Assignment :

Simulation of Structure, Intensity, Landfall, and Track of Tropical Cyclone "**Mocha**" Using NWP Models

Course Name : **Applications of NWP Modeling**

Course Code : MetLb 406

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Lifecycle of Very Severe Cyclonic Storm **'Mocha'**

Figure 1: *Lifecycle of ESCS Mocha according to IMD bulletin.*

Background of Cyclone Mocha

Cyclone Mocha was an **Extremely Severe Cyclonic Storm** that originated in the Southeast Bay of Bengal in May 2023. It followed a well-defined lifecycle, transitioning from a cyclonic circulation into an extremely intense cyclonic storm.

- **Formation:** The initial cyclonic circulation was observed on May 6, 2023. It evolved into a low-pressure area by May 8 and further intensified into a well-marked low-pressure system on May 9. By the evening of May 9, it developed into a depression over the Southeast Bay of Bengal.

- **Intensification:** Over the next few days, the storm rapidly intensified. It became a deep depression on May 10 and subsequently Cyclone Mocha by May 11. By May 12, it had transformed into a Very Severe Cyclonic Storm, with wind speeds reaching 210-220 km/h, gusting to 240 km/h. At its peak, Mocha was classified as an Extremely Severe Cyclonic Storm.

- **Landfall:** On May 14, 2023, Cyclone Mocha made landfall near the north Myanmar-southeast Bangladesh coasts, with maximum sustained winds of 180-190 km/h. It caused significant damage due to its strong winds, heavy rains, and storm surge.

- **Dissipation:** After landfall, the storm rapidly weakened, transitioning into a depression over northwest Myanmar by May 15, 2023, as it lost energy due to land interaction and reduced moisture availability.

Radar Imageries

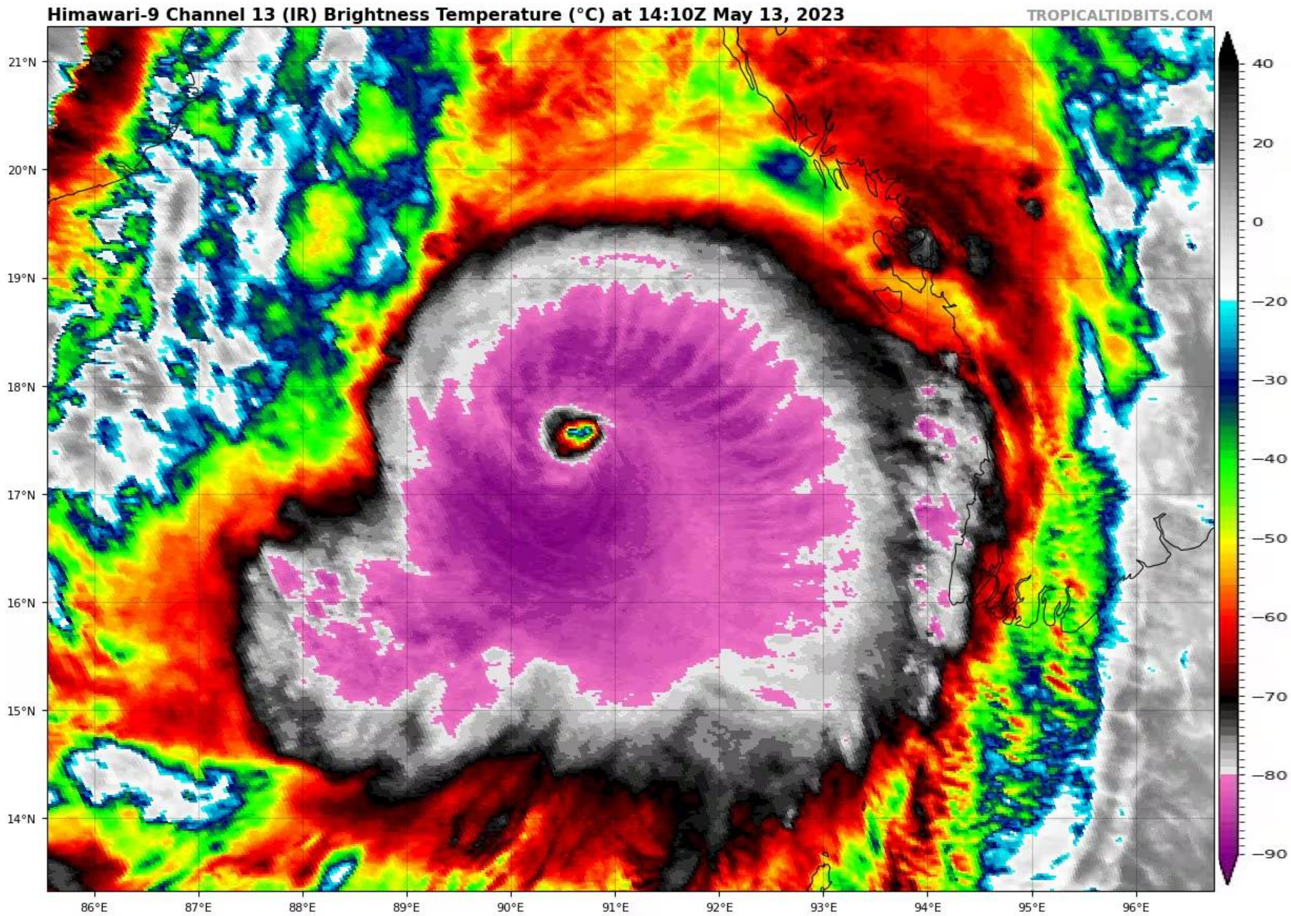

Figure 2: *Radar image from Himawari-9 Channel 13 (IR) shows the Cyclone Mocha captured on May 13, 2023, via infrared satellite imagery. The color bar showing temperature in Degree Celsius.*

This Himawari-9 infrared satellite image captures Cyclone Mocha on May 13, 2023. The well-defined eye at the center represents calm conditions, while the surrounding vibrant colors indicate intense thunderstorms in the eyewall. The coldest, most severe storm areas appear in pink and black, showing strong updrafts. The outer bands in red, yellow, and green signify less intense but still dangerous parts of the cyclone. This data is crucial for monitoring the storm's intensity and structure for accurate forecasting.

Domain Area

Cyclone Mocha formed in the Bay of Bengal, influenced by the Madden–Julian Oscillation. By 8 May, a low-pressure area developed, and on 9 May, it was upgraded to a depression. The system intensified rapidly due to high ocean heat content and low wind shear, becoming a cyclonic storm on 11 May. It peaked on 13 May with sustained winds of 240 km/h (150 mph). Mocha made landfall near Sittwe, Myanmar, on 14 May, with winds of 215 km/h (135 mph), before weakening over the rugged terrain and dissipating as a low-pressure area on 15 May.

This domain was chosen for research due to the Bay of Bengal's vulnerability to intense cyclones, with major implications for densely populated regions. Studying Cyclone Mocha enhances understanding of rapid intensification and provides insights for improving forecasting and disaster preparedness.

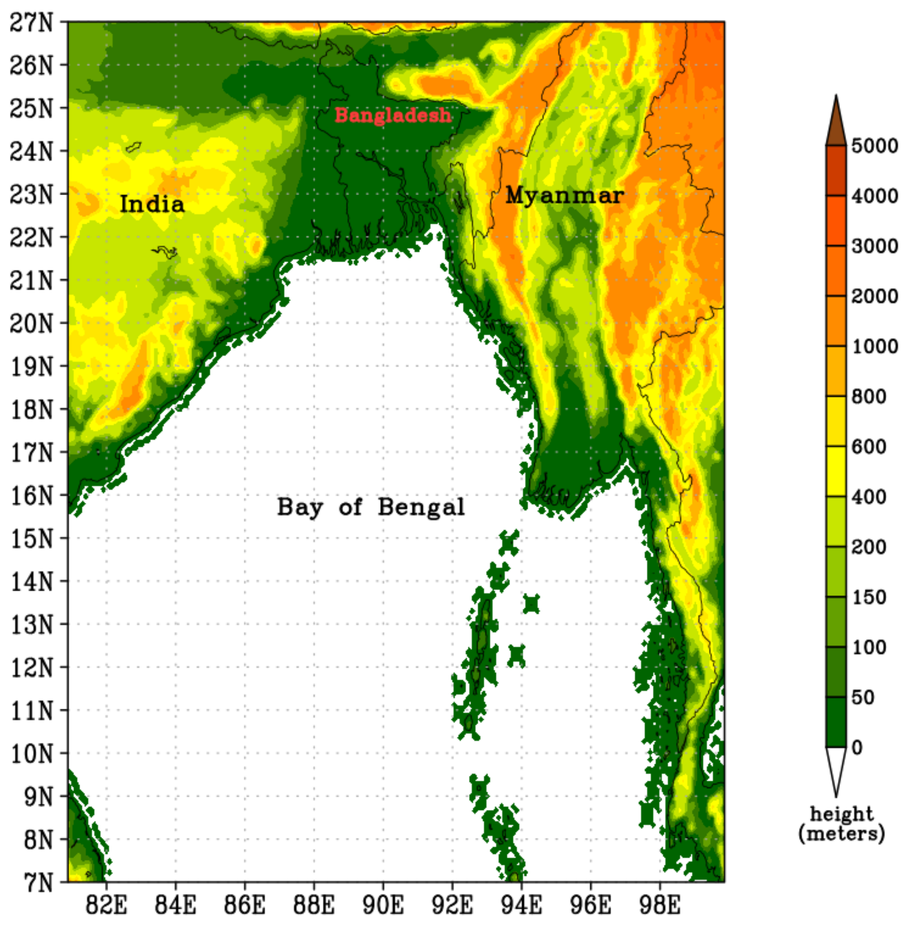

Figure 3: *Model Domain used in WRF for Cyclone Mocha Simulation with 9 km Resolution. The shading represents the terrain height in meters.*

Data Type

- **FNL Operational Model Data**:

  - Source: National Centre for Environmental Prediction (NCEP).
  - Resolution: 1.0° × 1.0° grids.
  - Coverage: Entire globe.
  - Frequency: Every 6 hours.
  - Purpose: Used as the initial and lateral boundary condition.

- **Terrain/Topography Data**:

  - Source: United States Geological Survey (USGS).
  - Resolution: 30 seconds.

- **Vegetation/Land Use Data**:

  - Source: United States Geological Survey (USGS).
  - Categories: 25.

Methodology

The Weather Research and Forecasting (WRF) model, developed by the National Centre for Atmospheric Research (NCAR) in collaboration with the National Oceanic and Atmospheric Administration (NOAA), the National Centre for Environmental Prediction (NCEP), and various universities, is used in this study.

The Weather Research and Forecasting (WRF) model (version 4.5) was utilized in this study to simulate and forecast the track and intensity of Severe Cyclone Mocha. The model simulation was initiated at **0000 UTC** on **11 May 2023** and ran for **96 hours**, until **0000 UTC** on **15 May 2023**, with a horizontal resolution of 9 km and a single domain setup. The WRF model, known for its ability to simulate atmospheric processes over a wide range of spatial and temporal scales, operates by solving mathematical equations that describe atmospheric dynamics based on initial conditions and boundary data, including temperature, pressure, humidity, and wind patterns. To capture the complex interactions within the atmosphere, WRF incorporates various physical parameterizations, such as cloud microphysics, convection, and boundary layer dynamics.

For this study, the simulations focused on key meteorological parameters, such as surface wind, the vertical profile of temperature and relative humidity, precipitation patterns, and low-level vorticity, which helped analyze the cyclone's structure and intensity. WRF's ability to produce detailed simulations provided crucial insights into Cyclone Mocha's behavior. The model predicted sea level pressure (SLP) and maximum wind speed (MWS) for different phases of the cyclone, and these simulated outputs were compared against observed data to evaluate the model's accuracy in forecasting the cyclone's progression and eventual landfall.

Key Factors Influencing Cyclone Development and Intensification

Temperature	• Warmer temperatures fuel cyclones by providing heat energy for convection.
Mean Sea Level Pressure	• Indicates areas of low pressure where cyclones typically form and intensify.
Heat and Moisture Flux	• Drives the energy transfer from the ocean to the atmosphere, intensifying cyclones
Wind Speed	• Determines the steering and structure of a cyclone through atmospheric motion.
Vertical Wind Shear	• Influences the cyclone's organization and potential for intensification.
Convergence and Divergence	• Surface-level Convergence causes rising air and convection, while upper-level divergence enables outflow, strengthening the cyclone.
Low-level Vorticity	• Represents the rotation and spin essential for cyclone development.
Horizontal and Vertical Profile of Relative Humidity	• Impacts moisture availability, crucial for cyclone growth.
Rainfall	• Indicates the potential impacts of cyclones, including flooding and storm intensity.

Results and Discussion

1. Temperature Analysis

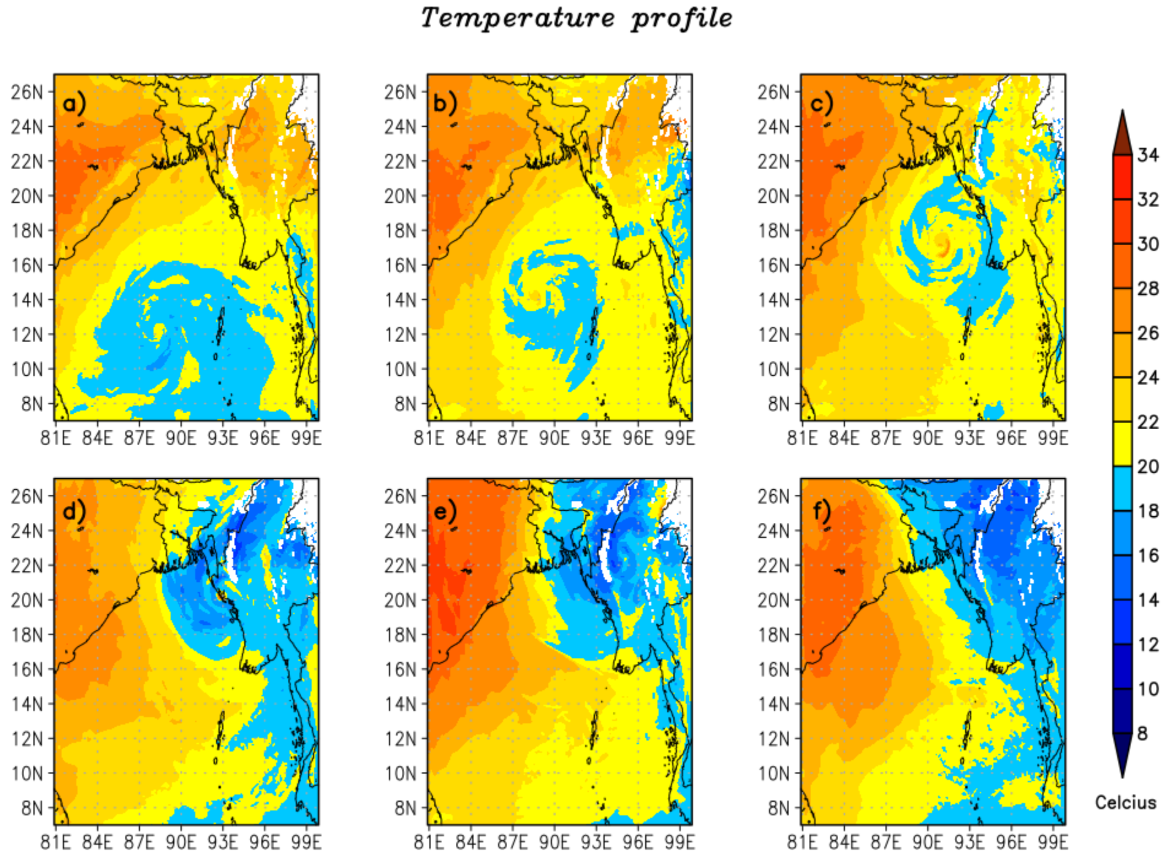

Figure 4: *Model Simulated Temperature Profile of Cyclone Mocha at 850mb Valid for (a) 11 May 1200 UTC, (b) 12 May 1200 UTC, (c) 13 May 1200 UTC, (d) 14 May 0300 UTC, (e) 14 May 1200 UTC, and (f) 14 May 2100 UTC.*

The temperature distribution over both the Bay of Bengal and adjacent land regions plays a critical role in the development and sustenance of cyclonic activities. The provided figure depicts the temperature profile at the 850 mb level, showcasing the thermal evolution of Cyclone Mocha over time. The warm core of the cyclone, a defining feature of tropical cyclones, becomes increasingly pronounced with progression, reflecting its intensification. Initially, the core exhibits a moderate positive temperature anomaly, which strengthens over time due to latent heat release from vigorous convection. The anomaly reaches its peak during the cyclone's mature stage, with a significant temperature gradient between the core and its surroundings. The center has comparatively higher temperature but the surrounding area of eye is cooler which is around 16-20 degree Celsius at 1200UTC of 12 May and 13 May. The subsequent lateral extension of the warm core indicates a redistribution of energy, often associated with the weakening phase of the cyclone. After the landfall at around 14 May 0300 UTC the cyclone dissipates and the temperature cools in an unorganized pattern over the land.

2. Mean Sea Level Pressure Analysis

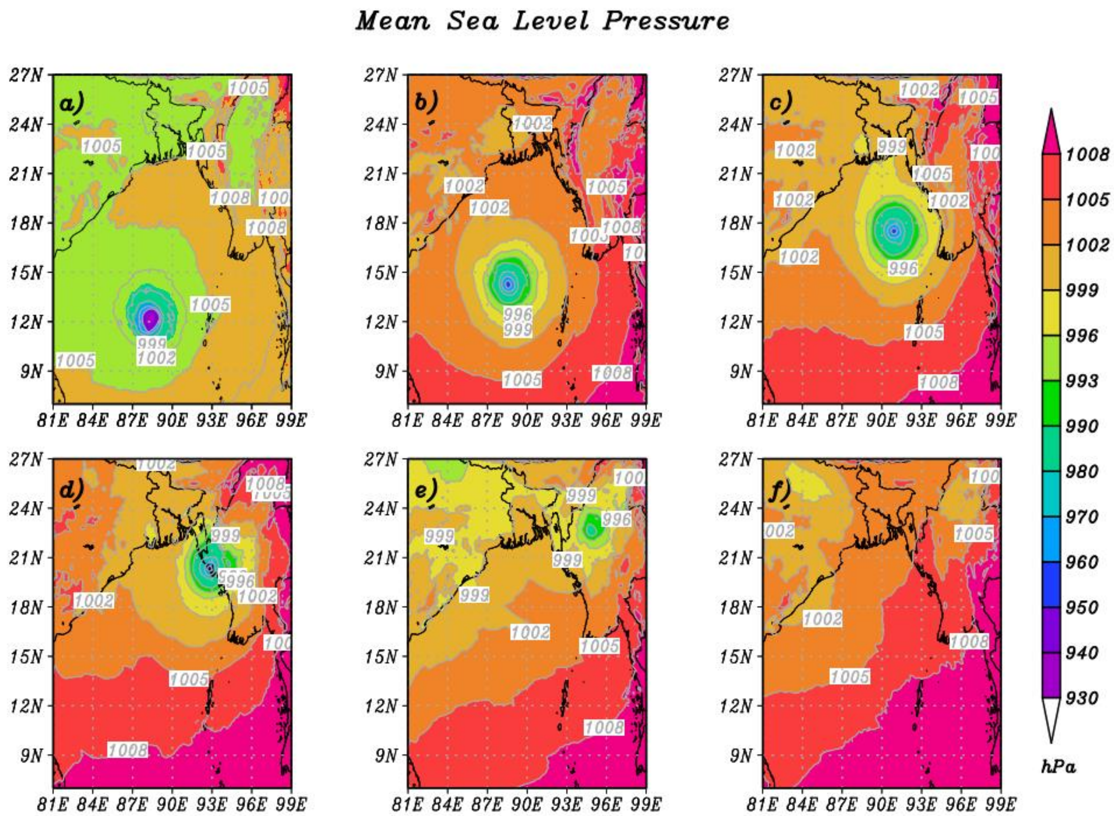

Figure 5: Model Simulated Mean Sea Level Profile of Cyclone Mocha Valid for ((a) 11 May 1200 UTC, (b) 12 May 1200 UTC, (c) 13 May 1200 UTC, (d) 14 May 0300 UTC, (e) 14 May 1200 UTC, and (f) 14 May 2100 UTC.

Initially, the cyclone is characterized by a modest low-pressure center (~1000 hPa), reflecting the early stages of cyclogenesis. Over time, the central pressure drops significantly, with a steep gradient forming around the core. This intensification is associated with the cyclone's development, driven by latent heat release from deep convection and the inward spiral of moist air.

At its mature stage, the cyclone exhibits a well-defined low-pressure center (~995 hPa) surrounded by tightly packed isobars, signifying a strong pressure gradient. This configuration is indicative of robust cyclonic activity and increased wind speeds around the core. The symmetry of the isobars during this phase underscores the organization of the system.

Before landfall the cyclone reached its lowest pressure of 931 hPa. This drop of pressure made the cyclone stronger and it lasted longer. As the cyclone approaches land, the dissipation is evident in the reduced pressure gradient and the normalization of MSLP values across the region (~1005 hPa). The weakening is likely a result of reduced moisture supply and increased friction over land.

3. Heat and Moisture Flux Analysis

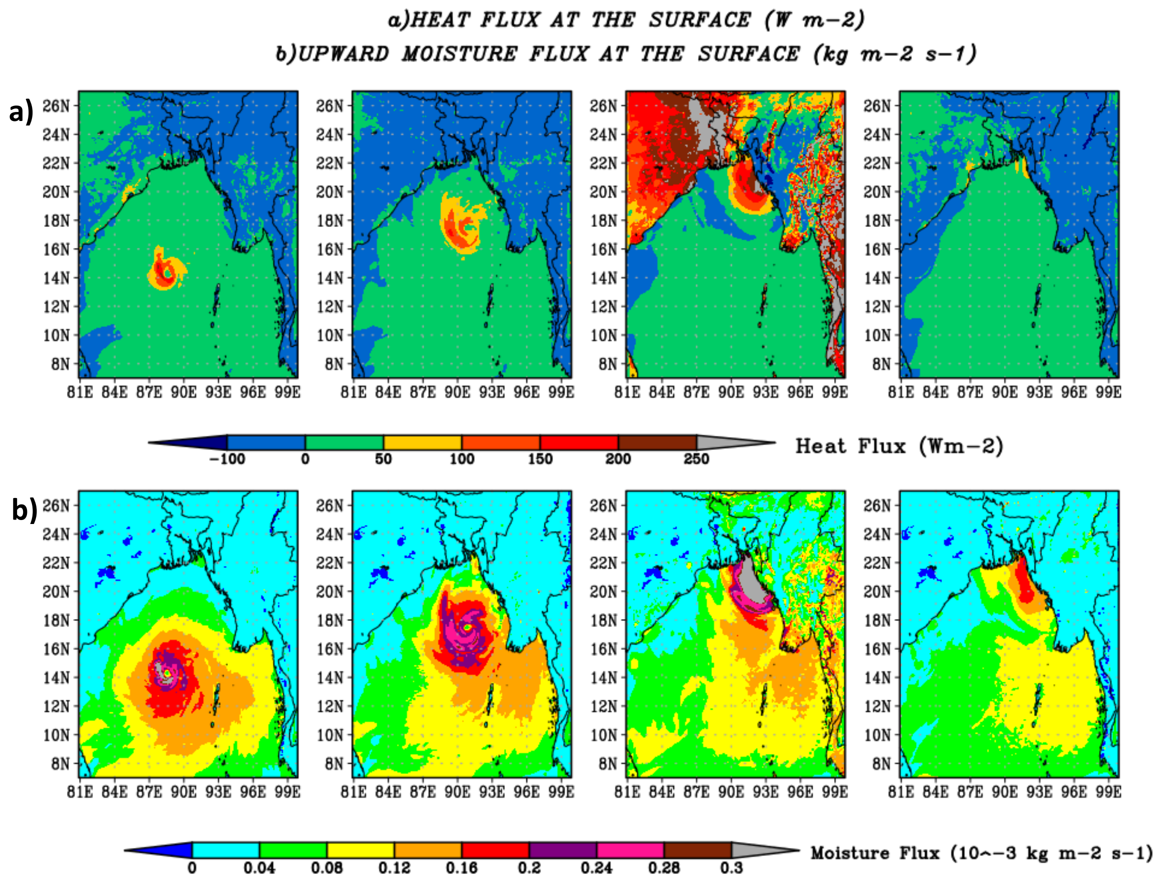

Figure 6: *The figure illustrates the model-simulated surface conditions during* ***Cyclone Mocha****, focusing on two variables:* ***(a) heat flux at the surface*** *(W m^{-2}) and* ***(b) upward moisture flux at the surface*** *(kg m^{-2} s^{-1}) for 12 May 1200 UTC, 13 May 1200 UTC, 14 May 0300 UTC, 14 May 1200 UTC,*

The image presents the model-simulated surface conditions during Cyclone Mocha, showcasing heat flux and upward moisture flux at the surface across different times of its life cycle. The energy and moisture drive convection and determines the energy available for cyclone intensification, directly impacting its strength and development.

Heat Flux (a): The heat flux indicates significant energy transfer over the Bay of Bengal, with higher values (>150 W m^{-2}) concentrated near the cyclone's core. On 12 May, the flux starts increasing as the system strengthens. By 13 May, the heat flux intensifies near the center, fueling the cyclone. On 14 May 0300 UTC, heat flux remains elevated near the core as the system moves northward. By 14 May 1200 UTC, the flux diminishes near the Bay while spreading over coastal regions, consistent with land interaction and cyclone weakening showing reduced energy input over land and adjacent ocean regions.

Upward Moisture Flux (b): Upward moisture flux shows strong moisture transport near the cyclone center, critical for its intensification. On 12 May, flux values are moderate near the core. By 13 May, flux intensifies (≥0.24 kg m^{-2} s^{-1}), supporting the cyclone's peak intensity. On 14 May 0300 UTC, high flux persists near the center and northern sectors as the system approaches land. By 14 May 1200 UTC, flux reduces over the Bay, with moisture transport shifting inland, reflecting the cyclone's weakening after landfall. As the cyclone makes landfall, the upward moisture flux decreases, indicating a weakening storm as it loses access to the ocean's moisture supply, a key factor in sustaining its strength.

4. Wind Flow Analysis

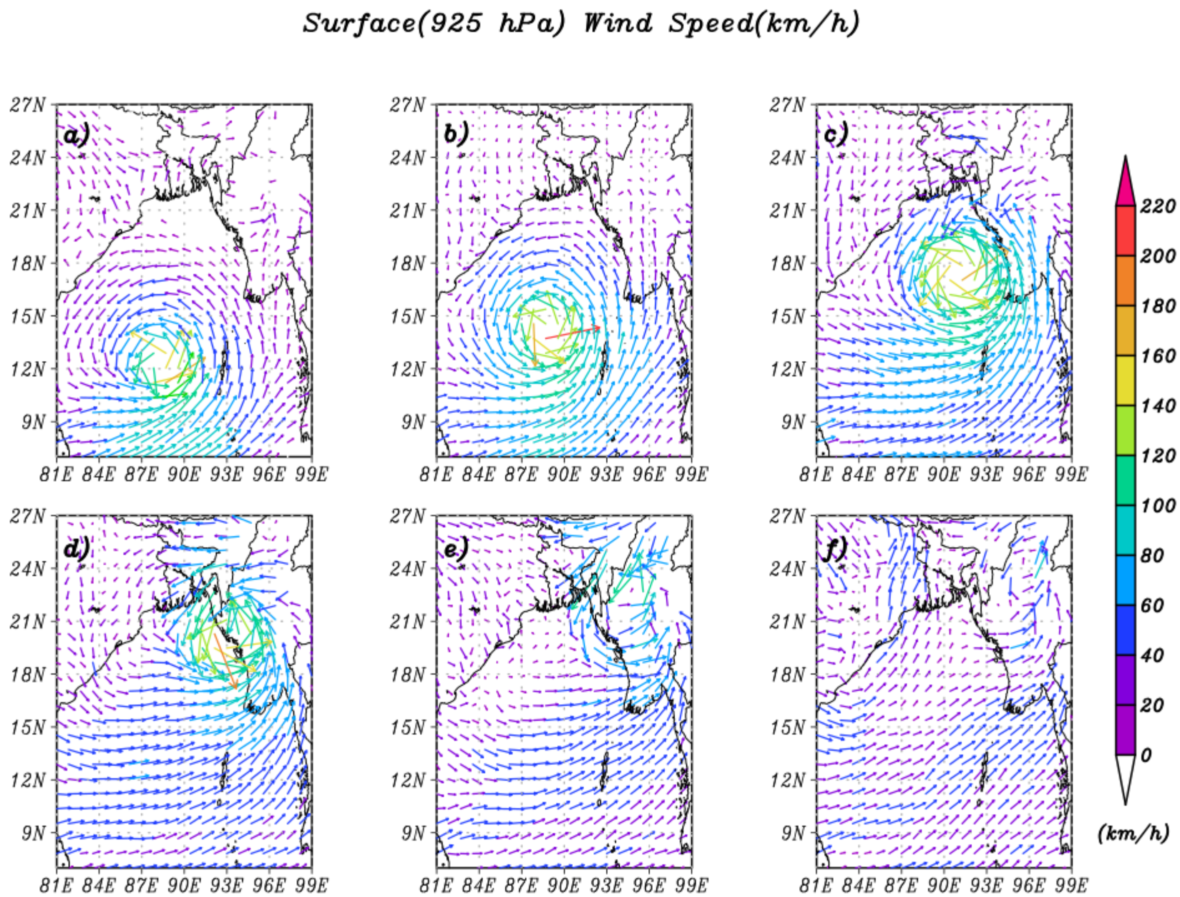

Figure 7: *Model Simulated Surface Wind of Cyclone Mocha Valid for (a) 11 May 1200 UTC, (b) 12 May 1200 UTC, (c) 13 May 1200 UTC, (d) 14 May 0300 UTC, (e) 14 May 1200 UTC, and (f) 14 May 2100 UTC.*

The wind field at the surface (925 hPa) depicts the cyclonic evolution of Cyclone Mocha with its characteristic anti-clockwise movement, typical of low-pressure systems in the Northern Hemisphere. On 11 May 1200 UTC, a weak cyclonic circulation is evident over the Bay of Bengal, with wind speeds peaking at moderate levels (~100 - 140 km/h) near the center. This distribution corresponds to the early stage of cyclogenesis, where the cyclone begins to organize under favorable atmospheric and oceanic conditions.

As the cyclone intensifies on 12 May 1200 UTC and 13 May 1200 UTC, the wind speeds increase significantly, exceeding around 180 km/h near the center. The tightly spiraled wind patterns and the concentration of higher wind speeds around the core highlight the strengthening of the system.

This intensification is driven by increased convection and the influx of moist air, which fuels the cyclone's development.

On 14 May 0300 UTC, during its mature stage, the cyclone exhibits maximum wind speeds, with values almost 200km/h. The well-defined spiral structure of the wind field signifies a strong and organized cyclonic system. The symmetry and compactness of the high-wind-speed region reflect the peak intensity of the cyclone during this phase.

As the cyclone approaches land and begins to weaken on 14 May 1200 UTC and 14 May 2100 UTC, the wind speeds decrease, and the spiral structure becomes less defined. The dissipation of the cyclone is evident from the reduction in wind speed (~100-120 km/h) and the expansion of weaker wind fields across the region. This phase is typically associated with increased frictional effects over land and reduced moisture availability.

5. Vertical Wind Shear Analysis

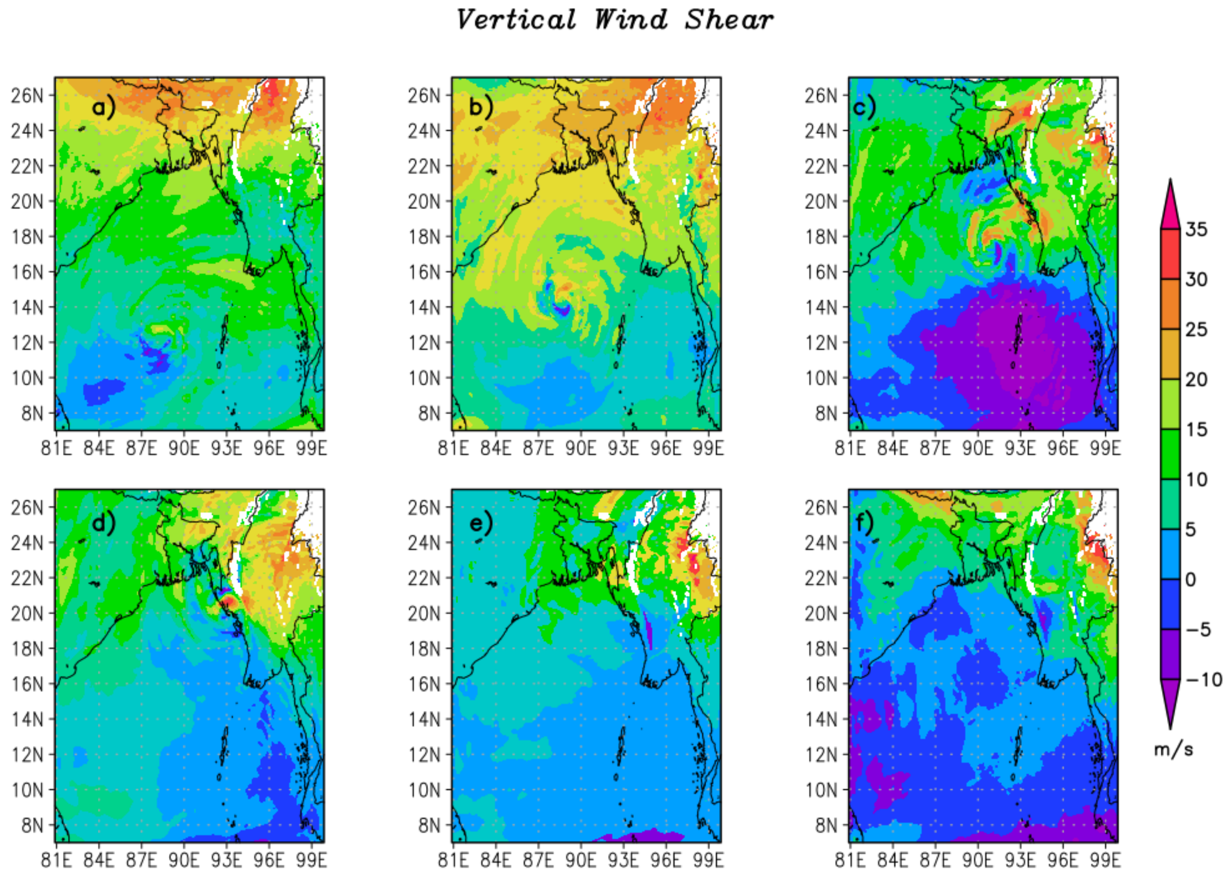

Figure 8: *Model Simulated Vertical Wind Shear of Cyclone Mocha Valid for (a) 11 May 1200 UTC, (b) 12 May 1200 UTC, (c) 13 May 1200 UTC, (d) 14 May 0300 UTC, (e) 14 May 1200 UTC, and (f) 14 May 2100 UTC.*

The image represents the spatial distribution of vertical wind shear over the Bay of Bengal during the evolution of Cyclone Mocha. Vertical wind shear, defined as the difference in wind speed or direction between the lower troposphere (at 850 hPa) and the upper troposphere (at 500 hPa), is a critical parameter influencing the formation, intensification, and structure of tropical cyclones. The above figure illustrates the temporal variability of wind shear, the scale denoting shear magnitudes in meters per second (m/s). Regions of low shear, conducive to cyclone intensification, are contrasted with areas of higher shear, which can inhibit cyclone development by disrupting its vertical alignment.

The figures reveal that the core region of Cyclone Mocha is characterized by low vertical wind shear, signifying a favorable environment for intensification. At 12 May 1200 UTC the circulation pattern is quite visible where the wind shear at the core is low but the outward wind shear is around

20-25m/s. In contrast, higher shear values in the surrounding areas may have influenced the cyclone's outer structure and trajectory by introducing asymmetries. At the time of landfall 14 May 0300 UTC the wind shear at the center was maximum around 30-35m/s. And after the landfall, wind shear at the Bay of Bengal reduced but increased (more than 35 m/s) significantly over the land areas, notably in Myanmar. This spatial variability of wind shear highlights its dynamic role in modulating the cyclone's lifecycle. The analysis underscores the importance of examining vertical wind shear patterns in understanding the atmospheric conditions that govern tropical cyclone behavior in the Bay of Bengal.

6. Convergence and Divergence Analysis

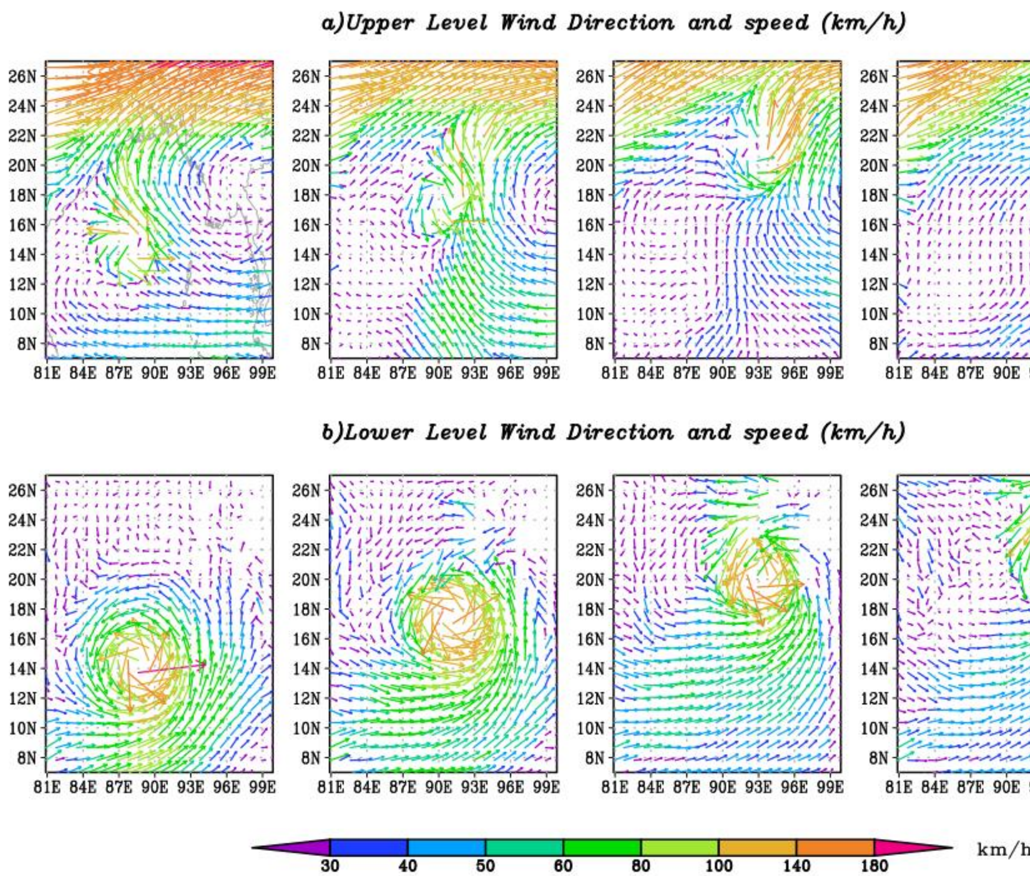

__Figure 9__: The figure illustrates the model-simulated convergence and divergence during Cyclone Mocha, focusing on two parameters: (a) upper-level wind direction and (b) lower-level wind direction for 12 May 1200 UTC, 13 May 1200 UTC, 14 May 0300 UTC, and 14 May 2100 UTC

The image displays the model-simulated wind direction and speed during Cyclone Mocha, focusing on (a) Upper-level divergence and (b) Lower-level convergence.

(a) **Upper-Level Divergence (200 hPa)**: The figures(a) show wind direction and speed at the 200 hPa level, highlighting upper-level divergence during Cyclone Mocha. Notably, the strongest winds are located away from the storm's center, particularly in the outer bands of the cyclone. This pattern reflects the nature of upper-level divergence, where air is spreading outward from the center of the system. The outflow at this altitude allows the cyclone to maintain its structure by facilitating the removal of air that rises from the surface. The areas with the highest wind speeds are situated farther from the eye, supporting the cyclone's growth by efficiently evacuating air from the system’s core to maintain its strength.

(b) **Lower-Level Convergence (925 hPa)**: The second figures(b) illustrate the wind direction and speed at the 925 hPa level, representing lower-level convergence. Here, the winds converge toward the storm’s center, drawing in warm, moist air that rises and fuels the storm's convection processes. The wind speeds are highest near the cyclone’s core, though significant wind speeds are also evident in the outer bands. This lower-level convergence is critical for the storm’s intensification, as it supplies the energy necessary for the storm to develop further. The inflow at this level plays a key role in sustaining the cyclone's intensity by feeding the system with moisture and heat.

7. Low-level vorticity Analysis

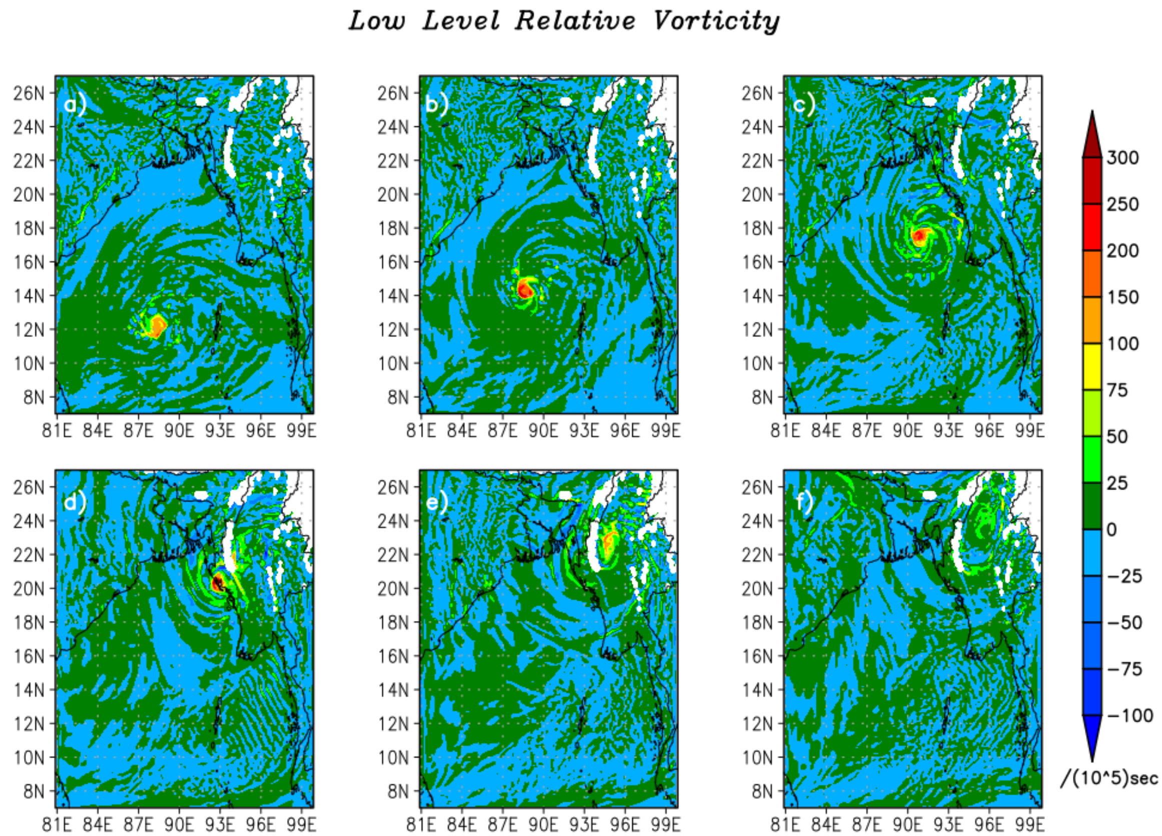

Figure 10: Model Simulated Low Level Relative Vorticity of Cyclone Mocha Valid for (a) 11 May 1200 UTC, (b) 12 May 1200 UTC, (c) 13 May 1200 UTC, (d) 14 May 0300 UTC, (e) 14 May 1200 UTC, and (f) 14 May 2100 UTC.

Low-level relative vorticity is a key parameter for understanding the dynamics of tropical cyclones. The figure shows that Cyclone Mocha had strong low-level vorticity throughout its formation, intensification, and dissipation stages.

The highest simulated vorticity reached approximately 300×10^{-5} s^{-1} at the cyclone's core, as indicated by the red regions in the figure. The core area of high vorticity expanded as the cyclone intensified, reflecting the strengthening of the system. Additionally, the spiral banding structure around the core is distinctly represented in the vorticity distribution, highlighting the well-organized nature of Cyclone Mocha.

As the cyclone approached landfall, the vorticity weakened but remained concentrated near the center, signifying a gradual reduction in intensity due to interaction with land. Post-landfall after 14 May 0300 UTC, the vorticity field further dissipated as the system lost its energy source over land.

8. Vertical and Horizontal Profile of Relative Humidity Analysis

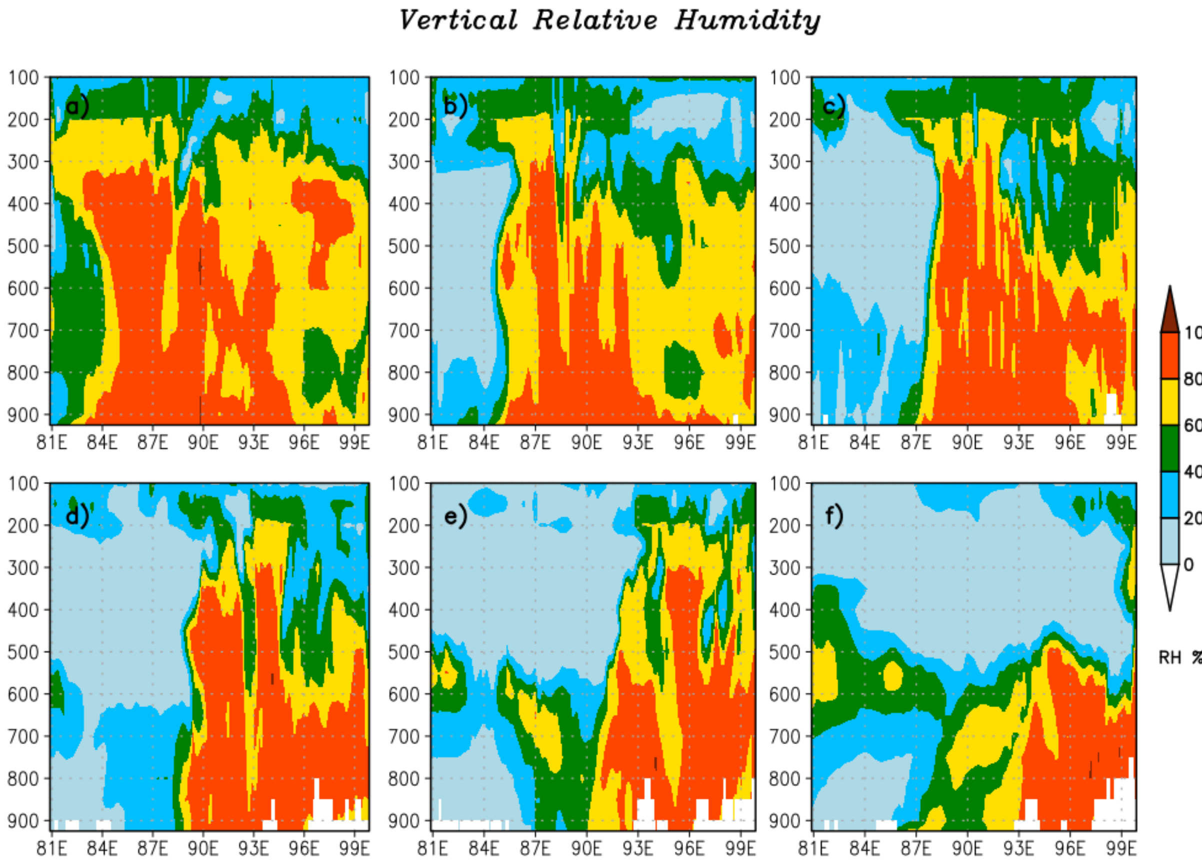

***Figure 11**: Model Simulated Vertical Relative Humidity of Cyclone Mocha Valid for (a) 11 May 1200 UTC at 12.17 °N Latitude, (b) 12 May 1200 UTC at 14.25 °N Latitude, (c) 13 May 1200 UTC 17.5 °N Latitude, (d) 14 May 0300 UTC 20.3 °N Latitude, (e) 14 May 1200 UTC 22.6 °N Latitude, and (f) 14 May 2100 UTC at 14.1 °N Latitude*

The vertical relative humidity (RH) figures illustrate the moisture distribution at various altitudes and latitudes during Cyclone Mocha's lifecycle. High RH levels (above 80%) are crucial for cloud and rain formation, while low RH levels indicate dry air, which prevents cloud formation and results in clear skies. The relative humidity decreases as it moves away from the area of higher humidity or center of the cyclone, with moisture levels ranging from 60% to 80%. On 11 May 1200 UTC, high RH dominates the lower to mid-levels (below 500 hPa) near 90°E–96°E, indicating favorable conditions for cyclone development. By 12 May 1200 UTC, mid-level moisture persists, but drier regions appear above 500 hPa near 93°E. On 13 May 1200 UTC, moist conditions remain prominent below 400 hPa near 90°E–95°E, while the upper levels stay dry. By 14 May 0300 UTC (Figure d), lower levels remain moist, with slightly reduced mid-level RH near 93°E. On 14 May 1200 UTC during landfall, mid-to-upper levels (above 400 hPa) become drier, though lower levels near 90°E–95°E retain moisture. Finally, by 14 May 2100 UTC, drier conditions dominate above 400 hPa, with limited lower-level moisture lingering indicating the dissipation of the cyclone.

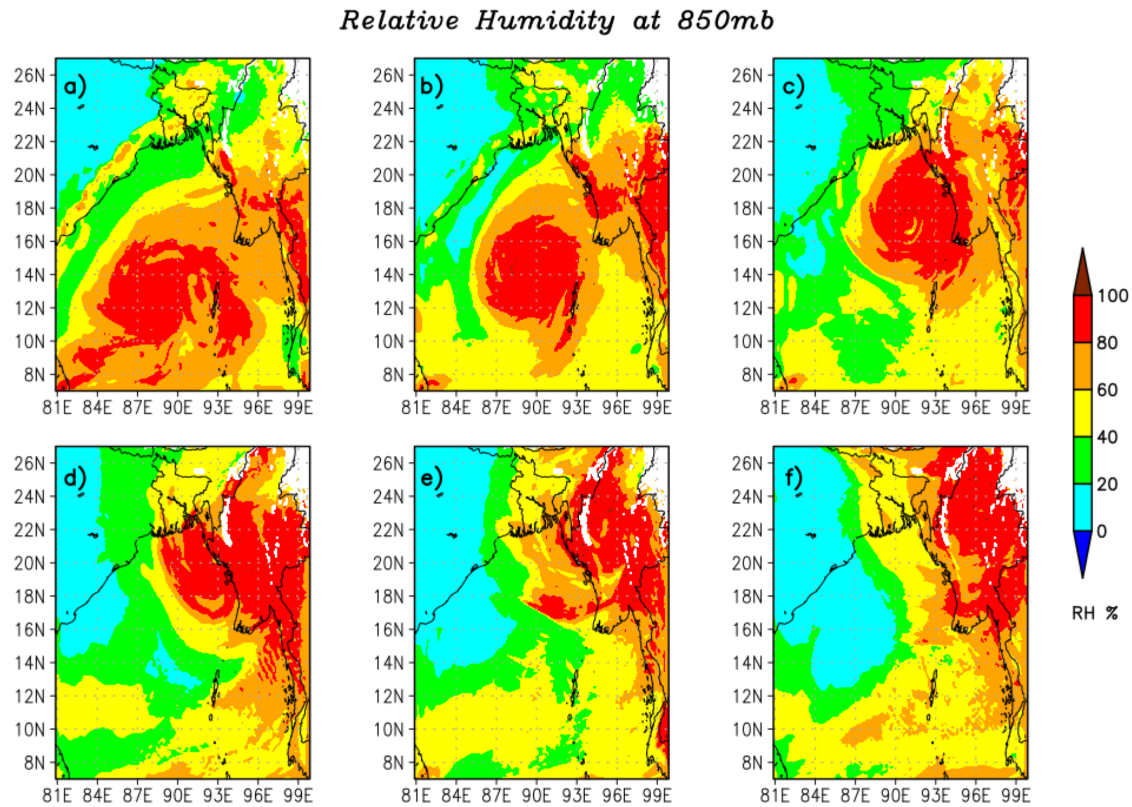

Figure 12: Model Simulated Relative humidity at 850mb of Cyclone Mocha Valid for (a) 11 May 1200 UTC, (b) 12 May 1200 UTC, (c) 13 May 1200 UTC, (d) 14 May 0300 UTC, (e) 14 May 1200 UTC, and (f) 14 May 2100 UTC.

The figures illustrate the horizontal distribution of relative humidity (RH) at 850 mb for Cyclone Mocha through various stages of its lifecycle. The RH values, shown as percentages, highlight areas of moisture availability, on 11 May 1200 UTC, high RH (≥80%) is concentrated near the central Bay of Bengal, indicating a moisture-rich environment conducive to cyclone formation. A clear structure of cyclone Mocha at BoB is visible. By 12 May 1200 UTC, the moist region shifts northward, aligning with the system's development. On 13 May 1200 UTC (Figure c), a well-defined circular high-RH zone forms near 18°N and 92°E, signifying the intensification of the cyclone. By 14 May 0300 UTC, this high-RH zone moves further north-northeast, consistent with the cyclone's movement toward landfall. On 14 May 1200 UTC during landfall, the moist region begins to spread inland over Myanmar and parts of Bangladesh, reflecting the system's weakening. Finally, by 14 May 2100 UTC, RH decreases significantly over the Bay of Bengal as the cyclone dissipates, leaving residual moisture over land.

9. Rainfall Analysis

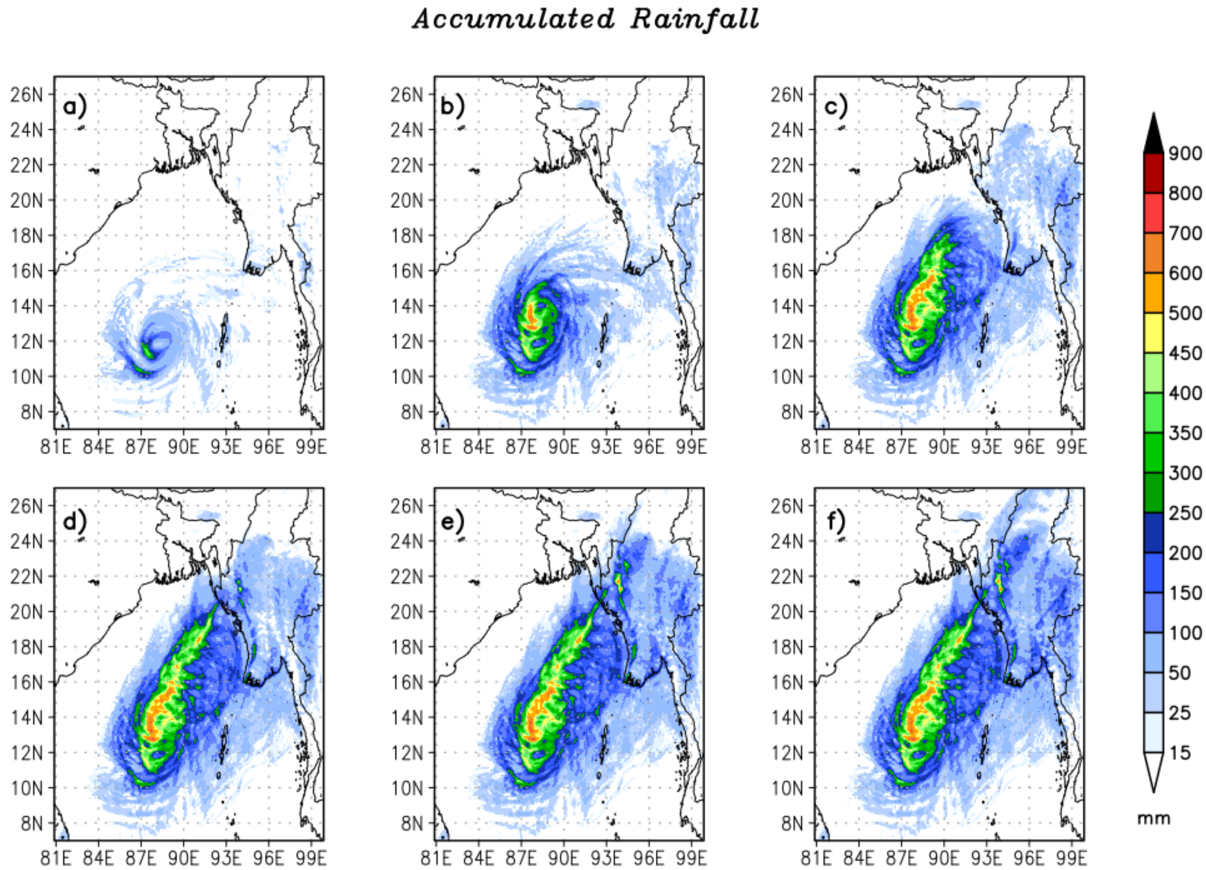

Figure 13: *Model Simulated Accumulated Rainfall of Cyclone Mocha Valid for (a) 11 May 1200 UTC, (b) 12 May 1200 UTC, (c) 13 May 1200 UTC, (d) 14 May 0300 UTC, (e) 14 May 1200 UTC, and (f) 14 May 2100 UTC.*

The figure showing the model-simulated accumulated rainfall for Cyclone Mocha from 11–14 May displays a detailed temporal and spatial evolution of rainfall associated with the storm. On 11 May (a), rainfall is mostly confined to the cyclone's core, with accumulations ranging from 15 to 100 mm in the Bay of Bengal. By 12 May (b), the cyclone intensifies, and the rainfall area expands, with localized accumulations exceeding 250 mm around the core. On 13 May (c), the cyclone strengthens further, with heavy rainfall (up to 450 mm) concentrated near its center and extending outward. During landfall on 14 May 0300 UTC extreme rainfall is observed, with areas exceeding 500 mm, particularly over the coastal regions of Myanmar and northeastern India. The figures also depict the widespread distribution of rainfall over the ocean and land during this time, with accumulations of 100–300 mm persisting inland after landfall.

Comparison between Simulation and Observation

1. Track Forecast

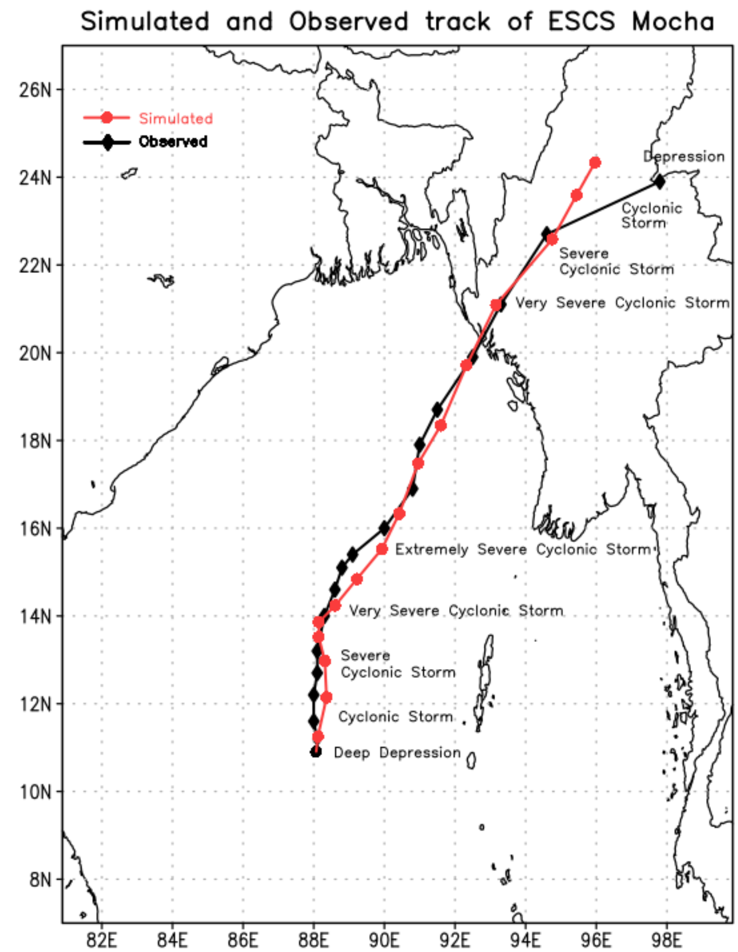

Figure 14: *Comparison of Model Simulated Forecast Track (based on 0000UTC 11 May 2023) with the observed of IMD Best Track.*

The figure shows the simulated track **based on 11 May 00 UTC** and observed tracks of Extremely Severe Cyclonic Storm (ESCS) Mocha from 00 UTC on 11 May 2023 to 00 UTC on 15 May 2023. Both tracks align closely, showing the cyclone's progression from a deep depression over the central Bay of Bengal. It intensifies into a cyclonic storm, severe cyclonic storm, very severe cyclonic storm, and eventually reaches the extremely severe cyclonic storm stage. The cyclone follows a north-northeastward path before making landfall along the Myanmar coast near the northern Bay of Bengal. Post-landfall, it weakens rapidly, transitioning into a depression.

The simulated track matches the observed one very well, especially during the cyclone's strengthening and movement over the sea. Both tracks show the same stages of development: cyclonic storm, severe cyclonic storm, and very severe cyclonic storm, before reaching maximum strength. **After landfall**, there are similarities but towards the **end of the track there is significant differences in the tracks**, mostly in how quickly the cyclone weakened and its exact path. These differences might be due to the way land interactions are modeled.

2. Mean Sea Level Pressure

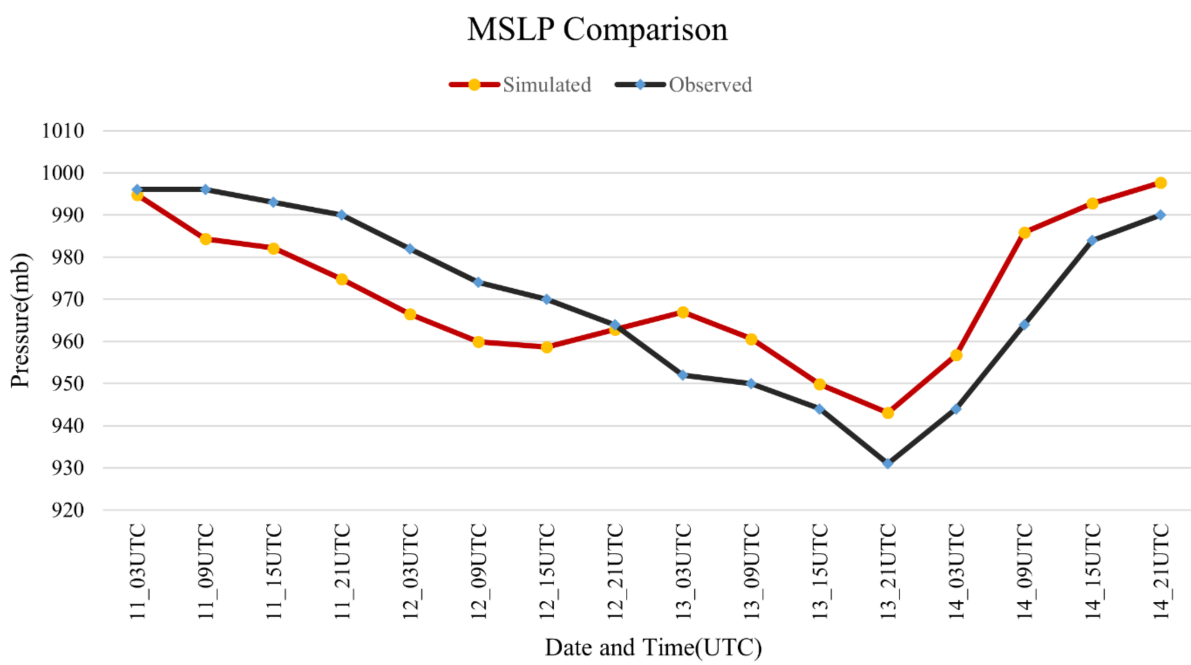

Figure 15: *Time Series of Model Simulates and Observed Mean Sea Level Pressure (mslp)*

The **MSLP comparison** graph for **Cyclone Mocha** illustrates the differences between the **simulated** and **observed** pressure over time. Initially, the simulated MSLP underestimates the observed values from **11 May 03:00 UTC to 12 May 03:00 UTC**, with the observed pressure showing slightly higher values during the cyclone's early development. At **12 May 21:00 UTC** the simulated and observed pressure is similar. As the cyclone intensifies, both the simulated and observed pressures drop, with the model capturing the trend more closely between **12 May 03:00 UTC and 13 May 15:00 UTC**. However, the model simulates a sharper and more rapid intensification, particularly noticeable around **13 May 21:00 UTC**, where it predicts a lower MSLP than observed. In the weakening phase after **13 May 21:00 UTC**, the simulated MSLP rises faster than the observed, indicating that the model predicts a quicker recovery. Overall, while the model captures the cyclone's general trend, it overestimates the rate of intensification and weakening, particularly during the peak and recovery phases, showing notable discrepancies during those periods.

3. Wind Speed

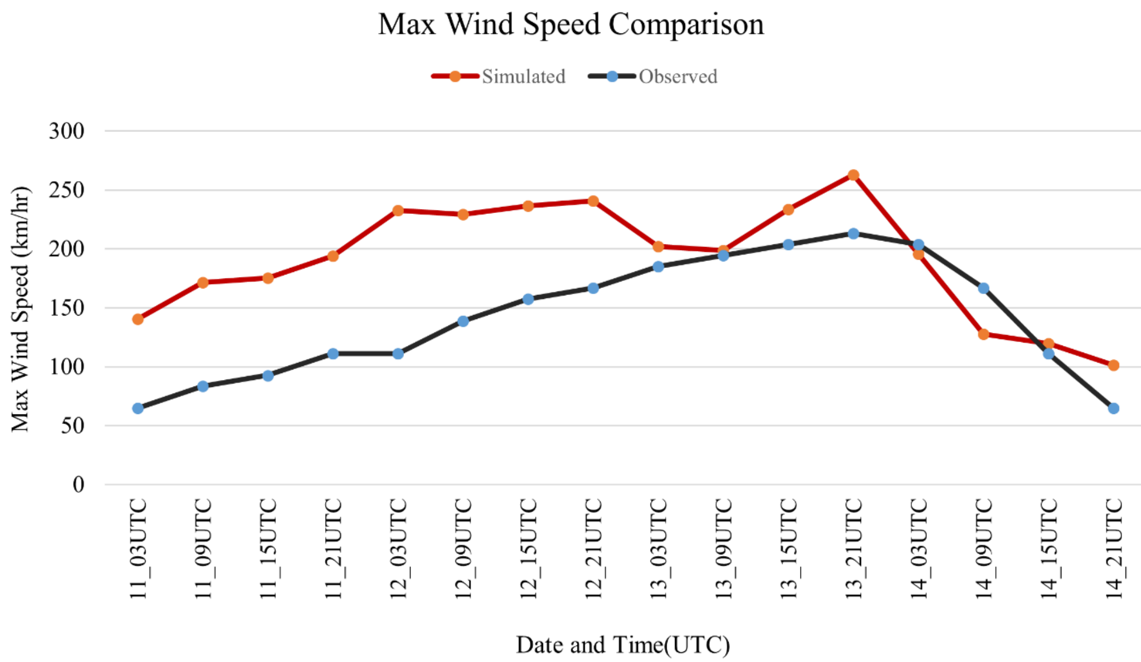

Figure 16: *Time Series of Model Simulates and Observed Maximum Surface Winds (kmph)*

The Max Wind Speed comparison for Cyclone Mocha shows that the simulated wind speeds consistently overestimate the observed values throughout most of the cyclone's lifecycle. From **11 May 03:00 UTC** to **13 May 03:00 UTC**, the model predicts significantly stronger winds than observed. As the cyclone intensifies, both the simulated and observed wind speeds rise, with the simulated peak reaching around **250 km/hr** on **13 May 15:00 UTC**, compared to the observed peak of approximately **200 km/hr**. Although the model follows the general trend of wind speed, it overestimates the cyclone's intensity at its peak. As the cyclone weakens after **13 May 15:00 UTC**, the model predicts a faster decrease in wind speed than observed, with the simulated values eventually falling below the observed wind speeds by **14 May 21:00 UTC**, indicating a quicker dissipation than in reality. At 13 May 09:00 UTC, 14 May 03:00 UTC and 14 May 15:00 the simulated and observed wind speed is at similar value. Overall, the model captures the cyclone's development but tends to exaggerate both the peak intensity and the rate of weakening.

Conclusion

The analysis of Cyclone Mocha highlights its complete lifecycle, dynamics, and associated atmospheric parameters, providing valuable insights into the behavior of severe tropical cyclones. Cyclone Mocha evolved from a low-pressure system to a Extremely Severe Cyclonic Storm (ESCS) within a few days, illustrating the rapid intensification that occurred under favorable environmental conditions, such as high sea surface temperatures (SST) and low vertical wind shear. This development aligns with the typical behavior of tropical cyclones in the Bay of Bengal. The parameters illustrated explains the behavior and evolution of the cyclone.

Additionally, the analysis reinforced the importance of moisture flux, vertical wind shear, and low-level vorticity in the formation and intensification of cyclones. The findings demonstrated how heat and moisture fluxes from the ocean play a critical role in sustaining the cyclone's strength, while the vertical wind shear analysis showed that low-shear environments were conducive to the cyclone's intensification.

Including **low-level relative vorticity**, a key parameter in cyclone dynamics, was significant throughout all stages of Cyclone Mocha's lifecycle. The simulation revealed peak vorticity values of approximately $300 \times 10^{-5}\ s^{-1}$ at the cyclone's core, which expanded as the system intensified. The presence of spiral banding structures around the core was also evident, highlighting the well-organized nature of the cyclone as it reached its peak intensity. The analysis underscores the importance of examining **vertical wind shear** patterns in understanding the atmospheric conditions that govern tropical cyclone behavior in the Bay of Bengal. The **upper-level divergence** at 200 hPa and **lower-level convergence** at 925 hPa during Cyclone Mocha demonstrate the crucial dynamics of air flow that sustain the storm's structure and intensification by efficiently evacuating air at higher altitudes and drawing in warm, moist air at lower levels.

Additionally, the analysis of **pressure** and **wind fields** demonstrated a substantial drop in central pressure and an increase in wind speeds during the cyclone's peak. These patterns are consistent with the development of a strong and well-defined cyclonic system, validated further by comparison of the model's outputs and observed data. The **rainfall** distribution, particularly during the landfall stage, emphasized the heavy precipitation and strong winds associated with Cyclone Mocha, resulting in significant impacts on the affected regions.

However, the analysis also revealed some discrepancies between the simulated outputs and observed data, especially in terms of wind speed and sea level pressure. The model tended to overestimate the maximum wind speeds during the cyclone’s peak intensity and predicted a more rapid intensification and weakening than what was observed. Similarly, while the simulated track closely aligned with the observed one during the cyclone's development and movement over the sea, differences emerged post-landfall, particularly in how quickly the cyclone weakened and the exact path it followed. These discrepancies highlight the challenges associated with accurately modeling the internal dynamics and land interactions of such a complex storm system. The overestimation of wind speeds and variations in track evolution suggest that further calibration of model physics, particularly in relation to convection, moisture processes, and land interaction dynamics, is necessary to enhance the accuracy of predictions.

In conclusion, the simulation of Cyclone Mocha highlighted both the strengths and limitations of NWP models in forecasting tropical cyclones. The analysis of Cyclone Mocha illustrates the crucial role of atmospheric dynamics, such as low-level vorticity and pressure changes, in influencing the lifecycle and impacts of tropical cyclones. The findings emphasize the importance of accurate modeling and monitoring for effective early warning systems and disaster preparedness. Cyclone Mocha serves as a critical case study to improve our understanding of cyclonic systems in the Bay of Bengal, offering valuable lessons for enhancing climate resilience and adaptation strategies in vulnerable regions.

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