Orographic impacts of Réunion Island and Madagascar on heavy rainfall during Tropical Cyclone Batsirai (2022)

By K. O. Lee et al.

Reply to the referee's comments

In the following, the comments made by the referees appear in black, while our replies are in red, and the proposed modified text in the typescript is in blue.

Referee #2 comments

Summary general Comments

This paper investigates the orographic effects of a small island (Réunion Island) and a medium-sized island (Madagascar) on tropical cyclone (TC) track, intensity, and precipitation. The authors conducted a control experiment together with three sensitivity experiments with modified orography. The results show that the orography of Réunion Island has little impact on the TC track, while it plays an important role in controlling heavy precipitation over the island. In contrast, the orography of Madagascar slightly modifies the TC track and contributes significantly to heavy rainfall on the windward side of the island. The study clearly demonstrates the influence of island topography on TC behavior and associated precipitation. These findings are important for improving our understanding of orographic enhancement of TC-induced rainfall.

Overall, the manuscript is logically organized, and the scientific results are clearly presented. The reviewer finds the study valuable and believes that the manuscript has the potential to be accepted for publication. However, several issues should be addressed before publication. The reviewer kindly requests that the authors consider the following comments in revising the manuscript.

We sincerely appreciate the time and effort you have devoted to reviewing our manuscript, as well as your insightful and constructive comments. We have carefully revised the manuscript in response to the reviewer's valuable suggestions. Our point-by-point responses to each comment are provided below.

Major issue:

Lines 318-333: In this study, the authors compare the CTL experiment with the FLTall experiment and conclude that the peak precipitation and the duration of heavy rainfall are significantly reduced in FLTall. However, the reviewer believes that the comparison should be made between CTL and FLTreu rather than between CTL and FLTall. As shown in Figure 6, the storm tracks in CTL and FLTreu are very similar, whereas those in CTL and FLTall differ by approximately 40 km. According to Figures 9 and 10, such a difference appears to be important because it changes the relative position of Réunion Island with respect to the storm structure. In CTL, Réunion Island is located beneath the outer rainband, whereas in FLTall it is situated between the outer and inner rainbands. This suggests that the precipitation weakened more rapidly in FLTall, resulting in a shorter duration of heavy rainfall. Since CTL and FLTreu exhibit similar tracks and similar locations of the outer rainband, it is expected that the persistence of precipitation in FLTreu would be comparable to that in CTL. Therefore, the reviewer kindly recommends that FLTreu, rather than FLTall, be used for the comparison to isolate the effect of the orography of Réunion Island.

We fully agree with the reviewer's comment. Changes in the TC's position relative to Réunion Island between FLT_{all} and FLT_{reu} can affect local precipitation, particularly its timing, duration, and location. Because the TC trajectory in FLT_{reu} closely resembles that in CTL, using FLT_{reu} instead helps to more clearly isolate the terrain effect of Réunion Island on local heavy precipitation. As suggested, we have reproduced Figures 8a, 10, and 11 using FLT_{reu} instead of FLT_{all}; the relevant explanations are revised.

♣ Page 15, Figure 8a

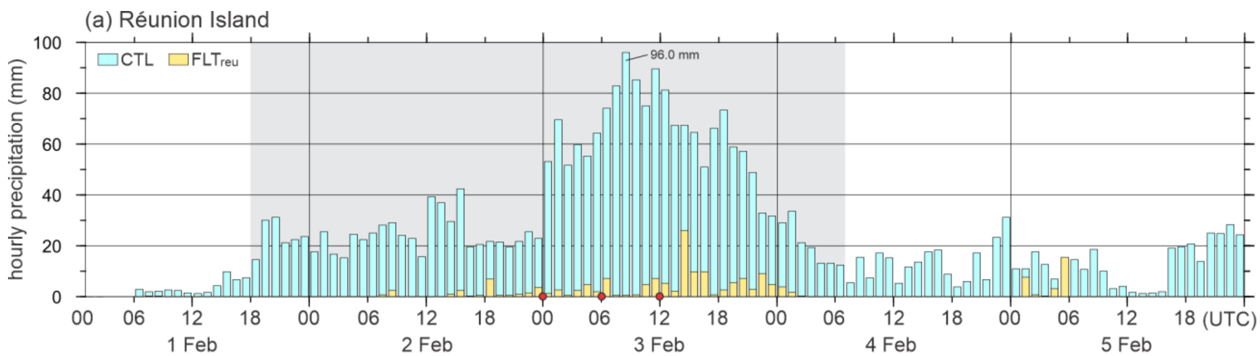

Figure 8. Temporal evolution of the simulated maximum precipitation within the analysis domains: (a) the Réunion Island region, from the CTL (light blue bars) and FLT_{reu} (yellow bars) experiments, and (b) the eastern Madagascar region, from the CTL (light blue bars) and FLT_{all} (yellow bars) experiments. The horizontal extent of the analysis domains is shown by the boxes in Fig. 7. Red circles along the x-axis indicate the selected times presented in Figs. 9, 10, and 12. The grey-shaded areas highlight period during which precipitation ≥ 10 mm h^{-1} persists in CTL experiment. Results of the first 6 hours of the spin-up period were excluded from the analysis.

The two key message obtained from Figure 8a with FLT_{reu} remain identical to those captured with FLT_{all}: (i) persistent heavy precipitation lasting about 60 hours in CTL, and (ii) only a few hours of heavy precipitation (3 hours in FLT_{reu} *versus* 4 hours in FLT_{all}) simulated with the flat island.

♣ Page 13, lines 356–378

"A box centered on Réunion Island (55–56°E, 20.8–21.5°S; rectangle in Fig. 7) is used to analyze hourly precipitation over land during the passage of TC Batsirai. The five-day evolution of the maximum hourly precipitation over Réunion Island (Fig. 8a) reveals (i) persistent heavy precipitation (≥ 10 mm h^{-1}) lasting approximately 60 hours in CTL (light blue bars within the grey-shaded period from 18 UTC on 1 February to 07 UTC on 4 February), whereas (ii) only three hours of heavy precipitation are simulated in FLT_{reu} (yellow bars from 14 UTC to 16 UTC on 3 February). During this period, the peak hourly precipitation reaches 96 mm h^{-1} in CTL, compared to only 26 mm h^{-1} in FLT_{reu}. A sharp increase in hourly precipitation to above 50 mm h^{-1} occurs at 00 UTC on 3 February in CTL, and very intense precipitation (≥ 50 mm h^{-1}) persists for nearly one day while TC Batsirai passes near Réunion Island (section ii marked in Fig. 6a). After 4 February, when the TC moves away from the island, FLT_{reu} produces little to no precipitation, whereas CTL continues to simulate weak to intense precipitation ranging from 2 to 30 mm h^{-1}. […]"

♣ Page 17, Figure 10

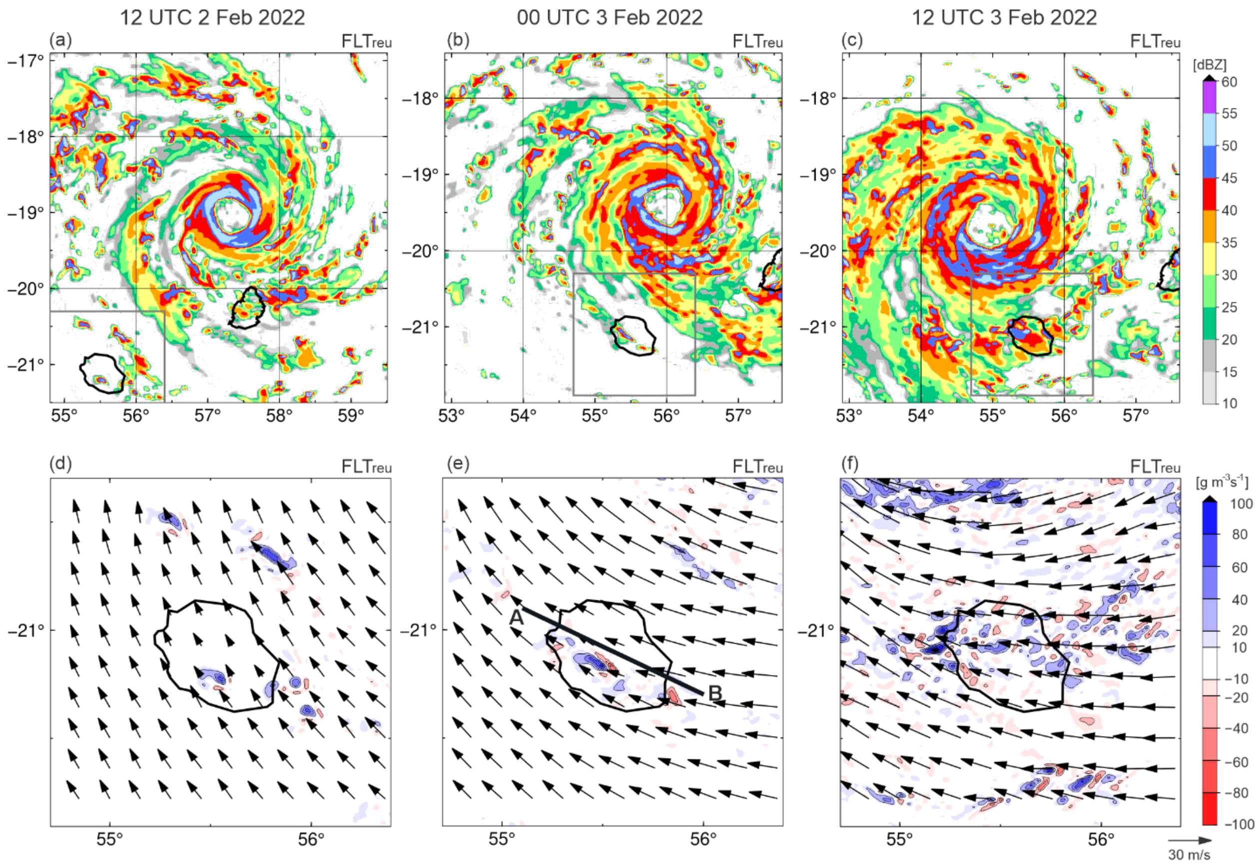

Figure 10. Same as Fig. 9, but showing horizontal distributions of reflectivity at 3 km above sea level (a–c) and low-level moisture flux convergence below 3 km (d–f) from the FLT_{reu} simulation.

The key message obtained from Figure 10 with FLT_{reu}, by comparing it with CTL, remains identical to that captured with FLT_{all}. While the positions of the TC center in CTL and FLT_{reu} were very close to each other, the orographically-induced low-level wind deflections simulated in CTL were absent in FLT_{reu}, as similarly seen in FLT_{all}.

♣ Page 18, line 446

"[…] In contrast, these wind structures are absent in FLT_{reu} at the same time […]"

♣ Page 18, lines 46–464

"In contrast, the strong reflectivity cores and organized low-level moisture flux patterns evident in CTL at 00 UTC are absent in FLT_{reu} at the same time (Figs. 10b, e). While the positions of the TC center in CTL and FLT_{reu} were similarly located between 19° and 20°S (Figs. 9a–c, 10a–c), spiral rainbands passed over Réunion Island. Unlike in CTL, relatively strong reflectivity and pairs of convergence and divergence were seen in FLT_{reu} only where the convective clouds existed within the spiral rainbands."

♣ Page 19, lines 508–510

"[...] In contrast, in *FLT$_{reu}$* (Figs. 10b–c, 10e–f), the convective regions and orographically induced wind patterns observed in CTL are absent. Instead, increased reflectivity and wind convergences associated with convective clouds within the spiral rainbands are apparent as similarly produced in CTL (Fig. 9)."

♣ Page 19, Figure 11

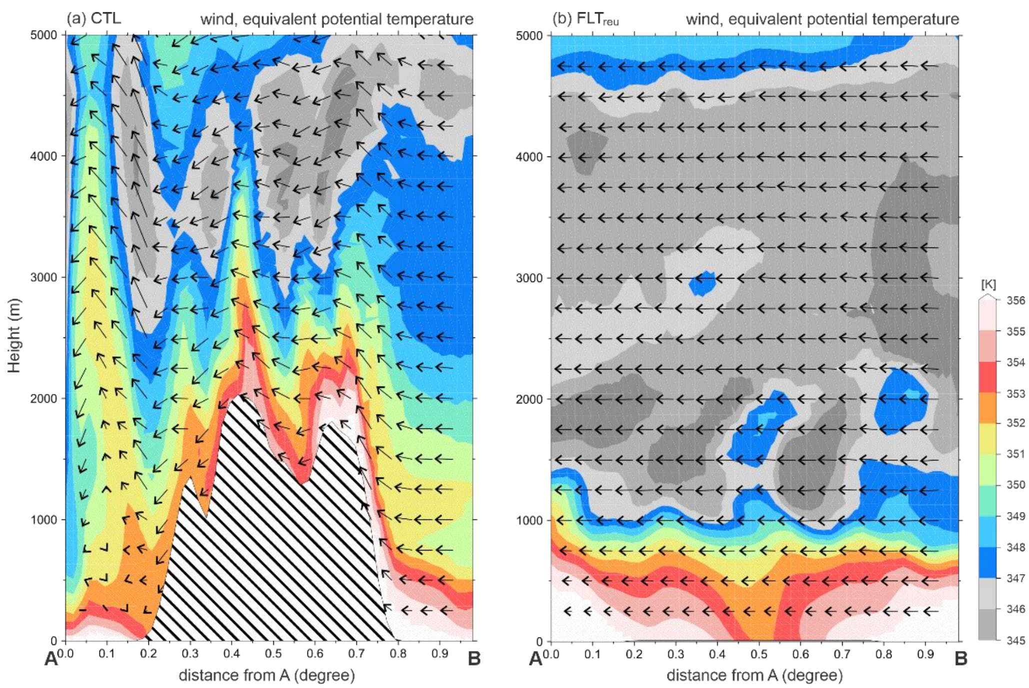

Figure 11. Vertical cross-sections of wind (u–w vectors) and equivalent potential temperature (θ_e, shaded) along the A–B line, simulated by (a) CTL and (b) *FLT$_{reu}$* at 00 UTC on 3 February. The location of the A–B line is shown by the green solid line in Figs. 9e and 10e for the CTL and *FLT$_{reu}$* simulations, respectively. The hatched area in (a) represents the topography.

The key message saying the absence of vertically extended warm and moist air mass ($\vartheta_e \geq 352$ K) along the terrain from the surface up to about 4 km above sea level in *FLT$_{reu}$*, remains identical as seen in *FLT$_{all}$*.

♣ Page 19, lines 496–500

"[...] In contrast, in *FLT$_{reu}$* (Fig. 11b), the warm and moist air ($\vartheta_e \geq 352$ K) remains confined below 1 km, and is distributed relatively homogeneously along the cross-section, with a drier air mass ($\vartheta_e \leq 350$ K) above. The comparison between CTL and *FLT$_{reu}$* (Fig. 11) clearly demonstrates that the high terrain of Réunion Island plays a critical role in lifting the abundant low-level moisture advected by TC Batsirai to altitudes above 4 km on the windward side and near the mountain crest, thereby contributing to the intense precipitation over the mountainous region."

Specific points:

1. Lines12-13: The statement that "the terrain of Réunion and Madagascar enhanced localized rainfall by 94% (2800 mm) and 82% (830 mm), respectively" is unclear. Does this imply that the increase in rainfall from the FLTxxx experiments to the CTL experiment corresponds to 94% and 82% of the rainfall amounts in the FLTxxx experiments? If so, this interpretation does not appear to be consistent with the presented results. The reviewer kindly requests that the authors clarify the basis of these percentages and explain more explicitly what is meant by these values.

As suggested, we have reclarified the percentages. To estimate the rainfall enhancement over Réunion Island, we compared the maximum 5-day rainfall accumulation between the CTL and FLT_{reu} experiments (3032 mm versus 126 mm, respectively), giving an enhancement of 95 %. Following another anonymous referee's suggestion, FLT_{all} has been replaced by FLT_{reu}, as the latter produces a TC trajectory closer to CTL near Réunion Island.

For the rainfall enhancement over Madagascar, the same calculation was applied using CTL and FTL_{all} experiments (1007 mm versus 177 mm, respectively), giving an enhancement of 82 %.

For readability, the corresponding sentence in the manuscript has been rewritten as below, and an additional Figure S1 has been added to the Supplement.

♣ Page 1, lines 12–14

"Relative to the flattened-terrain experiments, the presence of terrain increased localized rainfall by 95 % (2,906 mm) over Réunion Island (CTL versus FLT_{reu}) and by 82 % (830 mm) over Madagascar (CTL versus FLT_{all})."

♣ Page 13, lines 346–349

"The simulated localized heavy precipitation over the mountainous region of Réunion Island is absent in FLT_{reu}, in a manner nearly identical to FLT_{all}. The difference in five-day accumulated precipitation between CTL and FLT_{reu} (Fig. S1b) indicates that approximately 95% of the localized heavy precipitation (e.g. 2.906 mm) can be attributed to the steep terrain of Réunion Island."

♣ Supplement file

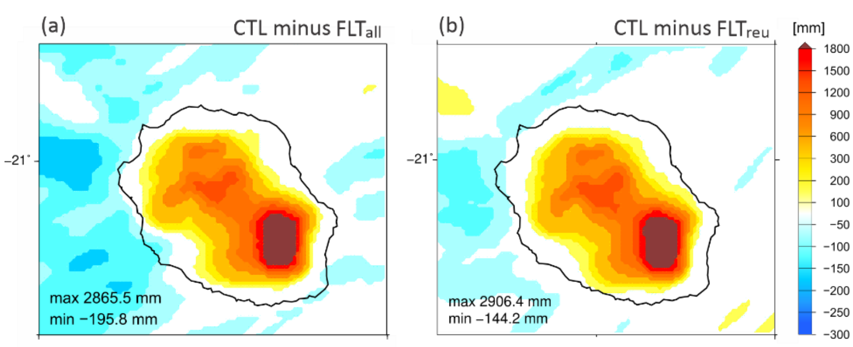

Figure S1. The difference in five-day accumulated precipitation (a) between CTL and FLT_{all} (CTL minus FLT_{all}), and (b) CTL and FLT_{reu} (CTL minus FLT_{reu}).

2. Line 169: What is “a monotonic Piecewise Parabolic Method”? a brief explanation is necessary for this.

As suggested, a brief explanation is included.

♣ Page 7, lines 179–183

“In conjunction with the leapfrog temporal scheme, momentum variables are advected using a centered fourth-order scheme, whereas scalar and other meteorological variables were advected using a monotonic Piecewise Parabolic Method (PPM; Colella and Woodward, 1984). The monotonic variant of PPM applies a limiter that constrains the reconstructed parabolic profiles, preventing spurious oscillations and negative values near sharp gradients and thereby ensuring physically realistic transport of scalars such as moisture and hydrometeors.”

3. Line 199: The expression “the lee side of Réunion” is ambiguous. A more specific description should be provided to clearly indicate the region being referred to.

Improved.

♣ Page 8, lines 220–221

“After passing offshore of the northwest of Réunion Island […]”

4. Lines 267-270: The authors attribute the discrepancy between the observed and simulated precipitation amounts to an overestimation in the CTL simulation. However, another possible explanation should also be considered. The rain gauges located near the summit region of Réunion Island may have suffered from reduced catch efficiency under strong wind conditions, which could have resulted in an underestimation of the observed precipitation.

We totally agreed. An additional sentence is added in this context.

♣ Page 11, lines 295–297

“[…] It should also be noted that the rain gauge network in the mountainous region has a relatively coarse spatial resolution. Additionally, rain gauges located near the summit may have suffered from reduced catch efficiency under strong wind conditions, which could have led to an underestimation of observed precipitation.”

5. Lines 331-333: This issue may be related to the major comment above. Why does the CTL experiment produce prolonged precipitation after 4 February? The authors should provide a physical explanation for the persistence of rainfall during this period.

An additional sentence for a physical explanation is added.

♣ Page 14, lines 377–381

“[…] After 4 February, when the TC moves away from the island, FLT_{all} produces little to no precipitation, whereas CTL continues to simulate weak to intense precipitation ranging from 2 to 30 mm h^{-1}. Even with the TC at a distance, southwesterlies prevailed around the Réunion Island region, supplying low-level moisture toward the mountain slopes (data not shown). The consistent ascent of this moist air along the slope prolongs the precipitation. ”

6. Lines 426-427: This issue may also be related to the major comment above. The absence of convective regions in FLTall may be attributed to the different relative position of Réunion Island with respect to the outer spiral rainband compared with CTL.

By using FLT_{reu} instead off FLT_{all}, the position of the TC center relative to Réunion Island in FLT_{reu} remains very close to that in the CTL experiment. Thus, convective regions within spiral rainbands are produced similarly in FLT_{reu} and CTL, allowing us to focus on the orographic effect of Réunion Island on precipitation and the corresponding local wind modification. The sentences have been revised (see our reply to the major comment above).

7. Line 454: The “minimum difference” may be “maximum difference”.

Corrected.

8. Lines 609-610: If the authors claim that equatorial Rossby waves play a dominant role in TC genesis, they should provide supporting evidence for this statement.

TCs developing in the SWIO basin are often strongly influenced by seasonal to sub-seasonal scale drivers such as Madden-Julien Oscillation (MJO), ENSO/IOD (Indian Ocean Dipole) modulation, subtropical-ridge, equatorial Rossby wave, and Kelvin waves (Bonnardot et al., 2022), particularly in terms of TC genesis and trajectory; however, their impacts on local heavy precipitation have not yet been examined. Prior to the genesis of TC Batsirai, we found that equatorial Rossby waves appeared to play a dominant role among the sub-seasonal drivers, compared with other modes such as the MJO. The influence of equatorial Rossby waves in modulating the genesis and trajectory of TC Batsirai would therefore be an interesting topic for future research. In the meantime, however, we decided to exclude this discussion here in order to keep the present study more focused and constructive.