has multiple parameterizations of physical phenomena such as surface interactions, turbulence, microphysics, convection and radiation. Two-way grid nesting with customizable vertical and horizontal resolutions and movable domains can be used to



**FIGURE 2** Difference from the average of (a)  $|\Delta D|$  in degree, (b)  $|\Delta V|$  in m/s, (c)  $10^* \Delta CI$  for the class ALL (see Table 1). Same but for class MTS for (d)  $|\Delta D|$ , (e)  $|\Delta V|$ , (f)  $10^* \Delta CI$  for class STS for (g)  $|\Delta D|$ , (h)  $|\Delta V|$ , (i)  $10^* \Delta CI$  and for class TC for (j)  $|\Delta D|$ , (k)  $|\Delta V|$ , (l)  $10^* \Delta CI$ . The grey-shaded area defines the limit of influence of Reunion Island where the statistical test is accepted (see Table 1). Grey crosses represent data and the wide bars represent 50-km spatial averages

simulate various scales of phenomena. Many idealized or real TC case studies (Nuissier *et al.*, 2005; Nan *et al.*, 2014) have shown that the model is skillful in the prediction of TC track, intensity and structure.

To study the influence of an island such as La Reunion on TC track and intensity, idealized numerical experiments are carried out at 12 and 4-km horizontal resolutions using a double nested mesh with 35 vertical levels extending to 24 km. The density of vertical levels is increased in the low and upper layers to more effectively represent the boundary layer convergence and upper-level divergence. The 12-km resolution grid covers a domain of  $3,000 \times 1,800$  km that stretches from  $48.05^\circ$  to  $77.00^\circ$ E and from  $12.80^\circ$  to  $28.95^\circ$ S.

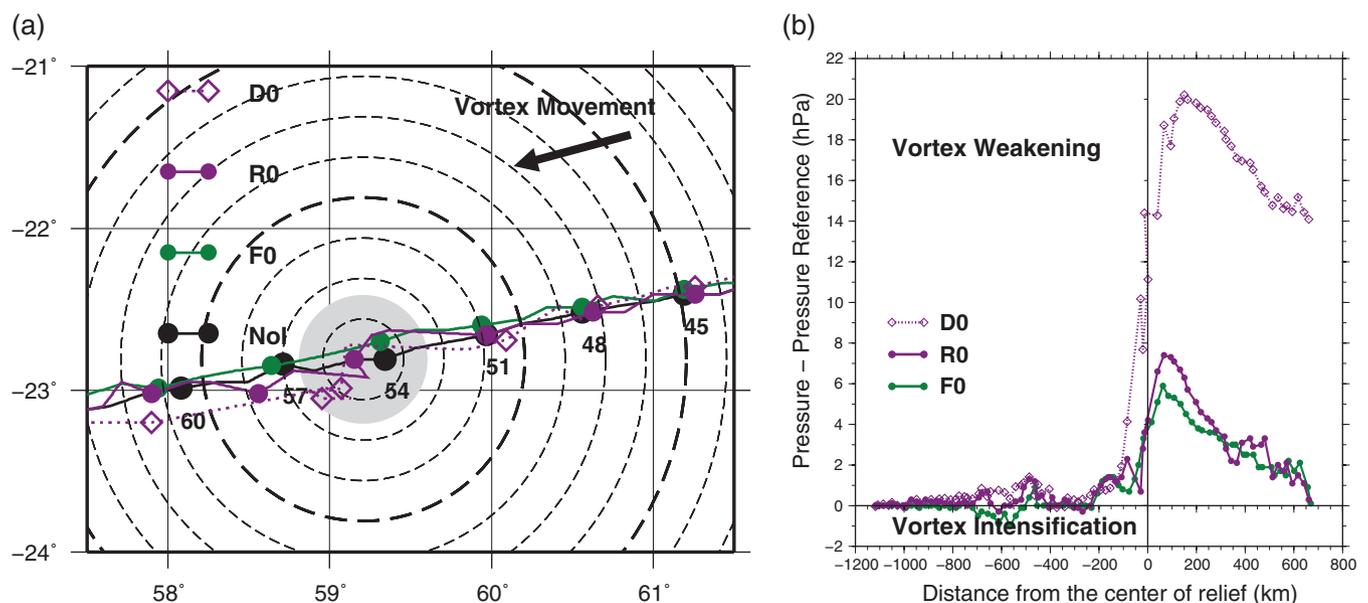
The 4-km resolution grid is centered at  $21.27^\circ$ S and  $58.97^\circ$ E and extends over  $960 \times 1,440$  km, completely encompassing the area represented by Figure 3a. The fine-mesh forecast is two-way nested in the coarse grid and the  $\beta$ -effect is taken into account.

Same parameterizations are used for the two grids except for the convective parametrization, which is only activated in the outer domain. The initial storm environment is based on a typical radiosounding (McBride, 1981) that includes trade winds of 5 m/s. In order to initialize the TC, a no-axisymmetric vortex is inserted according to the formulation of Holland (1980). For practical purposes a uniform sea surface temperature (SST) field of  $26.6^\circ$ C was prescribed for all grids. The position of the storm center is diagnosed from the minimum sea level pressure (MSLP) in model outputs. In order to better define the vortex parameters and the environmental conditions with respect to the relief, a preliminary study on the non-dimensional flow parameters (Lin *et al.*, 2005) was made. This climatological study (not shown) made it possible to define average deflection conditions thus

tabulating the vortex and environment characteristics used in the configuration of the idealized simulations.

Meso-NH is first run during 84 hr over the ocean. In this basic configuration, hereafter called NoIsland (NoI), the vortex spins up and its fine-scale structure is progressively refined. For this NoI simulation, the TC reaches the central longitude at 54 hr with a value of  $R_{vmax} = 44$  km. Then, 13 other configurations are performed to analyze the sensitivity of TC prediction with respect to the relative latitudinal position of the island, by inserting an idealized terrain (a truncated bell shaped) resembling the orography of Reunion Island in the fine-mesh grid, at the initial time. The characteristics of the bell shape make it possible to define a relief with a maximum height of 3,000 m and a radius of 40 km. The simulation named  $R_nD$  has terrain centered at the central longitude of the 4-km resolution grid and located at  $n$  times the radius of maximum winds ( $R_{vmax}$ ) of the storm toward the cardinal direction  $D$  ( $n = 1, 2, 3, 4, 6$  or  $8$  and  $n = 0$  without cardinal direction). So, in R2N the terrain is located  $2R_{vmax} = 88$  km north of the TC. Two other sensitivity experiments were defined by introducing, at the initial time, a flat island (named F0) and a larger island (named D0) at the same position than R0 simulation, at the initial time. For the enlarged island, the maximum height becomes 4,000 m and the radius 80 km.

To quantify the effect of terrain on TC track and intensity, results from F0 and the thirteen  $R_nD$  simulations are compared to the reference simulation NoI. The representation of the track is used to display the pattern of deflection, but values of deflections are characterized via the longitudinal (along-track, AT) and transverse (cross-track, CT) distances relative to the NoI simulation. A negative (resp. positive) longitudinal AT distance indicates a delay (resp. an



**FIGURE 3** (a) Focus of simulated TC tracks corresponding to experiments NoI (black), R0 (purple), D0 (purple not filled) and F0 (green). The numbers near symbols represent the forecast time. The grey-shaded area defines La Reunion Island and circles are drawn every 25 km from its center. (b) MSLP difference (hPa) between R0, D0 or F0 and NoI (the reference) as a function of the distance to the island

advance) and a right (resp. left) deviation is shown by a positive (resp. negative) transverse CT distance.

### 3.2 | Results of idealized simulations with landfall

The results of the four simulations NoI, F0, R0 and D0 are compared to assess the effect of orography during TC landfall. No matter the orography, inserting the island causes the generation of waves that slightly modify the large-scale flow, even at long ranges (Wu *et al.*, 2015). Such effect can be referred to as indirect influence. This can explain the delay/deflection in the tracks in order of one grid-point and the difference in intensity of less than 1 hPa before the possible direct orographic effect. Figure 3b further shows that the effect of the island on TC intensity starts as far as 600 km for an indirect influence and less than 300 km for a direct influence, due to the short-distance orographic effect.

TC landfall causes a sudden pressure increase of about 7 hPa (Figure 3b) for Experiment R0, meaning a weakening of vortex, which is still quite low compared to the vortex intensity of 968 hPa for the reference NoI. There are two additional effects of orography in compared to the friction induced by the presence of ground (i.e., Experiment F0). First, TC weakening is more pronounced for a mountainous than a flat island and occurs upstream of the island: at  $-125$  km for R0 versus  $-75$  km for F0. Second, a sporadic intensification is also noticeable for R0 at  $-25$  km. After passing over the island, the pressure difference gradually decreases, resulting in a slight re-intensification of the vortex as one moves away from the island. It therefore appears that the effect of orography is not predominant in this configuration. The comparison with the Experiment D0 however shows that this effect becomes predominant with an additional difference of 12 hPa when the orography is more marked.

Regarding the TC track, a flat or mountainous island has different effect on TC track behavior (Figure 3a). While the effect is almost negligible, it is more pronounced in the presence of orography and induce fast changes of storm speed and direction from  $-100$  to  $100$  km away from the island. A blockage in the leeward side of the terrain is directly noticeable (Figure 3a) inducing a deflection of 25 km towards the right followed by one of 25 km towards the left and an advance of 30 km followed by a delay of 10 km during a 3 hr period. This effect is more marked for the case of an exaggerated orography (Experiment D0). The oscillating character persists while the storm moves away from a mountainous island.

### 3.3 | Results of idealized simulations without landfall

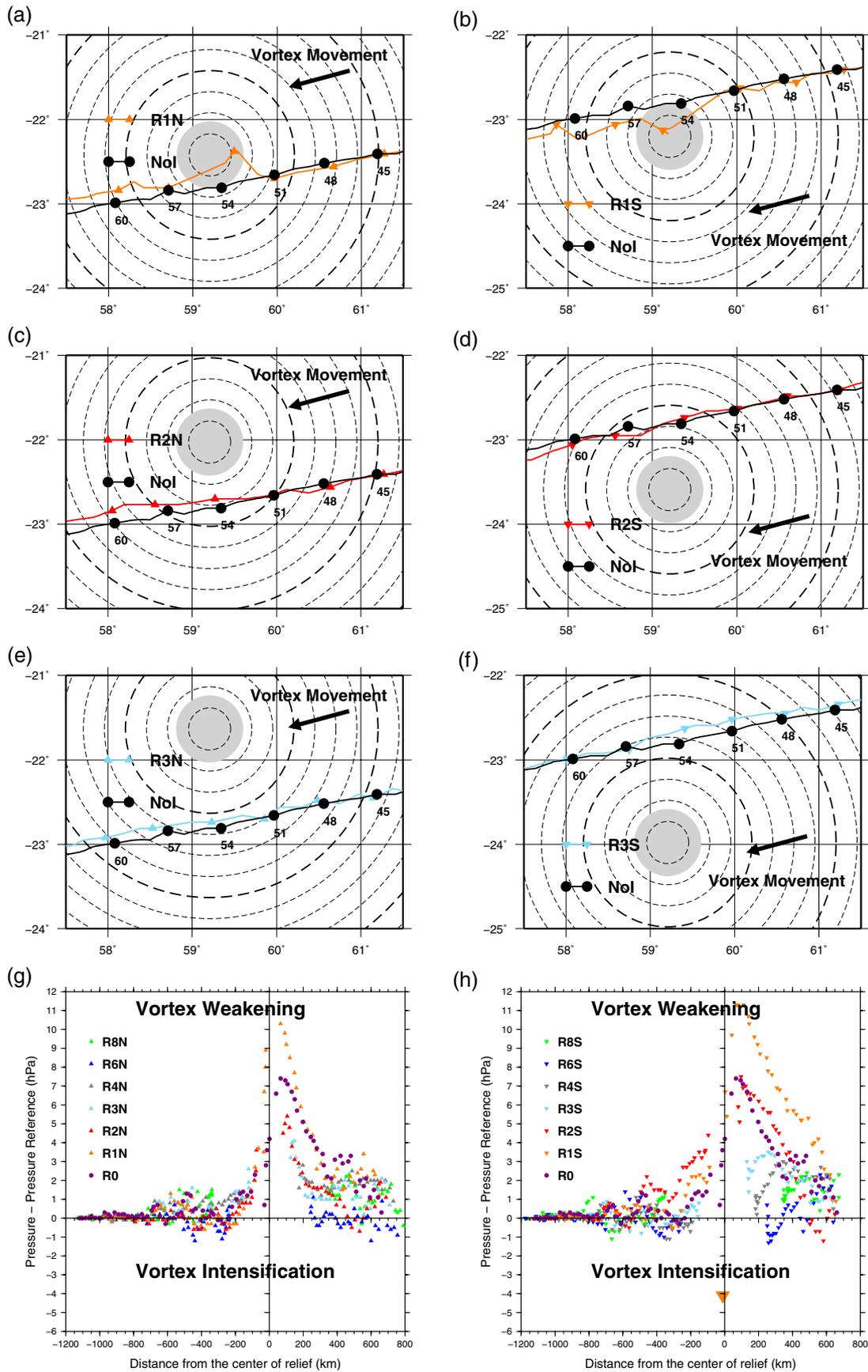
The remaining twelve *RnD* experiments with  $n \neq 0$  are used to estimate the impact of terrain when the storm track does not intercept the island. As previously mentioned, one can systematically note oscillations away from the island. This

effect can be noticed in all simulations with a varying amplitude. Overall, it causes a slight decrease in pressure lower than 2 hPa (Figure 4g,h for a distance between  $-800$  and  $-400$  km) as well as a deflection mostly to the right and a delay (partly illustrated in Figure 4a–f) with regards to the NoI configuration.

The overall distribution of the points for AT and CT parameters (not shown) indicates that terrain effects are weak but detectable with maximum deviations of 30 km. Therefore, we only represent in Figure 4a–f the tracks for the *RnD* experiments up to  $n = 3$ : no direct impact is noticeable for greater values of  $n$ .

Figure 4g,h also shows differences in behavior between TCs passing north or south of the island. Weakening is slightly stronger for TCs evolving north of the island (RnS experiments, Figure 4h) and is emphasized when the storm approaches the land. This indicates that the distance of influence of the island is higher when TCs evolve north of it (RnS experiments). This asymmetry is linked to the beta effect taken into account in the simulations. The wind being stronger in the southern sector (in the southern hemisphere), the action of orography is then more marked for the RnS cases. This induces a stronger weakening of the vortex for cases circulating to the north of the island. A precise inspection of Figure 4g,h shows a variation of the pressure difference greater than  $+2$  hPa (in addition to the oscillation induced by the indirect effect) for R0, R1N, R1S, R2N and R2S at a distance of approximately  $-100$  km, that is to say about  $2-3R_{V_{max}}$ . When the storm moves away from the island, it take a greater distance ( $400$  km, i.e.,  $8R_{V_{max}}$ ) for the pressure to return to the threshold value  $\Delta P = +2$  hPa. Overall, weakening occurs just before the TC gets past the island. We can notice that there is only one case of intensification and it occurs for R1S: a 4 hPa intensification can be seen in Figure 4h close to the island (it is indicated by the biggest orange symbol).

Regarding the influence of terrain on TC track, a delay is prevalent for approaching TCs evolving north of the island (Figure 4, right). Conversely, some of the TCs evolving south of the island accelerate at  $-400$  km (not shown). An acceleration occurs between  $-150$  and  $-100$  km for cases closer than  $2R_{V_{max}}$ , followed by a deceleration at lower distance of the island (R1N, R2N, R1S and R2S). The R1N experiment stands out with a deceleration over all the integration time. The initial deviation to the right veers to the left for some TCs evolving north of the island (Figure 4, right). Track changes are maximized for the two closest storms (R1N and R1S) with a cross-track difference peaking at 40 km. The difference between these two cases (Figure 4a,b) result in different location of the windless area, which directly positions the minimum pressure. Thus, in the case of a passage to the north (RnS), the minimum pressure will be located on the leeward side and in the case of a



**FIGURE 4** As in Figure 3 for various  $R_nD$  experiments (in colors). Left panel represents the TC tracks (a, c, e) and MSLP difference in hPa (g) for a passage to the south of the island. Right panel (b, d, f, h), for a passage to the north of the island

passage to the south (RnN), it will be located on the windward side of the relief.

### 3.4 | Distance of influence and interpretation

In the light of the previous discussion and of Figure 4, the terrain effect on TC track and intensity can be summarized by the following consecutive patterns:

- TC acceleration when the storm moves toward the mountainous island.
- TC deflection toward the terrain (suck-in like effect) associated with wind deceleration and intensity weakening.
- A temporary slowdown after passing the island, which may cause a blocking effect in the leeward side of the terrain.
- An acceleration of the vortex moving away from the island and returning in the flow with an oscillating track, accompanied by continuous storm deepening.

The distance of influence (on track and intensity) can be estimated at  $2R_{V_{\max}}$  (about 100 km in the case of the idealized experiments carried out to this study). With trade winds of 5 m/s used in this numerical setup, speed and direction changes occur within a 24-hr period. Therefore, in the case of landfall, observations with a sampling period of 6 hr are theoretically sufficient to detect the terrain effect, even if increasing the sampling period would likely reveal more details in the changes. This is not true for systems passing nearby at 200 km distance or embedded in a fast flow: track changes in such cases may go undetected in the best-track database because of its 6 hr resolution.

## 4 | CONCLUSIONS AND PERSPECTIVES

The present study used observations and idealized experiments to investigate the possible orographic influence of Reunion Island on TC track and intensity. A peculiar attention was dedicated to the existence of a distance of influence. Using best-track data from RSMC La Reunion from 1981 to 2015, the statistical test of Mann and Whitney (1947) was applied to determine the distance of significant influence. An objective analysis showed that the island impact was detectable up to 150–200 km away from the island for the TC track and up to 50 km for a decreased TC intensity. This effect is also detectable if we focus on Mauritius although the distance may be different. We can assume that this effect is detectable for many other islands with sufficient topographic features.

Results from idealized experiments indicate a smaller distance equivalent to  $2R_{V_{\max}}$  (about 100 km). The effect of the mountainous island is similar to vortex suck-in and is accompanied by storm weakening, notable features in the

track of TC Bejisa (December 2013–January 2014) and TC Berguita (January 2018) in Figure 1b. The impact is more pronounced when TC passes at  $1R_{V_{\max}}$  from the island and a sporadic intensification is then possible. The presence of the island results in an asymmetry between storms passing north and south of the island. These results should help TC forecasters to take into account possible track alterations for TCs evolving in the vicinity of small mountainous island. Such alterations may result in the TC coming closer to the island, possibly degrading weather conditions and increasing risks and potential damages.

In order to further understand the main processes responsible for track changes one could compute a vorticity budget analysis such as Lin and Savage (2011) in case of no landfall near a small island.

The blocking effect on the approach of the terrain simulated by Chambers and Li (2011) and observed by Roux *et al.* (2004), exists only for the direct impact case in our study. Therefore, another perspective would be to use non-dimensional flow parameters (Lin *et al.*, 2005) to choose other environmental conditions in the initial experimental setup to make this blocking effect appear more clearly, for no landfalling cases. To go further in the discussion about non-dimensional flow parameters and distance of influence, it would be interesting to study the importance of the minimum approaching distance on similar cases of Huang *et al.* (2016) for non-landfalling cases. According to Huang *et al.* (2016), the non-dimensional flow parameter  $R_{V_{\max}}/L_y$  (where  $R_{V_{\max}}$  the radius of maximum wind,  $L_y$  the mountain meridional elongation length scale) is an essential parameter to determine the influence of terrain on the track deflection for landfalling cases and with  $R_{V_{\max}}/L_y$  values below 0.08. In our study, the values of this parameter are much higher (in the order of 0.5), meaning that such parameter may not be that meaningful in our cases. Defining  $\text{Dist}_{\min}$  as the minimum approach distance of the vortex to the maximum topography, the parameter  $F = (1 - \text{Dist}_{\min}/nR_{V_{\max}})$  could then be considered as an attenuating factor of the effects of the relief, with  $n$  defining a threshold value from which the terrain no longer has an effect on the track deflection. For a direct impact, that is,  $\text{Dist}_{\min} = 0$ , there is no attenuation. For  $\text{Dist}_{\min} \geq nR_{V_{\max}}$ , the attenuating factor  $F$  becomes zero because the distance of the vortex to the maximum topography is sufficiently large so that the relief no longer has an effect on the track. In our case, the value of  $n$  could be higher than 2 but may be different for other cases like Taiwan. Applied this attenuating factor to the non-dimensional flow parameters (Lin *et al.*, 2005; Huang *et al.*, 2016) requires a modification of these numbers in order to maintain a variation similar to that described by their authors. For example, following Huang *et al.* (2016) a small value of  $R_{V_{\max}}/L_y$  induces a strong effect that will become an important value of  $F^*L_y/R_{V_{\max}}$  to reflect a significant effect. With

an attenuating factor  $F < 1$ ,  $F^*L_y/R_{vmax}$  becomes smaller which is consistent with a limited influence of the relief.

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## ORCID

David Barbary  <https://orcid.org/0000-0002-0454-5839>

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