Chapter 6
Print ISBN: 978-81-976653-2-5, eBook ISBN: 978-81-976653-8-7

Evolution of 2007-08 Madden-Julian Oscillation (MJO07-08) Passing over the New Guinea Highlands (Part III): Effects Orographic Blocking and Diurnal Heating on MJO07-08 during the Splitting Stage

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DOI: https://doi.org/10.9734/bpi/strufp/v8/1071

Peer-Review History:
This chapter was reviewed by following the Advanced Open Peer Review policy. This chapter was thoroughly checked to prevent plagiarism. As per editorial policy, a minimum of two peer-reviewers reviewed the manuscript. After review and revision of the manuscript, the Book Editor approved the manuscript for final publication. Peer review comments, comments of the editor(s), etc. are available here: https://peerreviewarchive.com/review-history/1071

ABSTRACT

In this study (Part III), effects of the mechanical and thermal forcing on the 2007-08 Madden-Julian Oscillation (MJO07-08) system during the splitting stage over the New Guinea Highlands (NGH) are investigated. During the splitting stage of MJO07-08 convective system following the blocking stage highlights the relatively stronger role played by thermal forcing associated with the NGH, owing to the interaction between land/sea breeze and the basic flow. Moreover, the mechanical forcing influences the amount of rainfall along NGH as the weakened mesoscale convective system (MCS) and incoming flow associated with MJO07-08 interact with the complex terrain of NGH. This study also explores how the common ingredients and major mechanisms for heavy rainfall, as identified in the previous studies, are affected during the splitting of the MCS around NGH. In short, this research provides in-depth insights into the roles of mechanical and thermal forcing on the rainfall modification and propagation of MJO07-08 over the NGH. By employing the Weather and Research Forecasting (WRF) model, the research uncovers the significance of these factors influencing orographic blocking, flow regimes, and the NGH modification of the MJO07-08 rainfall.

Keywords: Madden-Julian oscillation; rainfall; orographic blocking effect; diurnal heating.

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1. INTRODUCTION

In Part I [1] of a series of studies of the evolution of the 2007-08 Madden-Julian Oscillation (MJO07-08) passing over the New Guinea Highlands (NGH), we have investigated the orographic effects on the propagation and rainfall modification of MJO07-08. They identified three stages of the MJO07-08: blocking, splitting, and merging stages, with the MJO07-08 passing through these stages as it crossed the NGH. During the blocking stage, the propagation of the MJO was slowed, leading to flow and MJO convection transitioning to the splitting stage before the merging stage upon arrival at the southeastern corner of the NGH.

In Part II, Riley and Lin [2] (referred to as RL24 or Part II hereafter) further investigated how the thermal and mechanical effects of the NGH influenced the enhancement and ingredients of orographic rain associated with the MJO07-08. Their WRF analysis showed that both mechanical and diurnal thermal forcing impacted propagation and rainfall during the blocking and splitting stages of the MJO07-08 [3-12]. Note that this approach follows Doswell et al.'s [13] ingredient approach, in which the rainfall associated with a convective system is proportional to the upward motion over a flat terrain, which could be approximately decomposed into the orographically and environmentally forced components when the convective system is moving over mountains [14]. However, Riley and Lin [2] found that mechanical forcing plays a more significant role in generating orographic rain compared to diurnal thermal forcing. They also found two three-dimensional (3D) flow regimes associated with the MJO07-08 during the blocking stage. In the flow-around regime, the airflow split at the northwest corner of the NGH due to strong orographic blocking. The flow splitting leads to the splitting of MJO-associated convective system, which is named at splitting stage in Part I [1]. Based on a series of sensitivity tests with varying mountain height using the Advanced Research Weather Research and Forecasting (WRF) model, the flow-around regime occurs when the mountain height exceeded 50% of the original height, and orographic rainfall increased as the mountain height increased. In contrast, the flow-over regime occurred when the mountain height was below 50% of the original mountain height, with the convective system moving over the NGH with minimum to no orographic terrain blocking. When the mountain height was exactly 50%, the convective system occurred in both flow-around and flow-over regimes, with orographic rainfall linearly increasing until the mountain reached 75% of the original height, after which there was a plateau in rainfall production. They also determined the orographic ingredients associated with the MJO07-08 event, despite it not being a rotating convective system like a hurricane.

The splitting of the MJO is caused by the mechanical and thermal forcing of the NGH, which weakens the MJO07-08 to a point where the mass convective system splits into two convective cells. Because of these two forcings acting upon the propagation of MJO07-08, we must differentiate their roles. In Part II, RL24 emphasized that the mechanical forcing is mainly attributed by the interaction of the MJO and the orographic terrain of the NGH during the blocking stage. The thermal forcing is attributed to the diurnal heating/cooling of the island, which causes the MJO07-08 to interact with the land/sea breeze associated with the island. To further understand the impacts of mechanical and thermal forcing on the MJO's behavior during its interaction with the NGH, several sensitivity tests will be performed using the same WRF model and domain defined for this study.

Both studies mentioned above have helped us understand how the MJO07-08 interacts with the NGH during the blocking stage. However, we are still lack of an in-depth understanding of how the mechanical and thermal forcing of the MJO07-08 interacts with the NGH during the splitting stage. Given that MJO07-08 passed through a blocking stage after interacting with the northwest (NW) corner of the NGH, we would like to investigate further the orographic impacts on the convective system associated with MJO07-08, including orographic initiation of new convection and enhancement of existing convection, on the NW NGH during the splitting stage. The orographic forcing on the incoming airstream is highly dependent on the mountain and incoming flow's detailed characteristics, such as mountain height, width (in both along or perpendicular to the airstream), basic flow speed and direction, buoyancy (Brunt-Vaisala) frequency, geometry, etc., [15]. To understand the orographic modifications on rainfall on the NW area of New Guinea, we will take the ingredient approach (Eq. (8) of Lin et al. [14]) to investigate how the ingredients are affected during the splitting stage.

Following Lin et al. [15] and RL24 (denoted as RL24 or Part II), we will try to identify key ingredients responsible for producing orographic rainfall, from the following common ingredients: (1) strong orographic lifting due to the steepness of the NGH, (2) conditional instability due to a large amount of convective available potential energy (CAPE), (3) very high-water vapor mixing ratio, (4) strong environmental vertical motion, (5) large convective system, and (6) a slow-moving MJO system. We aim to study these orographic ingredients during the splitting stage to see if they are like the ingredients in the blocking stage defined in Sec. 3 of this extended study.

In addition, we will compare the results obtained during the splitting stage with those obtained during the blocking stage to determine whether there are any significant differences in the orographic impacts on the MJO07-08 rainfall in the NW area of the NGH. In Sec. 4, we will draw conclusions from our study and discuss their implications for future research. Overall, our study aims to provide a better understanding of the orographic impacts on the convective system and rainfall associated with the MJO07-08 passing over the NW corner of the NGH during the splitting stage. By investigating the mechanical and diurnal thermal forcing associated with the orography on MJO, the modifications of orographic rain associated with MJO passing over the NGH, and the ingredients of orographic rainfall on the NW area of the NGH, our study will contribute to the broader field of atmospheric science and help improve our ability to forecast and mitigate the impacts of extreme weather events.

2. NUMERICAL MODEL DESCRIPTION AND EXPERIMENTAL DESIGN

The WRF model version 3.9.1 [16] is adopted for making numerical simulations of MJO07-08 passing over the NGH. The WRF model is a three-dimensional, nonhydrostatic, fully compressible model that uses terrain-following vertical coordinates with stretched grid resolution. The governing equations of the WRF model are written in flux-form with conserved mass and dry entropy. Thus, the WRF model provides a flexible and robust platform for operational forecasting while offering more options in the advanced scheme in physics parameterizations and numerical methods, including data assimilation techniques. Details of the model are given in Skamarock et al. [16].

Simulation of the control case (CNTL) conducted in this study is very similar to that in Parts I [1] and II (RL24). There is only one domain used for all the simulations, which includes the island of New Guinea and its surrounding oceans, as shown in Fig. 1 of Part II, which expands from (122ºE, -15ºS) at the southwest corner to (162ºE, 2ºN) at the northeast corner. The domain contains 887 x 376 horizontal grid points with 5 km horizontal grid resolution and 32 vertically stretched grid levels. The time interval is 30 s. The physics parameterization schemes selected for the simulations are summarized in Table 1.

The first sensitivity test is with the mountain removed (NoMT), which will be used to investigate how the mechanical forcing of the complex terrain of the NGH affects MJO07-08 propagation and rainfall after it has been weakened during the blocking stage and begins to split around the NGH. This test will show the MJO's response to the absence of the mechanical forcing of the NGH during the splitting stage. The second sensitivity test is with the diurnal heating and cooling deactivated (NoHT), which will be used to study the impacts of diurnal heating and cooling on the MJO as it propagates over the NGH. This test will investigate the sea and land breeze's interaction with the MJO07-08 during the splitting stage and help determine which forcing is more dominant impact on the MJO system propagating over the island. The final sensitivity test is to deactivate the diurnal heating and remove the mountain (NMNH), which will explore the flow behavior under no mechanical and thermal forcings during the propagation of the MJO over the NGH. This sensitivity test will allow us to see how much the mechanical and thermal forcing of the NGH affects the structure and rainfall associated with the MJO07-08.

Table 1. Parameterization schemes used for physical processes

Physical Process	Parameterization Scheme
Cumulus Convection	Grell 3D Scheme
Microphysics	WSM6
Planetary boundary layer	YSU
Longwave radiation	RRTM
Shortwave radiation	RRTMG

Overall, these sensitivity tests will provide valuable insights into the mechanisms of the MJO's interactions with the NGH and how the mechanical and thermal forcing of the NGH impacts the MJO's behavior during its propagation. The results of these numerical experiments will contribute to a better understanding of the MJO's role in the global climate system and improve our ability to predict and prepare for weather patterns and precipitation associated with the MJO's propagation. These sensitivity experiments and their key characteristics are summarized in Table 2.

Table 2. The control and all sensitivity cases performed in this study

Case	Key Changes
CNTL	Same as the CNTL case of Part II (RL24, or Riley and Lin, 2024), with SST updated every 6h and initialized with the ERA-Interim data.
NoMT	Same as the CNTL case, but domain are all the mountains removed.
NoHT	Same the CNTL case, but with diurnal heating/cooling deactivated.
NMNH	Same as CNTL but with all the mountains removed and diurnal heating/cooling deactivated.

3. RESULTS

3.1 Mechanical and Thermal Forcing during the Splitting Stage

3.1.1 With both orographic blocking and Diurnal heating (CNTL Case)

As discussed in Part II (RL24), two forcings affecting the eastward propagation and rainfall of the MJO07-08 as it passes over the NGH are mechanical and thermal forcings. The mechanical forcing is caused by the complex terrain of the NGH; during the blocking stage most of the orographic rainfall is produced as the MJO07-08 is blocked by the NGH mountains, and the thermal forcing is caused by the diurnal heating or cooling associated with the island of New Guinea on the southeastward incoming airflow. During the blocking stage, the thermal forcing does not have a huge impact on the blocking of the MJO07-08 but does help producing orographic rainfall over the NGH. Based on the sensitivity tests of WRF-simulated fields, RL24 found that the orographic blocking plays a larger role than the diurnal heating or cooling on the modification of MJO-rain during the blocking stage. However, it remains to be investigated whether the finding of Part II (RL24) is applicable during the splitting stage of MJO07-08. To answer this question, we will look at the heating or cooling rate, surface temperature, moisture flux convergence, and precipitation for the sensitivity test during the splitting stage.

To further investigate the interaction between MJO07-08 and NGH during the splitting stage, we conducted a thorough analysis of the CNTL case. Our aim was to establish a baseline of the mesoscale environment during this critical period. Specifically, we focused on the times between 12/31/07L (12/30/21Z) and 01/01/04L (12/31/18Z), which marked the onset of the MJO07-08 splitting around NGH. Note that L and Z denote the local time and UTC, respectively, with L = UTC + 10h. To ensure the accuracy of our simulation, we analyzed the surface temperature and heating and cooling rate during this period. Fig. 1 shows the horizontal flow and temperature fields near the surface at 2 m height, which indicates that the land was cooler than the surrounding ocean during the early morning hours. This resulted in cooler air moving down the NGH and off the island's coast. The land breeze interacted with the northwesterly wind that had split around NGH, creating a complex mesoscale environment.

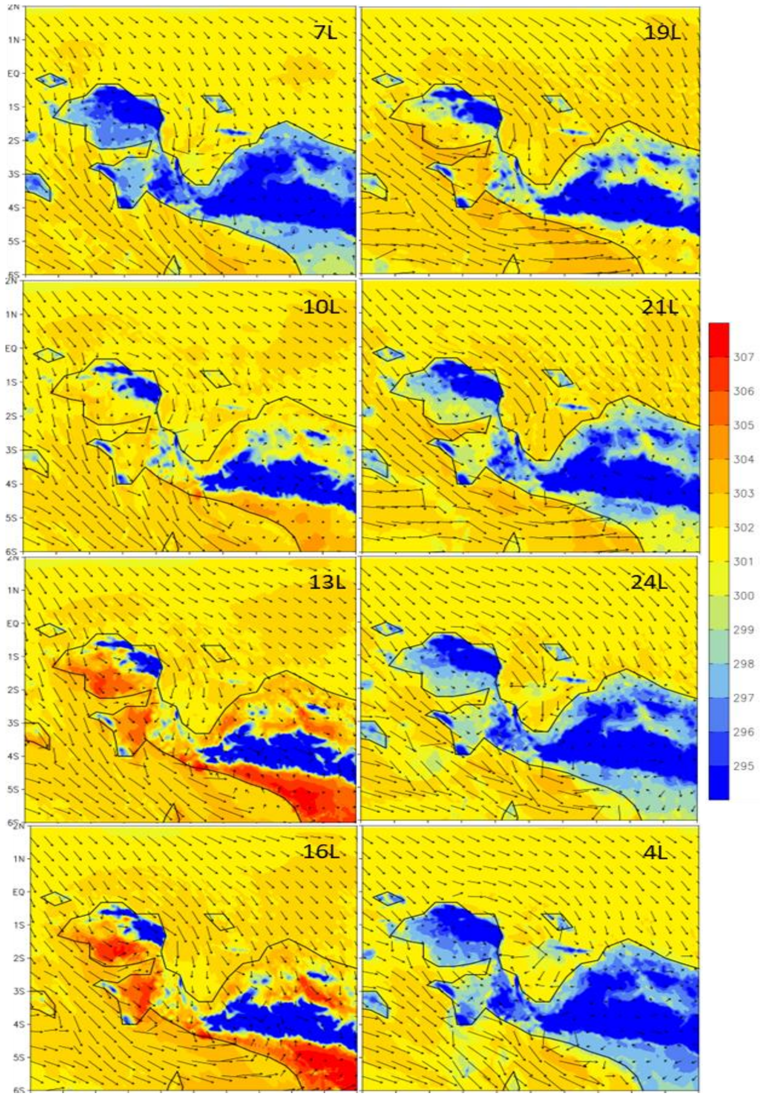

Fig. 1. [CNTL] Near-surface (2 m) temperature (*K*) and horizontal wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z), where Z and L denote UTC and local times, respectively, and L = UTC+10h

As time progressed, the land began to warm up, and the cooler winds coming off the coast of the island were replaced by cooler winds from the ocean surrounding the island. This transition from land to sea breeze was evident in the heating and cooling rate plots (Fig. 2) during the same period. We observed significant heating during the early morning hours, corresponding to the strongest land breeze at 7L. As time progressed, the heating decreased, and the cooling increased, marking the transition to the sea breeze, which peaked around 16L.

Overall, our analysis of the CNTL case provides a valuable baseline for understanding the complex mesoscale environment during the interaction between MJO07-08 and NGH in the splitting stage. By examining the surface temperature, heating and cooling rate, and winds, we were able to confirm the presence of land and sea breeze in the mesoscale environment and establish a clearer understanding of the complex interaction between the wind field and diurnal surface heating and cooling.

This transition between sea and land breezes can be seen from the vector wind fields associated with the MJO07-08 convective system in both Figs. 1 and 2. From the vector wind fields, we can see the flow of the land breeze as it moves away from the island. However, the flow from the land breeze is weaker than the surrounding flow that is splitting around the New Guinea island. This is compared to the incoming sea breeze in the later hours, which is associated with the northwesterly flow that the MJO07-08 is following and is splitting around the NGH.

Comparing the moisture flux (Fig. 3) during the same period, we can see that during the early morning and late evening in the splitting stage, a significant amount of moisture flux is generated in the environment located between the peninsula and the main island of New Guinea. This is due to two factors occurring in this area. First, the incoming northwesterly flow has split due to the complex terrain of the island, colliding with the land breeze flowing off the coast, creating a lot of convergence and leading to potential precipitation production. Second, the incoming flow is interacting with the complex terrain of the NGH, and during this time, the moisture flux is closer to the coast and the NGH, producing rainfall along the NGH. This indicates that the thermal forcing of the island may play a more significant role in the splitting of the MJO07-08 compared to the mechanical forcing of the NGH during the splitting stage.

From the precipitation distribution during this period (Fig. 4), there are two distinct periods of high rainfall. The first period occurs when the incoming flow interacts with the land breeze coming from the island, resulting in most of the rainfall associated with MJO07-08 being in the gulf between the peninsula and the main island or along the coast of the island. This can also be seen in Fig. 3, where the precipitation is located concerning the moisture flux in the same area. The second period occurs when the incoming flow and the sea breeze interact with the NGH, producing most of the rainfall along the coast and the NGH. This can also be seen by comparing the precipitation locations to the location of moisture flux in Fig. 3. While more rainfall is off the coast when the flow and land breeze collide with each other, there is a larger amount of precipitation when the flow and sea breeze both interact with the complex terrain. Therefore, thermal forcing may be helping with the splitting of the MJO07-08 during the earlier and night hours when the land breeze is present and mechanical forcing is enhancing rainfall production during the later evening hours when the sea breeze is present.

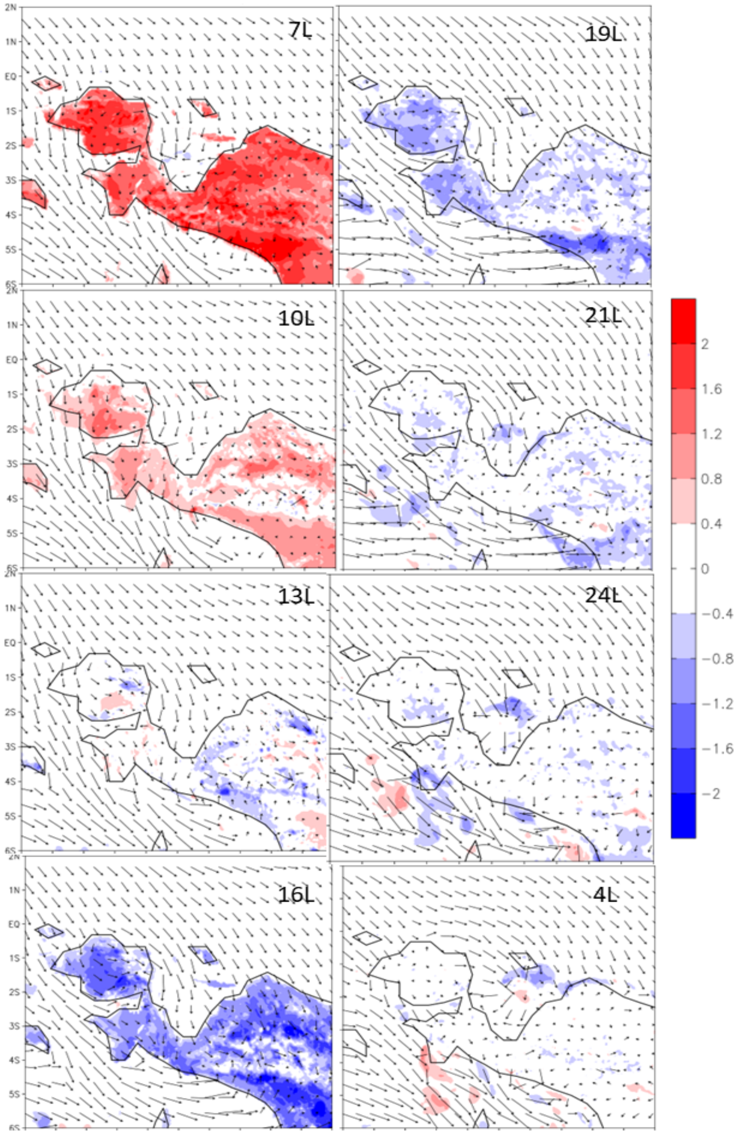

Fig. 2. [CNTL] Diurnal heating rate and surface (2-m height) wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z), where Z and L denote UTC and local times, respectively

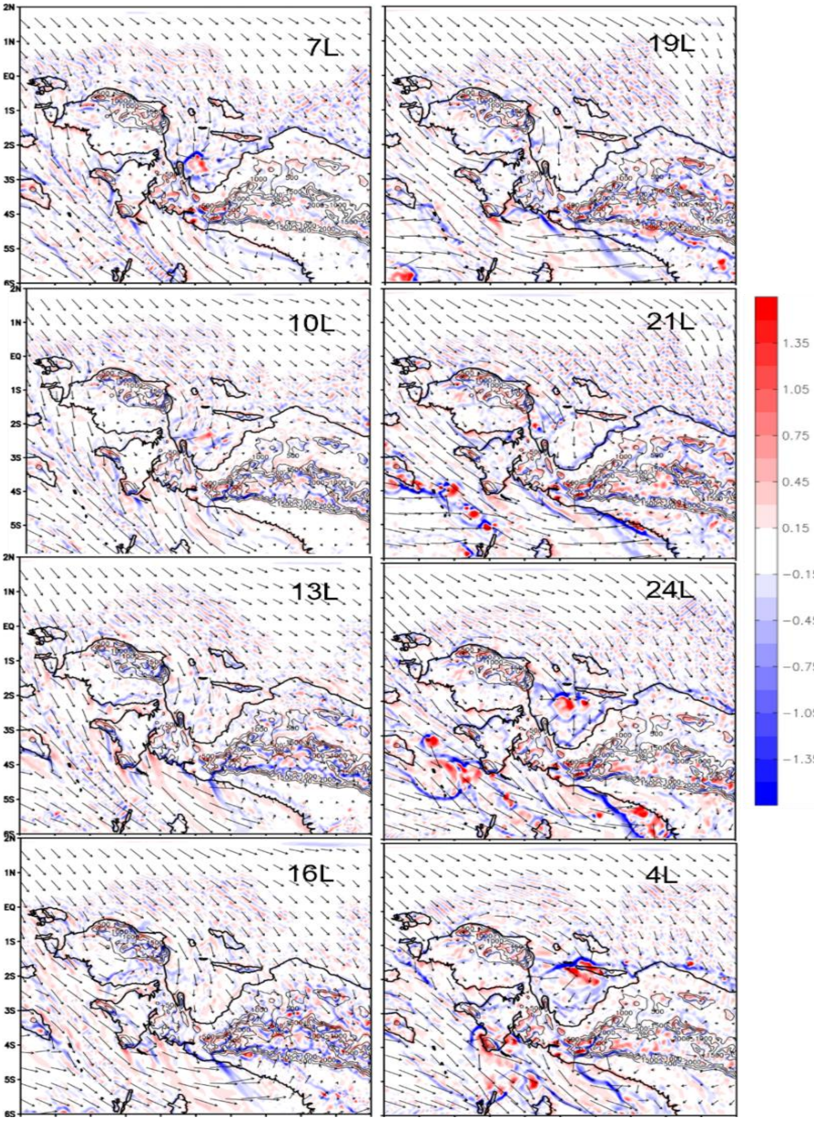

Fig. 3. [CNTL] Moisture flux convergence and surface wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

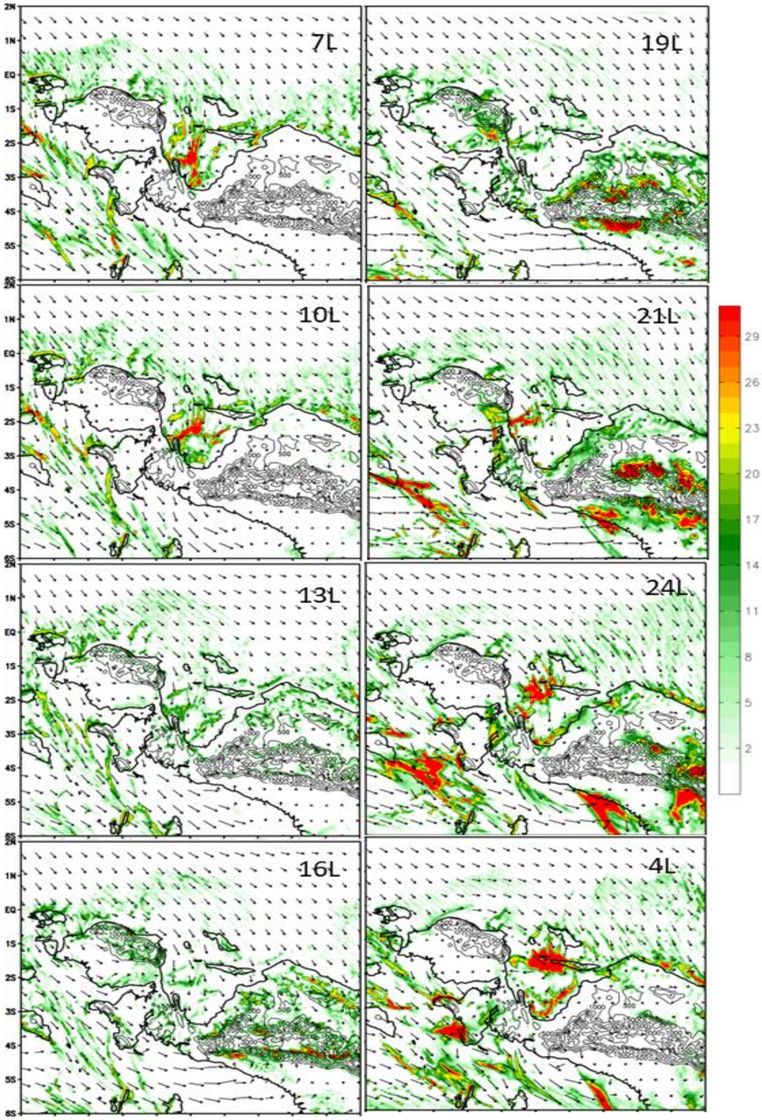

Fig. 4. [CNTL] The 3-h precipitation and horizontal wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

3.1.2 No Diurnal heating case (NoHT)

The impact of diurnal heating on rainfall production during the splitting stage of MJO07-08 is significant. To examine the effect of diurnal heating from the mesoscale environment on MJO07-08, we conducted simulations with the diurnal heating turned off. We verified the absence of diurnal heating by analyzing the surface temperature plots (Fig. 5) and observing that the temperature of the island remains constant and much cooler than the surrounding ocean water. The absence of diurnal heating implies that the temperature over the land remains mostly cooler than the surrounding ocean water, and incoming flow does not interact with any thermal forcings present in the case.

Fig. 5 shows the surface temperature plots for both the CNTL case and the simulation with diurnal heating turned off. The CNTL case shows a clear land-sea breeze interaction with the land heating up during the day and cooling down at night, creating a barrier around the island that affects the flow of the MJO07-08. In contrast, the simulation with diurnal heating turned off shows a constant temperature over the land, indicating the absence of diurnal heating and the land-sea breeze interaction.

With the diurnal heating turned off, we observed the disappearance of the land breeze in the earlier parts of the morning, and the presence of a weak sea breeze due to the warmer ocean water surrounding the island. However, there was little to no barrier present compared to the CNTL, as seen in the moisture flux results (Fig. 6) for the NoHT case. Fig. 6 shows the moisture flux for both the CNTL case and the NoHT case. The CNTL case shows a strong barrier around the island, while the NoHT case shows little to no barrier, indicating the absence of diurnal heating.

The moisture flux was mainly present along the complex terrain of the NGH or farther off the coast, suggesting that the barrier around the island could be a combination of the forcing interacting with the MJO07-08 and the complex terrain of the NGH. Analysis of precipitation (Fig. 7) revealed a reduction in the amount of rainfall along the coast of the island and a decrease in orographic rain along the NGH in the NoHT case. Fig. 7 shows the precipitation analysis for both the ~~case~~ CNTL and NoHT cases. The CNTL case shows significant rainfall production along the southern part of the island due to the land-sea breeze interaction, while the NoHT case shows little to no rainfall along the coast of the island and a decrease in orographic rain along the NGH.

Despite the reduction in rainfall, the flow of the MJO07-08 still splits around the island, which suggests that the splitting is primarily caused by the flow of MJO07-08 interacting with the complex terrain of the NGH. These results suggest that diurnal heating plays a significant role in the production of rainfall during the splitting stage of MJO07-08, and the complex terrain of the NGH also plays a significant role in the splitting of MJO07-08.

3.1.3 No orographic blocking (NoMT Case)

Mechanical blocking associated with NGH mountains is an important aspect of atmospheric processes that we need to consider when studying the impact of complex terrain on weather patterns. When air flows over a mountain range, it experiences changes in pressure, temperature, and humidity, leading to complex wind patterns and precipitation distribution on both sides of the mountain. This phenomenon is known as the orographic effect, which can significantly influence the local climate and weather patterns. In the case of the NGH, its complex terrain and height can lead to orographic lifting of air, which can result in enhanced precipitation and cloud formation on its windward side. On the other hand, the leeward side of the mountain can experience a rain shadow effect, which can lead to drier conditions and reduced precipitation. Therefore, understanding the role of orographic effects in the interaction between the MJO07-08 and the NGH is crucial for accurately predicting weather patterns and associated impacts on local communities. Our simulation results provide a starting point for investigating the impact of the NGH on the MJO during the splitting stage, and future research can further explore the role of orographic effects in other stages of the MJO and other weather patterns.

To check to see if the mechanical forcing from the complex terrain of NGH on the MJO07-08 during the splitting stage, we decided to run a simulation but remove the NGH from the island. This simulation should remove most if not all the mechanical forcing that is present in the simulation. When comparing the heating/cooling (Fig. 8) rate to the other simulations, we see that the transition from land to sea breeze is still present in the NoMT case. However, because the flow of the MJO07-08 is no longer interacting with the complex terrain of the NGH, the land breeze that is seen in the earlier hours of the morning is a lot stronger than the sea breeze that is seen in the late hours of the day. Even though Fig. 8 shows that there is a much larger difference in the amount of cooling in the NoMT case compared to the CNTL case.

The near-surface temperature plots of Fig. 9 reveal an interesting phenomenon. It appears that the removal of the NGH causes the island to cool down slower during the day compared to the CNTL simulation. This could be the reason why the land breeze is stronger, and the sea breeze is weaker in the NoMT simulation. With the absence of mechanical forcing from the NGH, the flow of the MJO07-08 passes over the island without any complications. This suggests that the thermal forcing associated with the land and sea breeze is not entirely strong enough to block the MJO07-08 itself.

To further support this observation, we can turn to the precipitation plots (Fig. 10), which show the rainfall associated with MJO07-08 propagated with the flow of MJO07-08 without any complications from the island. This implies that MJO07-08 can propagate through the island with ease despite the presence or absence of mechanical forcing from the NGH. Therefore, the influence of the NGH on the MJO07-08 appears to be relatively minimal during the splitting stage. However, it's important to note that the role of the NGH in other stages of the MJO07-08 still requires further investigation. Overall, our simulations provide valuable insights into the complex interactions between the MJO07-08 and the NGH, highlighting the need for more detailed studies to improve our understanding of the role of terrain in the atmospheric processes.

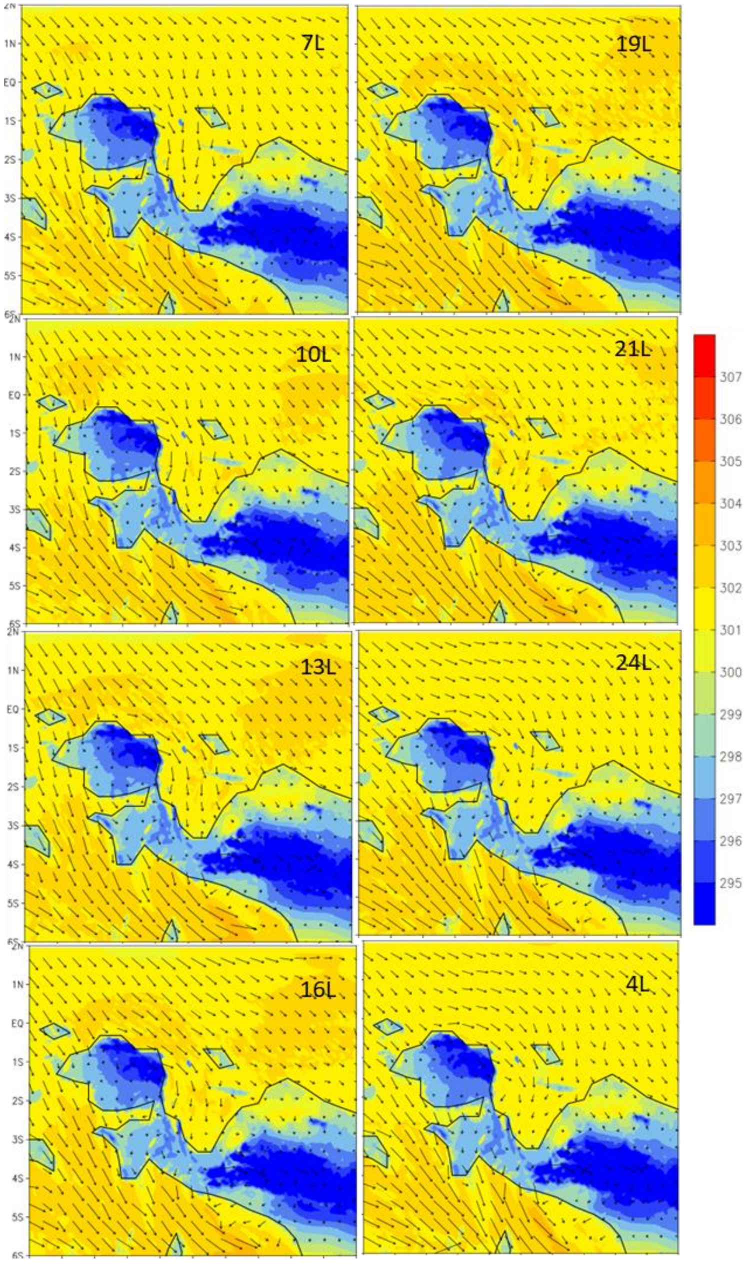

Fig. 5. [NoHT] Surface temperature (K) and horizontal wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

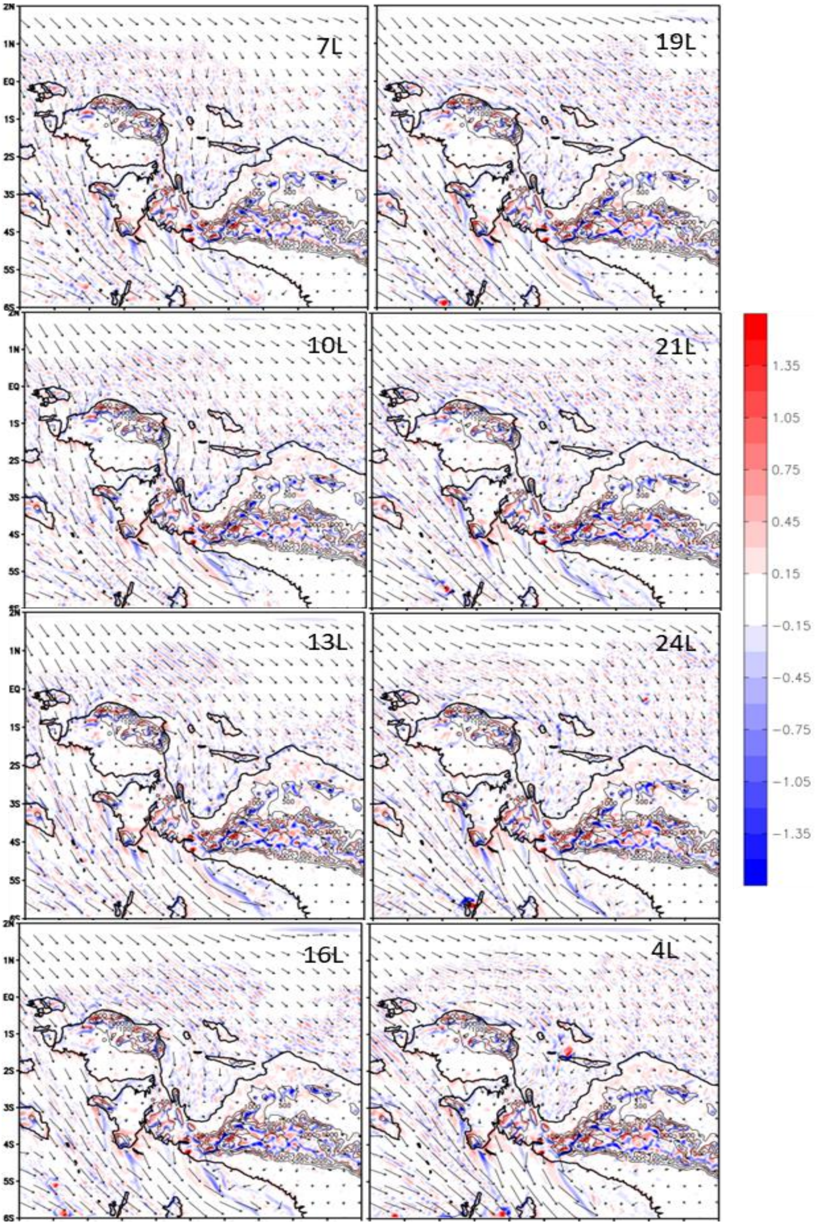

Fig. 6. [NoHT] Moisture flux and horizontal wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

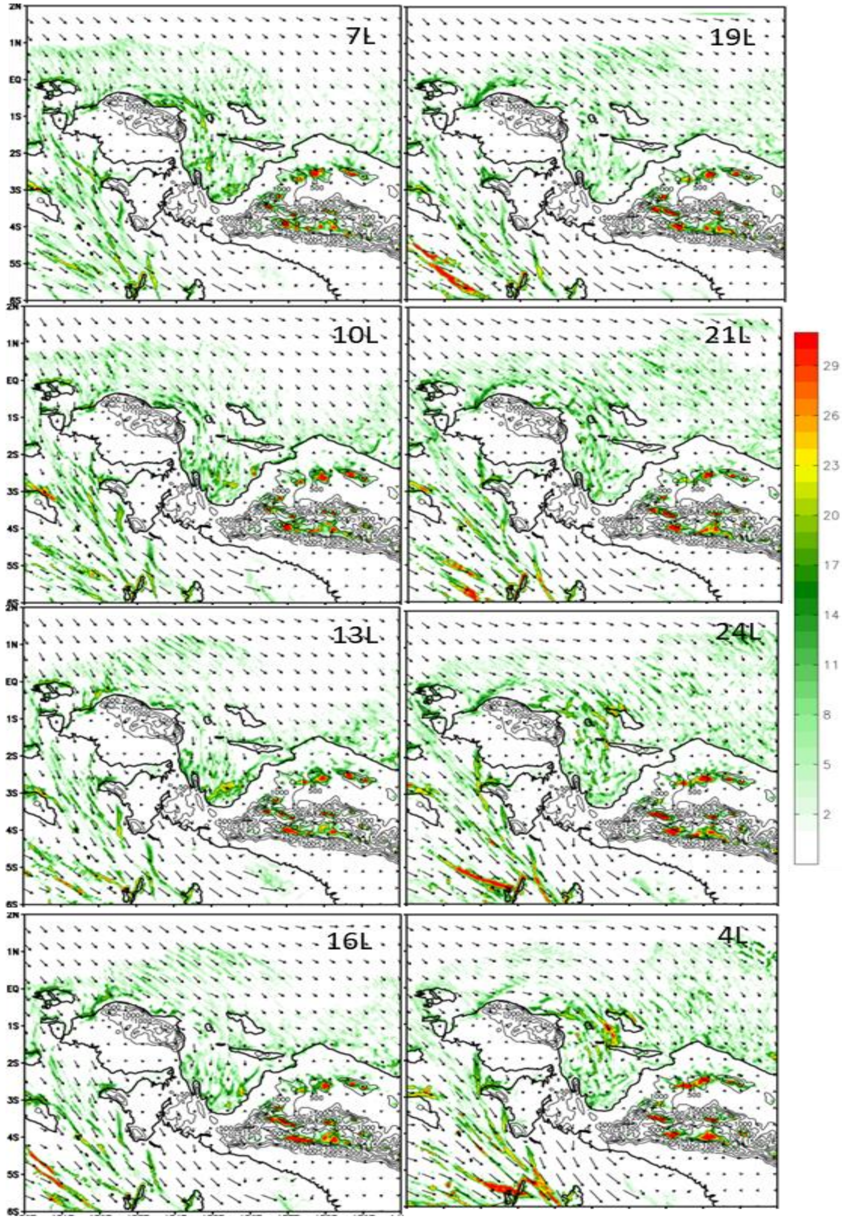

Fig. 7. [NoHT] The 3-h precipitation and horizontal wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

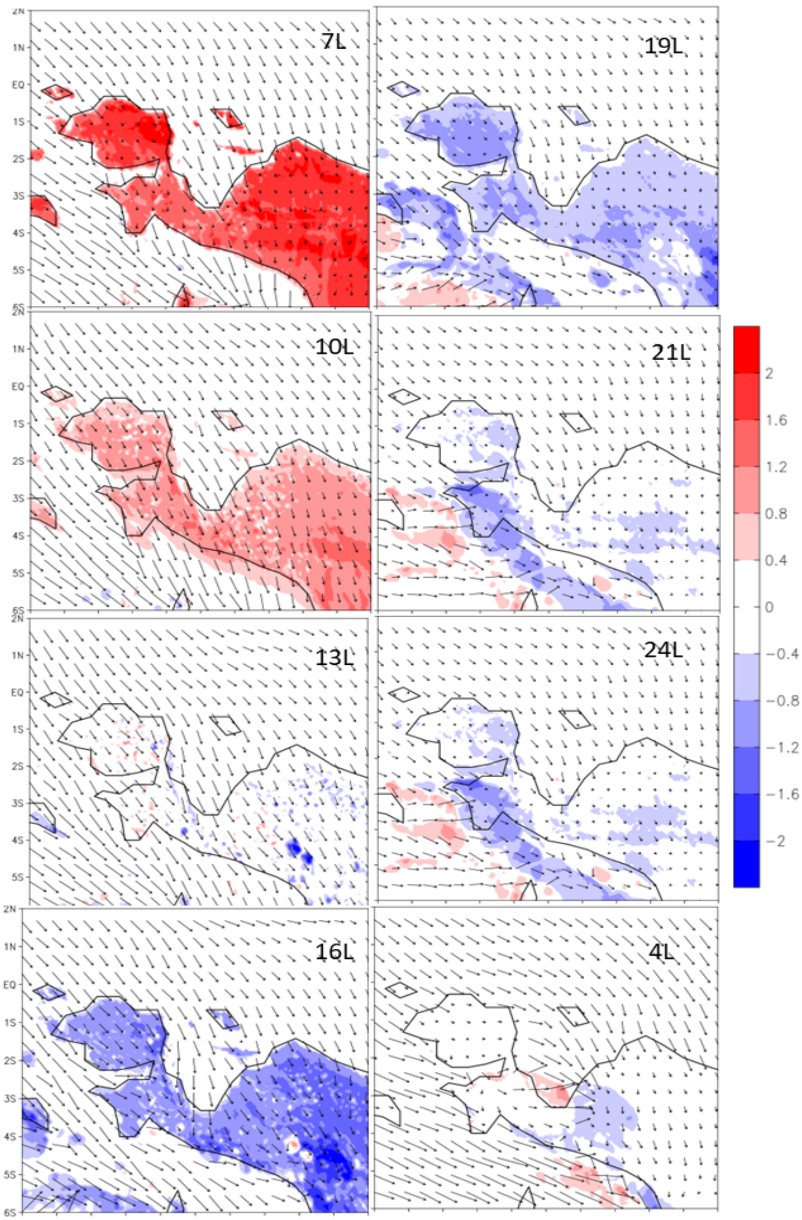

Fig. 8. [NoHT] Diurnal heating and surface wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z). Similar to Fig. 2 except for NoMT case

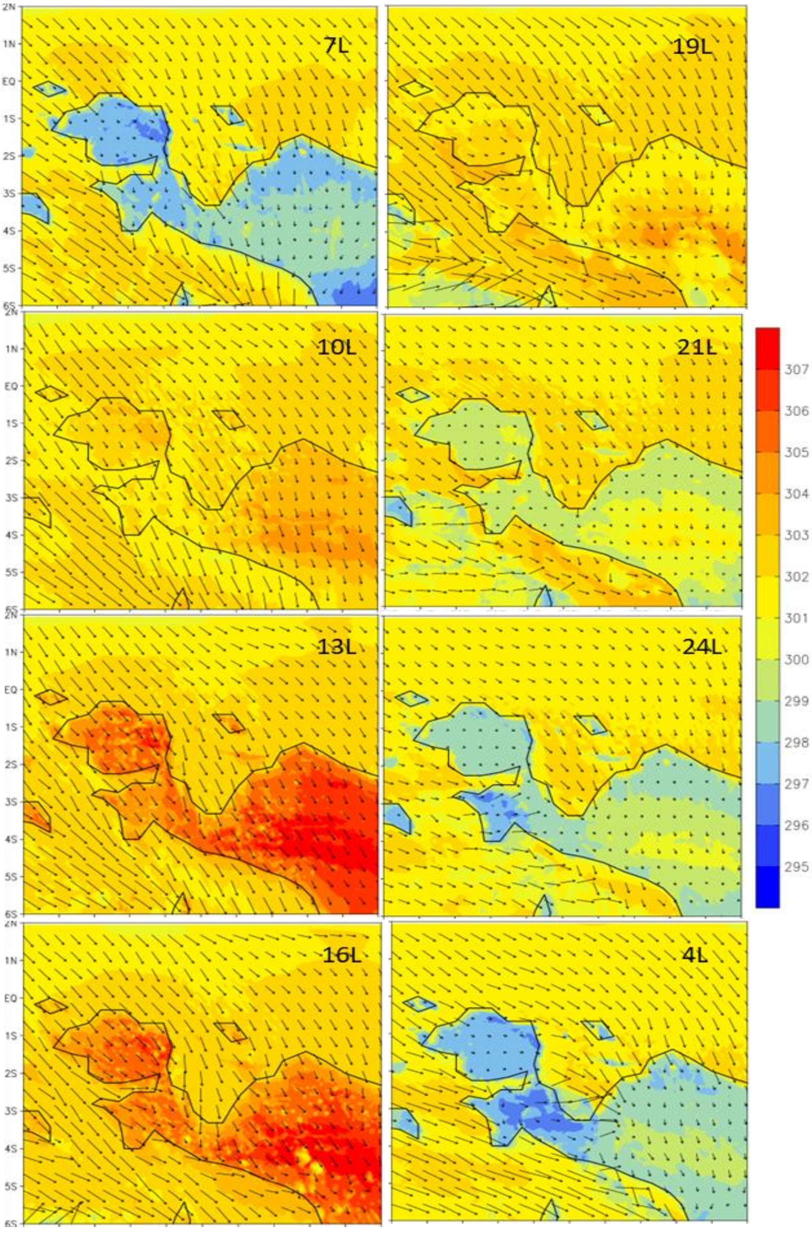

Fig. 9. [NoMT] Near-surface (2 m height) temperature (K) and horizontal wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

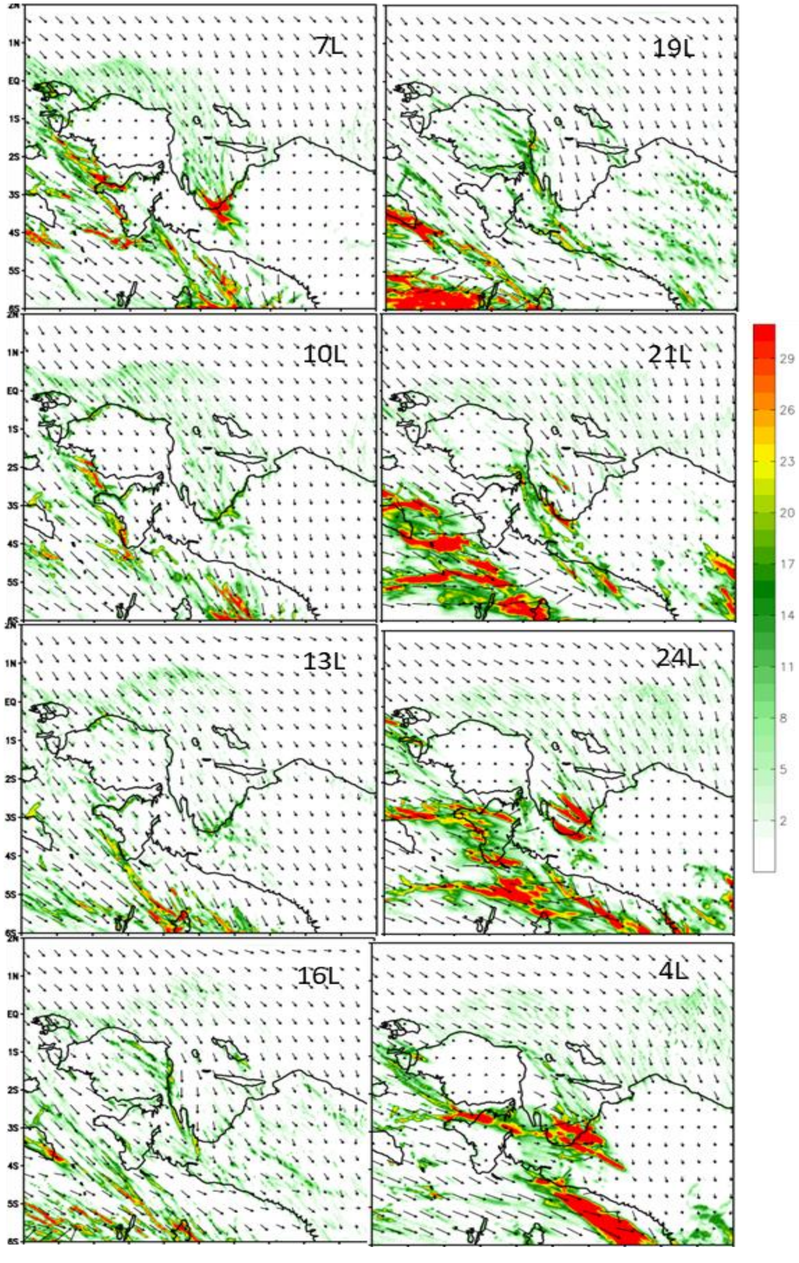

Fig. 10. [NoMT] The 3-h precipitation and horizontal wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

3.2 Orographic Rainfall Ingredients During the Splitting Stage

Part II (RL24) discussed the orographic ingredients associated with the MJO07-08, during the blocking stage as it propagates over the NGH. We found that the orographic ingredients associated with the MJO07-08 event are (1) strong w_{oro} (orographically induced vertical motion) due to the steepness of the NGH, (2) conditional instability due to a large amount of CAPE, (3) very high-water vapor mixing ratio, (4) strong w_{env} (environmentally induced vertical motion), (5) large convective system and, (6) a slow-moving MJO system. However, we did not investigate how the ingredients for orographic rainfall were impacted by the barrier effect of the NGH. To understand the production of orographic rainfall, we must study how the orographic ingredients are enhanced or reduced as the MJO07-08 moves into the splitting stage.

When looking at the vertical motion associated with the MJO event, we need to investigate how the splitting stage affects both the w_{oro} and w_{env}. It is found that both w_{oro} and w_{env} are important ingredients in the production of orographic rainfall *(e.g.,* Lin et al., [14]; Rostom and Lin, [17]; RL24). We also found that the w_{env} had a larger significance to the production of orographic rain compared to the w_{oro}. To look at the impact the splitting stage has on the vertical motion necessary for orographic rain, we will be looking at the total w in the environment.

When looking at the total w for the CNTL case (Fig. 11), we can see that starting around 13Lthat there is a large amount of upward motion along the NGH. This upward motion is forming during the transition from land breeze to sea breeze. This large amount of upward motion is the w_{oro} that is important to the production of orographic rain and shows that we have strong orographic lifting associated with the NGH. Later during the period, when there is a transition from sea breeze to land breeze, we can observe that a large amount of upward motion moves off the coast of the island in the gulf between the peninsula and the main body of the island. During this transition, we would see the strong w_{env}, which is also necessary to produce orographic rain. This large amount of upward surrounds the island and creates a barrier along the coast. We can see the incoming flow split around the island and into an upward motion on both sides of the island.

We also see that there is still a large slow moving convective system during the splitting stage. However, instead of the MCS associated with the MJO07-08, we now see two convective systems that have formed and are moving around the island. The OLR (Fig. 12) shows how the two slow-moving convective systems follow the incoming flow that splits around the island. We can also see that part of the convective system that split off strengthens as it interacts more with the NGH.

Just like in the blocking stage (Figs. 13a and 13b), which has been studied in Part II (RL24), we still see the area with large amounts of CAPE (Fig. 13c and 13d) staying around the island. This would cause the conditional instability needed to produce orographic rain during the splitting. However, the level of CAPE has been weakened during the splitting stage, compared to the CAPE during the blocking stage. This could mean a reduction in the amount of orographic rain being produced. The same can be said for the water vapor ratio (Fig. 15) as well. During the splitting stage, we see an average amount of about 15 g/kg in the area. This is a reduction of the 20 g/kg that we see in the previous study. This would also lead to a reduction of orographic rain.

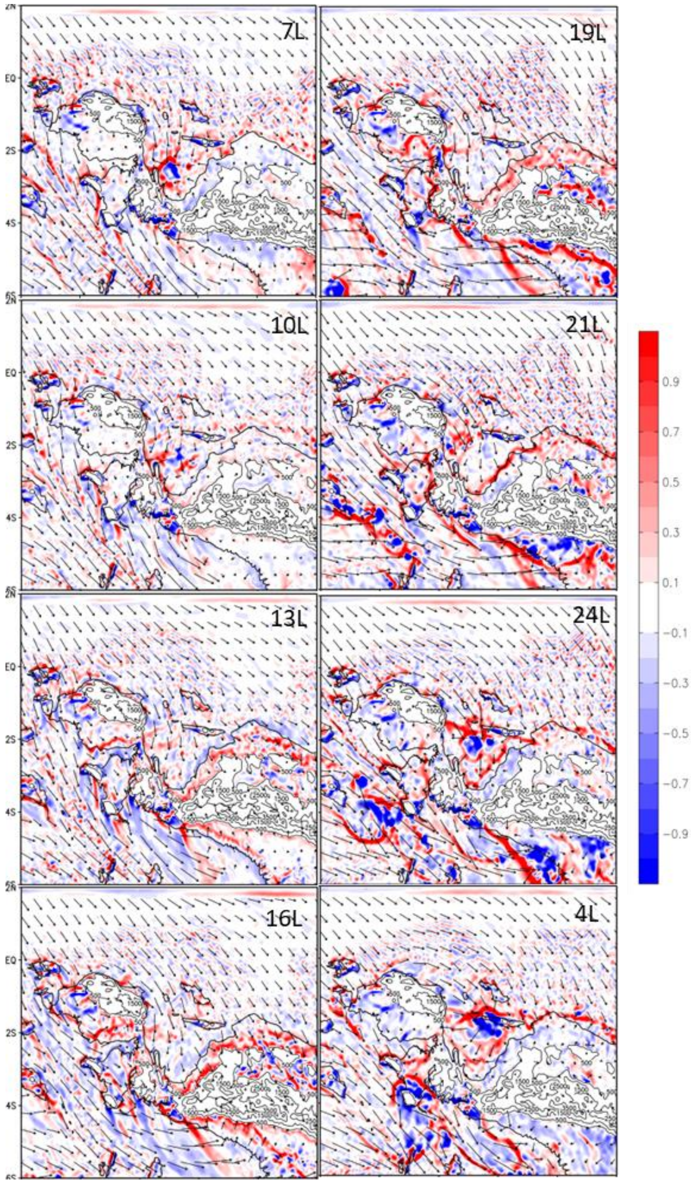

Fig. 11. [CNTL] Total vertical motion and horizontal wind fields during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

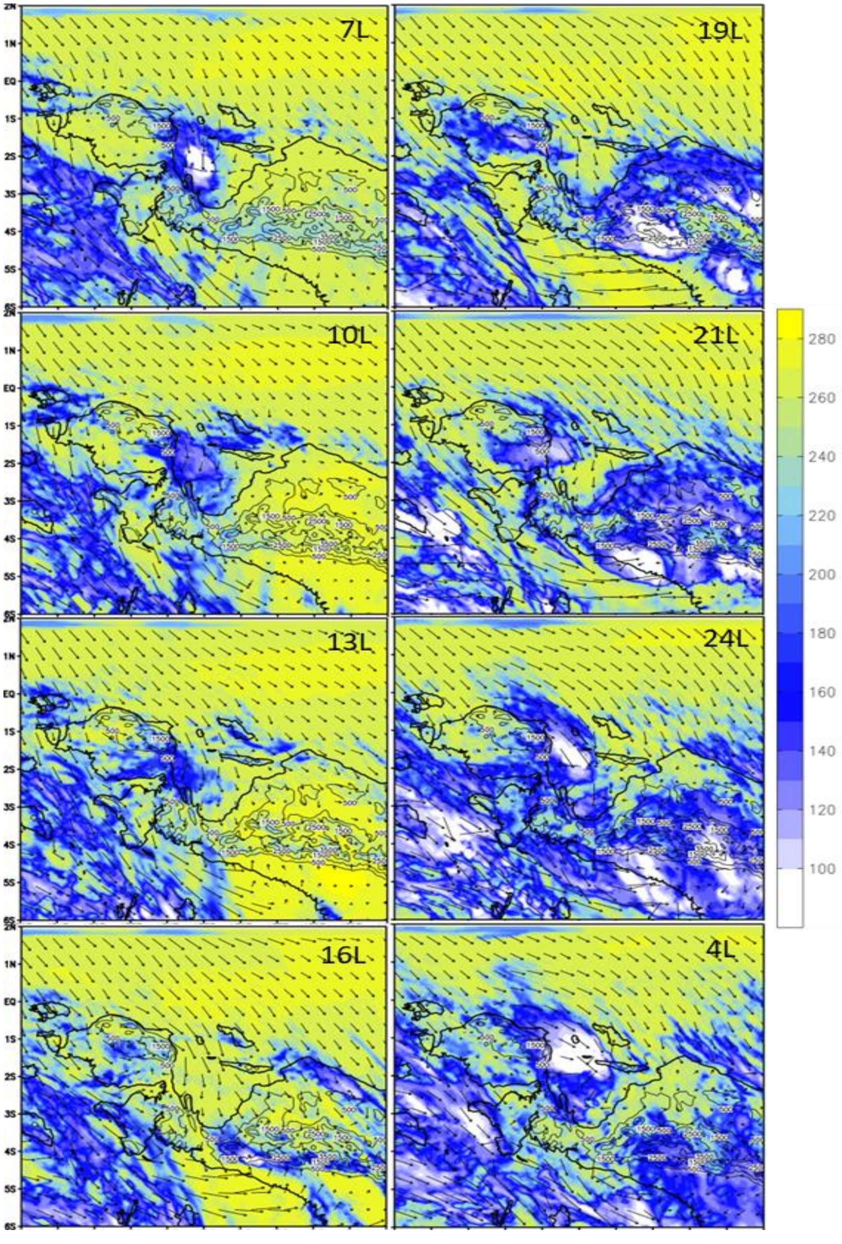

Fig. 12. [CNTL] Outgoing longwave radiation (OLR) and horizontal wind fields during the splitting stage from 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

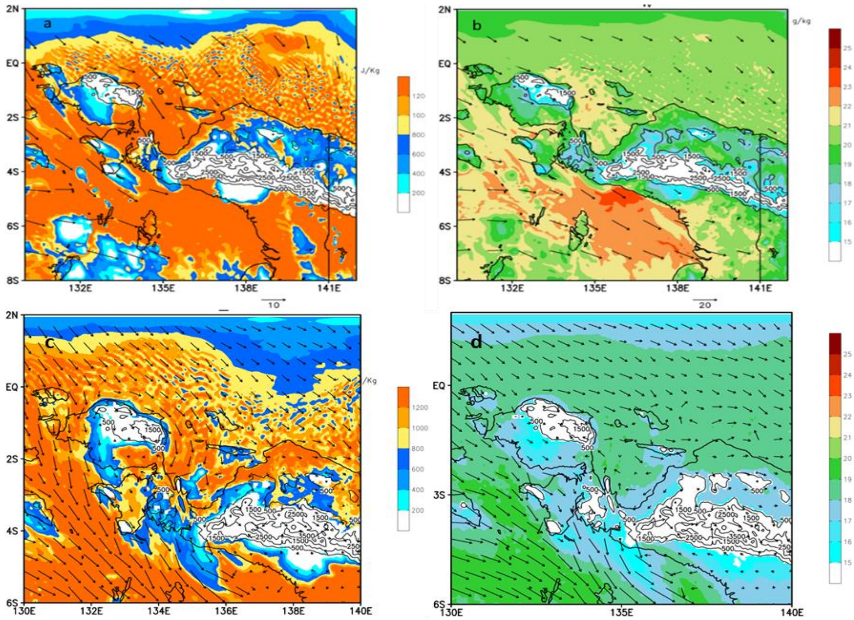

Fig. 1. [CNTL] (a)-(b): The sfc-850 hPa CAPE (in *J/kg*) and water vapor mixing ratio (q_v, in *g/kg*) during the blocking stage; (c)-(*d*): Same as (a)-(b) except during the splitting stage

Comparing the results from the NoMT and NoHT cases will help differentiate each of the forcings affecting the orographic ingredients during the splitting stage. If we compare the results of the NoMT case to the results of the CNTL case, we observe that there is indeed a reduction in the amount of w overall in the earlier hours of the day. We do see an increase in the overall *w* (Fig. 14) in the later part of the day, however, that is associated with the MJO07-08 propagating over the island without any complications, The thermal forcing of the island does have some effect on the propagation of the MJO event, but it is not a strong effect to completely block the propagation over the island. This is why we can see a large amount of rainfall passing over the island in Fig. 9 compared to the rainfall in Fig. 5, where most of the rainfall is spread along the NGH. The removal of the mechanical forcing means little to no orographic rainfall being produced, due to no w_{oro} present and the reduction of w_{env} because of the weakened land breeze off the island.

Just like the CNTL, the OLR of the NoMT case (Fig. 16) shows that there is still a massive convective system in the area which is necessary to produce orographic rain. However, compared to the CNTL case, there is only one convective system, since the MJO07-08 does not split during the splitting stage due to the removal of the mechanical forcing and the weakening of the thermal forcing. Also, because there is no complex terrain to slow the propagation of the MJO07-08, this means that the cs of the MJO07-08 is much faster in the NoMT case compared to the cs in the CNTL. This would mean that there would be a reduction in the amount of orographic rain being produced.

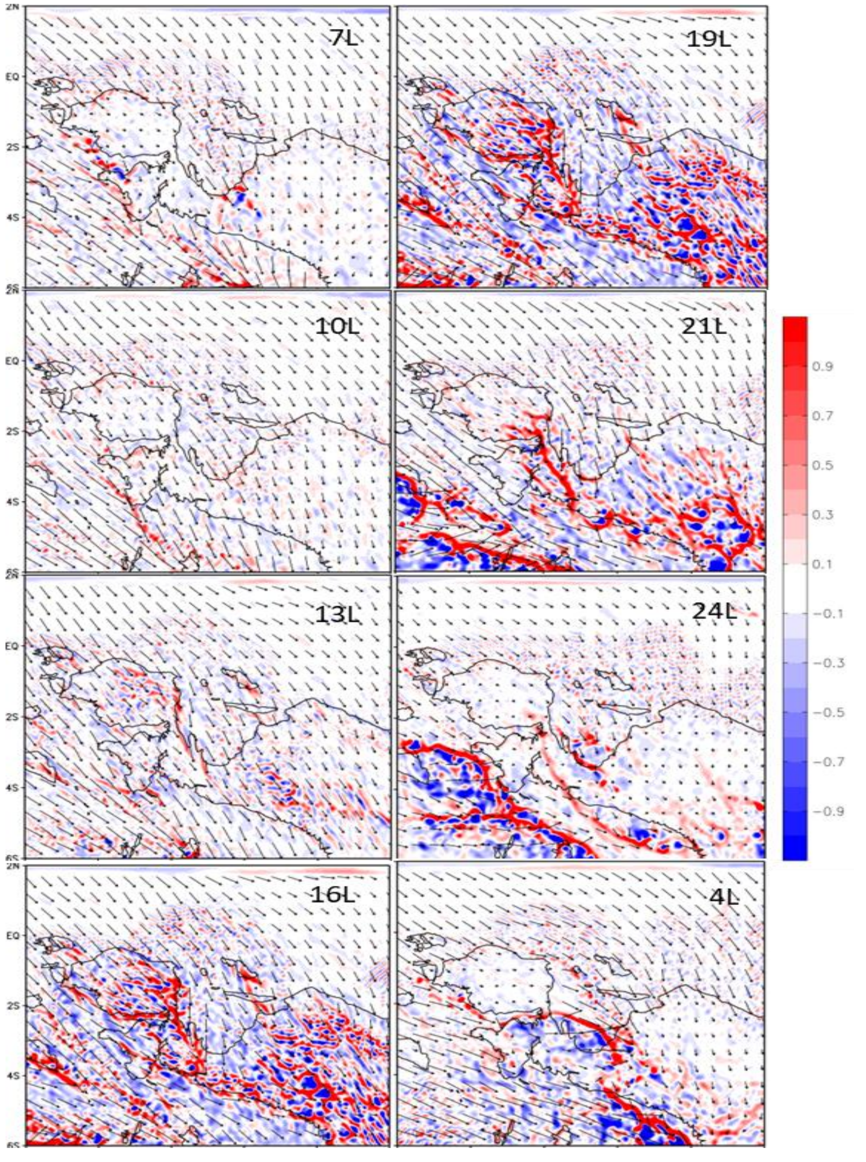

Fig. 14. [NoMT] Total vertical motion and horizontal wind fields for the case with mountains removed during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

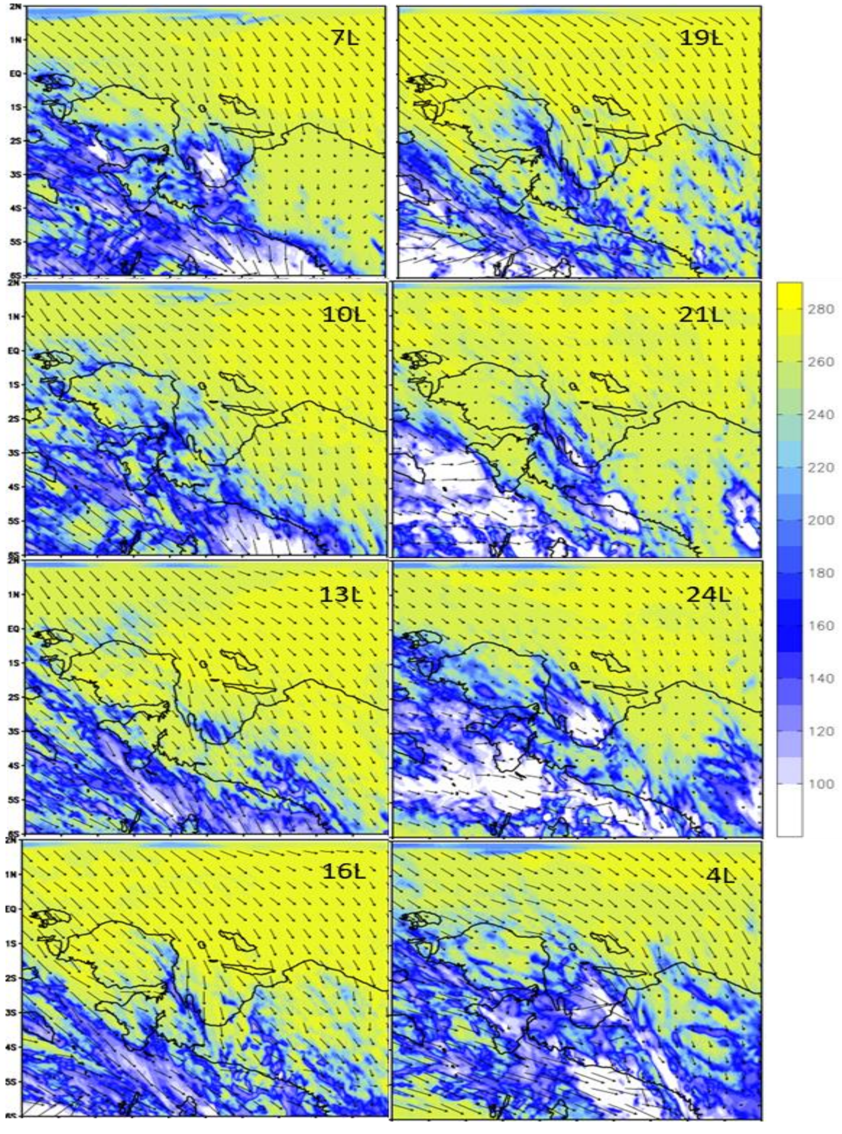

Fig. 15. [NoMT] Outgoing longwave radiation (OLR) and horizontal wind fields for the case with mountains removed during the splitting stage from 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

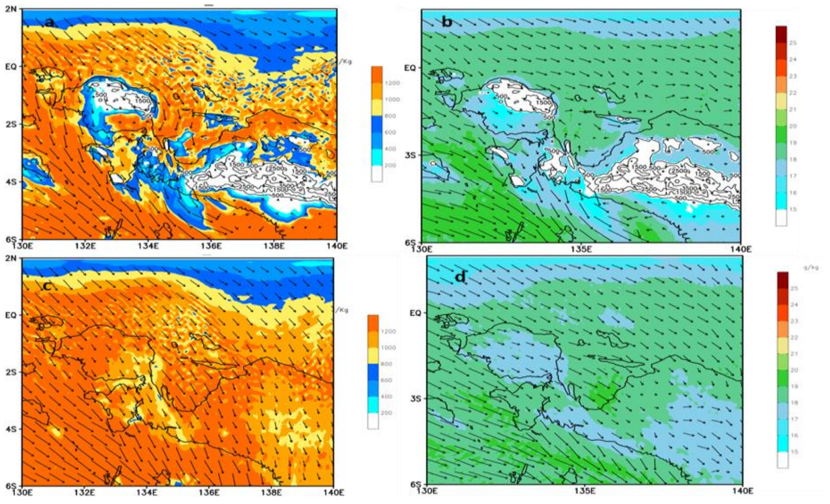

Fig. 16. (a)-(b): [CNTL] The sfc-850 hPa CAPE (in *J/kg*) and water vapor mixing ratio (q_v, in *g/kg*) during the blocking stage; (c)-(d): [NoMT] same as (a)-(b) except for the case with mountains removed. All of the fields are at the splitting stage

When looking at the CAPE (Fig. 17) in the NoMT case, we can see that there is a significant increase in the area compared to the amount of CAPE in the CNTL case. This is because the removal of the NGH has allowed the amount of CAPE to increase over the island itself. A large amount of CAPE is needed to produce orographic rain and the increase of CAPE over the land would mean an increase of orographic that is produced. The water vapor ratio (Fig. 15) is like the CNTL case, which had a reduction to what is seen during the blocking stage. Once again, the reduction in the water vapor ratio could mean a reduction in the production of orographic rain.

Finally, if we compare the results of the NoHT case to the results of the CNTL case, we observe that there is indeed another reduction in the amount of w (Fig. 18) in the area. This time, the reduction is for the entire period time during the Splitting stage. There is still enough upward motion to help with the splitting of MJO07-08 since then we do observe the flow split around the terrain of the NGH. However, there is a major reduction in the w_{env} and w_{oro} in the area. Which would mean little to no orographic production during the splitting stage in the NoHT.

Finally, when looking at the CAPE (Fig. 19) in the NoHT case, we can see that the NoHT case is like the CAPE in the CNTL case. However, when looking that the island itself, we can see lower levels of CAPE on the coast compared to the levels of CAPE along the coast in the CNTL case. This suggests, once again, little to no orographic rain production and confirms what we see in Fige 19. The water vapor ratio (not shown) also shows similar results to the CNTL case, but we do observe a lower number along the coast of the island and the NGH. These results also show how important thermal forcing is to the production of orographic rain during the splitting stage.

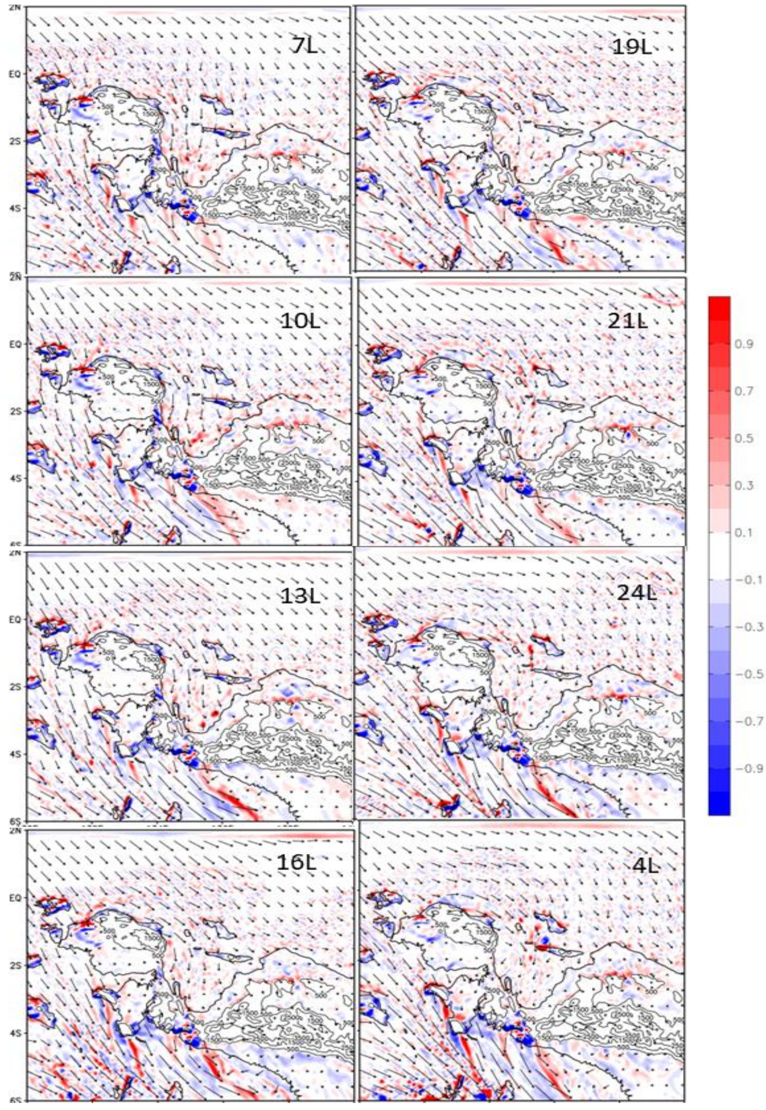

Fig. 17. [NoHT] Total vertical motion and horizontal wind fields for the case with no diurnal heating during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

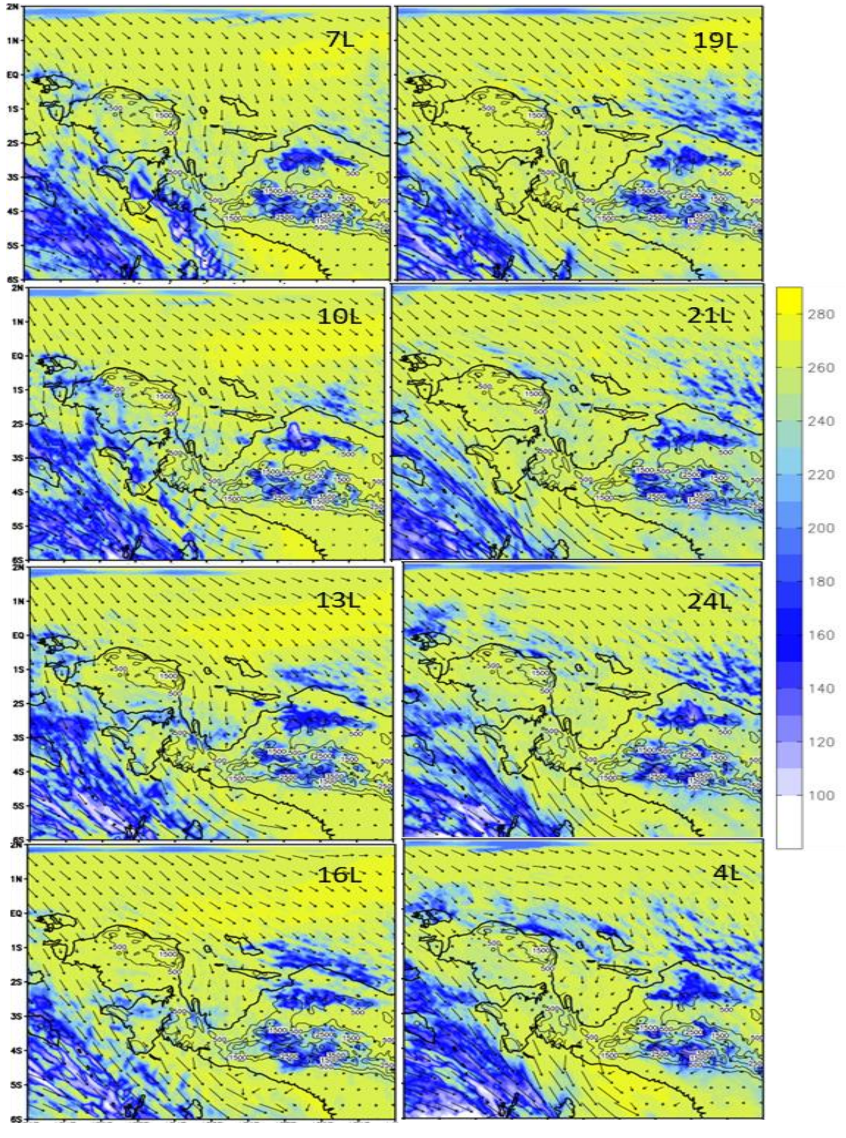

Fig. 18. [NoHT] Outgoing Longwave Radiation (OLR) fields for the case with no diurnal heating during the period of 12/31/07L (12/30/21Z) – 01/01/04L (12/31/18Z)

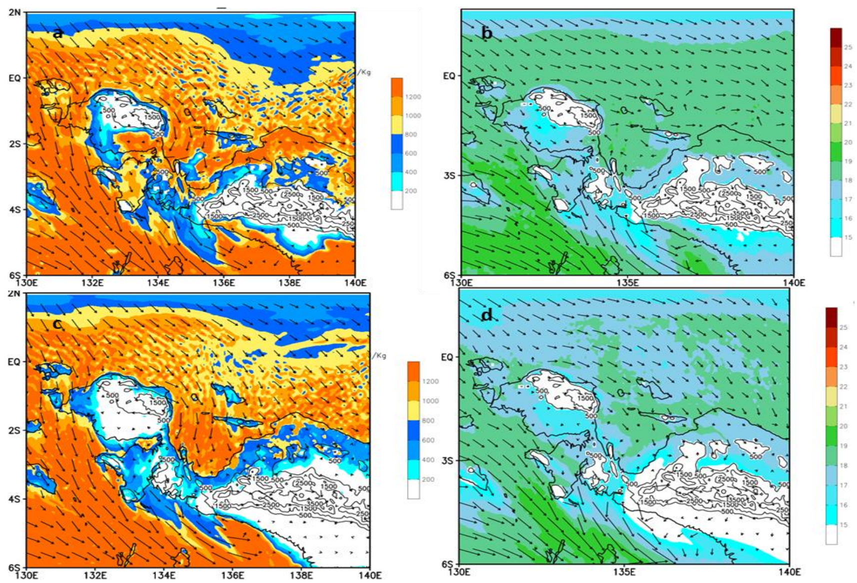

Fig. 19. (a)-(b): [CNTL] The sfc-850 hPa CAPE (in *J/kg*) and water vapor mixing ratio (q_v, in *g/kg*) during the blocking stage; (c)-(d): [NoHT] same as (a)-(b) except for the case with no diurnal heating. All of the fields are at the splitting stage

4. DISCUSSION AND CONCLUSION

In this part (Part III) of the research, we examined how the mechanical and thermal forcing plays in the splitting stage of the MJO07-08 passing over the NGH. The results from each of the cases show that both forces have a major impact on the splitting of the MJO07-08 during this stage. The thermal forcing of the NGH helps to enhance the moisture flux convergence near the coast and gulf of the island and helps enhance the production of orographic along the NGH and creates a barrier that helps with the splitting, due to the MJO's interaction with the land and sea breeze associated with the NGH and the island of New Guinea. The mechanical forcing is responsible for the blocking and splitting of the convective cells associated with the MJO event. As the flow interacts with the complex terrain of the NGH, the MJO07-08 weakens to the point where it splits and becomes two distinct cells. During the splitting stage, most of the rainfall however seems to be produced more by the thermal forcing instead of the mechanical forcing. This is different from the findings of RL24, where it was found that the mechanical forcing had a larger impact on the enhancement of the rainfall associated with MJO07-08.

Finally, in examining the key orographic ingredients during the splitting stage shows that the same ingredients we found in our previous studies (Parts I and II) are still playing the same roles, but the production of orographic rain is reduced during this stage. The reduction is due to the reduction in the size of the convective system as it is split into two cells, the reduced levels of CAPE compared to the levels of CAPE found during the blocking stage, the reduction of water vapor ratio along the coast, and NGH compared to the blocking stage, and finally the reduction of the w_{env} and w_{oro} in the area which is needed for orographic rain production. Also, we found that the thermal forcing also has a larger impact on the ingredients during the splitting stage, compared to the mechanical forcing at the same stage. This is completely different from the previous study, where we found that mechanical forcing had a larger impact on the ingredients during the blocking stage.

Further research is necessary to fully understand the interaction between diurnal heating, land-sea breeze interaction, and complex terrain and their impact on rainfall production during the splitting stage of MJO07-08.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

ACKNOWLEDGEMENTS

The authors would like to thank Drs. A. Mekonnen, J. Zhang, and L. Liu at North Carolina A&T State University for their comments on this research. This research was supported by the Title Fellowship and the NSF Awards 1900621 and 2022961. The supercomputing time awarded by the NCAR CISL (now NUSD) for their support of computing time on the Cheyenne supercomputer (Project No. UNCS0030) and ECMWF for using ERA-interim reanalysis data from the Copernicus EU data archive.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-Review History:
This chapter was reviewed by following the Advanced Open Peer Review policy. This chapter was thoroughly checked to prevent plagiarism. As per editorial policy, a minimum of two peer-reviewers reviewed the manuscript. After review and revision of the manuscript, the Book Editor approved the manuscript for final publication. Peer review comments, comments of the editor(s), etc. are available here: https://peerreviewarchive.com/review-history/1071