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Key factors behind super cyclone Gonu (1-7 June 2007) over the Arabian Sea

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सार – सुपर साइक्लोन गोनू (1-7 जून 2007) अरब सागर में दर्ज किया गया पहला श्रेणी 5 उष्णकटिबंधीय चक्रवात था और पिछले 35 वर्षों में भारतीय मौसम विभाग द्वारा रिपोर्ट किए गए केवल पाँच सुपर साइक्लोनिक तूफानों में से एक था। भारतीय ग्रीष्मकालीन मॉनसून की शुरुआत के तुरंत बाद निर्मित, चक्रवातजनन के लिए आमतौर पर प्रतिकूल अवधि के दौरान गोनू की तीव्र तीव्रता जलवायु संबंधी मानदंडों से एक उल्लेखनीय विचलन का प्रतिनिधित्व करती है। यह अध्ययन ERA5 पुनर्विश्लेषण, NOAA OISST और IMD बेस्ट ट्रैक डेटा का उपयोग करके इसके विकास को सक्षम करने वाले वायुमंडलीय और महासागरीय कारकों की जांच करता है। विश्लेषण से पता चलता है कि असामान्य रूप से उच्च समुद्री सतह का तापमान, मध्य से ऊपरी क्षोभमंडलीय आर्द्रता में वृद्धि, और निम्न से मध्यम ऊर्ध्वाधर पवन कतरनी ने एक अत्यधिक अनुकूल ऊष्मागतिक वातावरण बनाया। मध्य-अक्षांशीय पश्चिमी पवनों के दक्षिण की ओर प्रवेश ने उष्णकटिबंधीय पूर्वी जेट को बाधित कर दिया, जिससे ऊपरी-स्तरीय विचलन में वृद्धि हुई और प्रबल गहन संवहन को बल मिला। ऊर्ध्वाधर रूप से एकीकृत आर्द्रता परिवहन ने चक्रवात केंद्र में प्रबल दक्षिण-पश्चिमी अंतर्वाह किया, साथ ही भारतीय उपमहाद्वीप से आर्द्रता का भी विचलन हुआ, जिससे मॉनसून की प्रगति में अस्थायी रूप से देरी हुई। जीपीसीपी और आईएमडी डेटासेट से प्राप्त वर्षा विश्लेषण तटीय क्षेत्रों में महत्वपूर्ण पर्वतीय वृद्धि के साथ तीव्र और असममित वर्षा का संकेत देते हैं। संगठित निम्न-स्तरीय भंवरता और निरंतर आर्द्रता अभिसरण ने गोनू की संरचनात्मक अखंडता को भूस्खलन तक बनाए रखा। ये निष्कर्ष प्रारंभिक मौसम चक्रवातजनन में महासागर-वायुमंडलीय अंतःक्रियाओं, बड़े पैमाने पर परिसंचरण, जेट स्ट्रीम परिवर्तनशीलता और वर्षा गतिशीलता के परस्पर प्रभाव को उजागर करते हैं और बदलती जलवायु में चरम उष्णकटिबंधीय चक्रवातों के लिए एकीकृत पूर्वानुमान के महत्व पर बल देते हैं।

ABSTRACT. Super Cyclone Gonu (1–7 June 2007) was the first recorded Category 5 tropical cyclone in the Arabian Sea and one of only five Super Cyclonic Storms(SuCS) reported by the India Meteorological Department(IMD) over the past 35 years. Forming shortly after the onset of the Indian Summer Monsoon, Gonu's rapid intensification during a typically unfavorable period for cyclogenesis represents a remarkable deviation from climatological norms. This study examines the atmospheric and oceanic factors that enabled its development using ERA5 reanalysis, NOAA OISST, and IMD Best Track data. Analyses show that anomalously high sea surface temperatures, elevated mid- to upper-tropospheric humidity, and low-to-moderate vertical wind shear created a highly favorable thermodynamic environment. A southward intrusion of midlatitude westerlies disrupted the Tropical Easterly Jet, enhancing upper-level divergence and supporting vigorous deep convection. Vertically integrated moisture transport revealed strong southwesterly inflow into the cyclone core, with concurrent diversion of moisture from the Indian subcontinent, temporarily delaying monsoon progression. Rainfall analyses from GPCP dataset indicate intense and asymmetric precipitation, with significant orographic enhancement over coastal regions. Organized low-level vorticity and persistent moisture convergence sustained Gonu's structural integrity until landfall. These findings highlight the interplay of ocean–atmosphere interactions, large-scale circulation, jet stream variability, and precipitation dynamics in early-season cyclogenesis and emphasize the importance of integrated forecasting for extreme tropical cyclones in a changing climate.

Key words Super Cyclone Gonu (SuCS), Arabian Sea, rapid intensification, Indian Summer Monsoon, moisture transport.

1. Introduction

Tropical cyclones that experience rapid intensification tend to cause greater damage compared to those that intensify more gradually. Their destructive power is closely linked to how quickly they reach their peak strength, with higher maximum intensification rates leading to more severe impacts (Nekkali *et al.*, 2024). Understanding the mechanisms governing their formation and intensification has become increasingly critical under climate variability, as cyclones are showing trends of increased strength and unpredictability. Rapid intensification (RI) an increase in maximum sustained wind speed of ≥30 knots within 24 hours is a particularly important process, as it significantly amplifies a cyclone's destructive potential with limited warning time (Nekkali *et al.,* 2024; Li *et al.*,2025., Vinodhkumar *et al.,* 2022; Kranthi *et al*. 2023). While RI can occur in cyclones of varying intensities, its consequences are most severe in super cyclones, which pose substantial risks to coastal populations. Historically, the Arabian Sea has been less active for intense cyclones; however, recent decades have witnessed an increase in both frequency and intensity, elevating risks for coastal regions and affecting the ISM (Deshpande *et al.,* 2021; Baburaj *et al.,* 2020). Despite progress in cyclone research, the relationship between cyclone intensity, structure, and impacts in the North Indian Ocean remains underexplored (Nekkali *et al.,* 2024).

Over the past 35 years, the India Meteorological Department (IMD) has recorded only five Super Cyclonic Storms (SuCS) in the North Indian Ocean, with Cyclone Gonu (1–7 June 2007) being the first Category 5 storm in the Arabian Sea. Gonu is unique because it developed immediately after the onset of the ISM, a period typically unfavorable for intense cyclogenesis due to strong vertical wind shear and the presence of the Tropical Easterly Jet (TEJ). The TEJ, along with the low-level jet (LLJ) and the Tibetan anticyclone, constitutes a crucial component of the Asian summer monsoon system, maintained by upper-tropospheric thermal contrasts. Observations indicate that weakening of the TEJ in recent decades has reduced vertical wind shear, creating conditions conducive to tropical cyclone formation. Interannual variability in the TEJ is closely linked to changes in the Walker and local Hadley circulations (Koteswaram,1958; Joseph and Raman, 1966; Findlater, 1966; Krishnamurti and Bhalme, 1976; Sathiyamoorthy, 2005).

Gonu's rapid intensification was facilitated by a combination of favorable oceanic and atmospheric conditions. Anomalously high sea surface temperatures (>1.5 °C above normal), low vertical wind shear resulting from a weakened TEJ, enhanced LLJ activity, mid-latitude intrusions supplying additional instability, elevated mid-tropospheric relative humidity (>70%), and strong upper-level divergence associated with a well-established outflow collectively drove its exceptional strengthening (Dhavale *et al.*, 2022; Krishna & Rao, 2009). In contrast, post-monsoon cyclones such as Kyarr (October 2019) intensified under more conventional favorable conditions, including low shear, high ocean heat content, and abundant mid-level moisture. Despite reaching similar intensities (Category 4–5), Gonu and Kyarr developed under fundamentally different atmospheric and oceanic conditions: Gonu represents a rare early-season cyclone during the ISM onset, whereas Kyarr followed typical post-monsoon development pathways (Wang *et al.,* 2022; Nekkali *et al.*, 2024). Comparative analyses of these events can enhance understanding of cyclone–monsoon interactions.

Operational forecasting of Gonu's RI was challenging, as most numerical models underestimated its intensity despite early satellite detection. Geostationary satellites such as INSAT and Meteosat provided high-frequency visible, infrared, and water vapor imagery, allowing continuous monitoring of its position, cloud structure, and eye formation. Intensity estimates using the manual Dvorak technique (T6.5, ~127 knots, 912 hPa) and the Advanced Dvorak Technique (T7.0, ~140 knots, 894 hPa) were crucial for identifying the RI phase and classifying Gonu as a SuCS. At its peak, mean sea level pressure (MSLP) anomalies reached –10 to –12 hPa below climatology. Rainfall patterns were asymmetric, with maximum totals in the north-eastern quadrant and significant orographic enhancement along Oman's coast, reaching up to 610 mm, 6–10 times the regional annual average. Daily precipitation from GPCP dataset revealed a strong link between cyclone intensity and hydrological impacts, especially in arid regions. Recent studies on North Indian Ocean cyclones, including Tauktae (May 2021), Amphan (May 2020), Asani (May 2022), and Dana (October 2024), provide additional context for understanding extreme cyclogenesis (Vishwakarma & Pattnaik, 2025; Vidya *et al.,* 2023; Kumar *et al.,* 2025). Unlike these pre- or post-monsoon cyclones, Gonu's formation during the monsoon onset phase resulted in distinctive TEJ–LLJ interactions, vertical shear transitions, and moisture redistribution, highlighting the uniqueness and societal relevance of this event.

This study focuses on identifying the atmospheric and oceanic factors responsible for Gonu's rapid intensification, with particular attention to monsoon features such as the disruption of the TEJ by southward intrusion of the Subtropical Westerly Jet (SWJ), Midlatitute Trough and the formation of an upper-level anticyclone. We examine how these dynamics generate strong upper-level divergence, enhance upward motion, and create large-scale conditions conducive to rapid strengthening of Gonu in combination with anomalously warm sea surface temperatures and low vertical wind shear. By elucidating these mechanisms, this work aims to improve understanding of early-season cyclogenesis during the onset phase of the ISM, enhance forecasting of extreme Arabian Sea cyclones, and support early warning systems for vulnerable coastal populations. The manuscript is organized as follows: Section 2 details datasets and methodology, Section 3 presents results and discussion, and Section 4 summarizes conclusions and implications.

2. Data and methodology

This study investigates the formation and rapid intensification of SuCS Gonu (1-7 June 2007) using a combination of observational and reanalysis datasets. Cyclone track and intensity data were obtained from the IMD best track data (rsmcnewdelhi.imd.gov.in) which provides historical records of track position, intensity, and duration over the North Indian Ocean (NIO). Satellite observations, which have significantly improved cyclone monitoring since 1980, were used to validate and track the real-time evolution of Gonu. To assess oceanic conditions, daily sea surface temperature (SST) anomalies were derived from the NOAA Optimum Interpolation Sea Surface Temperature (OISST) dataset at 0.25° × 0.25° resolution. Atmospheric fields, including wind components, relative humidity, mean sea level pressure (MSLP), and vorticity, were analyzed using the ECMWF ERA5 reanalysis dataset at 0.25° × 0.25° resolution. Furthermore, vertically integrated moisture transport (VIMT) was computed to quantify the total moisture flux in the atmospheric column using the formulation.

$$Q = \frac{1}{g}\int_{p_t}^{p_s} q\vec{V}\,\mathrm{d}p$$

where **q** is the specific humidity (kg kg⁻¹), **V** = (**u, v**) represents the horizontal wind components (m s⁻¹), $\mathbf{p_s}$ and $\mathbf{p_t}$ denote the surface and top pressure levels, respectively, and **g** is the acceleration due to gravity (9.8 m s⁻²). The integration was carried out over pressure levels from 1000 hPa to 300 hPa to capture the full vertical contribution of moisture fluxes during the cyclone's evolution. Separate calculations were also performed for the zonal (**u**) and meridional (**v**) components to analyze directional moisture transport, and for specific humidity alone to estimate the total column-integrated moisture and vertical shear of the the zonal wind between 200 hPa and 850 hPa have been calculated.

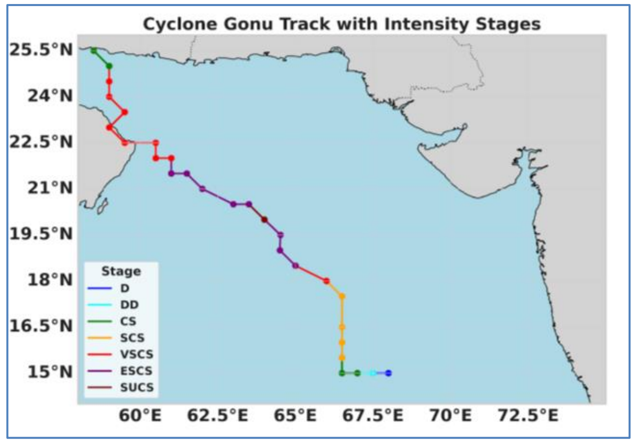


Fig 1. Track of Super Cyclone Gonu (1-7 June 2007) derived from IMD Best Track data, showing intensity stages from depression to super cyclonic storm

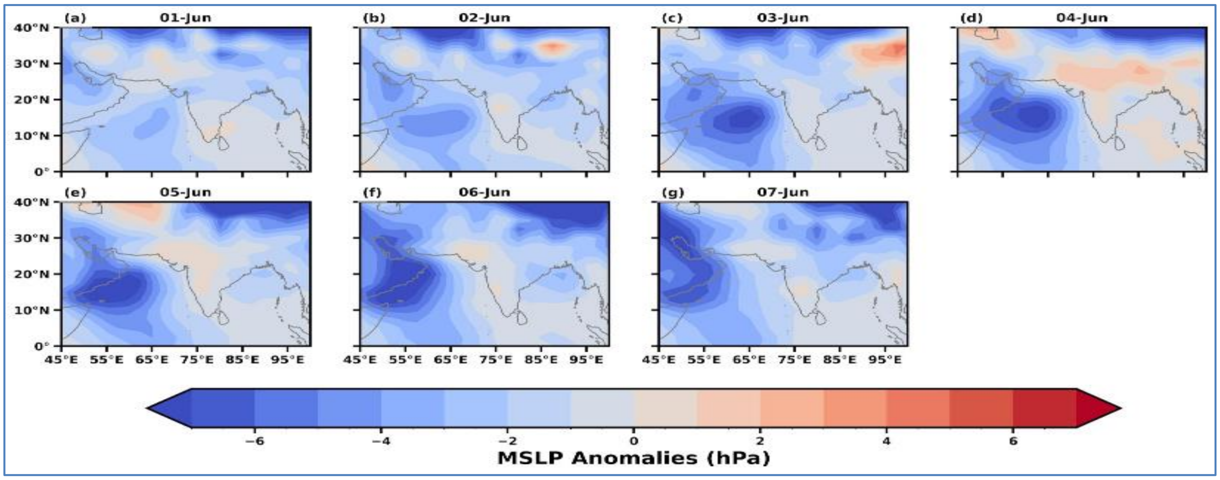
3. Results and analysis

3.1. *Synoptic evolution of super cyclone Gonu*

Fig. 1 depicts the track of SuCS, Gonu, recognized by the IMD as one of the strongest cyclones recorded in the Arabian Sea. The cyclone formed over the east-central Arabian Sea on 1 June 2007, shortly after the official onset of the ISM over Kerala (28 May). From its initial position near 15° N, 69° E, Gonu moved predominantly west-northwestward, intensifying rapidly to reach Category 5/ SuCS intensity by 4 June around 19° N, 64° E. The cyclone maintained extreme strength over a stretch of approximately 600 km across the central Arabian Sea. Following this trajectory, Gonu made an unusual double landfall, first along the eastern coast of Oman on 6 June while still a very severe cyclonic storm, and later on southern Iran on 7 June. This rare path highlights the exceptional nature of Gonu and its significance in the historical record of Arabian Sea cyclones.

Fig. 2 illustrates the evolution of MSLP anomalies during SuCS Gonu, highlighting the dramatic pressure changes associated with this extreme tropical cyclone Figs. 2(a-g). The observed MSLP anomalies reveal a well-defined low-pressure center that intensified steadily from 1 June, reaching its maximum deepening by 4 June (Fig. 2d), corresponding to Gonu's peak strength. The closely spaced pressure contours around the cyclone core indicate exceptionally steep gradients, driving the intense winds. The minimum central pressure dropped below 920 hPa at peak intensity, marking Gonu as one of the most intense cyclones recorded in the Arabian Sea from the IMD best-track data.

The MSLP anomalies further emphasize the extreme nature of Gonu, with negative anomalies of less than -6 hPa at the cyclone center relative to the climatological mean



Figs. 2(a-g). Mean Sea Level Pressure anomalies (hPa) during the Super Cyclone Gonu (1–7 June 2007)

from the 1980 to 2024 Figs. 2(c-f). This demonstrates that Gonu produced an unprecedented low-pressure system for the region and season. The anomaly pattern extended over a wide area of the Arabian Sea, indicating that the cyclone's impact on regional pressure patterns was both strong and spatially extensive Figs. 2(c-f), influencing large-scale atmospheric circulation beyond the immediate vicinity of the cyclone core.

3.2. *Disruption of the tropical easterly jet (TEJ)*

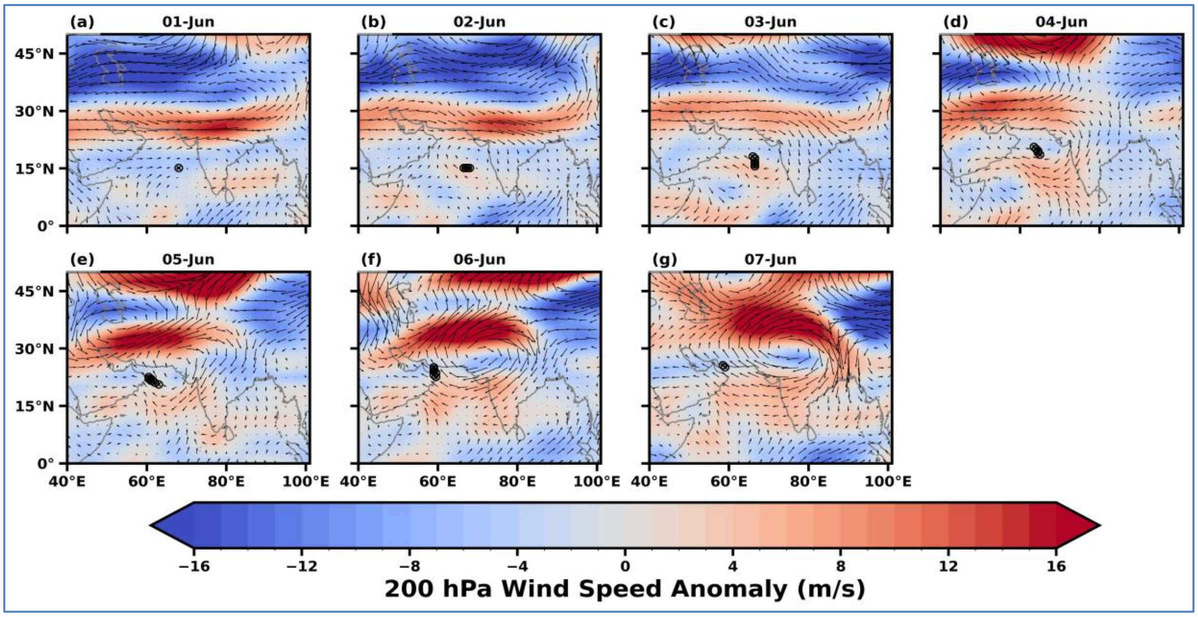
The disruption of the TEJ at 200 hPa plays a crucial role in modulating upper-tropospheric circulation, thereby influencing monsoon dynamics and potentially affecting tropical cyclone intensification. During SuCS, Gonu, observations indicate a pronounced weakening of the TEJ, which altered upper-level divergence patterns and created conditions favorable for rapid cyclone strengthening and an unusual track evolution Figs. 3(a-g).

Typically, a strong and well-organized TEJ provides upper-level divergence that supports deep convection and enhances monsoon rainfall (Sripathi *et al.*, 2024). A weakened or disrupted TEJ reduces this divergence, often resulting in suppressed or erratic precipitation patterns and modifications in the broader monsoon circulation through changes in the thermal wind balance and vertical wind shear. Such disruptions can also contribute to delays in monsoon onset and weaken its progression. Previous studies (Krishna and Rao, 2009) have suggested that rising sea surface temperatures (SSTs) linked to global warming, combined with a reduction in vertical wind shear, have increased the frequency of cyclones over the Arabian Sea, likely due to weakening of the TEJ. The 200 hPa wind analysis during Gonu reveals critical upper-level dynamics enabling rapid intensification despite climatologically unfavorable monsoon onset conditions. The wind magnitude fields show a systematic weakening of the TEJ, with strong easterly winds (>40 m/s) south of 20° N largely diminished during June 2-4 Figs. 3(b-d), coinciding with the cyclone's most rapid strengthening from tropical storm to SuCS intensity.

Wind speed anomalies further clarify the mechanism behind this TEJ disruption. A pronounced southward intrusion of midlatitude westerlies occurred during June 2-5 Figs. 3(b-f), producing strong positive subtropical westerly anomalies of 12-16 m/s across the Arabian Sea and northern Indian Ocean. This anomalous circulation reversed the typical easterly flow, representing a substantial departure from the climatological mean (1980-2024) and highlighting the exceptional atmospheric conditions during Gonu's formation.

The weakening of the TEJ removed the usual upper-level inhibiting effect on tropical cyclone intensification while simultaneously enhancing divergence above the cyclone core. The resultant anticyclonic outflow supported vigorous deep convection and strong updrafts necessary for rapid intensification. The spatial extent of these anomalies indicates that the dynamic disturbance influenced circulation patterns across the entire North Indian Ocean basin, demonstrating that large-scale atmospheric changes can create favorable conditions for extreme cyclogenesis even during periods typically unfavorable for intense tropical cyclones.

During the onset phase of the ISM, the TEJ is a key upper-tropospheric feature that supports large-scale divergence and deep convection. Over the Arabian Sea and peninsular India, its southward displacement enhances zonal wind shear (Sripathi *et al.,* 2024), generally suppressing cyclone intensification despite favouring monsoon depressions.



Figs. 3(a-g). Daily evolution of upper-tropospheric wind speed anomalies (m s^{-1}) at 200 hPa during the development of Super Cyclone Gonu (1–7 June 2007)

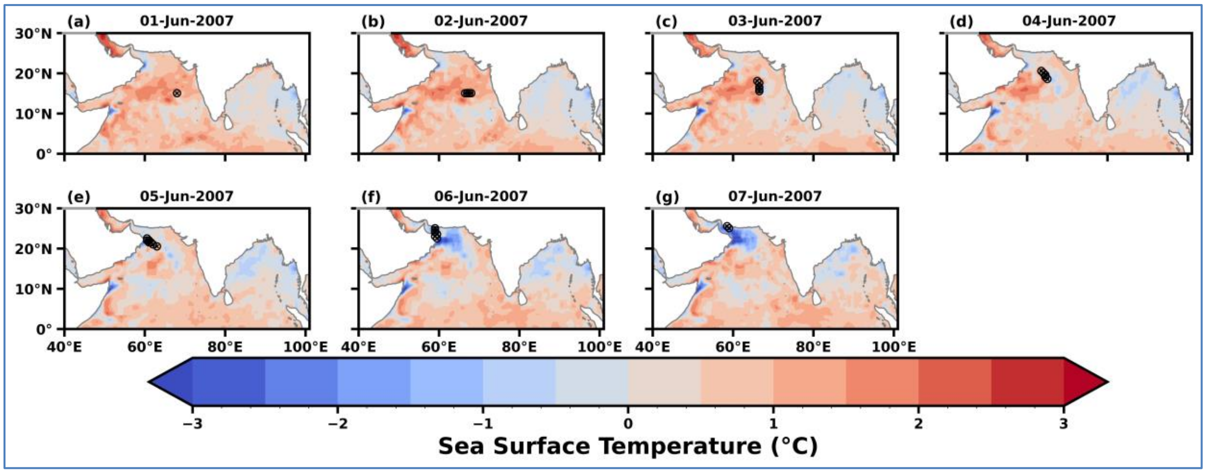
In the case of SuCS Gonu, however, upper-tropospheric dynamics deviated from this canonical behaviour. Between 2-6 June, a midlatitude anticyclonic system, along with associated trough-ridge patterns Figs. 3(b-f), migrated southward into the Arabian Sea, resembling a "Silk Road" circulation. This intrusion disrupted the TEJ, reduced vertical shear, and enhanced divergence aloft, thereby sustaining deep ascent over Gonu. The weakening of the TEJ, together with warm SSTs and anomalous upper-level divergence, created a unique environment for rapid intensification under unfavourable monsoon-onset conditions. By 7 June, the TEJ re-established, underscoring the transient nature of this circulation re-organization (Fig. 3g).

The 200 hPa wind analysis (vectors; m/s) highlights this evolution, the normally robust TEJ (>40 m/s at 10° - 20° N) progressively weakened or vanished over the Arabian Sea from 2-4 June Figs. 3(b&d), while anomalous westerly intrusions promoted divergence. This interplay between TEJ disruption and midlatitude wave propagation provides a novel mechanism for early-season super cyclone development in the Arabian Sea.

The meridional extent of the westerly intrusion, spanning approximately 15 degrees of latitude, indicates that the atmospheric disturbance influenced circulation patterns across the entire North Indian Ocean basin, creating a regional environment exceptionally conducive to extreme cyclogenesis during a period typically hostile to intense tropical cyclone formation. TEJ over the Arabian Sea and the South Peninsula of India enhance the deep-layer wind shear, particularly the shift of the TEJ to the southward of its original position and enhance the zonal wind component. This increased wind shear favors the genesis of monsoon depressions; however, it concurrently inhibits their intensification into tropical cyclones (Sripathi *et al.*, 2024; Gollapalli *et al.*, 2024).

3.3. *Thermodynamic drivers of rapid cyclone intensification*

Rapid intensification of tropical cyclones is strongly governed by several key thermodynamic factors. One of the primary drivers is high SSTs, typically exceeding 28 °C, which provide the latent heat energy necessary to fuel intense convection. Along with SSTs, a deep oceanic mixed layer ensures a sustained heat supply, preventing the cyclone from cooling the surface waters through upwelling. Another critical factor is high mid-tropospheric moisture content, which supports persistent convection and reduces the likelihood of dry air intrusion that can weaken storm development. Additionally, low vertical wind shear allows for the vertical alignment of the cyclone's structure, enabling efficient heat and moisture transport from the ocean surface to the upper troposphere. Together, these thermodynamic conditions create a favorable environment for the rapid intensification of tropical cyclones. Recent studies (Kranthi *et al.*, 2023) show that rapidly intensifying (RI) tropical cyclones have positive low-level relative vorticity, strong upper-level divergence, and weaker vertical wind shear near the center, particularly during the pre-monsoon period. Higher mid-level relative humidity in RI TCs promotes convection and latent heat release, further strengthening the storm.



Figs. 4(a-g). Sea surface temperature (SST) anomalies (°C) relative to the 1991–2024 climatology from NOAA OISST during 1–7 June 2007

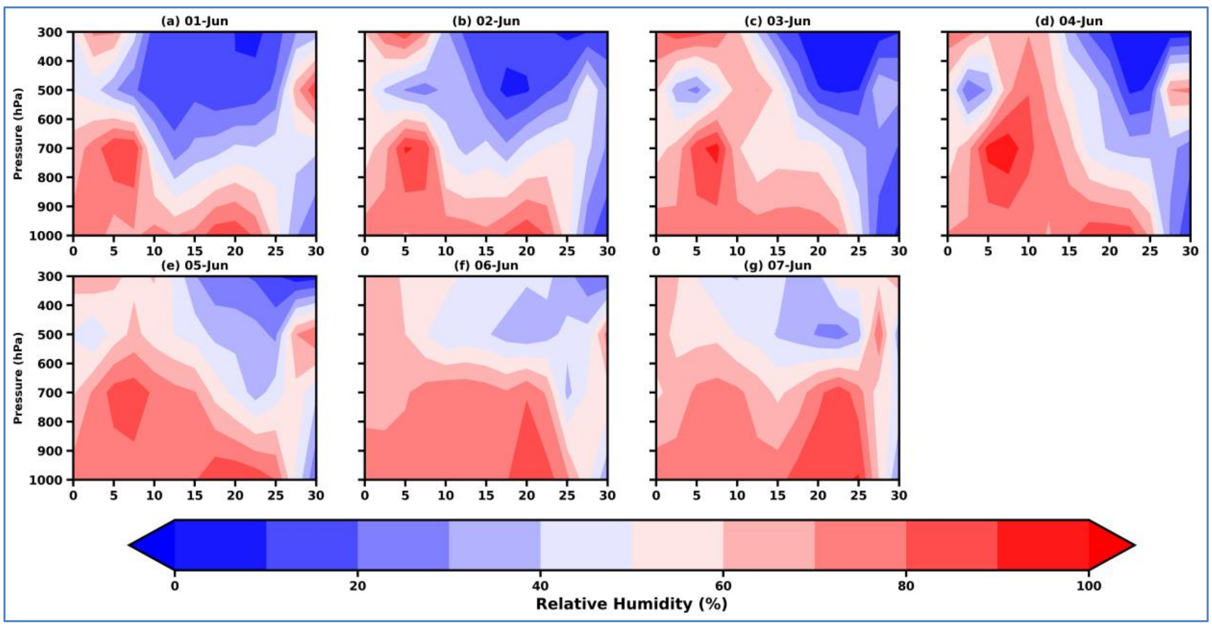


Fig 5. Latitude–pressure cross-sections of relative humidity (%) along the track of Super Cyclone Gonu during 1-7 June 2007

3.3.1. *Sea surface temperature anomalies*

The SST anomalies reveal exceptionally favorable thermal conditions that supported rapid intensification throughout the cyclone's evolution of Gonu (Fig. 4). During 1-4 June 2007, positive SST anomalies exceeding +1 °C were concentrated over the east-central Arabian Sea, coinciding with the region of Gonu’s most rapid intensification Figs. 4(a-d). These warm anomalies enhanced ocean-atmosphere heat exchange, increasing latent heat fluxes that sustained deep convection and supported the cyclone’s transition from a tropical cyclone to a very severe cyclonic storm.

A notable transition in the SST pattern becomes evident during June 5-7 Figs. 5(e-g), when significant cooling develops along Gonu's track, with negative anomalies reaching -1 to -2 °C, reflecting the intense ocean-atmosphere heat and momentum exchange during the cyclone's passage, including wind-driven mixing that brought cooler subsurface waters to the surface and substantial latent heat extraction to fuel the storm's convective processes. The rapid development of this cooling wake coincides with Gonu's peak intensity phase, demonstrating the cyclone's ability to efficiently extract thermal energy from the ocean surface, while these SST patterns align with broader regional warming trends, as recent studies indicate that Arabian Sea temperatures have increased by 1.2 to 1.4 °C over the recent decades, creating increasingly favorable baseline conditions for tropical cyclogenesis (Singh and Roxy 2022). The combination of this long-term warming trend with the specific anomalous conditions during June 2007 created an optimal thermal environment that contributed significantly to Gonu's historic intensification over the Arabian Sea.

3.3.2. *Vertical moisture distribution during 1-7 June 2007*

Vertical moisture distribution, especially mid-level relative humidity, is critical for cyclone intensification. Wu *et al*. (2015) showed that while warm SSTs favor development, strong vertical shear and dry mid-level air suppress intensification, emphasizing the interplay between environmental conditions.

Fig. 5 shows the Latitude–pressure cross-sections of relative humidity (%) along the SuCS Gonu's track. Analysis of the relative humidity reveals that exceptionally favorable moisture conditions persisted throughout the troposphere along the cyclone's track from June 1-7 Figs. 5(a-g). The vertical moisture structure shows relative humidity values consistently exceeding 70-80% throughout the mid and upper-troposphere (700-300 hPa), creating a deeply saturated environment that eliminated the typical constraints imposed by dry air entrainment. This sustained high-humidity profile was instrumental in maintaining vigorous convective processes and supporting the development of deep cloud columns that characterize rapidly intensifying tropical cyclones. The absence of significant dry air intrusion prevented convective suppression mechanisms that typically limit storm development, allowing continuous latent heat release throughout Gonu's intensification period and contributing directly to the cyclone's ability to achieve super cyclonic storm intensity despite the climatologically challenging monsoon onset environment. The persistence of these favorable moisture conditions across multiple atmospheric levels demonstrates the exceptional nature of the thermodynamic environment that enabled Gonu's unprecedented strengthening over the Arabian Sea.

3.4. *Dynamical parameters*

The dynamical environment during SuCS Gonu's development is characterized through comprehensive analysis of several key atmospheric parameters that govern tropical cyclone intensification and structural evolution. To better understand the dynamical characteristics associated with this unprecedented Arabian Sea cyclogenesis event, three critical parameters were examined: relative vorticity at 850 hPa, which indicates the low-level circulation strength and organization; vertically integrated moisture transport (VIMT), which quantifies the atmospheric moisture flux convergence supporting convective processes; and the vertical shear of the zonal wind, which determines the environmental constraints on storm structure and intensification potential. The spatial & temporal variations of these dynamical parameters during June 1-7, 2007, provide insights into the atmospheric conditions that enabled Gonu's rapid intensification despite the typically unfavorable monsoon onset environment. Analysis of these parameters reveals the complex interplay between large-scale circulation patterns, moisture transport mechanisms, & local vorticity dynamics that collectively created an optimal environment for extreme cyclone development over the Arabian Sea, contributing to Gonu's achievement of super cyclonic storm intensity and its unusual northward track progression during this climatologically challenging period.

3.4.1. *Vertical shear of the zonal wind during super cyclone Gonu (June 1–7)*

Fig. 6 presents daily evolution of vertical wind shear (200-850 hPa) during SuCS development (June 1-7, 2007). The magnitude of zonal wind shear (m/s), where negative values (blue shading) indicate lower-level westerly shear and positive values (red shading) represent upper-level easterly shear. Black dots mark daily cyclone center positions from IMD best-track data. The progressive transition from moderate easterly shear to near-neutral conditions along Gonu's track created increasingly favorable dynamic environments that supported rapid intensification despite climatologically challenging monsoon onset conditions.

The vertical wind shear environment during Super Cyclone Gonu's development demonstrates a progressive evolution from moderately constraining to highly favorable conditions that directly enabled the cyclone's unprecedented intensification over the Arabian Sea Figs. 6(a-g).

During the initial cyclogenesis phase on June 1-2 Figs. 6(a, b), Gonu formed within a region of moderate easterly shear ranging from -8 to -12 m/s, representing relatively favorable conditions compared to the stronger easterly shear typically associated with the fully established TEJ during monsoon onset periods. The shear environment remained conducive for intensification during June 3-4 Figs. 6(c&d), with values maintaining a moderate range of -6 to -10 m/s in the cyclone's immediate vicinity, allowing Gonu to undergo rapid strengthening while preserving its vertical structural coherence and enabling efficient convective organization. A critical environmental transition occurs during June 5-6 Figs. 6(e, f) as Gonu approaches peak intensity, when the vertical shear in the storm's environment decreases to near-neutral values ranging from -3 to +3 m/s, providing optimal conditions for the maintenance of SuCS intensity and facilitating the cyclone's achievement of maximum strength despite the

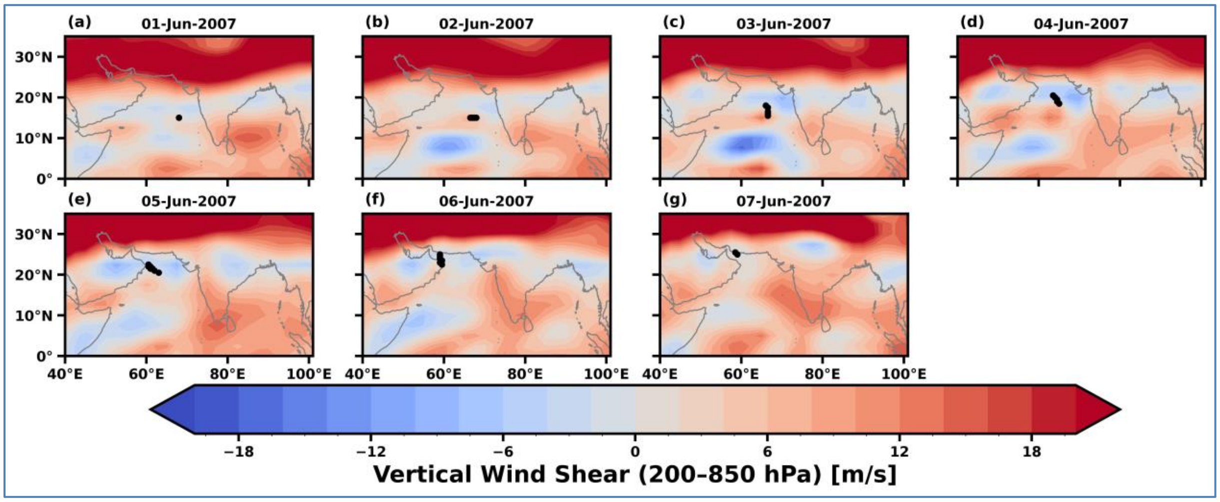


Fig. 6. Daily evolution of vertical wind shear (200-850 hPa) during Super Cyclone Gonu development (June 1-7, 2007)

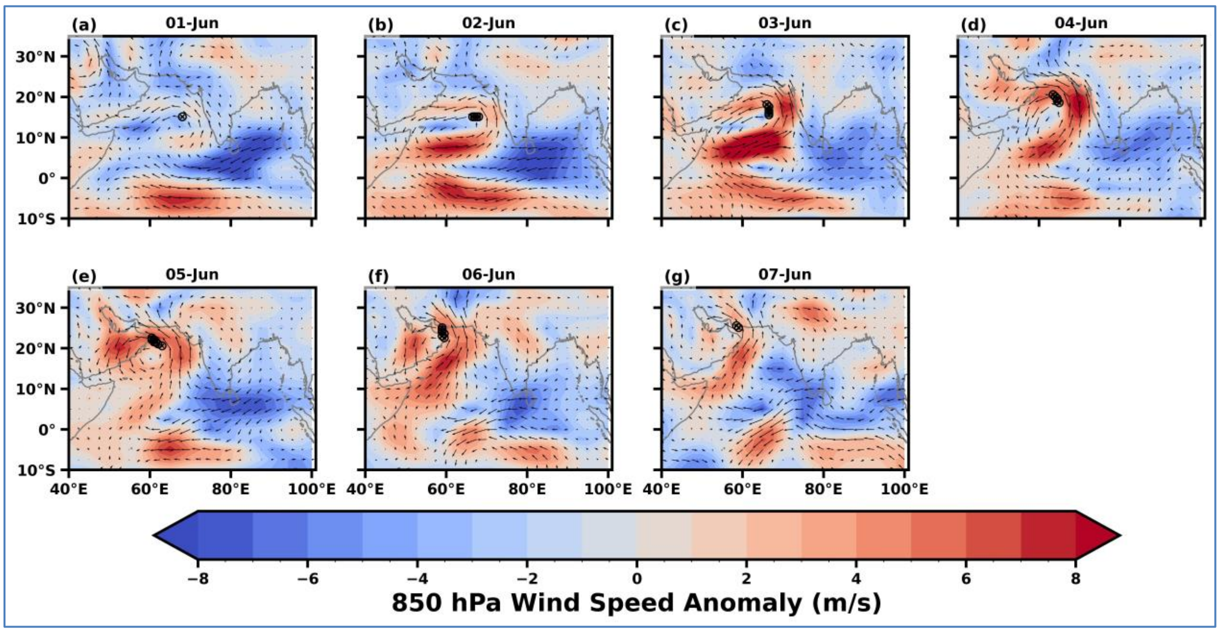


Fig. 7. Daily 850 hPa wind speed anomalies (shaded) relative to the 1980–2024 climatology with overlaid wind vectors (contours; m/s) during the development of Super Cyclone Gonu. Black dots mark daily cyclone center positions from IMD best-track data

climatologically challenging monsoon period. Throughout Gonu's northwestward track progression from the east-central Arabian Sea toward the Oman coast, the consistently low to moderate shear magnitude prevented the structural disruption that typically limits tropical cyclone intensification during monsoon onset, with the environmental wind remaining sufficiently favorable to support the development and maintenance of one of the most intense cyclonic systems ever recorded in the Arabian Sea. The spatial distribution of shear patterns reveals that Gonu's trajectory consistently followed regions of minimal vertical shear, demonstrating how the cyclone's path fortuitously aligned with the most dynamically favorable corridor available during this period, while the temporal evolution shows a systematic reduction in shear magnitude that parallels the storm's intensification timeline, ultimately contributing to its unprecedented strength and sustained intensity until landfall on the Arabian Peninsula.

Fig. 7 shows daily 850 hPa wind speed anomalies (m/s) and wind vectors during SuCS Gonu development. The wind speed anomalies relative to climatology with overlaid wind vectors indicating flow direction and magnitude. Negative anomalies (blue shading) represent weaker than normal winds, while positive anomalies (red shading) indicate stronger than normal flow.

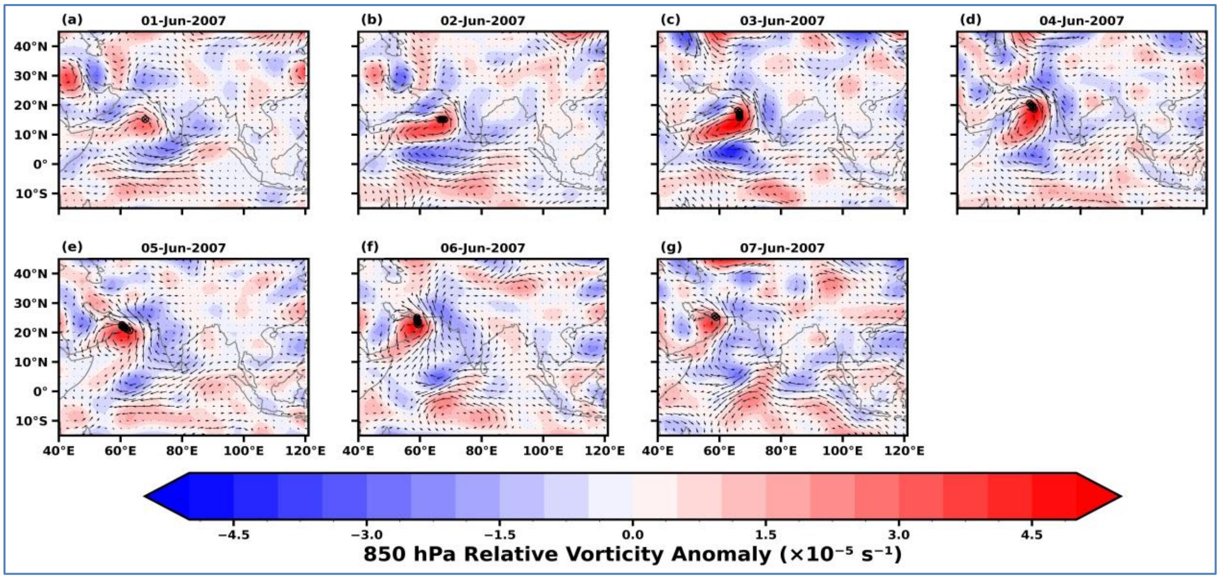


Fig 8. Evolution of 850 hPa relative vorticity anomalies ($\times 10^{-5}$ s^{-1}) relative to 1980-2024 climatology during Super Cyclone Gonu

The 850 hPa wind analysis during SuCS Gonu's development reveals the complex interaction between cyclonic circulation and monsoon flow patterns that characterized this exceptional Arabian Sea cyclogenesis event (Fig. 7). The wind vector fields demonstrate the establishment of strong southwesterly flow over the Arabian Sea beginning June 1st, indicating that monsoon onset conditions were actively developing across the region concurrent with Gonu's formation (Fig. 7a). During June 1-2, the wind speed anomaly patterns show the initial development of cyclonic organization, with negative anomalies of -4 to -6 m/s appearing in regions where the nascent circulation disrupted the established flow, while positive anomalies of +2 to +4 m/s began developing in areas where the cyclonic circulation enhanced the ambient wind anomalies Fig. 7(a,b). The progressive intensifycation of Gonu during June 3-5 is clearly reflected in the wind anomaly evolution, with increasingly organized patterns of alternating positive and negative anomalies surrounding the cyclonic storm center Figs. 6(c-e), indicating the strengthening cyclonic circulation & its growing influence on the regional wind field. The most pronounced anomaly patterns occur during June 4-5, when positive

3.4.2. *Relative vorticity at 850 hpa during super cyclone Gonu (June 1-7)*

Fig. 8 represents the evolution of 850 hPa relative vorticity during SuCS Gonu reveals the systematic intensification and structural development of this exceptional tropical cyclone. The vorticity anomalies demonstrate the progressive organization of cyclonic circulation, with weak, diffuse vorticity patterns on June 1st gradually concentrating into a well-defined, intense vortical structure by June 4-5th, when Gonu reached peak intensity Figs. 8(d&e). The anomalies provide crucial context by revealing how dramatically Gonu deviated from climatological norms, with positive vorticity anomalies reaching 3-4$\times 10^{-5}$ s^{-1} throughout the cyclone's core region. These anomalies demonstrate that Gonu's vorticity patterns were significantly stronger than typical June conditions in this region, highlighting the cyclone's exceptional nature. The spatial extent of positive anomalies encompasses a broader area than the actual vorticity core, suggesting that Gonu's influence on atmospheric circulation patterns extended well beyond its immediate center, affecting regional-scale dynamics across the Arabian Sea and surrounding areas The spatial extent of positive anomalies encompasses a broader area than the actual vorticity core, suggesting that Gonu's influence on atmospheric circulation patterns extended well beyond its immediate center and affected regional-scale dynamics across the Arabian Sea and surrounding areas, while the temporal progression shows the most significant vorticity intensification occurring during June 3-5, coinciding precisely with the cyclone's rapid strengthening phase and indicating the development of the intense rotational structure necessary to support SuCS intensity Figs. 8(c-e). The persistence of strong positive vorticity anomalies throughout Gonu's development demonstrates the sustained departure from climatological conditions, with the cyclone maintaining anomalously intense low-level circulation that enabled its unprecedented intensification and structural integrity despite the typically constraining environmental conditions associated with monsoon onset over the northern Indian Ocean basin.

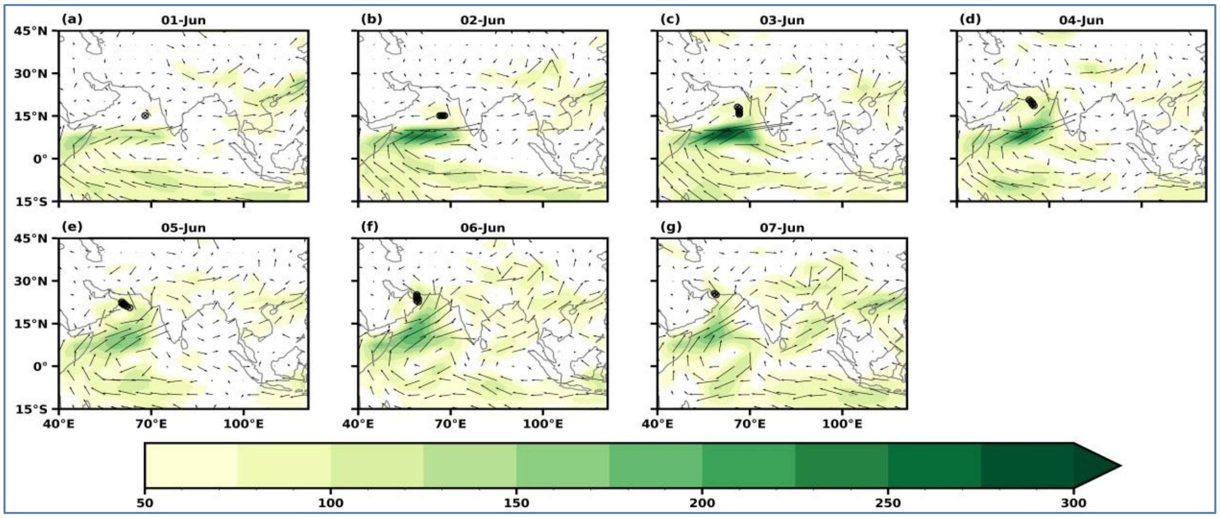


Fig. 9. Daily evolution of vertically integrated moisture transport (VIMT) during Super Cyclone Gonu (1–7 June 2007). The VIMT is integrated from 1000 to 300 hPa (kg m^{-1} s^{-1}), with shading representing magnitude and vectors indicating the direction of moisture transport

3.4.3.1. *Vertical integrated moisture transport during super cyclone gonu (June 1-7)*

Fig. 9 illustrates the daily evolution of vertically integrated moisture transport (VIMT) during Super Cyclone Gonu. The total column VIMT integrated from 1000 to 300 hPa (kg m^{-1} s^{-1}) showing magnitude fields with vectors indicating the direction of moisture transport. The intensification and organization of southwesterly moisture flux toward the cyclone, with strong VIMT feeding convection and contributing to Gonu's intensification.

During the early phase June 1-3, VIMT was relatively weak, with modest southwesterly transport over the central Arabian Sea Fig. 9(a-c). As Gonu developed and moved northwestward observed during the June 4-6, the VIMT field intensified, forming a well-organized, concentrated corridor of strong southwesterly flux directed toward the cyclone center Fig. 9(d-f). Peak values exceeded 300 kg m^{-1} s^{-1}, providing a continuous supply of moisture that fueled convection and aided the cyclone's rapid intensification. By 7 June Fig. 9g as Gonu approached the Arabian Peninsula coast the high-magnitude VIMT shifted westward along with the cyclone, consistent with its weakening. The spatial and temporal evolution of VIMT demonstrates that the organized southwesterly moisture transport from the equatorial Indian Ocean was a key factor in strengthening and sustaining Super Cyclone Gonu.

3.4.3.2. *Rainfall Pattern Analysis*

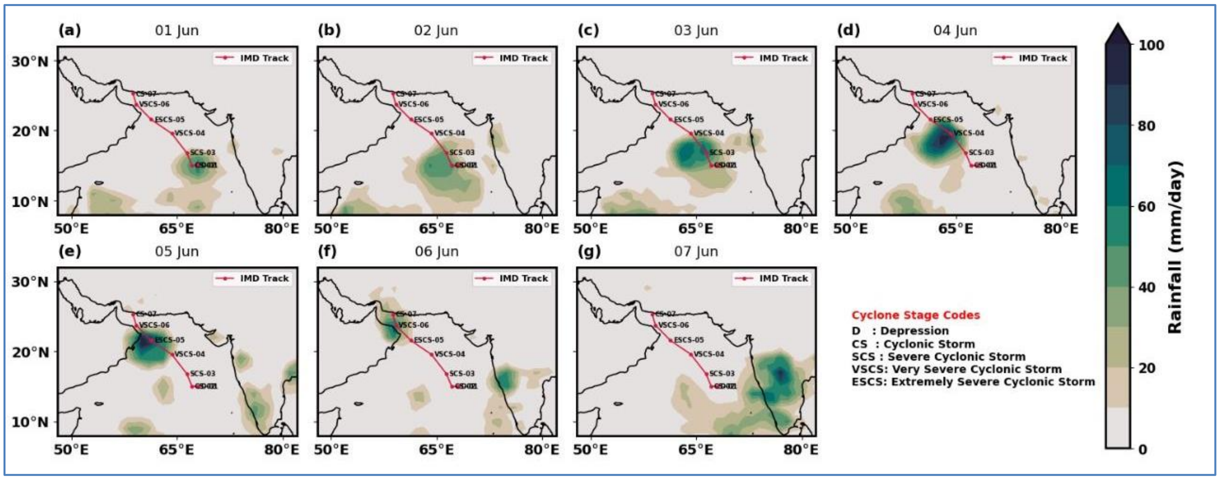
The precipitation linked to Super Cyclone Gonu displayed distinct spatiotemporal variability throughout its lifecycle. Analysis of GPCP daily rainfall data helped identify the cyclone's intensification stages and their corresponding impacts on regional rainfall patterns.

During the initial development phase June 1-2, rainfall was concentrated within a compact, nearly symmetric core of ~100 km radius around the cyclone center, with intensities ranging from 30-40 mm/day Figs. 10(a, b). As the cyclone rapidly intensified, peak rainfall rates exceeded >100 mm/day during 3-5 June, coinciding with the cyclone's maximum intensity Figs. 10(c-f). A pronounced asymmetric distribution developed, with the northeastern quadrant receiving 30-40% higher rainfall, reflecting the combined influence of environmental wind shear and storm motion.

In the mature phase June 5-6, the precipitation expanded to a diameter of ~500 km. Secondary rainfall maxima formed along the cyclone's spiral bands, with orographic enhancement exceeding 100 mm/day over the Western Ghats & Oman regions. During landfall & weakening phases June 7 & after onwards, the rainfall pattern became more diffuse, with core intensities declining to greater than 100 mm/day, while moderate precipitation (50-100 mm/day) extended well inland over the Arabian Peninsula (Fig. 10g). These high-intensity, large-extent & prolonged rainfall events contributed to severe flooding & hydrological impacts across the affected areas. Overall, the results demonstrate a clear quantitative link between cyclone intensity & precipitation, highlighting the asymmetric rainfall structure typical of intense Arabian Sea cyclones.

4. **Conclusions**

Super Cyclone Gonu (1-7 June 2007) represents a landmark event in the Arabian Sea, being the first recorded Category 5 cyclone in this region. Its rapid intensification during the early phase of the ISM, a period generally considered unfavorable for cyclone development due to



Figs. 10(a-d). Daily GPCP rainfall (mm day^{-1}) during 1-7 June 2007, overlaid with the IMD best-track positions of Super Cyclone Gonu, highlighting the evolution of precipitation along the cyclone's track

strong vertical wind shear & the dominance of the TEJ highlights its anomalous nature. This study examined the atmospheric & oceanic conditions that facilitated Gonu's extraordinary growth using multiple datasets, including ERA5, NOAA OISST, IMD best-track data, GPCP rainfall. The results indicate that a combination of unusually warm SSTs (>28 °C), high mid- to upper-tropospheric humidity, and moderate vertical wind shear created an exceptionally conducive environment for rapid intensification.

Upper-tropospheric processes were supporting the cyclone's development. A southward intrusion of midlatitude westerlies weakened the TEJ, producing westerly wind anomalies that enhanced upper-level divergence and sustained deep convection in the cyclone core. At the same time, analyses of VIMT revealed a strong southwesterly inflow from the equatorial Indian Ocean, which not only supplied the cyclone with moisture but also temporarily altered regional moisture pathways, likely delaying the monsoon progression over parts of the Indian subcontinent.

At lower levels, Gonu's formation and intensification significantly modified the synoptic-scale circulation over the Arabian Sea. Enhanced 850 hPa relative vorticity confirmed the development of a compact, well-organized cyclonic core that maintained intensity until landfall, while moderate negative vertical shear (−8 to −12 m/s) supported vertical alignment and energy transfer within the storm. These observations underscore the importance of multi-scale interactions among oceanic conditions, upper-level jet dynamics, and lower-tropospheric circulation in driving early-season cyclogenesis under atypical environmental conditions.

In conclusion, SuCS Gonu demonstrates the complexity and potential unpredictability of tropical cyclones in the Arabian Sea, particularly during transitional periods such as the monsoon onset. The findings highlight the need for continuous monitoring of ocean-atmosphere interactions, as ongoing climate change and warming seas may increase the likelihood of extreme cyclones forming outside their climatologically favored periods. Gonu thus provides a valuable case study for understanding the processes that enable early-season super cyclones and for improving forecasting strategies in the North Indian Ocean region.

Data availability

All the data used in this study is available on request

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Authors' Contributions

Nagalakshmi K: led the conceptualization, analysis, plotting, and writing.
Susmitha Joseph: supervised and contributed to writing.
A. Dharma Raju and M. Mohapatra assisted in drafting and reviewing.
G. Sripathi and Babji S. H. supported plotting and review.
Sunitha Kumar, Venkata Jagannadh Kumar, and Shashi Kant contributed to reviewing.

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