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ARTICLE

Role of Mid-Level Vortex in the Genesis of Tropical Cyclone over the North Indian Ocean Using WRF Model

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ABSTRACT

The formation of a tropical cyclone (TC) involves complex dynamic and thermodynamic processes. Understanding the role of mid-level vortices in the genesis of TCs over the NIO is crucial for improving TC forecasting. This study aims to enhance the field of meteorology by providing insights into these genesis processes. We utilized the National Centre for Environmental Prediction (NCEP) FNL reanalysis 1×1 data as input for the Weather Research and Forecasting (WRF) model version 4.0.3. The model was configured with one-way nesting between the parent and child domains. For the simulations, we employed the Kain-Fritsch (new Eta) scheme and the WRF Single-Moment 6-class graupel scheme (WSM6) as options for cumulus and microphysics. Our study identified the development of top-down vortices over the Arabian Sea (AS) and bottom-up vortices over the Bay of Bengal (BOB). We found that area-averaged mid-level relative vorticity (MRV) below $8 \times 10^{-5}\,\mathrm{s}^{-1}$ over a 6×6 area does not support the formation of TCs. Also, changes in mid-level temperature, whether increases or decreases, corresponded with the behaviour of MRV. Low-pressure systems (LPS) where vertical wind shear (VWS) did not exceed $10\,\mathrm{ms}^{-1}$ were prone to evolve into TCs. We also found that an increase in MRV, accompanied by VWS exceeding $10\,\mathrm{ms}^{-1}$, hindered the development of the mid-level vortex. Furthermore, there was an inverse relationship between geopotential height (GPH) and MRV, which favoured TC formation. The trends in MRV

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calculated by our model were comparable to those found by the European Centre for Medium-Range Weather Forecasts (ECMWF). Therefore, the results of this study are both valid and significant.

Keywords: Genesis; Tropical; Weather; MRV; Geopotential; WRF

1. Introduction

Generally, in the tropics, a mid-level vortex leads to the spin-up of the underlying low-level vortex. Deep convection with higher sea surface temperatures (SSTs) over tropical areas, such as the Western Tropical Pacific (WTP), the Western Atlantic, and the Caribbean, produces a top-heavy convective mass flux profile. This convection appears with substantial lateral mass inflow in the mid-troposphere and organizes a mid-level vortex. This mid-level vortex, through a series of processes, generates cool anomalies in the underlying area and warm anomalies in the upper troposphere. An intense mid-level vortex enhances the higher low-level mass inflow and vorticity convergence that favours tropical cyclogenesis [1].

Kutty et al. observed that the vortex initially develops in the mid-troposphere and subsequently extends downward over time. The upward-to-downward transition of the mid-level vortex favoured its intensification. However, the rapid dissipation of the mid-level vortex over time ultimately contributed to the weakening of the tropical storm [2].

Venkatesh T. N. et al. introduced a novel technique that posits the merger of mid-level vortices during the initial stages of tropical cyclone genesis over the Bay of Bengal. Utilizing this methodology, the researchers effectively detected the emergence of a tropical cyclone approximately 48 hours before the system reached the storm stage, a significant early warning for the same geographic area [3,4].

A mid-level vortex establishes a conducive environment for the formation of a pre-tropical cyclone vortex. Such environmental condition plays a significant role in the formation of warm-core structures, generating a substantial vertical mass flux that ultimately facilitates the emergence of tropical cyclones [5].

A shallow initial vortex results in a more stable atmosphere characterized by a relatively weaker gradient of angular momentum in the mid-to-upper troposphere. These tropospheric conditions impede deep convection and inhibit the intensification of the vortex at middle to upper levels. Consequently, in contrast to a deep initial vortex, a shallow initial vortex serves to moderate the rate of early tropical cyclone development [6].

During the initial phase of intensification, the vortex's radius of maximum wind (RMW) experiences decreased inertial stability within the RMW. This reduction promotes enhanced convective activity in the outer-core region while concurrently diminishing boundary layer inflow in the inner-core region [7].

Dry air entrainment from the upper troposphere and environmental easterly winds initiate a warm-core mid-level vortex, which develops with its downward extension toward the surface. This mid-level vortex evolved into a tropical cyclone under favourable dynamic and thermodynamic conditions [8,9].

A mid-to-upper tropospheric moisture environment and vertical alignment of the vortex favour tropical cyclogenesis. Moderate wind shear, accompanied by the vertical alignment of the vortex, accelerates the development of tropical cyclones [10].

The vertical distribution of initial vorticity is a significant factor in determining the timing of tropical cyclone development. Notably, cyclone formation is more efficient when there are substantial initial columns of integrated absolute vorticity. Before the genesis of a TC, a mid-level vorticity maximum is a common occurrence, regardless of the location of the initial vorticity maximum [11,12]. In the course of an observation campaign conducted in the western North Pacific in 2010, titled "Understanding Climate Change" (PALAU2010), Yoshida, et al. identified that the alignment of low-level and mid-level vortices, coupled with substantial moisture in proximity to this alignment, enhances the conditions favourable for the formation of tropical cyclones [13].

Shenglan Wu and Juan Fang conducted a statistical analysis that reveals a significant insight: the majority of tropical cyclones in the Western North Pacific region originate from low-level vortices (LV), mid-level vortices (MV), and relatively deep vortices (DV). These vortices, with substantial vorticity in both the lower and middle troposphere, play a crucial role in the dynamics of tropical cyclones. This understanding not only enriches our knowledge of TC dynamics but also has profound implications for forecasting and disaster management on a global scale. Furthermore, their research underscores that the rate of TC development from mid-level vortices is notably higher in the North Atlantic and Eastern Pacific regions than in the Western North Pacific [14,15].

Juan Fang and Fuqing Zhang found that the genesis of TC in the Atlantic Basin developed following a complex vortex bottom-up process. This intricate process involves the low-level vorticity undergoing a stretching effect. This stretching effect, when combined with moist convection, converges the ambient vorticity and leads to the spin-up of the system-scale vortex. The downward extension of the mid-level vortex didn't take place to favour the genesis of TC [16].

In a comparative study conducted by Rajasree et al. it was found that the intrusion of dry air did not inhibit the formation of TC over the BOB. Conversely, the entrainment of dry air into the core of the cyclonic vortex, extending up to 700 hPa from the upper levels, resulted in a delay in the intensification of TCs over the Atlantic Ocean [17].

Raymond and Sessions suggested that early-stage convection creates a mid-level vortex in the formation of tropical cyclones. This mid-level vortex sets up a more stable environment in a weak temperature gradient, favouring further development. This stable environment leads to heavy rainfall and low-level inflow, two critical components that are essential for the development of warm-core tropical cyclones (TCs) [18].

Raymond et al. analyzed tropical cyclogenesis from tropical disturbances in the northwest Pacific, with significant implications for our understanding of this phenomenon. They observed an intense mid-level circulation formed with the cold core beneath and the warm core aloft in the pre-genesis stage. This mid-level circulation triggered a spin-up of the low-level vortex, accompanied by variations in the vertical mass flux profile of deep convection. They propose that intense horizontal deformation at the mid-level is ruinous to tropical cyclogenesis [19].

This research aims to enhance the understanding of the role of mid-level vortices in the genesis of TC. This research will help in comprehending the types of vortices produced over the NIO and their impact on the development of TC from the existing tropical disturbances.

2. Data and Method

The WRF-ARW model, version 4.0.3, was employed to simulate the dynamic and thermodynamic characteristics of tropical cyclones (TCs). The simulation was conducted using the best track positions and statuses of tropical events over the North Indian Ocean (NIO), as determined from satellite imagery provided by the India Meteorological Department (IMD) (**Table 1**). The modelling utilised 1x1-degree FNL reanalysis data from the National Centers for Environmental Prediction (NCEP). The configuration of the model domains was achieved through a one-way nesting method, with horizontal resolutions of 21 km for the parent domain and 7 km for the child domain. The grid distribution was established using Arakawa C-grid staggering, and the model projection employed was the Mercator map. In the execution of this model, a coupling of the Kain-Fritsch (new Eta) cumulus scheme and the WSM6-class graupel microphysics scheme was implemented. This study, with its comprehensive analysis, focused on outputs from the inner domain, which encompasses an area of $10^0 \times 10^0$. The analysis included calculations of MRV at the 500 hPa level, low-level wind speed at 850 hPa, central pressure, and vertical wind shear (VWS) between 850 and 200 hPa within the inner domain. The resultant outputs were visualised using the GRADS software. Furthermore, a comparative analysis of MRV was undertaken between the results from the WRF model and those obtained from the ECMWF Reanalysis 5th Generation (ERA5), which provided hourly data at a horizontal resolution of 0.25°× 0.25°.

Table 1. Schedule of WRF Model run for the genesis part following IMD satellite based best track positions.

Event Name	Location	Model Run start at	Model Run end at	Initial Condition	End Condition	Maximum Intensity
DD1	BOB	0600UTC on November 7, 2015	0600UTC on November 10, 2015	LPA	WML	DD
DD2	AS	1800UTC on October 8, 2015	1800UTC on October 11, 2015	LPA	D	DD

Table 1. *Cont.*

Event Name	Location	Model Run start at	Model Run end at	Initial Condition	End Condition	Maximum Intensity
DD3	BOB	1200UTC on November 04, 2014	1200UTC on November 07, 2014	LPA	D	DD
Ashoba	AS	0600UTC on June 05, 2015	0600UTC on June 08, 2015	CC	CS	CS
Titli	BOB	0600UTC on October 06, 2018	0600UTC on October 09, 2018	CC	CS	VSCS
Mekunu	AS	1200UTC on May 19, 2018	1200UTC on May 22, 2018	CC	CS	ESCS
Luban	AS	0000UTC on October 05, 2018	0000UTC on October 08, 2018	CC	CS	VSCS
Amphan	BOB	1200UTC on May 13, 2020	1200UTC on May 16, 2020	LPA	CS	SuCS

3. Synoptic Study of the Studied Events

In meteorology, conducting a synoptic study of tropical cyclones (TCs) is a crucial step in accurately forecasting the tracks and intensity changes of these robust weather systems. This analysis enhances our understanding of the processes involved in the formation, intensification, movement, and dissipation of tropical cyclones. By identifying the atmospheric conditions that influence the behaviour of TCs, such as pressure, troughs, wind patterns, and temperature, we can develop more effective preparedness and response strategies, ultimately saving lives and resources.

3.1. DD1

On November 4th, 2015, an upper air cyclonic circulation was observed over the south-west BOB and the adjoining equatorial IO. This upper-air cyclonic circulation extended to mid-tropospheric levels on November 5th, 2015. Subsequently, a low pressure area (LPA) formed over the southwest BOB on the morning of November 6th. By November 7th, this system appeared as a well marked low(WML) over the same region. It developed into a depression (D) on November 8th/0300 UTC over the south-west BOB off the coast of Tamil Nadu. A decrease in vertical wind shear (VWS), high SST, increased poleward outflow and suitable Madden-Julian Oscillation (MJO) conditions led to the intensification of a DD on November 8th/1800UTC. However, as the system approached the coast on November 9th/0300 UTC, it underwent land interaction and hindered further intensification. The system experienced weakening due to land interaction and a slight increase in VWS. It then started moving northward. As it traveled the coast adjacent to the north of Pondicherry on November 9th/1800 UTC, the moisture supply decreased and the system encountered higher VWS. The system started to weaken and turned into a depression at 0300 UTC on 10th November and eventually dissipated into a WML by 0600 UTC on the same day. Despite its brief existence, the system accompanied adverse weather conditions, including heavy rainfall and squally winds.

3.2. DD2

On October 6th, 2015, there was an upper air CC over the east-central AS, stretching up to middle troposphere. The system had transformed into LPA over the same region by the early morning of 8th October, then developed into WML later that morning. The SST was 29–30 °C, low level convergence (LLC) was (5–10) × 10^{-5} s^{-1}, ULD was about 20 × 10^{-5} s^{-1}, relative vorticity at low-level was about (100–150) × 10^{-5} s^{-1}, and VWS was low to moderate (5–10 ms^{-1}) surrounding the systems' centre. Due to increasing low-level vortex (LLV) and ULD, the LPA gradually moved north-northwestward and became a depression over the central east AS at 0000 UTC on 9th October, located 410 km away from the west of the southwest of Goa and 630 km from the south of the southwest of Mumbai. The system then intensified to a DD at 0600 UTC on 10th October primarily for the existence of weak to moderate wind shear (5–10 ms^{-1}), warmer SST (29–31 °C), higher ocean thermal energy (60–80KJ/cm^2), and the inflow of warmed moist air from the south. As the system moved further northwards, it encountered moderate to high southeasterly wind shear (8–13 ms^{-1}) and the intrusion of dry air from the northwest, leading to its weakening into a depression at 0300 UTC on October 11th and a WML at 0300 UTC on October 12th. Finally, it weakened into an LPA by the morning of October 13th and became less marked by October 14th over the sea and made no landfall.

3.3. DD3

An LPA formed due to an active northeast monsoon in the BOB on 3rd November 2014. Low to moderate VWS of 5–10 ms^{-1}, high value SST of 29–30 °C, medium ocean Thermal Energy(OTE) of about 60–80 kJ/cm^2, and increasing positive relative vorticity at low-level around the LPA favoured the formation of LPS from the existing LPA. As convection became more organized, the LPA developed into a depression over the central and adjoining southeast BOB at 0900 UTC on November 5, 2014. Initially, the system was steered northwards on the 5th November due to its location to the south and adjacent to the western edge of the upper tropospheric ridge at the 200 hPa level. Environmental conditions, such as medium VWS, high SST, medium OTE, increasing LLV and LLC, and intense poleward outflow due to the ACC to the east-northeast of the LPS centre, led to its intensification into a DD on the 6th. As the LPS traveled northwards, it experienced higher VWS (10–15 ms^{-1}) and lower ocean thermal energy. Because of the presence of high VWS, low OTE, and colder SST, the system commenced to dissipate and became a depression at 0300 UTC on the 7th.On the 7th, the systems' centre was positioned south of the ridge of the upper troposphere and was moved westwards by the ACC to the north. During this movement, it weakened again into a WML at 0300 UTC on the 8th. Despite this, it carried on with its westward movement and passed the coast of Andhra Pradesh on the morning of the 9th as a WML. On November 9th and 10th, 2014, light to moderate rainfall was recorded in various regions of Andhra Pradesh.

3.4. Ashoba

Due to the southwest monsoon onset over Kerala a low-level CC developed over southeast AS on 5th June, 2015. It moved northwards and concentrated into an LPA over the southeast and adjoining east-central AS by the morning of 6th June. High values of SST, LLC, ULD, low-level relative vorticity and moderate VWS favoured the transition of the system into a depression at 0300 UTC on 7th June over the centre of east AS. The system travelled north-northwestward and concentrated into DD at 0000UTC on 8th June. At 0300 UTC on 8th June, the system transformed into CS Ashoba. It carried on with its north-northwestward movement till 0900 UTC on 8th June and then travelled northwards till 0600 UTC on 9th June. After that, it advanced west-northwards till 0600 UTC on 10th June and moved west-south westwards till 0000UTC on 11th June. Later, the system moved slowly westwards and turned into DD at 1800 UTC on 11th June. It then dissipated into a depression at 0000 UTC on 12th June and WML in the northwest AS and adjoining the coast of Oman at 1200 UTC on 12th June .Tropical Cyclone Ashoba made landfall in Oman, resulting in substantial flooding, particularly in the eastern regions. Notably, Masirah Island experienced significant rainfall during this event.

3.5. Titli

A VSCS Titli developed over the southeast BOB has been taken into consideration in our current study. This system emanated from the LPA over the southeast BOB and adjoining north Andaman Sea at 0300 UTC on 7th October, 2018. It transformed into a WML at 1200 UTC on 7th October, 2018. It then turned into a depression (D) over the east-central BOB at 0300 UTC on 8th October. The system moved to the west of the north-westward and concentrated into a DD over central east BOB at about 1800UTC on 8th October, 2018 and then developed into cyclonic storm (CS) Titli at about 0600UTC on 9th October. It strengthen into an SCS at 2100UTC on 9th October, at the time of its north-westward movement. Further it advanced north-northwestwards at 0600 UTC on 10th October and finally intensified as a VSCS, the peak intensification stage in its life cycle. It passed the coasts of north Andhra Pradesh and south Odisha near Palasa at the location 18.8 °N and 84.5 °E throughout 2300UTC on 10th October and 0000UTC on 11th October as a VSCS. During this passing's, the wind speed was 140–150 Kmph gusting to 165Kmph. It then advanced north-westward and dissipated into an SCS about 0600UTC on 11th October and into a CS by 1200UTC on the same day. It transformed into a DD in the south of Odisha at midnight by 1800UTC on 11th October Titli caused extensive damage and disruption in India and Bangladesh, particularly in Odisha and Andhra Pradesh. Its strong winds and heavy rainfall destroyed infrastructure, including over 8,000 houses in Andhra Pradesh. Titli impacted more than six million people and caused considerable road disruptions, communication disruptions, and electricity services.

3.6. Mekunu

An LPA over the south-east AS at 0300 UTC on 20th May 2018 formed due to the influence of CC over the Lakshadweep and its neighborhood. This LPA appeared as a WML over the southwest and adjoining southeast AS at 0000UTC on 21st May. The Madden Julian Oscillation of phase 2 favoured the cyclogenesis and further intensification of the system at 0300 UTC on 21st May. The environmental conditions such as SST, low-level positive relative vorticity, ULD and moderate VWS were supportive of cyclogenesis. This environmental condition persisted till 1200UTC on 21st May and the system transformed into a depression in the southwest and adjoining southeast AS. Moderate VWS and subsequent augmentation of low-level positive relative vorticity and ULD enhanced the further intensification of the system to DD at 0300 UTC on 22nd May. The system transformed into CS Mekunu at 1200UTC on the 22nd, SCS by 0300 UTC, VSCS by 0900 UTC on the 23rd of May. It reached its maximum intensity ESCS by 0300 UTC on the 24th of May, 2018. It passed the coast of south Oman as ESCS between 1830 and 1930 UTC on 25th May 2018. By 0300 UTC on 27th May 2018, Mekunu weakened into a WML over Saudi Arabia and adjoining areas of Yemen and Oman. Mekunu caused extensive damage and fatalities across Yemen, Saudi Arabia, and Oman. Its impact included heavy rainfall, flooding, numerous casualties, and infrastructure damage.

3.7. Luban

An LPA formed over Southeast Asia and the adjoining area at 0300 UTC on 5th October 2018 due to an upper air CC stretching up to the mid-troposphere. The system favoured by environmental conditions such as MJO with a phase 1 index with amplitude of more than 1, higher SST (29°–31 °C), weak to moderate VWS (3–5 ms^{-1}), high low-level positive relative vorticity and intense outflow in the troposphere. These favaourable conditions supported the system's intensification into a WML at 0000 UTC on 6th October over the southeast AS and adjoining east-central Asia. With continued favourable conditions, the system turned into a depression at 0900 UTC on 6th October, 730 km west-northwest of Minicoy. It then advanced west-northwestwards, concentrated into a DD and located over southeast AS and adjoining east-central Asia.

By 0000 UTC on the 8th October, the system transformed into a CS. It advanced west-northwestwards, centred over west-central AS and adjoining southwest Asia. It then intensified into an SCS and was centred over west-central and adjoining southwest Asia at 0900 UTC on 9th October. The system then moved northwestwards, intensified into VSCS at 0000 UTC on the 10th and located over west-central Asia. The system comenced weakening at 0300 UTC on the 11th during its west-northwestward movement, lying over west-central Asia. It dissipated into an SCS by 0300 UTC on the 12th October. Due to the cold and dry air entrainment from the northwest, it further weakened into a CS by 1800 UTC on the 12th. It continued its west-northwestward movement, it passing the coasts of Yemen and adjoining Oman at 0600 UTC on the 14th October as a CS. Due to the land-sea interaction, and cold and dry air entrainment from the west, the system promptly dissipated into a DD at 0900 UTC, and a depression at 1800 UTC on the 14th. The system weakened into a WML by 0300 UTC on 15th October and was located over Yemen and its adjoining area of Saudi Arabia. Cyclone Luban caused extensive flooding, displacement, and significant damage to infrastructure in Yemen's Al Mahrah Governorate.

3.8. Amphan

A new LPA formed over the southeast BOB and close to the south Andaman Sea at 0300 UTC on 13th May 2020 from a CC over the south Andaman Sea and adjoining southeast BOB from 6th to 12th May 2020. It concentrated in to WML over southeast BOB and its neighbouring area at 0300 UTC on 14th May. It turned into a depression under the favourable conditions at 0000UTC and appeared as DD at 0900UTC on 16th May over southeast BOB. The system further advanced in the north-northwestward and transformed into CS Amphan over southeast BOB at 1200 UTC on 16th May 2020. It then intensified into an SCS at 0300UTC, VSCS at 0900 UTC and ESCS at 2100 UTC on 17th May. It reached its peak intensity SuCS at 0600 UTC on 18th May 2020. This peak intensity sustained for one day and dissipated into ESCS over west-central BOB at 0600 UTC on 19th May. It passed a VSCS with a maximum sustained wind speed of 155-165 Kmph through the coasts of West Bengal – Bangladesh and crossed Sundarbans during 1000 – 1200 UTC on 20th May. The Amphan cyclone caused extensive destruction across Bangladesh and India, leading to significant fatalities, considerable damage to infrastructure, and substantial economic losses—the most pronounced impact reported in Eastern India, particularly in West Bengal.

4. Result and Discussion

The analysis of the WRF model's outputs is crucial in comprehending the genesis of TC. This research covers eight tropical events over the NIO. We expect valuable insights to come out of this analysis. These insights will enrich the study of complicated meteorological phenomena like TC genesis.

4.1. Evolution of Mid-level Vortex

Meteorologists concur that numerous tropical disturbances originate in the tropical oceans daily. Under appropriate environmental conditions, disturbances can accumulate substantial energy from the ocean's surface and evolve into cyclones. Low-level positive relative vorticity is a critical factor in the energy storage mechanisms of tropical cyclones. Consequently, positive relative vorticity is fundamental to the formation and intensification of these meteorological phenomena. In the genesis and strengthening of a TC, low-level positive relative vorticity facilitates the convergence of moisture towards the center. In contrast, negative relative vorticity at the upper levels aids in the divergence of dry air from the cyclone's center. The vortices associated with Ashoba, Mekunu and Luban exhibited both upward and downward expansion, whereas Titli and Amphan exposed vertical extension. This vertical development persisted until the conclusion of the model run. Top-down and bottom-up vortices were developed over AS and BOB respectively. Vertical expansion did not continue until the end of the model run among DDs.

The highest area average relative vorticity of Ashoba, Titli, Mekunu, Luban, and Amphan (over $6^0 \times 6^0$) varied between $8 \times 10^{-5} s^{-1}$ to $10 \times 10^{-5} s^{-1}$. On the other hand, the maximum value of area average relative vorticity was found to be $4 \times 10^{-5} s^{-1}$ to $8 \times 10^{-5} s^{-1}$ in DDs. Among the DDs, only vertical extension was observed in the vortex of DD1. Towards the end of the model run, the upper-level vorticity underwent downward motion, and the transition to the TC of DD1 may have been interrupted (**Figure 1**). The variation of model calculated mid-level relative vorticity (MRV) in the maximum wind speed was region, found to be identical to that calculated by the ECMWF. Among all the events, acute fluctuation of MRV found in DD2 and at the end of the model run its intense decline may have hindered the transformation to TC (**Figure 2**).

4.2. Variations in Intensity with MRV

Relative vorticity serves as the primary parameter in the genesis of TCs and plays a crucial role in their formation. The inflow of warm, humid air supplies the energy required for the development of a TC. The positive relative vorticity facilitates the required inflow for the genesis of a tropical cyclone (TC). This energy originates from warm seawater, which is subsequently transformed into the kinetic energy of the TC [20].

As illustrated in the accompanying figure, wind speed exhibits an increase corresponding with rising MRV. This phenomenon is observed more prominently in AS compared to BOB, rendering the genesis of TCs over BOB more complex (**Figure 3**). Conversely, a decrease in central pressure is associated with an increase in Mid-level relative vorticity (MRV). At the peak of MRV, the analysis reveals the maximum pressure drop within most of the studied events over both BOB and AS. The continuous increment of MRV until the conclusion of the model run supports a decline in pressure as well as an increase in wind speed, which in turn accelerates the genesis of TCs in both BOB and AS (**Figure 4**).

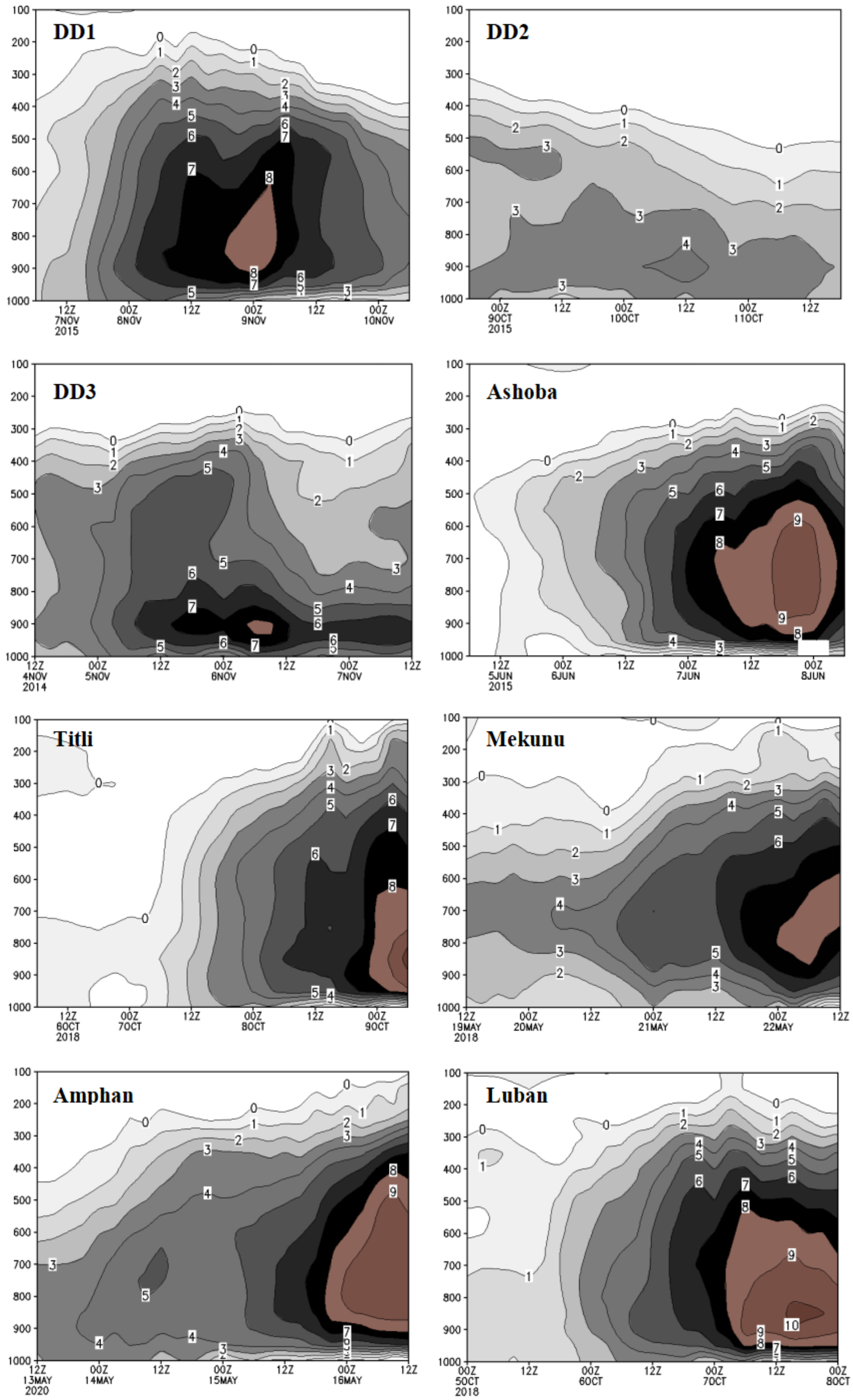

Figure 1. Evolution of area average relative vorticity ($\times10^{-5}s^{-1}$) over $6^0\times6^0$ around the centre (left side and right side showing the events over BOB and AS respectively).

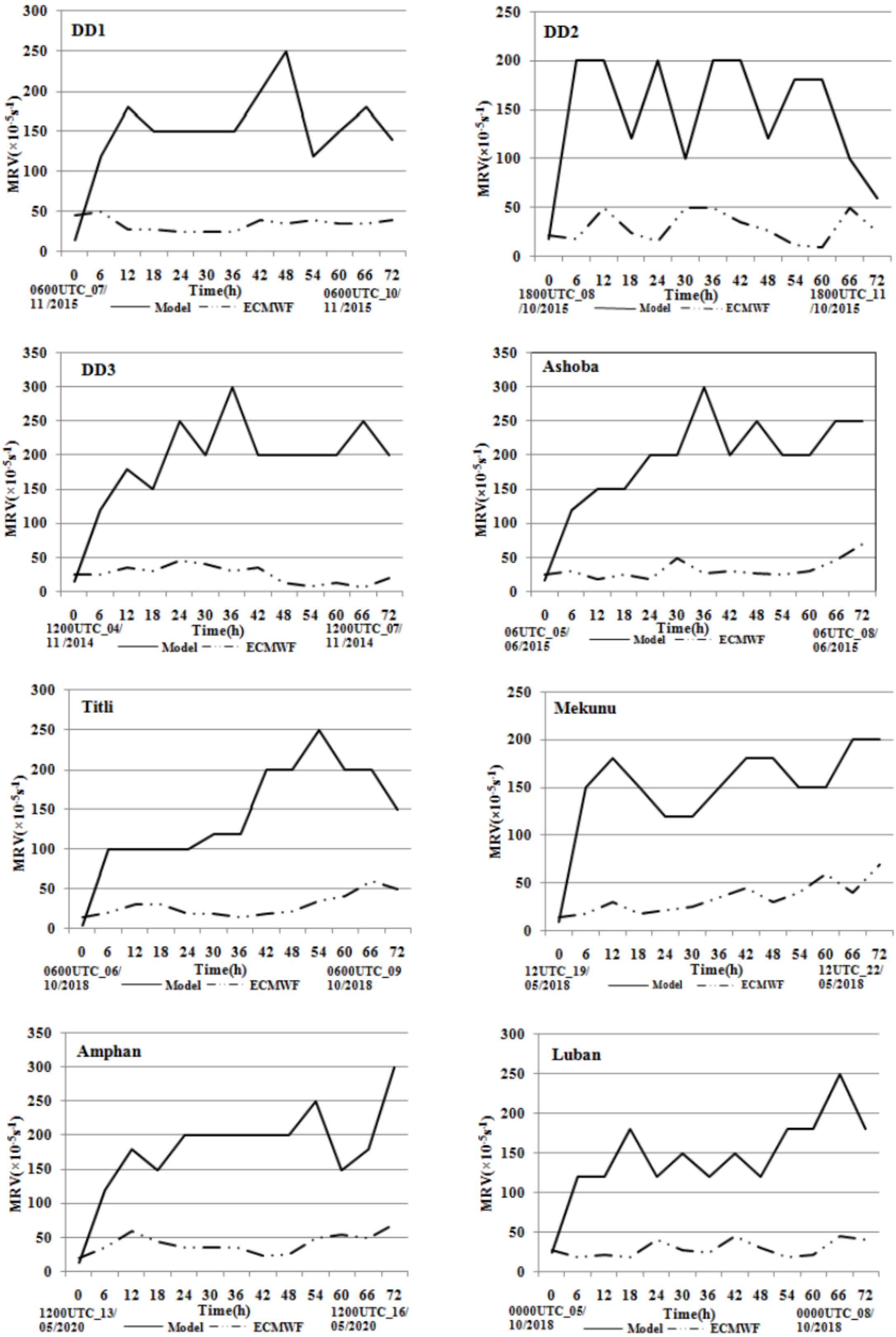

Figure 2. Temporal evolution of mid-level relative vorticity(for maximum wind speed location) around the system's centre.

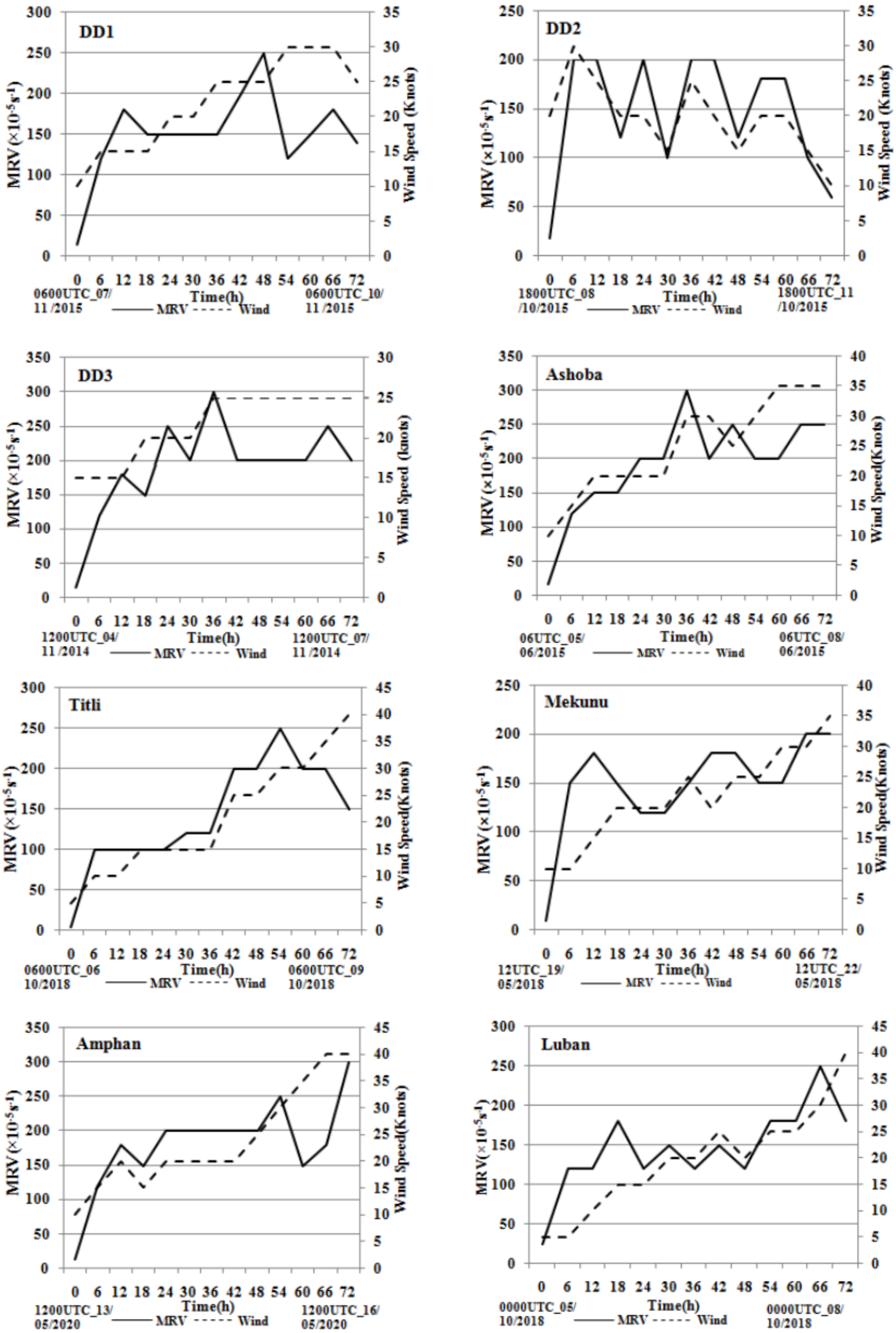

Figure 3. Variation of wind speed with MRV for 72 hours model run over NIO.

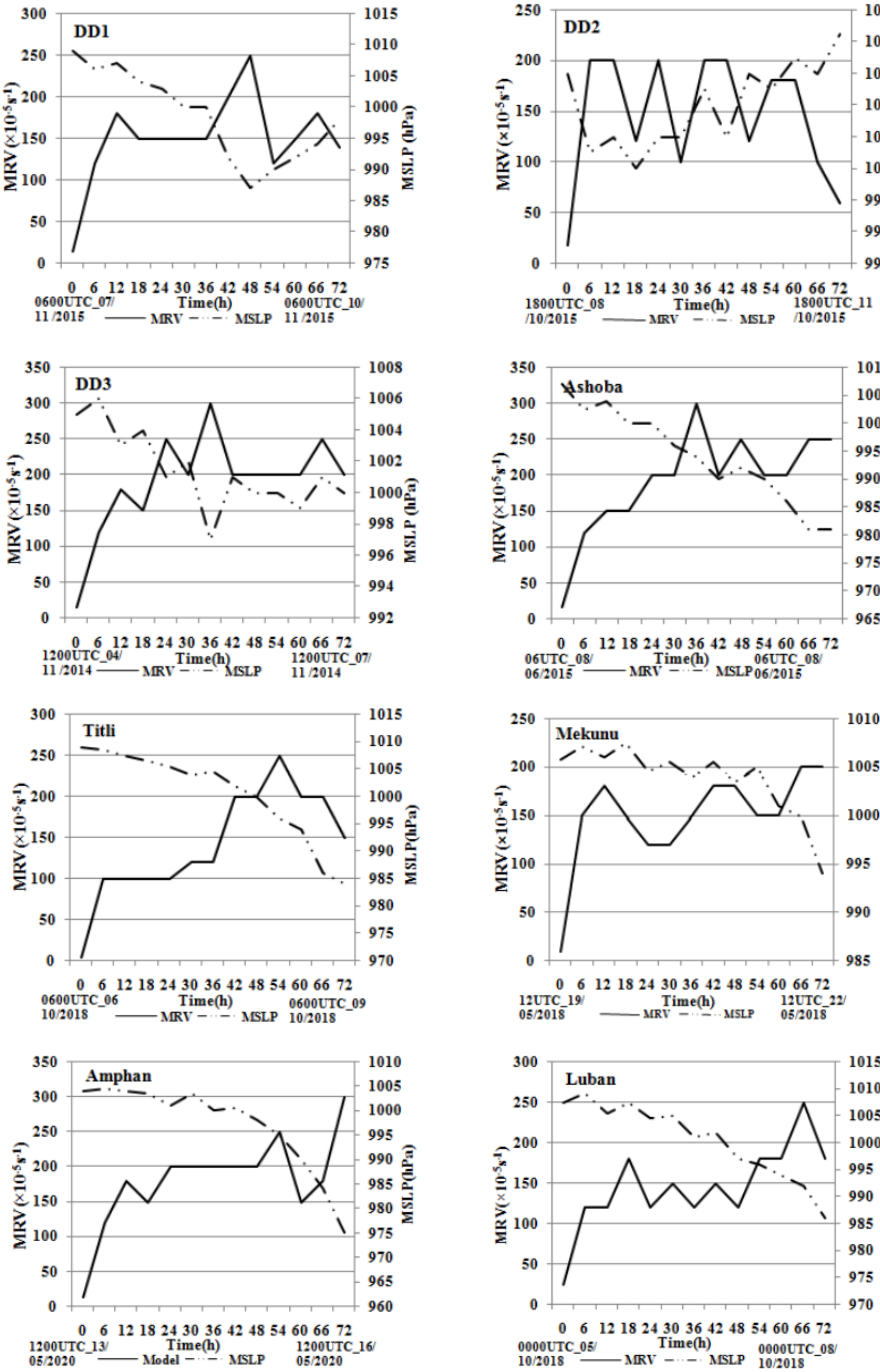

Figure 4. Variation of central pressure with MRV for 72 hours model run.

4.3. Role of MRV in the evolution of Vertical Wind Shear (VWS)

Vertical wind shear is crucial for the formation and intensification of tropical cyclones [21–23]. It refers to the variation in wind direction and speed with altitude in the atmosphere. Weak to moderate vertical wind shear allows for a more vertically aligned structure and a well-defined outflow channel at high altitudes, which enables warm air from the surface to rise efficiently. Those are more conducive to the development of a tropical cyclone (TC). On the other hand, high vertical wind shear introduces stable atmospheric conditions as well as the tilting of the storm. These conditions disrupt the formation of thunderstorms and hinder the development of TC.

In the events under research, the MRV demonstrated an enhancement corresponding to the increase in vertical wind shear. However, among the DDs, once vertical wind shear reached a value of 15 m/s, the MRV began to decline until the conclusion of the model run. These conditions impeded the further progression of DDs into tropical cyclones (TCs). Hence, we found that MRV increased with vertical wind shear, shear above 15 m/s hindered the evolution of the mid-level vortex, and shear below 15 m/s favoured the mid-level vortex. Elevated levels of vertical wind shear towards the end of the model run might have diminished low-level inflow, induced tilting of the storm structure, and suppressed thunderstorm formation by creating a more stable atmospheric environment. In the remaining storms, vertical wind shear did not surpass the threshold value of 12 m/s necessary for the genesis of tropical cyclones (**Figure 5**).

4.4. Relation of MRV with Geopotential Height (GPH)

Geopotential height denotes the elevation of a specific pressure level within the atmosphere. Elevated geopotential heights at various levels typically indicate stable air conditions, whereas reduced heights may imply atmospheric instability. Tropical cyclones typically develop in regions characterised by high instability. Geopotential height plays a crucial role in the formation of tropical cyclones. Since it impacts the atmospheric stability and the overall dynamics of the atmosphere. Comprehending how geopotential height interacts with other atmospheric parameters is essential for accurately forecasting both the formation and intensity of tropical cyclones.

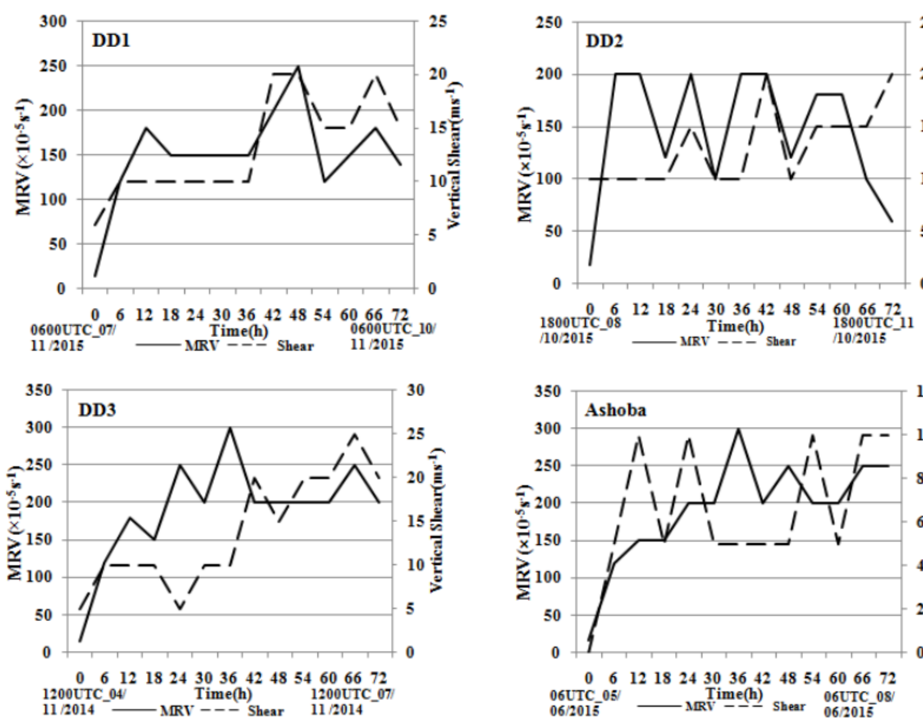

Figure 5. *Cont.*

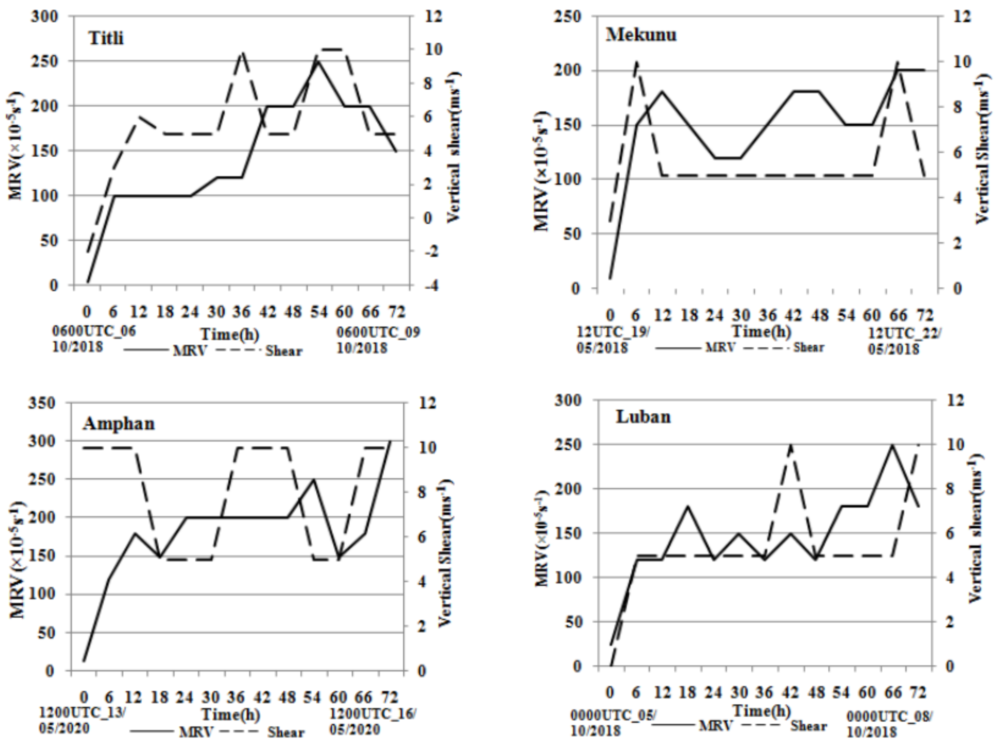

Figure 5. Variation of vertical wind shear with MRV.

In the studied storms, GPH varied inversely with MRV. In the figure, we see that a rapid increase in the MRV accelerated the reduction of GPH. Such reduced GPH area enhanced the pressure gradient, wind rotation, deep convection, and atmospheric instability, which favoured the formation of a tropical cyclone. At the peak value of MRV, GPH showed its lowest value among the events studied (**Figure 6**). The higher values of GPH toward the end of the model run in DDs impeded their formation as a TC.

4.5. Impact of the Evolution of MRV on Mid-Level Temperature

The mid-level vortex plays a significant role in transporting moisture from the environment around the centre into the storm, thereby enhancing convective activity. Investigating the role of the mid-level vortex (MRV) in the increase of mid-level temperatures may yield valuable insights into the genesis of TCs. The resultant rise in mid-level temperature alters convective dynamics and wind patterns, thereby creating favourable conditions for TC formation. Notably, the evolution of the mid-level vortex facilitates energy and heat exchange between the lower and mid-levels of the TC, a process essential for sustaining convection and heating the storm's core [24].

In our present study, the temporal variation of the MRV was found to be consistent with the mid-level temperature across all events analysed. This finding highlights a robust correlation between these two factors. The increase in mid-level temperature is sustained by the release of latent heat from the condensation of moist air within the mid-troposphere. During the event DD2, the mid-level temperature exhibited pronounced fluctuations. Such unstable conditions at mid-temperature may have hindered further intensification of the storm. We observed that the mid-level temperature enhanced and declined concurrently with the MRV in all events studied (**Figure 7**). Consequently, the increase in mid-level temperature supports sustained convection, multi-channel outflow, and the expulsion of dry air from upper levels surrounding the centres of events such as DD1, Ashoba, Titli, Mekunu, Luban, and Amphan.

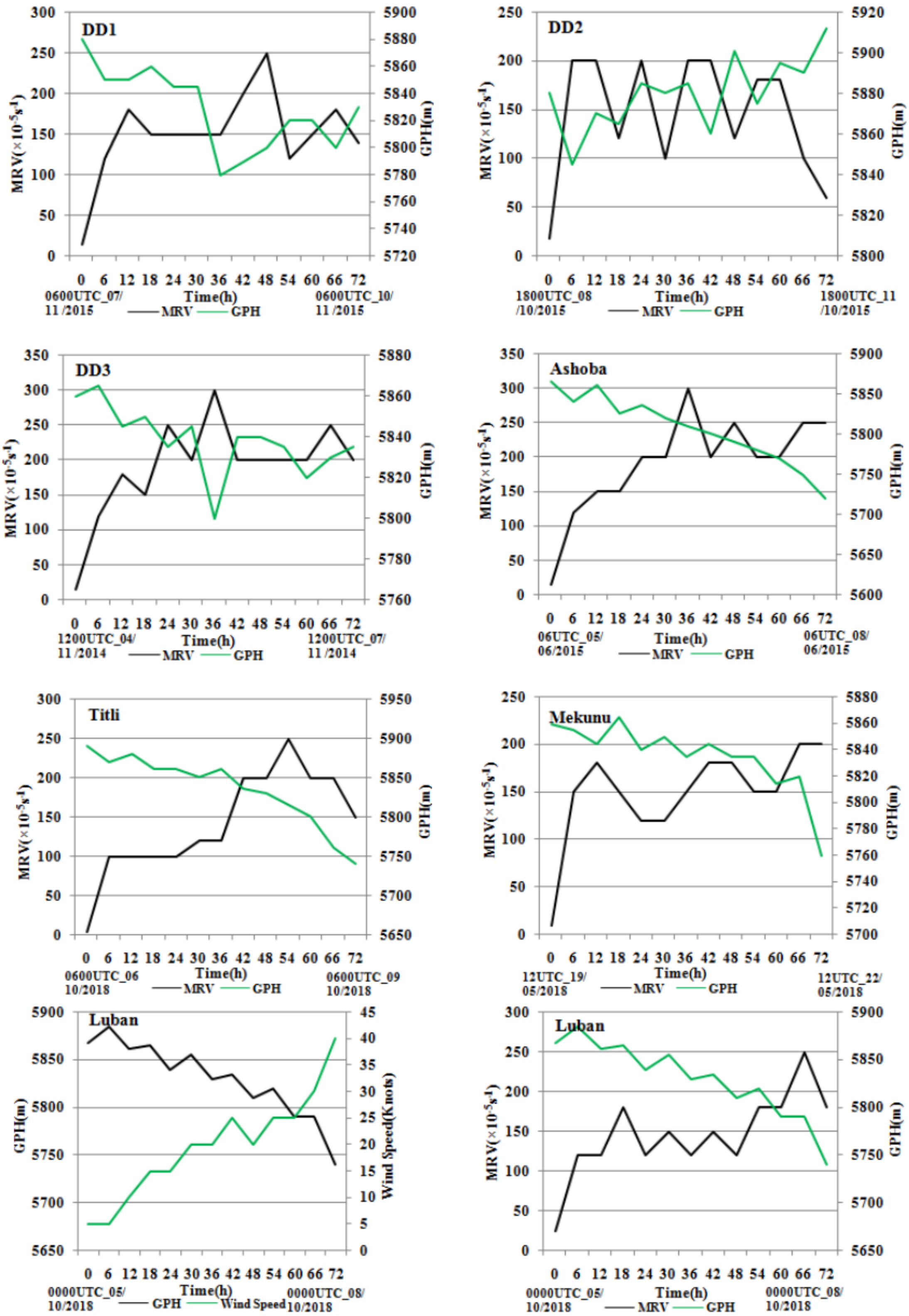

Figure 6. Temporal variation of GPH at the 500 hPa level with MRV.

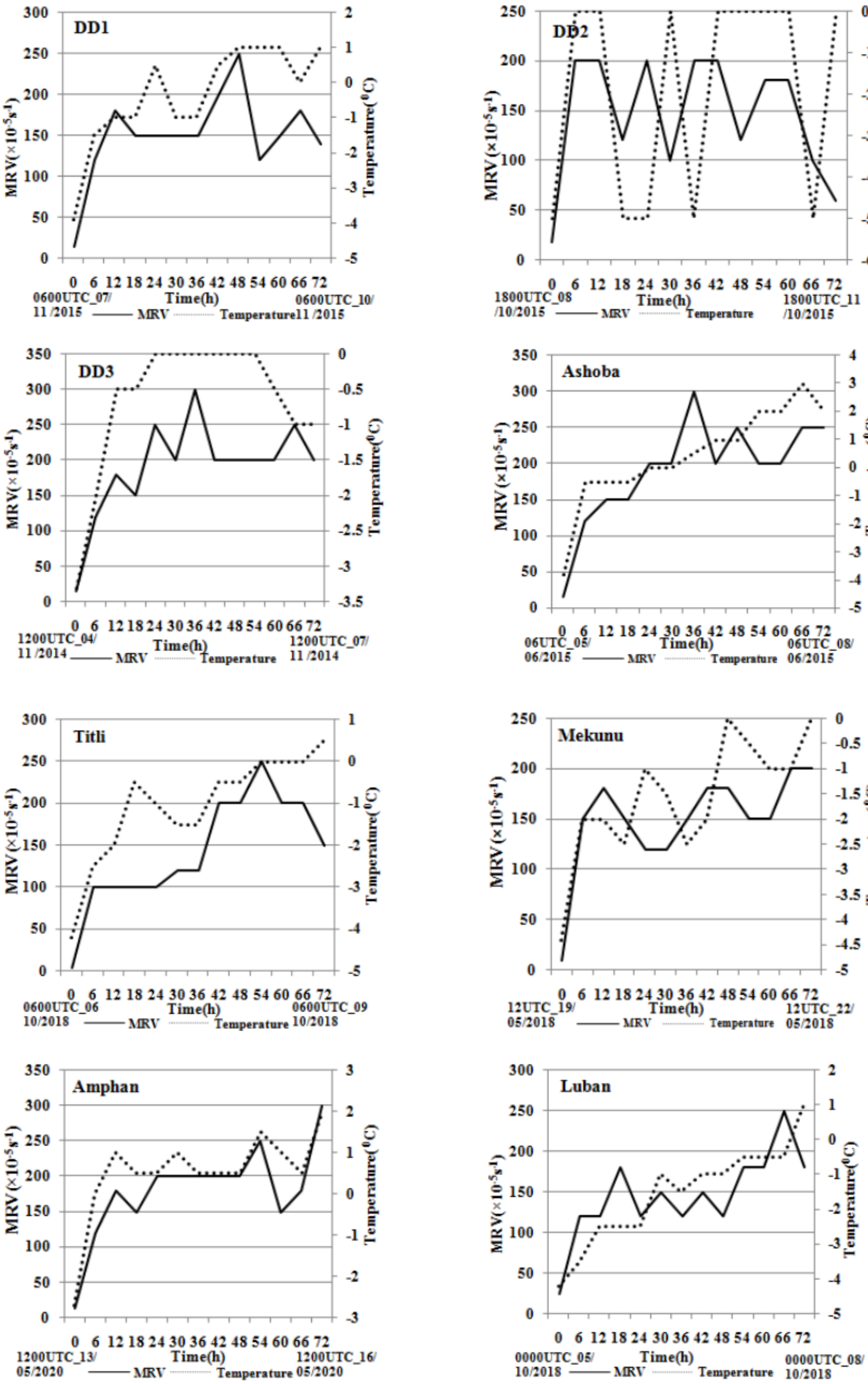

Figure 7. Temporal variation of mid-level temperature (around the centre) with MRV.

5. Conclusions

The genesis of TC is a complex dynamic and thermodynamic process. The significance of the mid-level vortex (MRV) is paramount for understanding the mechanisms underlying TC formation. The insights derived from this study will significantly contribute to the field of meteorology, particularly regarding the forecasting of TC genesis.

The analysis indicates that wind speed increases in correlation with rising MRV. This phenomenon is notably more pronounced in the Arabian Sea (AS) than in the Bay of Bengal (BOB). This observation implies that the processes involved in TC formation over the BOB are more intricate. Conversely, a decrease in central pressure correlates with an increase in MRV, and a rapid escalation in MRV leads to a marked reduction in pressure across most events studied in the North Indian Ocean (NIO). The sustained increase of MRV until the conclusion of the model run corroborates a decline in pressure and an increase in wind speed, thereby accelerating TC genesis in the NIO.

The study identified the development of top-down and bottom-up vortices over the AS and BOB, respectively. The area-averaged relative vorticity within a $6^0 \times 6^0$ area fluctuated between $8 \times 10^{-5} s^{-1}$ and $10 \times 10^{-5} s^{-1}$, thus facilitating TC formation in the NIO. Notably, area-averaged relative vorticity below $8 \times 10^{-5} s^{-1}$ does not support the genesis of TCs from low-pressure systems (LPS). The ongoing increase in MRV until the end of the model run indicates a consistent decline in pressure and an increase in wind speed, which further promotes TC genesis in both the BOB and AS.

The findings reveal that an MRV increase, in conjunction with vertical wind shear (VWS) exceeding 10 m/s, inhibited the development of the mid-level vortex. In comparison, shear values below 15 m/s were conducive to its evolution. Elevated levels of vertical wind shear towards the end of the model run may have diminished low-level inflow, induced tilting of the storm structure, and suppressed thunderstorm formation by fostering a more stable atmospheric environment. The LPS of which vertical wind shear did not surpass 10 m/s transformed into a TC.

In the analyzed storms, GPH displayed an inverse relationship with MRV. A rapid increase in MRV expedited reductions in GPH, with the areas of decreased GPH enhancing the pressure gradient, wind rotation, deep convection, and atmospheric instability—all of which are favourable for TC formation. At its peak, MRV and GPH recorded their lowest values among the events studied. Conversely, higher GPH values toward the conclusion of the model runs hindered TC formation.

The temporal variation in MRV demonstrated a consistent correlation with mid-level temperature across all analyzed events, underscoring a robust connection between these two parameters. The rise in mid-level temperature is sustained by the release of latent heat resulting from the condensation of moist air in the mid-troposphere. During event DD2, mid-level temperature exhibited pronounced fluctuations, potentially impeding subsequent storm intensification. The data indicates that mid-level temperature increased and decreased in tandem with MRV across all events studied. Accordingly, the elevation in mid-level temperature fosters sustained convection, multi-channel outflow, and the expulsion of dry air from the upper levels surrounding the centres of events such as DD1, Ashoba, Titli, Mekunu, Luban, and Amphan.

The results derived from this study will significantly contribute to the forecasting of tropical cyclone formation over the Northern Indian Ocean. Additionally, it is imperative to focus on the impact of mid-level vortices on the thermodynamic structure of tropical cyclones.

Author Contributions

A.H.M.F.R. was responsible for conducting model runs, maintaining records, performing data analysis, interpreting findings, and drafting manuscripts. I.M.S. and M.A.E.A. were integral to the design process, offering valuable suggestions and editing the manuscript. M.A.K.M. focused on reasoning, strategic planning, and computational tasks.

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Institutional Review Board Statement

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Informed Consent Statement

Not applicable.

Data Availability Statement

The data analysed in this research are the outputs of the WRF Model and the display of ERA5 data, and can be obtained through the email address rabbiphy@gmail.com.

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Conflicts of Interest

The authors and the funding organization have no conflicts of interest.

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