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(Research Article)

Analysis of major cyclone storms 'mocha 2023', 'Mandous 2022' of recent years over India

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Abstract

The current study outlines how ocean conditions contributed to the development, intensification and dissipation of the extremely severe cyclonic storms "Mocha" (ESCS) (2023), severe cyclonic storm (SCS) "Mandous" (2022), very severe cyclonic storm (VSCS) "Asani" (2022), and (ESCS) "Tauktae" (2021). 'Mocha' tropical cyclones (TC) formed over warm waters over the southeast Bay of Bengal and the adjacent northern Andaman Sea on May 11–12, 2023, 'Mandous' over the southeast Bay of Bengal on December 6-7, 2022. The European Centre for Medium-Range Weather Forecasts (ECMWF) generated ECMWF reanalysis V5 (ERA5), which is used in the present study to analyse the sea surface temperature (SST), latent heat flux, relative vorticity (RV), specific humidity, and relative humidity during the lifetime of the storm. The analysis of the TC's sea surface temperature data from satellites suggests that a much warmer SST was present throughout the cyclone's existence, which may have been the primary reason for the TC's fast intensification. Latent Heat flow (LHF) was found to be high along with SST values. As the TC approached the coast, an RV value that was both positive and significant was discovered. During intensification, Specific and Relative Humidity also had high levels.

Keywords: Tropical Cyclone Storm; Relative Vorticity; Sea Surface Temperature; Latent Heat Flux; Specific Humidity; Relative Humidity

1. Introduction

Tropical cyclones, notorious for their devastating impact, are among the most perilous weather phenomena globally. These expansive, rotating storms originate above warm tropical ocean waters. India's extensive 7500 km coastline exposes its coastal regions along the North Indian Ocean basin to heightened vulnerability from tropical cyclones originating in both the Bay of Bengal (BoB) and the Arabian Sea. Cyclones originating in the Bay of Bengal (BoB) and the Arabian Sea, prevalent during the pre-monsoon and post-monsoon periods, primarily affect India. These cyclones generally follow a west-to-northwest trajectory. With a typical lifespan of 4-6 days, their occurrence frequency averages at 4 over the Bay of Bengal and 1 over the Arabian Sea. Accurate early forecasts pertaining to the formation, progression, and path of these cyclones hold the potential to avert numerous fatalities [1]. As per previous research findings, tropical cyclones predominantly emerge over oceanic regions characterized by elevated Sea Surface Temperatures (SST) surpassing 26 °C. Factors such as Latent Heat Flux, Vorticity Mixing, High Wind Velocity, among others, also play significant roles in their development [2-8].

In recent times, The Severe Cyclonic Storms named as Mocha (2023), Mandous (2022), brought about significant devastation in the coastal regions of southeastern and western states of india. The India Meteorological Department (IMD) categorized these as a marginal cyclone originating within the BoB. As it made landfall, the cyclone transformed into a deep depression, leading to substantial agricultural losses. This occurrence in the month of May marked an

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unusual event, as cyclones of this magnitude are rare during this time. The cyclone's trajectory displayed variability, undergoing shifts in direction and eventually weakening within a single day.

The present study delves into the synoptic and dynamical factors that contributed to the genesis, intensification, and eventual weakening of the Severe Cyclonic Storm (SCS). Specifically, the investigation revolves around the impact of synoptic-scale elements such as upper-level dynamics, encompassing wind analyses at 850 hPa level. Moreover, the atmospheric parameters such as Specific and Relative Humidity, Relative Vorticity, Latent Heat Energy Fluxes, and Sea Surface Temperature (SST) are also scrutinized for their roles in the cyclone's behaviour and attributes.

2. Material and method

The current investigation employs satellite-derived daily sea surface temperature (SST) measurements, sourced from the ERA5 platform, to scrutinize the cyclone's formidable characteristics. The level 4 global data product, which combines data from several sensors, is the SST data that is used. Comprehensive information regarding this SST dataset can be accessed on the ECMWF website. Furthermore, the study utilizes ERA5 data encompassing 'Latent Heat Fluxes,' 'Wind Speed and Direction,' and 'Relative Vorticity', 'Specific and Relative Humidity', 'Total Column Ozone'. To facilitate this, ERA5 hourly data at single levels spanning from 1959 to the present can be obtained through the provided link. The observational best track data, were sourced from the India Meteorological Department (IMD) in New Delhi as shown in Fig.1. Additional details concerning the Extreme Severe Cyclonic Storm (ESCS), Very Severe Cyclonic Storm (VSCS), Severe Cyclonic Storm (SCS) Mocha and Mandous are available on the IMD's official website. All the Observed tracks of the Cyclone Storms were designed in ArcMAP 10.8.2. Data of SST, Relative Vorticity, Latent Heat Flux, and Specific and Relative Humidity from ERA5 were extracted and plotted by GrADS 2.2 and Python 3.11. The Cyclone Events are verified using true color images taken from NASA World View as shown in the Fig.2,3.

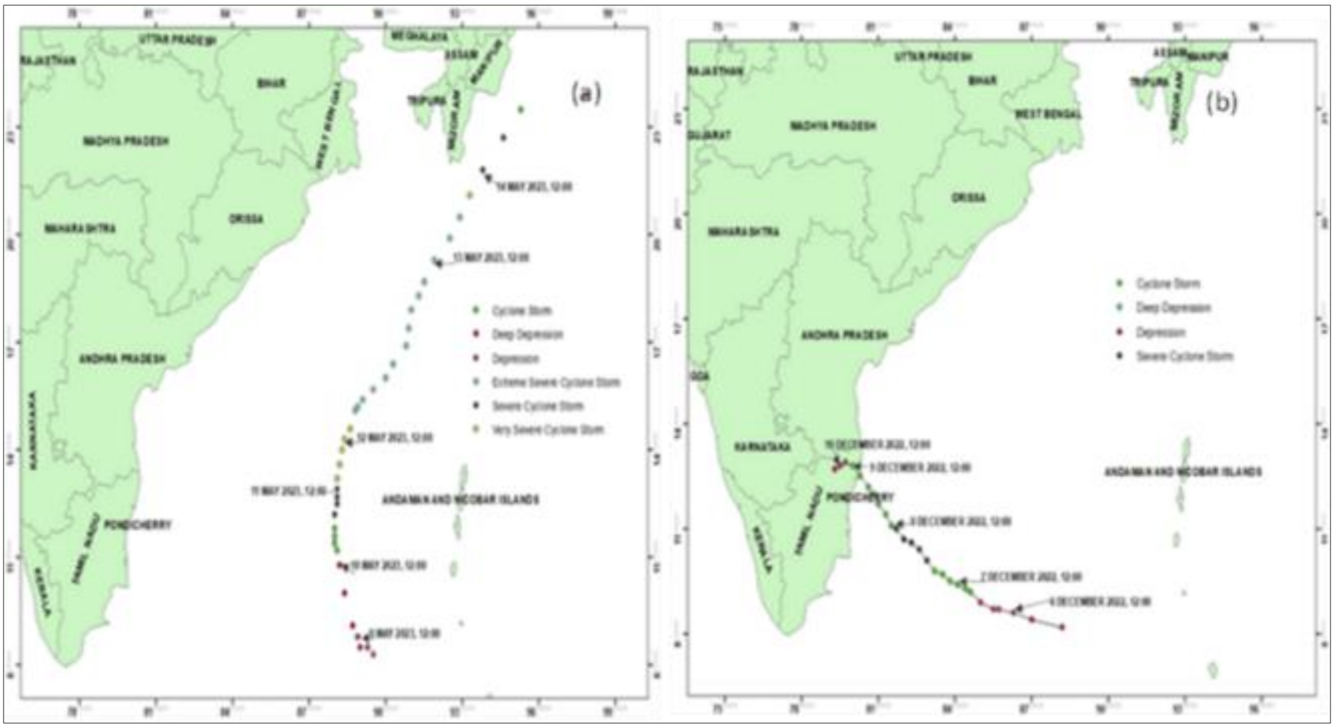

Figure 1 (a) Track observation for the ESCS "Mocha" (b) The SCS 'Mandous' track was seen. Using the best track data from the India Meteorological Department (IMD), the observed track has been plotted

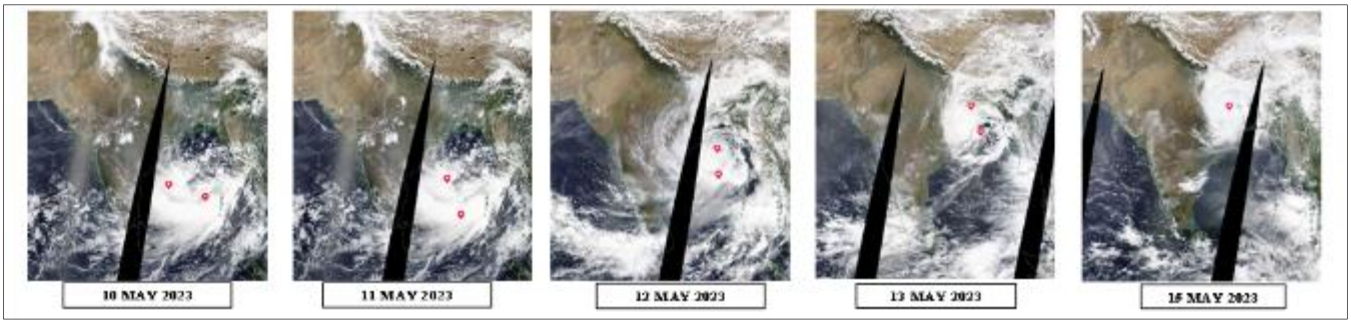

Figure 2 True Color Images of ‘Mocha’ Tropical Cyclone Storm by NASA World View

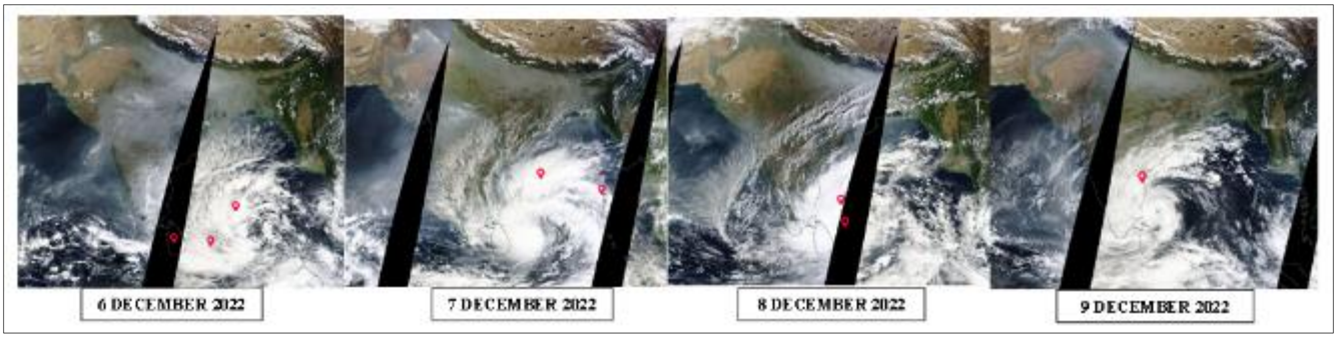

Figure 3 True Color Images of ‘Mandous’ Tropical Cyclone Storm by NASA World View

3. Results and discussion

3.1. Sea surface temperature

Academic literature extensively acknowledges the importance of sea surface temperature (SST) in the development and strengthening of tropical cyclones (TCs). Both the strengthening of tropical cyclones and their influence on SSTs themselves are critically dependent on SSTs [9]. Various factors like strong winds, evaporation, and dense cloud cover significantly impact the SST, affecting only the shallow surface layer of the ocean. The majority of tropical cyclones (approximately 98.3%) form when SSTs exceed 25.5 degrees Celsius [10]. It is noteworthy that the passage of cyclones into areas with warmer SSTs is directly related to the rapid intensification of cyclones [11]. Interestingly, when cyclones undergo rapid intensification and subsequently pass over regions, they induce a cooling effect on the SST by several degrees [12]. In this study, the authors investigated the daily SST variations during the occurrence of Extreme Severe Cyclonic Storm (ESCS) ‘Mocha’, Severe Cyclonic Storm(SCS) ‘Mandous’, Very Severe Cyclonic Storm(VSCS) ‘Asani’, Extreme Severe Cyclonic Storm(ESCS) ‘Tauktae’ aligning with the ‘SST theory’ of rapid intensification. Fig.6-9 Synoptic Plot illustrates the observed SST values over the lifespan of ESCS, VSCSs, and SCS ‘Mocha’, ‘Mandous’ (from 10th May to 15th May 2023), (from 6th December to 11th December 2022), respectively. Fig. 4,5 revealed that a warmer SST pool (~ 29-30 degrees Celsius) existed over the southeastern Bay of Bengal and the adjacent northern Andaman Sea during 11-12 May 2023 of ESCS ‘Mocha’, over Southeast Bay of Bengal during 6-7 December 2022 of SCS ‘Mandous’. This warmer SST region exhibited a temperature elevation of 2-3 degrees compared to its surroundings, creating favorable conditions for the genesis of a robust weather system. The existence of this warm SST pool likely contributed to the strengthening and progression of ESCS ‘Mocha’ and SCS ‘Mandous’. Notably, prior to landfall, the Indian Meteorological Department (IMD) reported rapid intensification of the cyclone on 12th May 2023, 8th December 2022, 9th May 2022, and 16th May 2021 respectively. Fig.4,5. displayed a region of elevated SSTs along the Bangladesh coast, South Andra coast, Andra coast, and Saurashtra coast respectively which could have fueled the rapid intensification process preceding landfall. Following landfall, a comparatively cooler SST (around 27-28 °C) could be seen in the respective Figures.

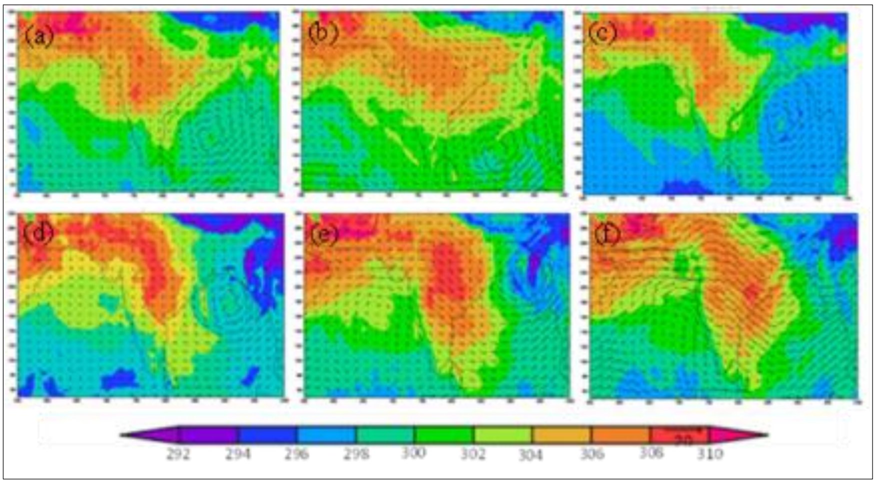

Figure 4 (a-f) Daily ESCS ‘Mocha’ sea surface temperature charts. Satellite observations were used to create the SST data. The values of the colour bars represent the observed SSTs in Kelvin. The plot was produced using the GrADS and Python programmes

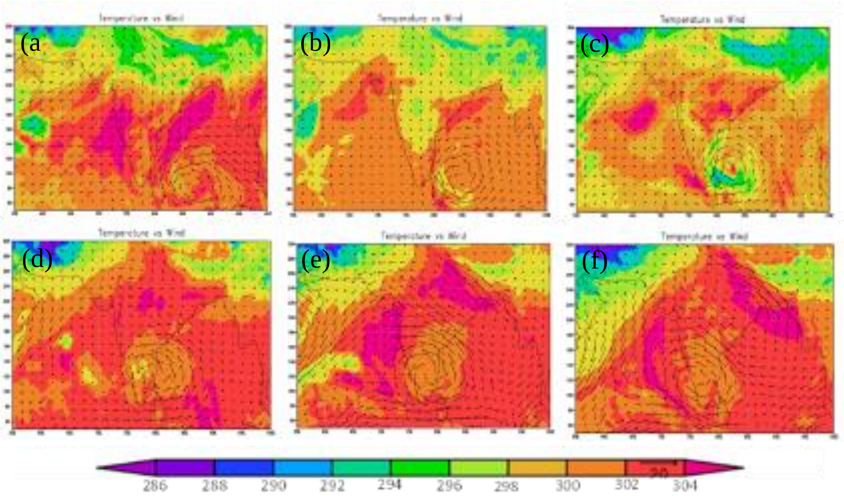

Figure 5 (a-f) Daily SCS ‘Mandous’ sea surface temperature charts. Satellite observations were used to create theSST data. The values of the colour bars represent the observed SSTs in Kelvin. The plot was produced using the GrADS and Python programmes

3.2. Latent heat flux

A region of high surface latent heat fluxes, which signifies the transfer of heat from the ocean to the atmosphere during a tropical cyclone’s strengthening phase, is often associated with an area where cyclones are rapidly intensifying [13]. The Clausius-Clapeyron equation, which explains how adding water vapour to warm, saturated air causes the air to able to contain more moisture, is what causes this heat transfer. Condensation, which occurs as the moist air rises in an ascending column, releases a substantial quantity of latent heat, especially in the cyclone’s eye-wall [14,15]. This ‘condensation process,’ in which a small portion of the energy generated during condensation is transformed into mechanical energy, is what drives the increased wind speeds inside tropical cyclones. These stronger winds in turn cause more evaporation and condensation as a result. As a result, condensation (or latent heat) and wind create a positive feedback loop, thus converting the cyclone into a heat engine. However, it’s essential to note that this heat engine relies on a continuous supply of atmospheric moisture, making it dependent on warm ocean waters. Therefore, when a tropical cyclone makes landfall, it loses its energy source and dissipates. The observed latent heat fluxes’(measured in Joules per square meter) daily variations associated with the Extreme Severe Cyclonic Storm(ESCS) ‘Mocha’, Severe Cyclonic Storm(SCS) ‘Mandous’ have been illustrated in Fig.6,7. Initially, a small patch of latent heat associated with the precursor instability can be observed near the cyclone’s genesis region (Fig. 6(a),7(a)). As the tropical cyclone evolves and systematically develops, the latent heat fluxes increase, reaching values exceeding 2500 Joules per square meter near the eye-wall region for Mocha (Fig. 6(b-d)), for Mandous 2600 Joules per square meter

(Fig. 7(c-d)). The story for May 13th, 2023 for Mocha (Fig. 6(d)) graphically depicts the tropical cyclone's quick intensification phase, same for Mandous (Fig. 7(d)) respectively, particularly in the central Bay of Bengal, Tamil Nadu and Coastal Andra Region respectively, where a significant amount of latent heat is emitted over a large area. Following landfall, the latent heat flux appears to decrease as shown in figures Fig. 6(f), Fig. 7(e), underscoring the significant contribution of latent heat release to the intense nature of Tropical Cyclone 'Mocha 2023' and 'Mandous 2022'.

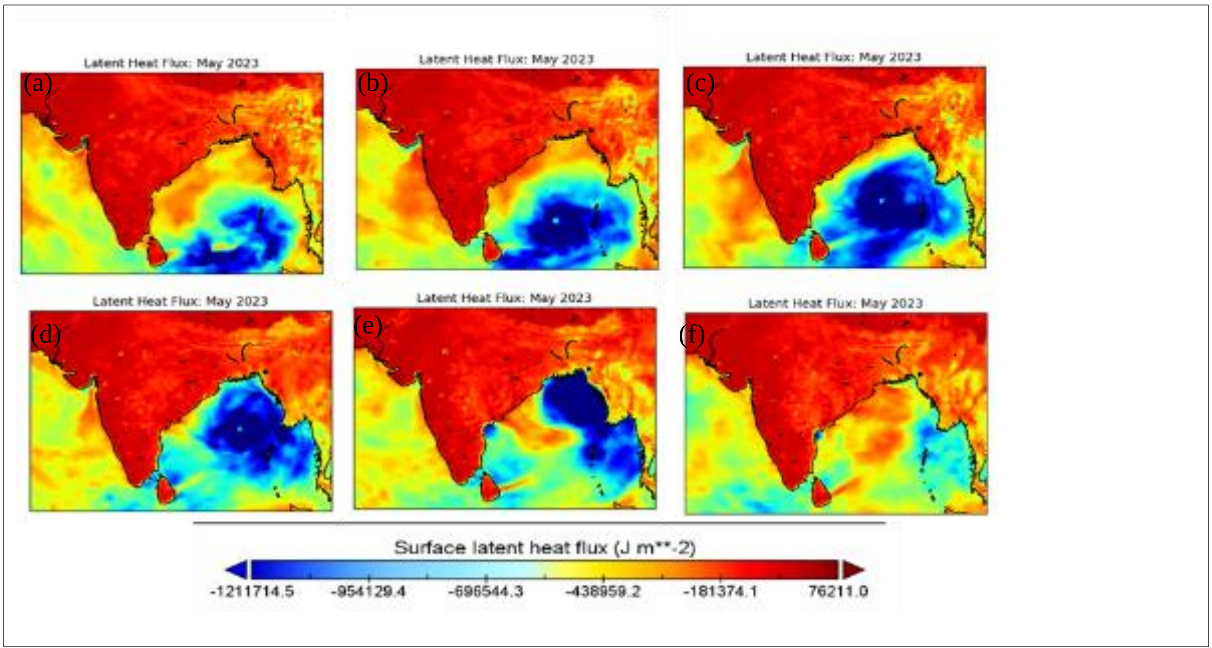

Figure 6 (a-f) Latent heat flow graphs on a daily basis for the ESCS 'Mocha'. The ERA-5 reanalyses were used to gather the latent heat data. Latent heat levels are displayed as color-coded bars with values in Joules meter^{-2}. The figure was created using Python and GrADS software

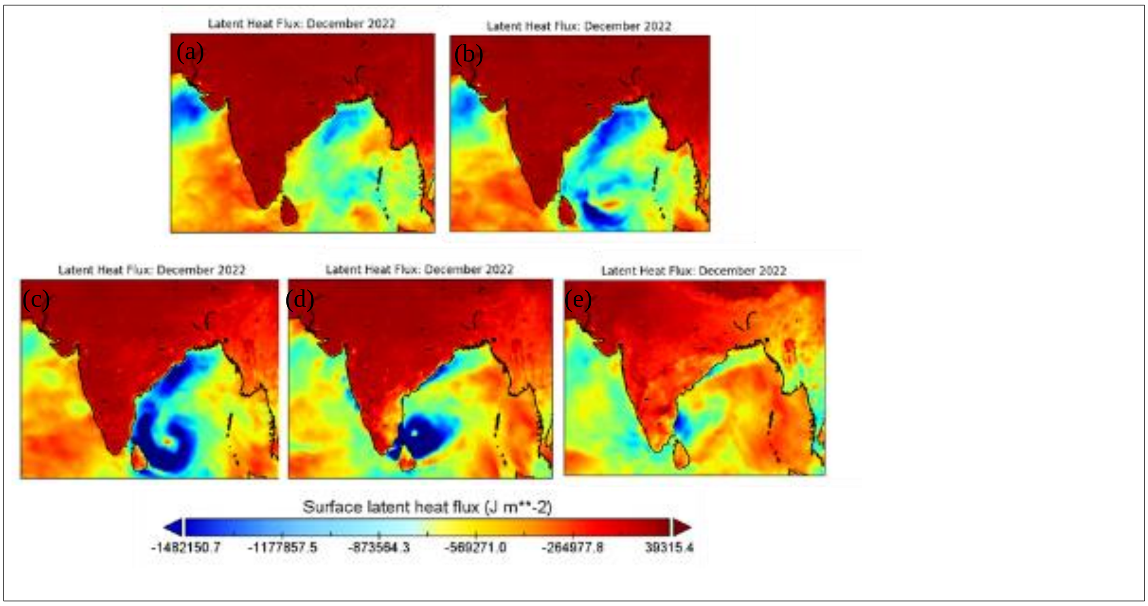

Figure 7 (a-e) Latent heat flow graphs on a daily basis for the SCS 'Mandous'. The ERA-5 reanalyses were used to gather the latent heat data. Latent heat levels are displayed as color-coded bars with values in Joules meter^{-2}. The figure was created using Python and GrADS software

3.3. Relative vorticity (RV)

Relative Vorticity(RV) has an impact on how quickly TCs emerge all over the world. The trio of "shear," "curvature," and "Coriolis" causes vorticity to form in cyclones [16,17].In general, a positive and high RV value in the lower troposphere (up to 850 hPa pressure level) favours the genesis and intensification of cyclones. However, the weakening of TCs is connected to the negative RV. RV in TCs is more than $10*10^{-5}$ per second at lower levels and within a 100-200 km radius. In relation to a fixed location on the earth's surface, RV measures the air's horizontal rotation around a vertical axis [18].

The cyclonic vortex is forced to migrate northward by the advective effect when a tropical storm is travelling in the direction of the biggest relative cyclonic vorticity tendency. The daily fluctuations in RV during the life cycles of the ESCS "Mocha" and SCS "Mandous" are shown in Fig. 8,9. The colour bar displays the RV's magnitude in "sec^{-1} " units. Plotting the RV variations was done using data from the ERA5. 'Mocha's' origin took place at an area where RV was roughly 0.0001125308 sec^{-1} or a little more, according to Fig. 8(a). Additionally, there was a steady increase in RV from May 11 to May 13, 2023 (Fig. 8(b-d)). The 14th May plot, or a decrease in RV (cooling of the ocean at the moment of landfall) is depicted in Fig. 8(f). that happened after ESCS "Mocha" passed. According to Fig. 9(a), 'Mandous's' genesis took place at an area where RV was roughly 0.000287 sec^{-1} or a little bit more. Additionally, there was a steady increase in RV from December 7 to December 8, 2022 (Fig. 9(b-d)). The graphic for December 9th, or Fig. 9(e), shows a decline in RV (ocean cooling at the landfall point), which happened after SCS "Mandous" passed.

3.4. Specific humidity

In the context of a cyclone or tropical storm, specific humidity refers to the actual concentration of water vapour in the atmosphere at a certain time and location.

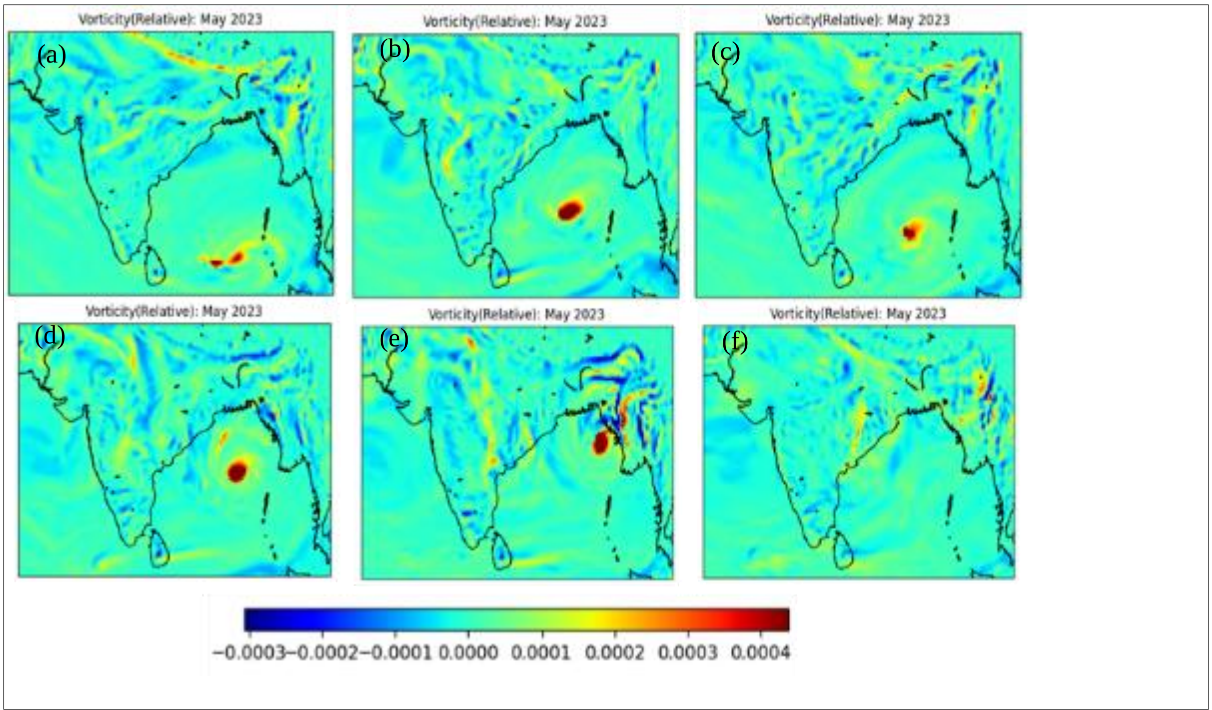

Figure 8 (a-f) Relative Vorticity RV graphs on a daily basis for the ESCS 'Mocha'. The ERA-5 reanalyses were used to gather the RV data. RV levels are displayed as color-coded bars with values in sec^{-1}. The figure was generated using Python and GrADS software

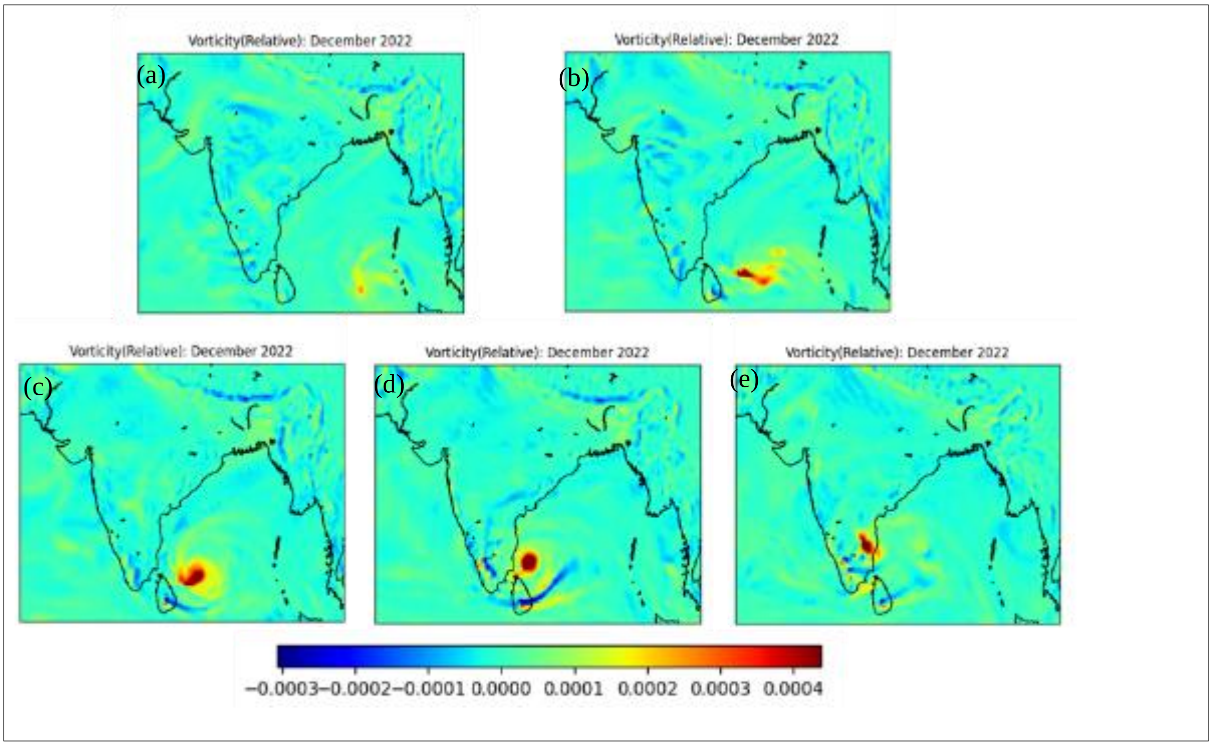

Figure 9 (a-e) Relative Vorticity RV graphs on a daily basis for the SCS 'Mandous'. The ERA-5 reanalyses were used to gather the RV data. RV levels are displayed as color-coded bars with values in sec^{-1}. The figure was generated using Python and GrADS software

It has been a crucial characteristic for comprehending the moisture content of the atmosphere inside and around a cyclone and is normally stated in kg of water vapour per kg of air. Specific humidity, which is the amount of moisture in the air that fuels the storm's energy and helps with processes like condensation, latent heat release, and precipitation, is vital to the genesis, intensification, and behaviour of cyclones. A warm, moist air mass coming into contact with a colder, drier air mass can cause a low-pressure system to form and start a cyclone. The warm, tropical locations where cyclones occur have high specific humidity, which supplies the moisture needed for these storms to grow and intensify[19]. Within a cyclone, latent heat is released when rising air causes water vapour to condense into liquid water. The fundamental energy source for cyclones, which fuels convective activity and intensification, is this heat release [20]. Fig. 10,11. show the daily fluctuations in specific humidity linked with the Extreme Severe Cyclonic Storms (ESCS) "Mocha," and Severe Cyclonic Storms (SCS) "Mandous". Near the cyclone's genesis region, a small patch of Specific Humidity connected to the antecedent instability can initially be seen (Fig. 10(a),11(a)). As the tropical cyclone develops and intensifies, the Specific Humidity rises, exceeding 0.001200 kg/kg of water vapour per kg of air near the eye-wall region for Mocha and 0.00112 kg/kg for Mandous (Fig. 10(b-d) and 11(b-d)). The plot for May 13th, 2023 for Mocha, and December 9th, 2022 for Mandous vividly illustrates the rapid intensification phase of the tropical cyclone, where a significant amount of latent heat is released over a vast area in the central Bay of Bengal, Tamil Nadu, and Coastal Andra, respectively. The specific humidity appears to decline after landfall, highlighting the crucial role that the specific humidity had in the intensity of Tropical Cyclones "Mocha in 2023" and "Mandous in 2022," as shown in Fig. 10(f), 11(f).

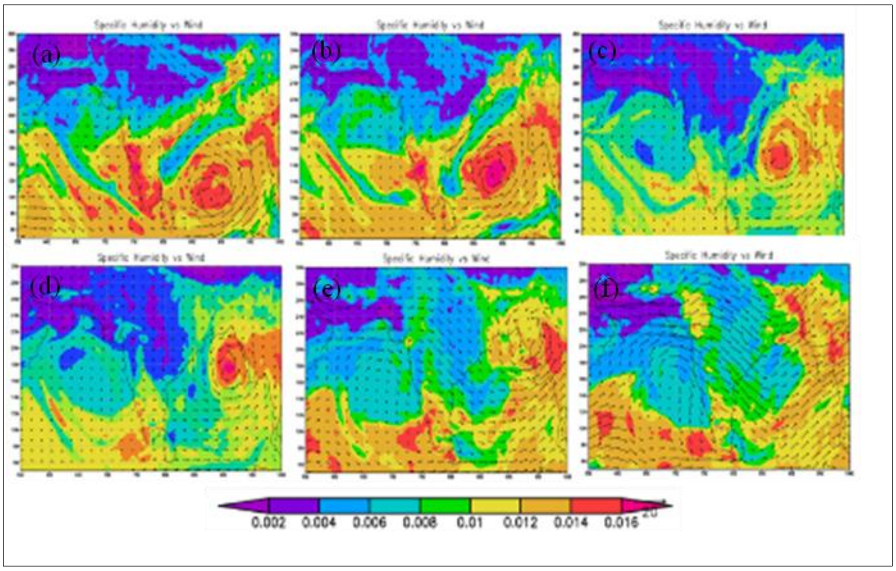

Figure 10 (a-f) Specific Humidity graphs on a daily basis for the ESCS 'Mocha'.The ERA-5 reanalyses were used to gather the Specific Humidity data.Specific Humidity levels are displayed as color-coded bars with values in kg/kg. The figure was created using Python and GrADS software

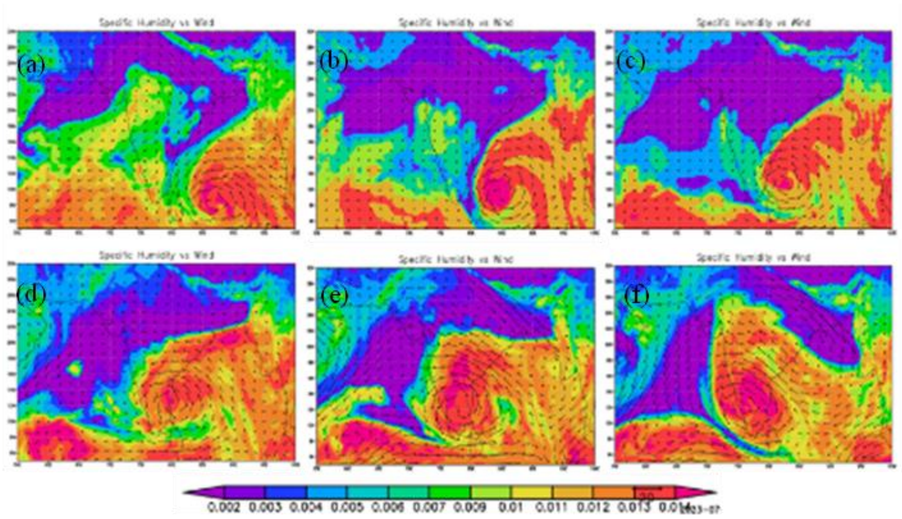

Figure 11 (a-f) Specific Humidity graphs on a daily basis for the SCS 'Mandous'. The ERA-5 reanalyses were used to gather the Specific Humidity data. Specific Humidity levels are displayed as color-coded bars with values in kg/kg. The figure was created using Pythonand GrADS software

3.5. Relative humidity

In the context of a cyclone or tropical storm, relative humidity refers to the air's moisture content in relation to its ability to retain moisture at a given temperature [21]. It is represented as a percentage and reveals how near to saturation with moisture the air is at a specific temperature. It offers information on the air's moisture content, the chance of condensation and the release of latent heat, as well as the likelihood that these weather systems may bring heavy rain. A key element in determining the stability of the environment is relative humidity. When the relative humidity in the air reaches 100%, the air is saturated and has a tendency to rise [22]. Rising air is necessary for the establishment of low-pressure systems at the surface, which are necessary for the development of cyclones [16]. It need a lot of relative humidity close to the surface for cyclones to form and intensify. The necessary moisture for these storms is provided by warm, moist air from the ocean. When the relative humidity is high, the air is almost completely saturated with moisture, which might help a storm intensify [22]. The convective process is encouraged by high relative humidity. At higher elevations, warm, humid air cools and condenses. Latent heat is released during this process, enhancing and increasing the storm's updraft. Cyclones can grow and intensify in environments with high relative humidity, particularly close to the surface [23]. The daily fluctuations in relative humidity during the life cycles of the ESCS 'Mocha' and SCS 'Mandous' are shown in Fig. 12,13. Plotting the fluctuations in relative humidity with data from the ERA5. 'Mocha's' origin took place in a location where Relative Humidity was close to 26% or a bit more, according to Fig. 22(a). Additionally, from May 11 to May 13, 2023, there was a steady increase in relative humidity that reached up to 107% (see Fig. 12(b-d)). The plot for May 14 (Fig. 12(e)) shows that after ESCS "Mocha" passed, there was a reduction in relative humidity (cooling of the waters near the landfall point). According to Fig. 13(a), the birth of "Mandous" took place in an area where the relative humidity was close to or slightly higher than 47%. Additionally, there was a steady increase in relative humidity from December 7 to 8, 2022, reaching up to 98 percent (see Fig. 13(b-d)). After SCS "Mandous" passed, the 9th December plot (i.e., Fig. 13(f)) shows a decline in Relative Humidity (cooling of the ocean at landfall point).

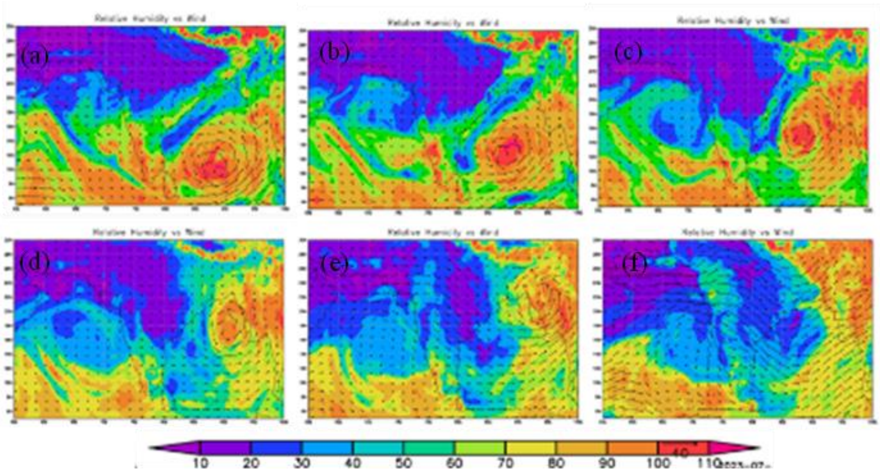

Figure 12 (a-f) Relative Humidity graphs on a daily basis for the ESCS 'Mocha'. The ERA-5 reanalyses were used to gather the Specific Humidity data. Specific Humidity levels are displayed as color-coded bars with values in kg/kg. The figure was created using Python and GrADS software

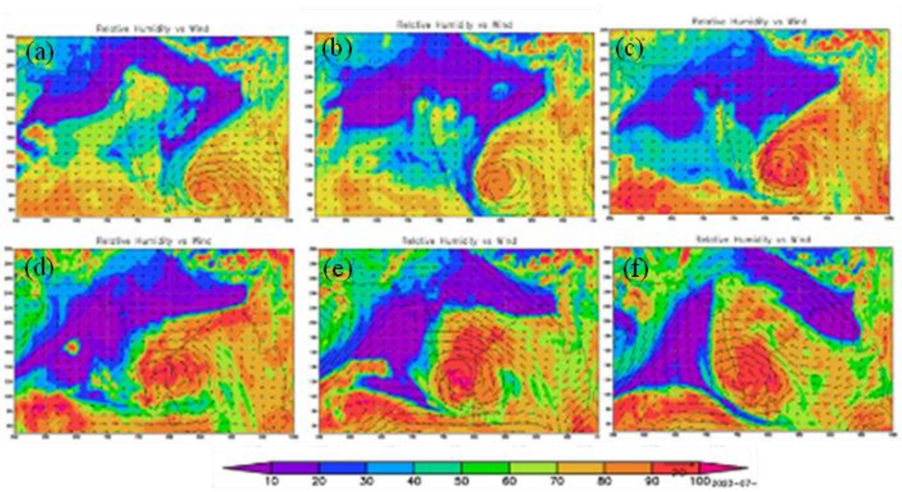

Figure 13 (a-f) Relative Humidity graphs on a daily basis for the SCS 'Mandous'. The ERA-5 reanalyses were used to gather the Specific Humidity data. Specific Humidity levels are displayed as color-coded bars with values in kg/kg. The figure was created using Python and GrADS software

4. Conclusion

In this study, the rapid rise in the sea surface temperature helped in the building up of SCS, VSCS and ESCSs. In particular for tropical cyclones, latent heat flow is a crucial factor in the development and intensification of cyclone storms. All of the cyclone storms we studied—Mocha and Mandous—had varying latent heat fluxes, but high latent heat flux release gave them strength and fueled their intensification. A crucial factor that influences the development, motion, and behaviour of cyclone storms is relative vorticity. While negative relative vorticity can hinder or weaken cyclones, positive relative vorticity is often favorable for cyclone growth and intensification. The airflow from the storm is enhanced by positive relative vorticity aloft (above the cyclone), improving its ability to ventilate. It encourages intensification. Inhibiting outflow and possibly introducing wind shear, negative relative vorticity aloft might throw off the storm's organisation and cause it to deteriorate. Cyclones arise in warm, tropical climates with high specific humidity, which supplies the moisture needed for these storms to grow and intensify. It offers information on the air's moisture content, the chance of condensation, and the release of latent heat, as well as the likelihood that these weather systems may bring heavy rain. Cyclones can grow and intensify in environments with high relative humidity, particularly close to the surface.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that they have no competing interests.

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