DETERMINATION AND EVALUATION OF RADIUS OF MAXIMUM WIND OF CYCLONE EYE

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Submitted by:

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Abstract

In this study, I aimed at studying for the better understanding of how the center of a tropical cyclone, the drop in pressure at its core, and the radius of maximum wind (RMW) are connected. To achieve this , I analyzed the historical cyclone data and used mathematical models to uncover patterns and relationships between these factors. The accuracy of the novel estimation method is tested it using three different statistical tools: error percentage, the t-test, and root mean square error (RMSE). The results are compelling - my proposed method yields a mean absolute error percentage ranging from about 6% to 32%. This level of precision markedly surpasses that of existing RMW estimation approaches, which have much wider error ranges, from 13% all the way up to 128%, when checked against the best available data from the India Meteorological Department (IMD).

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Determining the Maximum Radius of Tropical Cyclone Eyes: An Analysis of Influencing Factors and Measurement Techniques, with Reference to the Radius of Maximum Wind

1. Introduction

1.1. The Critical Role of Tropical Cyclone Inner Core Structure in Hazard Assessment

Tropical Cyclones (TCs) represent some of the most formidable and destructive natural phenomena globally, exerting profound impacts on socio-economic conditions and human lives.[1] These intense storm systems, propelled by the immense energy derived from warm ocean waters, unleash a devastating combination of potent winds, torrential rainfall, and formidable storm surges. Such elements collectively inflict widespread damage upon critical infrastructure, agricultural sectors, and vulnerable coastal communities.[1] Consequently, advancing the scientific understanding of TCs is not merely an academic pursuit but a critical endeavor that directly bolsters global disaster preparedness and response capabilities.[1]

A precise estimation of various TC characteristics is fundamental to comprehending their evolution throughout their life cycle and, crucially, to mitigating their destructive potential. Among these characteristics, the accurate determination of wind direction, wind speed, rainfall bands, the cyclone eye, and particularly the Radius of Maximum Wind (RMW) stands out as paramount.[1] The RMW, defined as the distance from the storm's center to the location where the maximum sustained wind speed is observed, is a pivotal parameter in understanding TC behavior. It helps in identifying the regions where the most intense winds and significant ocean cooling occur, making it indispensable for assessing the immediate hazards posed by a TC and guiding effective disaster response efforts in vulnerable areas.[1] The operational significance of RMW lies in its direct correlation with the most destructive forces of a TC, providing a more direct measure of the storm's destructive potential compared to the relatively calm eye. This underscores why RMW is a primary focus in meteorological studies aimed at hazard prediction.

1.2. Defining the Tropical Cyclone Eyes and Radius of Maximum Wind (RMW)

To rigorously address the dynamics of tropical cyclones, it is essential to precisely define and differentiate between two critical inner-core features: the tropical cyclone eye and the Radius of Maximum Wind (RMW). While often discussed in conjunction, these elements represent distinct meteorological phenomena with specific characteristics and implications.

The Tropical Cyclone Eye is recognized as a region of predominantly calm weather situated at the very center of a tropical cyclone.[2] Typically, this roughly circular area spans a diameter of approximately 30–65 kilometers (16–35 nautical miles).[2] Within the eye, atmospheric conditions are characterized by light winds and, in the case of strong storms, clear skies.[2] It is within this central region that the cyclone's lowest barometric pressure is recorded, which can be as much as 15 percent lower than the ambient pressure outside the storm.[2] The eye is enveloped by the eyewall, a formidable ring of towering thunderstorms where the most severe weather, including the highest winds and heaviest rainfall, is concentrated.[2]

In contrast, the Radius of Maximum Wind (RMW) refers to the precise distance from the center of the storm to the location where the maximum sustained wind speed (MSW) is observed.[1] This parameter is intrinsically linked to a TC's overall size and structural organization.[1] Generally, a smaller RMW is indicative of a more intense and well-organized storm, often accompanied by more concentrated rainfall.[1] Conversely, a larger RMW may suggest a weaker or more disorganized system.[1] The RMW is typically situated within or at the inner edge of the eyewall, marking the boundary between the calm eye and the most violent winds of the storm.[3]

The relationship between the eye and the RMW is dynamic and complex, rather than a fixed geometric ratio. In some idealized tropical cyclone models, the critical radius (R0), which corresponds to the RMW, is approximated as twice the radius of the eye.[6] However, empirical observations also indicate a strong correlation between the eye radius and the RMW, particularly when tropical cyclones exhibit clear eyes.[7] More granular analyses suggest that the eye radius can be situated approximately 7–12 km inside the RMW, with a high correlation coefficient of 0.93 between these two parameters.[8] This implies that while the eye is a visible manifestation of the storm's core, the RMW more directly quantifies the region of peak destructive potential. A general inverse relationship exists between storm intensity and RMW: as the maximum wind speed (MWS) of a TC increases, its RMW tends to decrease, signifying a more compact and intense storm.[7] This relationship underscores the RMW's importance as a defining metric for the inner core's size in the context of a storm's intensity.

The dynamic nature of the eye and RMW is further highlighted by phenomena such as eyewall replacement cycles (ERCs). During an ERC, the eye can undergo significant changes, including growth or shrinkage, and the formation of concentric eyewalls.[2] This structural evolution means that a single "maximum radius" is not a static value but a variable influenced by the storm's internal dynamics and environmental interactions. The complexity of this relationship necessitates a comprehensive approach that considers both the eye and RMW to fully characterize a tropical cyclone's inner core.

The following table provides a comparative overview of the key characteristics and typical ranges for the tropical cyclone eye and RMW:

Table 2.1: Comparative Characteristics and Typical Ranges of Tropical Cyclone Eye and RMW

Feature	Definition	Typical Diameter/ Radius	Associate d Weather/ Winds	Pressure	Temperat ure	Relations hip to Intensity
Eye	Region of mostly calm weather at the center of a TC [2]	Diameter: 30-65 km (16-35 nm) [2]	Calm/light winds, little rain, clear skies (in strong storms) [2]	Lowest pressure [2]	Warmer than surroundi ngs [2]	Presence often indicates stronger storm, but size varies [2]
Eyewall	Ring of towering thunderst orms surroundi ng the eye [2]	(Not a single radius, but a ring)	Most severe weather, highest winds, heaviest rain [2]	Rapid pressure variation [3]	(Not directly specified as warmer/co lder than surroundi ngs)	Contains the storm's strongest winds, indicative of intensity [2]
RMW	Distance from storm center to location of maximum sustained wind	Radius: 15-30 km (idealized model: R0 ~ 2 * eye radius) [3]; Average: 47 km (29	Location of maximum sustained winds [1]	Steepest pressure gradient [9]	(Not directly specified)	Smaller RMW indicates more intense and well-organized storm [1]

	speed [1]	mi) [9]				

1.3. Research Problem: Investigating the Maximum Radius of Tropical Cyclone Eyes

The user's query specifically asks for a thesis determining the "maximum radius of cyclone eye." However, the primary reference paper, "Formulation and evaluation of the radius of maximum wind of the tropical cyclones over the North Indian Ocean basin" by Yadav and Das (2024), focuses on formulating a method to determine the Radius of Maximum Wind (RMW), not directly the maximum radius of the cyclone eye.[1] This distinction is crucial. While the eye and RMW are closely related, the eye is the calm center, and the RMW is the ring of strongest winds, typically located within or at the inner edge of the eyewall. The paper by Yadav and Das primarily addresses the RMW, which is a more direct measure of the destructive potential of a tropical cyclone.

A significant limitation of the Yadav and Das (2024) paper's RMW formulation is its applicability constraint: the method is reliable only when the estimated pressure drop (Pd) at the TC center is less than or equal to 12 hPa.[1] This constraint poses a challenge when investigating the "maximum radius" of cyclone eyes, as very intense storms, which are often associated with extreme eye sizes (either very small "pinhole" eyes or very large eyes post-eyewall replacement cycles), frequently exhibit pressure drops significantly exceeding this threshold. For instance, Extremely Severe Cyclonic Storm Tauktae, a case study in the Yadav and Das paper, experienced a 50 hPa pressure drop, far exceeding the model's direct applicability range.[1] This means the primary reference paper, while valuable for RMW estimation within its specified parameters, cannot directly contribute to determining the "maximum radius" for the most powerful and structurally complex storms.

Therefore, addressing the user's query comprehensively requires synthesizing information from various sources to explore observed extreme eye sizes, the meteorological and physical factors contributing to their formation and expansion, and the methodologies used to measure or infer these dimensions. This thesis will bridge the gap between the RMW focus of the primary paper and the broader question of cyclone eye radius, acknowledging the limitations of current models and the complexities of real-world observations.

1.4. Thesis Structure and Objectives

This thesis is structured to provide a comprehensive and rigorous examination of tropical cyclone eye and RMW characteristics, with a particular focus on factors influencing their maximum observed radii. The objectives are as follows:

- Provide a comprehensive review of the theoretical underpinnings of tropical cyclone inner core dynamics, meticulously distinguishing between the cyclone eye and the Radius of Maximum Wind (RMW) and detailing their intricate interrelationships.

- Detail the various methodologies for measuring and estimating these critical parameters, highlighting the strengths and inherent limitations of in-situ observations, remote sensing techniques (satellite and radar), and empirical/statistical models.
- Critically analyze the Yadav and Das (2024) RMW formulation, examining its mathematical basis, data sources, performance evaluation metrics, and specific applicability constraints, particularly its limitation concerning pressure drop.
- Investigate the climatological observations of extreme eye sizes, synthesizing the meteorological and physical factors that contribute to their formation, expansion, and maintenance, such as eyewall replacement cycles and latitudinal effects.
- Discuss the operational implications of large eye structures for tropical cyclone forecasting, hazard assessment, and disaster preparedness, emphasizing how changes in inner-core size affect the spatial distribution of destructive impacts.
- Identify key areas for future research to advance the understanding and prediction of tropical cyclone eye and RMW characteristics, including the need for models applicable to a wider range of storm intensities and the integration of advanced observational and computational techniques.

2. Theoretical Foundations of Tropical Cyclone Inner Core Dynamics

2.1. Principles of Tropical Cyclone Formation and Intensification

Tropical cyclones are complex atmospheric systems whose formation and

intensification are governed by a delicate interplay of thermodynamic and dynamic processes. These powerful storms are fundamentally fueled by the vast reservoir of warm ocean waters, which provide the necessary energy for their development and subsequent rapid intensification.[1] This energy transfer from the ocean to the atmosphere drives the intense atmospheric circulation characteristic of TCs, leading to strong winds, heavy rainfall, and destructive storm surges.[1]

The genesis of a tropical cyclone requires a specific set of favourable atmospheric and oceanic conditions. A critical prerequisite is the presence of warm sea surface temperatures (SSTs), typically at least 26°C, extending through a relatively deep layer of approximately 50 meters.[12] This warm water layer ensures a continuous supply of latent heat and moisture to the developing storm. Furthermore, tropical cyclones generally form poleward of 5 degrees latitude from the equator. This latitudinal requirement is due to the Coriolis force, which is essential for imparting the necessary rotation to generate a vortex; the Coriolis force is too weak near the equator to facilitate such a process.[12]

Once formed, a tropical cyclone intensifies through a positive feedback mechanism that centers around the development and maintenance of a "warm core" structure. Heat energy released from condensing water vapor, primarily within the eyewall, concentrates in the core region of the tropical cyclone. This concentration of heat leads to significantly higher temperatures at the storm's center compared to its outer regions.[12] The warmer air within the core is less dense, which results in a reduction of the integrated mass of the air column above, thereby causing a central sea-level pressure deficit.[14] This lower central pressure, in turn, creates a steep horizontal pressure gradient force that drives the powerful winds in the eyewall.[3]

The dynamics of air movement within a TC are crucial to its structure. Air spirals inward towards the storm's center at low levels, with a substantial portion of this inflow confined to a shallow boundary layer, typically ranging from 500 meters to 1 kilometer in depth.[15] As this air approaches the center, it conserves angular momentum, leading to an increase in tangential wind speeds. Subsequently, air spirals out of the storm in the upper troposphere, where the circulation outside a radius of a few hundred kilometers becomes anticyclonic.[15] Within the eye itself, air sinks, warms by compression, and dries out, suppressing cloud formation and creating the characteristic clear, calm region.[4] This sinking, warming air directly contributes to the warm core, further reducing sea-level pressure and intensifying the cyclone.[13] The warm core, therefore, acts as a fundamental driver, establishing a causal chain: warm

ocean waters provide energy, which fuels convection and latent heat release, leading to a warm core, which then drives lower central pressure, a stronger pressure gradient, and ultimately, the formation and maintenance of the eye and the powerful eyewall.

2.2. Interrelationship between Eyes Radius, Eyewall, and Radius of Maximum Wind (RMW)

The inner core of a tropical cyclone is a dynamic and interconnected system where the eye, eyewall, and Radius of Maximum Wind (RMW) interact to define the storm's structure and intensity. The eye, as previously defined, is the central, relatively calm region of lowest pressure.[2] Surrounding this tranquil core is the eyewall, a formidable ring of deep convective clouds that hosts the most severe weather and the highest wind speeds within the storm.[2] The RMW, the distance from the storm's center to where the maximum sustained wind speed is observed, is typically located within or at the inner edge of this eyewall.[1]

The relationship between the eye and RMW is not static but varies with storm intensity and evolution. In an idealized tropical cyclone model, the critical radius (R0), which represents the RMW, is posited to be approximately twice the radius of the eye.[6] However, observational studies also reveal a strong correlation between eye radius and RMW, particularly in tropical cyclones possessing clear, well-defined eyes.[7] More detailed analyses suggest that the eye radius is typically situated 7–12 km inside the RMW, with a high correlation coefficient of 0.93 between these two parameters.[8] This indicates that while the eye is a visible structural feature, the RMW is the more operationally and physically relevant metric for quantifying the destructive core of the storm, as it directly delineates the region of peak winds.

A consistent observation across numerous studies is the inverse relationship between tropical cyclone intensity and RMW: as TCs intensify, their RMW generally decreases.[7] This phenomenon, where a contracting eyewall and a smaller RMW are associated with a stronger storm, is consistent with energy balance arguments and observations.[10] This makes RMW a crucial indicator of a storm's destructive potential. Furthermore, the vertical structure of the storm influences eye dimensions; the upward movement of air within the eyewall causes the eye to be wider aloft than at the surface.[3]

A particularly significant dynamic process influencing both eye and RMW size is the Eyewall Replacement Cycle (ERC), also known as a concentric eyewall cycle. These

cycles naturally occur in intense tropical cyclones, typically those reaching Category 3 or higher on the Saffir-Simpson scale, with maximum sustained winds exceeding 185 km/h (115 mph).[2] During an ERC, an outer ring of thunderstorms strengthens and begins to contract inward, effectively "choking off" the original, inner eyewall by robbing it of necessary moisture and angular momentum.[2] This process often leads to a temporary weakening of the storm as the inner wall collapses.[2] Eventually, the outer eyewall completely replaces the inner one, and the storm may re-intensify, often resulting in a larger but more stable eye.[2] ERCs are a primary mechanism by which tropical cyclones can significantly increase their overall size, including the diameter of their inner core, while sometimes experiencing a simultaneous, albeit temporary, decrease in peak strength.[16] This dynamic presents a paradox: while smaller RMWs are generally associated with higher intensity, the largest eye sizes may correspond to a mature, stable phase after an ERC, rather than the storm's absolute peak intensity. This complex evolution highlights the challenges in forecasting and the need to understand these structural changes.

2.3. Key Meteorological and Environmental Factors Influencing Eyes and RMW Variability

The size and characteristics of a tropical cyclone's eye and RMW are not static but are profoundly influenced by a range of meteorological and environmental factors. Understanding these influences is critical for accurate forecasting and for assessing the maximum possible radius of a cyclone's eye.

2.3.1. Central Pressure and Maximum Wind Speed

The relationship between central pressure, maximum wind speed, and RMW is fundamental to tropical cyclone dynamics. The lowest barometric pressure within a tropical cyclone is consistently found in its eye, with values potentially 15% lower than the surrounding environment.[2] This significant pressure deficit creates a rapid variation of pressure across the storm, particularly pronounced near the center. This steep pressure gradient force is directly responsible for driving the powerful winds observed in the eyewall.[3] As the sea-level pressure within the eye decreases, there is a corresponding increase in the maximum tangential surface winds (Mmax) observed around the eyewall.[6] This inverse relationship between central pressure and maximum wind speed is a cornerstone of tropical cyclone intensity estimation.

The Yadav and Das (2024) model, the primary reference for this report, explicitly incorporates the estimated pressure drop (Pd) at the TC center as a key parameter

for RMW estimation.[1] This choice is empirically grounded, as Pd is closely linked to the cyclone's intensity.[1] The model's reliance on Pd as a primary input for RMW underscores the direct causal link: a larger pressure drop signifies greater intensity, which in turn profoundly influences the RMW. However, a critical limitation of the Yadav and Das model is its applicability only when Pd is less than or equal to 12 hPa.[1]

This constraint means that the model may not accurately capture RMW for very intense storms, which often exhibit significantly larger pressure drops (e.g., ESCS Tauktae had a 50 hPa drop [1]). Consequently, the model's utility in determining the "maximum radius" for the most powerful and potentially largest-eyed storms is inherently limited, necessitating reliance on other observational data and theoretical understanding for these high-intensity scenarios.

2.3.2. Latitudinal Dependence and Coriolis Effects

Latitude plays a fundamental role in tropical cyclone dynamics, serving as a key indicator of both TC formation and movement.[1] The Coriolis effect, which arises from the Earth's rotation, is essential for the initial generation of the vortex that characterizes a tropical cyclone.[12] This fundamental force also exerts a significant influence on the size of the storm's inner core. Research indicates that the Radius of Maximum Wind (RMW) is known to increase with latitude.[18] This phenomenon is a direct consequence of the conservation of angular momentum, coupled with the tendency for storm intensity to decrease at higher latitudes.

This latitudinal dependence implies that tropical cyclones forming or moving into higher latitudes may naturally develop larger inner-core structures. For instance, climatological studies show that larger tropical cyclones are generally situated at higher latitudes, while smaller TCs tend to be found at lower latitudes.[19] This suggests that the Coriolis effect acts as a fundamental control on the overall structure and size of a tropical cyclone, contributing to the potential for larger RMWs and, by extension, larger eyes, as storms migrate poleward. This physical control is a first-order factor in understanding the potential for a "maximum radius" of a cyclone eye.

2.3.3. Vertical Wind Shear and its Structural Impact

Vertical Wind Shear (VWS), defined as the change in wind speed and direction with increasing altitude, is a critical environmental factor that profoundly influences the structure and intensity of tropical cyclones.[12] Weak VWS is highly conducive to the development and maintenance of tropical cyclones, allowing for a more symmetric and robust storm structure.[13] Conversely, strong VWS is detrimental to TC development and can significantly disrupt the storm's organization.

Under conditions of strong VWS, the convective clusters near the center of a tropical cyclone can become tilted. This tilting action weakens the storm's vertical atmospheric activities and displaces the crucial heat and moisture away from the core region.[12] Such disruption directly damages the warm-core structure, which is essential for eye formation and intensity maintenance, potentially leading to the storm's weakening or even dissipation.[12] Specifically, strong VWS can push the storm's thunderstorms away from its center, exposing the low-level circulation and disrupting the release of latent heat and the warming from sinking air that are vital for maintaining the warm core. This process tends to increase surface pressure near the storm's center, thereby weakening its overall intensity.[13]

The impact of VWS on the eye is significant: strong shear can prevent a well-defined eye from forming or cause an existing eye to become ragged, fragmented, or even dissipate.[2] This implies that the occurrence of a "maximum radius" eye, which typically requires a well-organized and stable inner core, is less likely under conditions of strong VWS. Conversely, a weak shear environment is a necessary prerequisite for the development and sustainment of a clear, potentially large, and symmetric eye structure. The influence of VWS highlights its role as a primary disruptor of inner core symmetry and intensity, directly affecting the potential for extreme eye sizes.

2.3.4. Oceanic Heat Content and Sea Surface Temperature Anomalies

The ocean serves as the primary energy source for tropical cyclones, making oceanic heat content and sea surface temperature (SST) anomalies critical environmental factors influencing their formation, intensification, and structural characteristics, including the eye. Warm sea surface temperatures provide the ideal breeding ground for TCs and supply the continuous energy necessary for their development and rapid intensification.[1] This thermal energy from the ocean's surface layers acts as the fuel for storms, enabling them to become more powerful and potentially more destructive.[20]

Oceanic heat content, which refers to the amount of heat energy stored in the upper layers of the ocean, is consistently identified as an important environmental factor directly related to changes in TC intensity and the process of eye formation.[14] A robust and sustained supply of heat from the ocean supports the deep convection and latent heat release that are fundamental to maintaining the storm's warm core.

Since eye formation is strongly associated with rapid intensification [14], a plentiful oceanic heat source is indirectly linked to the development of a clear, well-defined eye.

While not directly dictating the "maximum radius" of an eye, a sustained energy supply from the ocean enables the storm to maintain its structural integrity and intensity over prolonged periods. This sustained energy can facilitate internal dynamic processes, such as eyewall replacement cycles, which are known to lead to the expansion of the eye's diameter.[2] Therefore, the availability of high oceanic heat content and warm SSTs is a foundational element that allows for the development of the well-organized inner-core structure necessary for the manifestation of large and stable eyes.

2.3.5. Environmental Moisture and its Role in Convection

Environmental moisture plays a crucial role in modulating the convective activity within a tropical cyclone, thereby influencing the clarity, symmetry, and overall health of its eye. Sufficient moisture in the storm's environment is essential for sustaining the deep convection that forms the eyewall. Conversely, the intrusion of dry air into the inner core of a tropical cyclone can significantly limit its intensification.[24] This dry air can induce asymmetric convective activity, suppressing the vital thunderstorms in the eyewall and disrupting the storm's warm core structure.[24] Such disruption can prevent a well-defined eye from forming or cause an existing eye to become ragged and less distinct.[2]

Conversely, increased moisture, particularly in the rear quadrants of a storm, can favor intensification by providing a continuous supply of moisture to the inner core and promoting storm symmetry.[24] The presence of adequate environmental moisture supports the vigorous and symmetric convection required for a robust eyewall. Within the eye itself, the air descends, warms by compression, and consequently experiences a decrease in relative humidity. This dry, sinking air suppresses cloud formation, leading to the characteristic clear and calm conditions observed in the
eye.[4]

Therefore, environmental moisture acts as a critical modulator of eye clarity and symmetry. While not directly influencing the "maximum radius" of the eye in a primary sense, a moist environment is a prerequisite for the development of a well-formed, stable eye. This stability and organization are necessary for the storm to undergo processes like eyewall replacement cycles, which are the primary drivers of eye expansion. Thus, the moisture environment indirectly affects the potential for a tropical cyclone to achieve and maintain a large eye.

2.3.6. Eyewall Replacement Cycles (ERCs) and their Influence on Eye Expansion

Eyewall Replacement Cycles (ERCs), also known as concentric eyewall cycles, are a natural and significant internal dynamic process that occurs in intense tropical cyclones, particularly those that attain major hurricane strength (Category 3 or higher on the Saffir-Simpson scale, with maximum sustained winds generally exceeding 185 km/h or 115 mph).[2] This phenomenon is a primary mechanism driving the expansion of a tropical cyclone's eye and its overall wind field.

The process begins when an outer ring of thunderstorms, often originating from outer rainbands, strengthens and organizes itself into a new, outer eyewall.[2] This newly formed outer eyewall then slowly contracts inward, competing with and eventually "choking off" the original, inner eyewall by depriving it of the necessary moisture and angular momentum.[2] During this transitional phase, as the inner wall collapses, the storm typically experiences a temporary weakening in its maximum sustained winds.[2] This temporary weakening is a critical forecasting challenge, as it can mislead observers into believing the storm is dissipating when it is merely reorganizing.

Once the outer eyewall fully replaces the inner one, the storm often re-intensifies. Crucially, this replacement process typically results in a significantly larger but more stable eye.[2] The expansion of the eye is a direct consequence of the new, larger eyewall taking over the primary convective and wind-generating functions. ERCs can, therefore, greatly increase the overall size of tropical cyclones, including their inner core and the radial extent of their destructive wind field, while simultaneously causing a temporary decrease in their peak strength.[16] For example, Hurricane Milton, a historic Category 5 storm, underwent an ERC, causing its peak sustained winds to drop from 180 mph to 145 mph before re-intensifying to 160 mph with a new, larger eyewall.[17]

This mechanism is a key driver for the manifestation of exceptionally large eye sizes, making it a central factor in understanding the "maximum radius" of a cyclone eye. The paradox of a larger eye correlating with temporary weakening, contradicting the general rule that smaller RMWs indicate higher intensity, highlights the intricate nature of TC dynamics. It suggests that a "maximum radius" might not necessarily correspond to the storm's absolute peak intensity but rather to a mature, stable phase following an ERC. This process significantly alters the storm's hazard profile, spreading the destructive winds over a wider area.

3. Methodologies for Measuring and Estimating Tropical Cyclone Eye and RMW

Accurately measuring and estimating the parameters of a tropical cyclone's inner core, particularly its eye and Radius of Maximum Wind (RMW), is fundamental for both scientific research and operational forecasting. Various methodologies have been developed, each with distinct strengths and limitations.

3.1. Remote Sensing Approaches

Given the limitations of in-situ aircraft reconnaissance, remote sensing technologies, particularly satellite- and radar-based techniques, have become indispensable for monitoring tropical cyclones globally. These methods offer broader spatial coverage and more frequent observations, albeit with their own set of challenges.

3.1.1. Satellite-Based Techniques (e.g., Dvorak Analysis, Infrared and Visible Imagery)

Satellite-based techniques are widely employed for estimating tropical cyclone intensity and discerning inner-core features. The Dvorak technique stands as a standard method, relying on the subjective interpretation of satellite imagery, specifically infrared (IR) and visible (VIS) channels.[30] This technique utilizes empirically-based rules and image pattern recognition to assign a "T-number" (Tropical Number) that represents the cyclone's strength.[33] For storms exhibiting an eye pattern, the Dvorak technique assesses intensity by contrasting the coldness of cloud tops within the surrounding thunderstorms with the warmer temperature observed within the eye itself.[31] A larger temperature difference generally indicates a stronger tropical cyclone.[35] The India Meteorological Department (IMD) considers the radius of maximum reflectivity in visible imagery and the radius of the lowest cloud temperature in IR imagery as proxies for the RMW.[1]

To mitigate the inherent subjectivity of manual Dvorak analysis, which can lead to discrepancies between different analysis centers [32], objective versions such as the Objective Dvorak Technique (ODT) and Advanced Dvorak Technique (ADT) have been developed. These automated algorithms objectively identify cloud patterns and calculate eye/convection temperatures.[31] When tropical cyclones have clear eyes, the eye radii estimated from IR images show a high correlation with RMW values obtained from aircraft reconnaissance.[7] Linear regression methods applied to such data have demonstrated mean absolute errors of approximately 2 km in RMW estimation.[18]

Despite their broad utility, satellite-based methods face several limitations. Subjectivity remains a challenge in manual Dvorak analysis.[32] Detection becomes less reliable for "no eye" conditions or when the eye is obscured by a Central Dense Overcast (CDO), a dense mass of cold cloud tops that covers the storm center.[2] Furthermore, resolution constraints limit the ability to accurately resolve smaller- scale phenomena within the storm.[36] Cloud obstruction of lower atmospheric layers is a persistent issue, as satellites primarily observe cloud-top structures.[38] Distinguishing between different cloud layers in visible imagery or identifying low clouds in IR imagery, especially at night, can be difficult.[38] Automated detection algorithms, while improving objectivity, may not perform consistently across diverse datasets and can sometimes yield false

positives.[42] Moreover, intensity estimates for storms over open water often suffer from underestimation due to sparse
observational data.[30]

3.1.2. Radar-Based Techniques (e.g., Doppler Radar, Synthetic Aperture Radar - SAR)

Doppler Radar systems, particularly ground-based networks like NEXRAD, are capable of detecting tropical cyclone eyes when storms are near the coast.[2] For operational purposes, the radius of maximum reflectivity observed by radar is often considered as the RMW by agencies like the IMD.[1] Doppler velocity data can be processed to determine RMW and the circulation centers of tropical cyclones.[8] Airborne platforms also utilize Tail Doppler Radar (TDR), which measures near- vertical cross-sections of precipitation and winds. By compiling these cross-sections, scientists can construct three-dimensional images of the storm, delineating the location and extent of the strongest winds.[29]

Synthetic Aperture Radar (SAR) represents an advanced active microwave radar technology that offers unique capabilities. Unlike passive satellite sensors, SAR can "see" through clouds and rain, providing high-resolution images of the ocean surface imprint of a tropical cyclone.[11] This allows SAR to identify the eye at the surface level.[40] For measuring eye size, a common approach with SAR involves defining a 34- knot (34-kt) wind contour around the eye and then calculating the area of pixels within this contour.[40] SAR measurements can also provide independent and highly detailed measurements of maximum wind speed and RMW.[45]

Despite their advantages, radar-based techniques also face limitations. Ground- based radar systems have inherent range limitations, coverage gaps, and "blind spots" known as the "cone of silence" directly above the radar.[38] Beam blockage by terrain or structures can create data voids, and challenges exist in accurately detecting low-level drizzle or differentiating between precipitation types.[38] Non- meteorological echoes from aircraft, birds, or insects can generate false positives.[46] Furthermore, the strength of TCs estimated from Doppler winds can be underestimated when the RMW moves near the radar site due to geometrical limitations.[8] For SAR, a significant limitation is its limited swath width, meaning it typically does not cover the entire TC domain in a single image.[47] While SAR excels at high-resolution imaging, studies often focus on imagery containing obvious, complete eyes, making it challenging to analyze developing or declining storms that lack clear eye structures.[47]

The diverse strengths and weaknesses of satellite and radar systems highlight their complementary nature. No single remote sensing technique provides a complete picture of a tropical cyclone's inner core. Satellites offer wide spatial coverage but are limited by cloud obstruction and resolution for small features.[38] Radar provides detailed precipitation and wind data near the coast but is constrained by range and blockage.[38] SAR penetrates clouds for surface wind information but has limitations in its spatial coverage.[47] Therefore, a robust understanding and accurate estimation of tropical cyclone eye and RMW, especially for extreme sizes, necessitates the integration of data from multiple platforms. This multi-sensor approach is critical for overcoming individual sensor limitations and improving real-time analysis, allowing for a more comprehensive assessment of the storm's structure and potential impact. This also underscores a fundamental trade-off in remote sensing: achieving high resolution and accuracy often comes at the expense of broad coverage or continuous, real-time availability.

3.2. Empirical and Statistical Models for Eye and RMW Prediction

Given the inherent limitations and challenges associated with direct in-situ measurements and remote sensing observations, empirical and statistical models play a crucial role in estimating tropical cyclone eye and Radius of Maximum Wind (RMW) parameters. These models serve to bridge observational gaps and provide practical tools for operational forecasting.

Empirical models are developed by identifying and quantifying relationships between RMW and other readily available tropical cyclone variables. The Yadav and Das (2024) model, for instance, is an empirical function that relates RMW to the estimated pressure drop (Pd) at the TC center and the latitude (ϕ) of the TC center.[1] The mathematical formulation for this relationship is given by: $RMW=k\times e(aPd+b\phi)+c$ (Equation 1 in Yadav and Das, 2024 [1]). The constants (k, a, b, and c) in this equation are derived by fitting the model to a dataset of historical TC data from the North Indian Ocean (NIO) basin, which includes observed values of RMW, Pd, and ϕ.[1] This fitting process typically employs non-linear least squares optimization methods, such as the 'curvefit' function from 'scipy.optimize', to ensure robust parameter estimation.[1]

Beyond the Yadav and Das formulation, other empirical models exist for RMW prediction. For example, Willoughby et al. (2006) introduced an empirically derived model for the NIO basin: $RMW=46.6\times e(-0.015Vmax+0.0169\theta)$ (Equation 3 in Yadav and Das, 2024 [1]), where θ is latitude and Vmax is maximum wind speed. Similarly, Tan and Fang (2018) provided an expression relating RMW to the estimated central pressure (Pc) of the TC: $RMW=-26.73\times \ln(1013.25-Pc)+142.41$ (Equation 4 in Yadav and Das, 2024 [1]). These models, while varying in their input parameters and functional forms, all aim to quantify the influence of key meteorological variables on RMW.

Statistical models leverage historical storm behavior to predict typical outcomes for a TC in a specific location and environmental context.[48] Regression analysis is a common statistical technique employed to identify and quantify the relationships between variables such as central pressure, wind speed, latitude, and RMW.[1] The Dvorak technique, widely used for intensity estimation, is fundamentally a statistical method that uses satellite imagery patterns to infer cyclone strength [34] and, indirectly, eye size.[33] Furthermore, some empirical models predict minimum pressure by incorporating parameters such as maximum wind speed, the radius of 34-knot winds (R34kt), storm center latitude, and environmental pressure.[49]

The utility of empirical and statistical models lies in their ability to provide estimates of RMW and eye size even when direct observations are sparse or unavailable, which is particularly relevant for regions like the NIO where historical RMW data were limited until the early 2000s.[1] These models bridge observational gaps and provide crucial information for operational decision-making. The development of such models often involves a synergistic interplay between physical theory and statistical fitting. While empirical models are derived from observed relationships, they are frequently "based on the physics of the hurricane wind field" [49] or grounded in "fundamental conservation principles".[18] This hybrid approach, combining theoretical understanding with empirical data fitting, is essential for developing robust models that can

accurately estimate parameters like RMW and eye size, especially when considering their extreme values. This integration ensures that the models are not merely statistical correlations but are also physically plausible, enhancing their reliability and predictive power.

3.3. Inherent Challenges and Limitations in Real-time Measurement and Detection

The real-time measurement and detection of tropical cyclone eye and RMW characteristics are fraught with inherent challenges and limitations that impact forecasting accuracy and the ability to precisely determine extreme radii. These challenges stem from a combination of observational constraints, the dynamic nature of tropical cyclones, and the complexities of data processing.

One significant challenge is subjectivity in analysis. Manual interpretation, particularly in methods like the Dvorak technique, can introduce biases and lead to discrepancies between different analysis centers estimating the same storm.[32] This human element can create inconsistencies in real-time data, which are then used for forecasting.

Data gaps and resolution limitations further complicate accurate measurement. Observations are inherently prone to errors, and their spatial and temporal coverage can vary significantly, often being unrepresentative or even contradictory.[41] Remote sensing instruments, while providing broad coverage, have resolution constraints that affect their ability to accurately detect and characterize smaller-scale phenomena within the storm's inner core.[36] This means that fine details of the eye or RMW, especially during rapid changes, might be missed or poorly resolved.

Environmental conditions frequently obscure inner-core features. Cloud obstruction of lower atmospheric layers is a common issue for satellite sensors, which primarily observe cloud-top structures.[38] "Filled eyes" or eyes completely covered by a Central Dense Overcast (CDO) are difficult to detect and characterize accurately.[2]

Weaker or disorganized storms often have less well-defined eyes, making their detection and sizing even more challenging.[2]

Instrument limitations also contribute to measurement difficulties. Ground-based radar systems have restricted ranges, "blind spots" (known as the "cone of silence" directly above the radar), and issues with beam blockage by terrain.[38] Synthetic Aperture Radar (SAR), while capable of penetrating clouds, has a limited swath width, meaning it typically does not cover the entire tropical cyclone domain in a single image.[47] Furthermore, the relatively coarse resolution of some instruments can lead to under-sampling if the TC center is not precisely co-located with the instrument's field of view.[51]

The dynamic nature of tropical cyclones itself presents a formidable challenge. Rapidly intensifying storms can develop extremely small, clear, and circular eyes, often referred to as "pinhole eyes," which are prone to large and unpredictable fluctuations in intensity, posing significant difficulties for forecasters.[2] Eyewall replacement cycles (ERCs), which are common in intense storms, cause significant structural changes and temporary weakening, making it challenging to track the evolving eye and RMW in real-time.[16]

Historical data issues further complicate long-term analyses and model development. For instance, comprehensive RMW values for most tropical cyclones were not consistently available in historical records until observations became more routine around 2001.[1] Many past studies relied on subjective estimates of parameters like the radius of 34-knot winds (R34) and the radius of the outermost closed isobar (ROCI).[19]

Finally, real-time operational constraints impose significant pressure. "Working best track" data, used for immediate forecasting, are developed under tight time constraints, meaning that not all available data may be processed or incorporated.[41] Automated algorithms, while promising, sometimes struggle with real-time application due to the complexity of background noise in imagery or the need for specific tuning for different storm types or environments.[36]

These numerous limitations collectively create an "uncertainty cascade" in the estimation of eye and RMW parameters. Each measurement technique or modeling approach carries inherent flaws that propagate through the analysis process. This means that any determination of a "maximum radius" will inevitably be associated with a degree of uncertainty, particularly for historical events or rapidly evolving storms. This underscores the critical need for continuous advancements in observational technologies, data assimilation techniques, and modeling approaches to provide more reliable and timely information for forecasting and disaster mitigation. The operational imperative is to develop robust, automated solutions that can provide consistent, timely information to forecasters, even while acknowledging and striving to reduce the inherent errors.

4. Analysis of the Yadav and Das (2024) RMW Formulation for the North Indian Ocean

The paper by Yadav and Das (2024) presents a significant contribution to the estimation of the Radius of Maximum Wind (RMW) for tropical cyclones over the North Indian Ocean (NIO) basin. This section provides a detailed analysis of their proposed methodology, its performance, and its critical limitations.

4.1. Mathematical Formulation and Parameter Derivation

The primary objective of the Yadav and Das (2024) study was to formulate a novel method for calculating the RMW based on key characteristics of tropical cyclones, specifically the latitude (ϕ) of the TC center and the estimated pressure drop (Pd) at the TC center.[1] The selection of these two parameters, while deliberately excluding longitude, is rooted in established empirical evidence and theoretical understanding within tropical cyclone research. Latitude is considered a fundamental indicator influencing TC formation and movement across various ocean basins, while pressure drop is intimately linked to TC intensity, reflecting the energy release and strength of the storm.[1] The exclusion of longitude is justified by research indicating its less pronounced direct impact on TC intensity compared to factors like sea surface temperature and atmospheric conditions.[1]

The empirical function developed by Yadav and Das to determine RMW (expressed in nautical miles) is given by the following non-linear equation:

RMW=k×e(aPd+bϕ)+c (Equation 1 in Yadav and Das, 2024 [1])

In this formulation, Pd represents the estimated pressure drop at the TC center, and ϕ denotes the latitude of the TC center. The constants k, a, b, and c are crucial for the model's accuracy and are determined through a rigorous optimization process. To estimate these constants, the authors utilized a dataset of historical tropical cyclone data from the NIO basin that included observed values of RMW, Pd, and ϕ.[1] The estimation was performed using a non-linear least squares optimization method, specifically employing the 'curvefit' function from the 'scipy.optimize' library in Python. The 'maxfev' parameter was increased to 10000 during the optimization process to allow for a higher number of function evaluations, thereby enhancing the convergence of the solution and ensuring robust parameter estimation.[1]

Through this optimization, the authors derived the specific values for the constants, resulting in the final equation for determining RMW:

$RMW = -36640.61 \times e(0.00029Pd + 0.000029\phi) + 36732.39$ (Equation 2 in Yadav and Das, 2024 [1])

A critical applicability constraint of this method is that it provides reliable means of calculating RMW only as long as the value of the estimated pressure drop (Pd) is less than or equal to 12 hPa.[1] This implies that the atmospheric pressure at the center of the TC has decreased by 12 hPa or less compared to the surrounding environment. This limitation is significant, as very intense tropical cyclones, which are often associated with extreme eye sizes or RMWs, frequently exhibit much larger pressure drops. For example, ESCS Tauktae, a case study analyzed in the paper, experienced a 50 hPa pressure drop.[1] This means the Yadav and Das model, while effective within its specified range, cannot directly determine the "maximum radius" for the most powerful and structurally complex storms, creating a "blind spot" for extreme intensities. This inherent limitation must be considered when discussing the overall scope and utility of the model in the broader context of tropical cyclone eye and RMW prediction.

4.2. Data Sources and Methodological Approach

The Yadav and Das (2024) study relied on a comprehensive dataset and a well- defined methodological approach to develop and validate their RMW formulation for the North Indian Ocean (NIO) basin.

The primary data source for this study was the best track dataset obtained from the India Meteorological Department (IMD).[1] The IMD holds the designation as the Regional Specialized Meteorological Center for tropical cyclones over the NIO, making its dataset a authoritative source for TC characteristics in this region.[1] The dataset encompasses a variety of crucial metrics related to tropical cyclones, including the TC number, precise time (year, month, day, and hour), TC center locations (longitude and latitude), estimated central pressure (Pc), maximum wind speed (Vm), and the estimated pressure drop at the center (Pd).[1] These metrics were recorded at 6-hour intervals, providing a reasonably high temporal resolution for tracking storm evolution.[1]

A notable aspect of the data preparation involved addressing missing RMW values within the best track database. The authors employed polynomial interpolation, specifically Newton interpolation, to fill these gaps.[1] For instance, in the case of Extremely Severe Cyclonic Storm Tauktae, if RMW values were available for May 14th at 06 UTC and May 15th at 00 UTC, interpolation was used to estimate values for May

14th at 12 and 18 UTC.[1] To validate the proposed method, the interpolated RMW data were compared against RMW data from IMD bulletins.[1] For the model's development and evaluation, the dataset was partitioned: data from 25 tropical cyclones were used for training the model, and data from 4 distinct tropical cyclones were reserved for validation.[1]

The performance of the proposed RMW formulation was rigorously compared against two other existing models specifically designed for the NIO region:

1. Willoughby et al. (2006) model: This empirically derived model describes the structure of the hurricane vortex and provides an expression for RMW over the NIO: $RMW=46.6\times e(-0.015Vmax+0.0169\theta)$.[1] Here, θ represents latitude in degrees, and Vmax is the maximum wind speed in knots.
2. Tan and Fang (2018) model: This model focuses on simulating wind fields of historical TCs using parametric models and satellite data. Their expression for RMW over the NIO is: $RMW=-26.73\times \ln(1013.25-Pc)+142.41$.[1] In this equation, Pc refers to the estimated central pressure of the TC.

The reliance on IMD best track data, and particularly the use of polynomial interpolation for missing RMW values, introduces a potential source of uncertainty. While interpolation is a standard practice for filling data gaps, it means that not all RMW values used in the model's training and validation are direct observations. This could subtly influence the accuracy of the derived constants and the model's overall performance, especially for extreme RMW values that might be underrepresented or inaccurately interpolated. This nuance is important for a comprehensive understanding of the model's robustness.

4.3. Performance Evaluation: Error Metrics and Statistical Significance

The Yadav and Das (2024) study employed a robust set of statistical measures to evaluate the accuracy and performance of their proposed RMW formulation, comparing it against existing methods. The three primary evaluation techniques utilized were error percentage, statistical t-test, and Root Mean Square Error (RMSE).[1]

The error percentage was calculated by comparing the RMW values obtained from the proposed method with the actual data provided by the IMD, as well as with the results generated by the two comparative methods (Tan and Fang, 2018; Willoughby et al., 2006).[1] The formula used was: Error percentage = (Experimental Value - Actual Value) / Actual Value * 100.[1] Overall, the proposed method exhibited a mean absolute error percentage ranging from approximately 6% to 32% when compared to IMD best

track data.[1] In stark contrast, the formulations from other studies showed a considerably larger mean absolute error range, spanning from 13% to 128% concerning the IMD best track data.[1] This indicates a substantial improvement in accuracy by the Yadav and Das model.

The statistical t-test was conducted to formally determine if the observed differences in accuracy between the proposed method and the alternative approaches were statistically significant.[1] A t-test compares the means of two samples to ascertain if there is a significant difference between them. For this analysis, a significance level (α) of 0.05 was utilized.[1] The t-test consistently indicated that the proposed method is "statistically better" than the other two approaches, a conclusion supported by its consistently lower error percentages and RMSE values.[1] This statistical superiority means that the observed improvements in the proposed method's outcomes are unlikely to have occurred by chance, signifying a genuine advancement in RMW estimation for the NIO basin.

The Root Mean Square Error (RMSE) is a widely used metric that quantifies the average magnitude of the differences between predicted (or experimental) values and observed (or actual) values.[1] A lower RMSE value signifies that a model's predictions are, on average, closer to the observed values, indicating a higher level of accuracy.[1] The RMSE values for the proposed method were consistently lower than those generated by the Willoughby et al. (2006) and Tan and Fang (2018) models across all tested tropical cyclone cases.[1] This further reinforces the superior performance of the Yadav and Das formulation.

The following tables summarize the comparative performance of the proposed method against the existing models:

Table 4.1: Mean Absolute Error Percentages for RMW Estimation (Yadav & Das vs. Comparative Models)

Name of TC	Our method w.r.t. IMD (%)	Willoughby et al. w.r.t. IMD (%)	Tan and Fang w.r.t IMD (%)
Tauktae	19.42	25.99	54.85
Gulab	32.60	41.37	128.62
Mandous	29.63	35.80	79.23
Asani	6.33	12.74	21.73

Sitrang	15.21	18.42	62.679
Jawad	10.12	28.53	62.41
Yaas	24.45	38.17	29.10
Mean	19.68	28.72	62.80

Source: Adapted from Table 10 in Yadav and Das (2024) [1]

Table 4.2: Root Mean Square Error (RMSE) Values for RMW Estimation (Yadav & Das vs. Comparative Models)

Name of TC	Our method w.r.t. IMD	Willoughby et al. w.r.t. IMD	Tan and Fang w.r.t IMD
Tauktae	10.75	17.14	21.84
Gulab	10.06	12.37	34.69
Mandous	15.9	18.17	32.37
Asani	6.33	12.74	21.73

Sitrang	10.67	14.01	29.68
Jawad	6.73	16.63	28.71
Yaas	17.01	24.91	17.59
Mean	11.08	16.57	26.66

Source: Adapted from Table 9 in Yadav and Das (2024) [1]

While the Yadav and Das method demonstrates statistical superiority, it is important to note that the mean absolute error percentage still ranges from 6% to 32%.[1] For critical applications such as disaster preparedness and real-time forecasting, even a 6% error can be significant, potentially impacting the accuracy of warnings and resource allocation. This indicates that while the model represents a substantial improvement over previous formulations, there remains considerable room for further refinement to achieve even greater precision. This ongoing need for enhanced accuracy is a crucial area for future research, particularly as it relates to the precise prediction of RMW and, by extension, the maximum radius of cyclone eyes.

4.4. Case Studies: Application and Results for Selected North Indian Ocean Cyclone

To demonstrate the efficacy and validate the accuracy of their proposed RMW formulation, Yadav and Das (2024) applied their method to seven specific tropical cyclone cases that occurred over the North Indian Ocean (NIO) basin. These case studies provide a detailed view of the model's performance under various storm characteristics and intensity levels. The selected cases include: Extremely Severe Cyclonic Storm Tauktae (ESCS Tauktae), Cyclonic Storm Gulab (CS Gulab), Severe Cyclonic Storm Mandous (SCS Mandous), Severe Cyclonic Storm Asani (SCS Asani), Cyclonic Storm Sitrang (CS Sitrang), Cyclonic Storm Jawad (CS Jawad), and Very Severe Cyclonic Storm Yaas (VSCS Yaas).[1]

1. Extremely Severe Cyclonic Storm Tauktae (May 14-19, 2021): This was a powerful and destructive storm that primarily impacted the Arabian Sea and the western coast of India.

Tauktae rapidly intensified from 65 knots to 100 knots in 24 hours, reaching an ESCS category with maximum sustained winds of 85-90 knots (gusts up to 100 knots). Its lowest estimated central pressure dropped to 950 hPa, representing a significant 50 hPa decrease compared to the surrounding region.[1] Despite this large pressure drop, which exceeds the model's stated applicability range of Pd≤12 hPa, the proposed method demonstrated an average error of 19.42% for RMW estimation.[1] This suggests that while the model has a specified constraint, its performance for more intense storms might still be evaluated, though with potentially higher uncertainty.

2. Cyclonic Storm Gulab (September 24-28, 2021): Gulab formed during the active monsoon season and had a relatively shorter lifespan of approximately 90 hours, compared to the long-term average of 110 hours for such systems in the Bay of Bengal. It reached a peak intensity of 45 knots.[1] For CS Gulab, the proposed method yielded an average error of 28.49%.[1]

3. Severe Cyclonic Storm Mandous (December 6-10, 2022): Mandous was one of the severe cyclonic storms that made landfall along the Tamil Nadu coast. It followed a unique track, initially moving west-northwest, then northwest, and finally west-southwest after landfall. The storm maintained its existence for approximately 96 hours and achieved a peak intensity of 50 knots.[1] The proposed method exhibited an error rate of 29.63% for SCS Mandous.[1]

4. Severe Cyclonic Storm Asani (May 7-12, 2022): Asani developed over the South Andaman Sea and Southeast Bay of Bengal. It was characterized by unusually slow movement (5-6 km/h) and displayed multiple shifts in its trajectory, influenced by a westerly trough.[1] For SCS Asani, the proposed method showed a comparatively lower error percentage of 15.92%.[1]

5. Cyclonic Storm Sitrang (October 22-25, 2022): Sitrang formed over the North Andaman Sea and Southeast Bay of Bengal. It initially moved northwestward before recurving north-northeastwards and exhibited exceptionally rapid movement on October 24th. Its lifespan was approximately 69 hours, shorter than the long-term average for post-monsoon cyclonic storms in the Bay of
   Bengal.[1] The proposed method achieved an error rate of 15.21% for CS Sitrang.[1]

6. Cyclonic Storm Jawad (December 2-6, 2021): Jawad was the fifth tropical cyclone observed over the NIO in 2021 and the first during the post-monsoon season that did not make landfall in Odisha. It initially moved north- northwestward and began to recurve on its fourth day. Jawad reached a peak maximum sustained wind (MSW) of 40 knots but weakened due to unfavorable environmental conditions.[1] The proposed method yielded its lowest error rate of 10.12% for CS Jawad.[1]

7. Very Severe Cyclonic Storm Yaas (May 23-28, 2021): Yaas emerged in the Bay of Bengal just four days after ESCS Tauktae dissipated. It had a relatively smaller impact compared to Tauktae and followed a straight north-northwestward trajectory. Yaas reached a peak MSW

of 75 knots (gusts up to 85 knots) but experienced rapid weakening after making landfall.[1] The proposed method had
an error rate of 24.45% for VSCS Yaas.[1]

The analysis of these case studies reveals a significant variability in the model's performance across different storm types and intensity levels. While the overall mean error for the proposed method is lower than comparative models, individual case study errors range from 10.12% (Jawad) to 29.63% (Mandous).[1] This substantial variability suggests that the model's accuracy is not uniform across all TC characteristics or intensity ranges, even within the specified Pd≤12 hPa constraint.
This indicates that factors beyond just latitude and pressure drop might be influencing RMW, or that the model's derived coefficients are more robust for certain storm characteristics than others. This variability highlights a crucial area for future improvement, as the model's performance might be less reliable for the most extreme or atypical cases, which are often of greatest concern for understanding the "maximum radius" of cyclone eyes.

The following table provides a detailed RMW results and error analysis for ESCS Tauktae as an example of the granular data presented in the original paper:

Table 4.3: Detailed RMW Results and Error Analysis for ESCS Tauktae

Date/Ti me	IMD's RMW (nautic al miles)	Propose d RMW (nautic al miles)	Willoug hby et al. RMW (nautic al miles)	Tan and Fang RMW (nautic al miles)	E_1 (%)	E_2 (%)	E_3 (%)
14/06	40	58.82	38.571	66.288	47.05	3.57	65.72
14/12	29	32.18	39.46	64.21	10.96	36.06	121.41
14/18	36	42.20	47.12	60.98	17.22	30.88	69.38

15/00	60	48.20	31.69	60.7136	19.66	47.18	1.18
15/06	60	44.123	29.65	58.30	26.46	50.58	2.83
15/12	32	35.92	25.785	53.10	12.25	19.42	65.93
15/18	32	31.24	24.207	50.4	2.37	24.35	57.5
Mean	41.28	41.81	33.78	59.14	19.42	25.99	54.85

Source: Adapted from Table 2 in Yadav and Das (2024) 1

Note: E_1 indicates the error percentage between the proposed method and IMD, E_2 represents the error percentage between Willoughby et al.'s expression and IMD, and E_3 represents the error percentage between Tan and Fang's expression and IMD.

4.5. Critical Limitations and Applicability Constraints of the model

While the Yadav and Das (2024) RMW formulation represents a significant advancement for the North Indian Ocean basin, it is essential to acknowledge its critical limitations and applicability constraints. These limitations directly impact the model's utility, particularly when considering the broader question of determining the "maximum radius of cyclone eye."

The primary limitation of the proposed method is its strict applicability range: the model is reliable only when the estimated pressure drop (Pd) at the TC center is less than or equal to 12 hPa.[1] This constraint means that the model cannot accurately predict RMW for very intense tropical cyclones, which frequently exhibit much larger pressure drops. For instance, Extremely Severe Cyclonic Storm Tauktae, one of the case studies in the paper, experienced a central pressure drop of 50 hPa [1], far exceeding the model's operational threshold. This creates a significant "blind spot" for the model in predicting RMW for the most intense TCs. Since well-defined, and potentially very large or very small (pinhole), eyes are often associated with intense cyclones, the model cannot directly contribute to determining the "maximum radius" for these most extreme cases. This necessitates relying on other observational data and theoretical understanding for such high-intensity scenarios, underscoring the need for future model improvements to cover a wider range of storm intensities.

Another point of note is that the paper explicitly states no specific conditions are imposed on the latitude of the TC center within the NIO basin for the model's application.[1] While latitude is a parameter in the model, the absence of specific constraints on its range implies that the model is intended for broad application across the NIO, but its performance might vary at the extreme latitudinal boundaries of TC activity.

Furthermore, it is crucial to reiterate that the Yadav and Das paper focuses solely on RMW and does not provide a direct formulation for the cyclone eye radius.[1] The relationship between RMW and eye radius is inferred from other studies.[6] This highlights a gap in the primary reference for the user's explicit query about eye size. Although RMW and eye radius are related, a dedicated model for eye radius, potentially incorporating factors like eyewall replacement cycles (ERCs) that directly influence eye expansion, would be more directly relevant to the user's question, especially concerning its maximum extent. This suggests the need for a dedicated eye radius model that can capture the nuances of eye evolution, particularly for extreme sizes.

In summary, while the Yadav and Das model offers a statistically superior method for RMW estimation within a specific range of pressure drops, its limitations mean it cannot fully address the question of "maximum radius of cyclone eye" for all storm intensities. Future research efforts will need to overcome these constraints to provide a more comprehensive understanding and predictive capability for the full spectrum of tropical cyclone inner-core characteristics.

5. Investigating the Maximum Radius of Tropical Cyclone Eyes

The concept of a "maximum radius" for a tropical cyclone eye is not a fixed value but rather an extreme point within a wide spectrum of observed eye sizes, influenced by complex meteorological dynamics and environmental factors. This section synthesizes climatological observations, methodological approaches for inferring eye radius, and the factors contributing to exceptionally large eyes.

5.1. Climatological Observations of Extreme Eyes Sizes

Climatological studies of tropical cyclone eyes reveal a remarkable variability in their dimensions. A typical tropical cyclone eye is generally observed to have a diameter ranging from approximately 30 to 65 kilometers (16–35 nautical miles).[2] However, the observed range of eye sizes is far broader, extending from extremely small "pinhole" eyes, such as Hurricane Wilma's mere 3.7 km (2.3 mi) across, to exceptionally large eyes, exemplified by Typhoon Carmen's eye spanning 370 km (230 mi).[2] Hurricane Isabel, a powerful North Atlantic hurricane, notably sustained a wide eye of 65–80 km (40–50 mi) for several days, demonstrating that large eyes can persist in intense storms.[2]

A global climatology of tropical cyclone eyes, analyzing data from 1982 to 2015, indicates that over half of all tropical cyclones developed at least one eye during their lifespan, with an average eye duration of at least 30 hours.[52] Hurricane Ioke in 2006 holds the record for the longest-lived eye, persisting for 12 complete days.[52] Interestingly, this climatology also revealed geographical variations: eyes in the Southern Hemisphere were typically larger than their Northern Hemisphere counterparts.[52] Furthermore, a significant finding is that the geographical areas where tropical cyclone eyes occur have been expanding toward the poles.[52]

The vast range of observed eye sizes, from minuscule to exceptionally large, immediately addresses the "maximum radius" aspect of the query. This extreme variability, coupled with the observation that eye occurrence areas are expanding poleward, carries significant climatological implications. It suggests that the "maximum" is not a static boundary but rather a dynamic upper limit influenced by large-scale climate patterns and the evolving environment. This also implies that future climate change scenarios might lead to an increase in the average size of tropical cyclone eyes or a higher frequency of large-eye events, posing new challenges for hazard assessment.

5.2. Methodological Approaches for Inferring Eye Radius from RMW

While the Radius of Maximum Wind (RMW) is a critical operational parameter, directly measuring the precise radius of the calm eye itself can be challenging, especially for storms that are not perfectly symmetric or have obscured inner cores. Consequently, the eye radius is often inferred from RMW or other related meteorological observations.

The India Meteorological Department (IMD), for instance, considers the radius of maximum reflectivity in visible satellite imagery and the radius of the lowest cloud temperature in infrared (IR) imagery as proxies for RMW.[1] This approach leverages the fact that the strongest winds (and thus RMW) are typically associated with the deepest convection, which manifests as the coldest cloud tops in IR imagery and highest reflectivity in visible imagery.

For tropical cyclones with clear, well-defined eyes, studies have shown a high correlation between eye radii estimated from IR images and RMW values derived from aircraft reconnaissance data.[7] Advanced techniques, such as linear regression applied to these correlations, have improved the mean absolute error in RMW estimation to approximately 2 km.[18] In simplified, idealized models of tropical cyclones, the RMW (often denoted as R0) is approximated as twice the radius of the eye.[6] More detailed empirical relationships indicate that the eye radius tends to be 7– 12 km inside the RMW, with a strong correlation (0.93) between the two parameters.[8]

The Dvorak technique, a widely used satellite-based method for estimating tropical cyclone intensity, also indirectly accounts for eye size. In its "eye pattern" analysis, the technique uses the eye's size and clarity (from visible imagery) or its temperature (from infrared imagery) as "eye adjustments" to determine the storm's overall intensity.[33] This implies that eye characteristics are integrated into the broader assessment of storm strength.

Furthermore, active remote sensing technologies like Synthetic Aperture Radar (SAR) employ specific methods to measure eye size. SAR defines a 34-knot (34-kt) wind contour around the eye and then calculates the area of pixels within this contour to determine the eye's dimensions.[40]

The reliance on inferential methods highlights that the concept of "maximum eye radius" is often a derived quantity. Its accuracy is therefore dependent on the precision of RMW estimation and the validity of the empirical relationships used to link RMW to eye size. This reinforces the importance of robust RMW models, such as the one developed by Yadav and Das, for understanding the broader inner-core structure and, by extension, the characteristics of the cyclone eye.

5.3. Synthesis of Factors Contributing to Exceptionally Large Eye Radii

The occurrence of exceptionally large tropical cyclone eyes is not a random phenomenon but a result of specific dynamic and environmental factors that facilitate the expansion of the storm's inner core. A synthesis of current research points to several key contributors:

1. Eyewall Replacement Cycles (ERCs): This is the most significant and direct mechanism for eye expansion. As detailed in Section 2.3.6, ERCs occur in intense tropical cyclones when an outer eyewall forms and contracts inward, eventually replacing the original inner eyewall.[2] This process, while often leading to a temporary weakening of the storm, results in a larger and more stable eye.[2] ERCs are explicitly stated to "greatly increase the size of tropical cyclones" [16], making them the primary driver for extreme eye dimensions. This implies that while peak intensity might correlate with a small RMW, the largest eye could be a feature of a mature, major hurricane post-ERC.
2. Storm Intensity (Indirect Influence): While the general rule is that smaller

   RMWs are associated with higher intensity [1], the most intense storms (Category 3-5) are precisely those that undergo ERCs.[2] Therefore, a storm's ability to reach and sustain major hurricane intensity is a prerequisite for the dynamic processes that lead to eye expansion. This suggests that while rapid intensification might initially produce a very small "pinhole" eye [2], the largest eyes are typically a feature of a mature, powerful hurricane that has undergone structural reorganization.

3. Latitudinal Position: There is a clear relationship between a tropical cyclone's size and its latitude. Larger TCs are generally found at higher latitudes [19], and the RMW is known to increase with latitude.[18] This is a consequence of the Coriolis parameter's influence on angular momentum conservation. As storms move poleward, the increasing Coriolis force can contribute to the natural development of larger inner-core structures, including the eye. This provides a large-scale environmental context for the potential for maximum eye radii.
4. Favourable Environmental Conditions: While not directly causing eye expansion, environmental factors that support a well-organized and symmetric inner core are crucial prerequisites for the development and maintenance of a large eye. These include:
   - Weak Vertical Wind Shear (VWS): Strong VWS disrupts the storm's warm core and convection, leading to disorganized or dissipated eyes.[2] Conversely, weak VWS allows for the symmetric convection needed for a well-defined eyewall and clear eye, facilitating the conditions for ERCs.
   - Sufficient Environmental Moisture: Dry air intrusion can suppress convection and asymmetry, while adequate moisture promotes storm symmetry and intensification.[24] A moist environment supports the robust convection necessary for eyewall formation and expansion.
5. Diurnal Variation: Eye size is not static throughout the day; it can change inversely to the diurnal variation of convective activity. Specifically, eye size tends to become larger during the daytime. This is attributed to the dissipation of cirrus clouds from the eye region, leading to a clearer and seemingly wider eye.[23] This suggests a daily cycle of expansion and contraction that contributes to the observed variability in eye dimensions.

The complex interplay of these factors means that the "maximum radius" of a tropical cyclone eye is not simply tied to peak intensity but rather to a mature, post-ERC phase, further influenced by its latitudinal trajectory and the prevailing environmental conditions. This nuanced understanding is crucial for accurately characterizing and forecasting these extreme structural features.

5.4. Implications of Large Eye Structures for Forecasting and Disaster Preparedness

The occurrence of tropical cyclones with exceptionally large eye structures carries significant implications for meteorological forecasting and, critically, for disaster preparedness and mitigation efforts. A larger eye is not merely a meteorological curiosity; it fundamentally alters the hazard profile of a tropical cyclone, spreading its destructive potential over a wider geographical area.

One of the most direct consequences of a large eye, often resulting from an Eyewall Replacement Cycle (ERC), is the expansion of the storm's wind field.[16] This means that the area experiencing hurricane-force or damaging winds is considerably larger, impacting more people and a broader expanse of infrastructure. While the peak wind speeds might temporarily decrease during an ERC, the sheer spatial extent of the damaging winds increases, leading to more widespread wind damage across coastal and inland regions.[54]

Furthermore, the size of a tropical cyclone, particularly its Radius of Maximum Wind (RMW), is a key determinant of its storm surge potential.[9] The highest storm surge is typically coincident with the RMW.[9] Larger storms, with their expanded wind fields, push on a larger ocean area and sustain their influence over that area for a longer duration. This prolonged and widespread wind stress on the ocean surface translates into a higher and more extensive storm surge, inundating larger coastal areas.[55] This implies a shift in the nature of the hazard: from highly localized, intense damage associated with compact, intense storms, to more widespread, albeit potentially less extreme, damage over a broader region.

Beyond wind and storm surge, large eye structures also contribute to pervasive water intrusion. Even if the direct wind damage to structurally sound homes is reduced, the expanded wind field of a larger storm can drive rain over a wider area, leading to significant water intrusion through cracks, holes, and gaps in building exteriors. This wind-driven rain can cause catastrophic damage to walls, ceilings, and interiors, often resulting in major household disruption and mold growth, which can be as devastating as direct wind damage.[54]

The climatological observation that areas where tropical cyclone eyes occur are expanding toward the poles has profound long-term implications.[52] This poleward expansion means that new geographical regions and populations, historically unaccustomed to the direct impacts of tropical cyclones, are increasingly at risk.

These areas may lack the robust infrastructure, building codes, and community preparedness frameworks necessary to withstand the forces of a large tropical cyclone, amplifying the potential for devastating impacts.

For forecasting agencies, the presence of large eye structures necessitates adjustments in warning strategies. Broader warning areas are required to account for the expanded wind field and surge potential. Disaster preparedness efforts must shift from focusing solely on the immediate vicinity of the storm's center to a more expansive regional approach, considering the wider footprint of destruction. This includes planning for larger-scale evacuations, broader distribution of emergency resources, and enhanced public awareness campaigns in newly vulnerable areas. The "maximum radius" of a cyclone eye is thus not merely a meteorological characteristic but a direct determinant of the societal impact and a critical factor in effective disaster management.

6. Conclusion and Future Research Directions

6.1. Summary of Key Findings and Contributions

This thesis has undertaken a comprehensive examination of the tropical cyclone eye and Radius of Maximum Wind (RMW), with a particular focus on the elusive concept of maximum eye radius. A fundamental distinction was established between the calm, central eye and the RMW, the region of maximum sustained winds, emphasizing that RMW is the more direct and operationally critical metric for assessing a storm's destructive potential. While the eye is a visible manifestation of the storm's core, RMW directly quantifies the most hazardous wind field, with the eye typically located just inside the RMW.

The analysis critically reviewed the Yadav and Das (2024) model, a significant contribution to RMW estimation in the North Indian Ocean (NIO) basin. This empirical formulation, which leverages latitude and estimated pressure drop (Pd), demonstrated statistically superior performance compared to other existing models for the NIO, as evidenced by lower mean absolute error percentages (ranging from 6% to 32%) and Root Mean Square Error (RMSE) values.[1] This advancement represents a notable step forward in regional RMW prediction. However, a crucial limitation of the Yadav and Das model is its applicability constraint: it is reliable only for cases where the estimated pressure drop (Pd) is less than or equal to 12 hPa.[1] This constraint inherently limits its utility for assessing RMW in very intense storms, which often exhibit much larger pressure drops and are frequently associated with extreme

eye sizes.

The investigation into the "maximum radius" of cyclone eyes revealed that these extreme dimensions are not simply a function of peak intensity but are primarily driven by complex internal dynamics, most notably Eyewall Replacement Cycles (ERCs).[2] During ERCs, an outer eyewall replaces an inner one, often resulting in a larger, more stable eye, even if accompanied by a temporary decrease in peak intensity. Other contributing factors include latitudinal position, with larger TCs generally found at higher latitudes, and favorable environmental conditions such as weak vertical wind shear and sufficient moisture, which enable the maintenance of a well-organized inner core. Climatological observations indicate a vast range of eye sizes, from a mere 3.7 km to 370 km, and a poleward expansion of eye occurrence regions, highlighting the dynamic nature of these features and their sensitivity to large-scale climate patterns.

The various methodologies for measuring and estimating eye and RMW parameters— including in-situ aircraft reconnaissance, satellite-based techniques (e.g., Dvorak analysis), radar-based techniques (e.g., Doppler radar, SAR), and empirical/statistical models—were discussed, each with its inherent strengths and limitations. These limitations, such as subjectivity, data gaps, resolution constraints, environmental obscuration, and instrument-specific issues, collectively create an "uncertainty cascade" in real-time measurements, making precise determination of extreme radii challenging.

Finally, the implications of large eye structures for forecasting and disaster preparedness are substantial. A larger eye signifies a wider wind field and potentially a larger storm surge footprint, shifting the hazard from highly localized, intense damage to more widespread, albeit potentially less extreme, impacts. This necessitates broader warning areas and adapted mitigation strategies, underscoring that the "maximum radius" is a critical determinant of societal impact.

6.2. Addressing the Limitations of Current RMW and Eye Size Prediction Models

Despite the advancements presented by models like Yadav and Das (2024), significant limitations persist in the accurate prediction of RMW and, by extension, tropical cyclone eye size, particularly for extreme events. Addressing these limitations is paramount for enhancing forecasting capabilities and improving disaster preparedness.

The most prominent limitation of the Yadav and Das model is its strict constraint on the estimated pressure drop ($P_d \leq 12$ hPa).[1] This creates a "blind spot" for the model in predicting RMW for very intense tropical cyclones, which often exhibit pressure drops far exceeding this threshold (e.g., ESCS Tauktae with a 50 hPa drop [1]). Since the largest eyes, often resulting from Eyewall Replacement Cycles, typically occur in major hurricanes, current models are not yet robust enough to accurately characterize the full spectrum of TC intensities and associated structural changes. This means that for the most critical, high-impact storms, forecasters must rely on less precise methods or theoretical inferences for RMW and eye size. This gap in predictive capability across the full range of storm intensities is a major area requiring focused research to provide comprehensive hazard assessments.

Furthermore, while the Yadav and Das model is "statistically better" than its predecessors, its mean absolute error still ranges from 6% to 32%.[1] For operational applications, even a 6% error can translate into significant discrepancies in predicted wind fields or surge potential, highlighting the ongoing need for further refinement to reduce these error rates for more precise forecasting.

Beyond specific model limitations, current real-time measurement techniques continue to face challenges due to inherent data gaps, resolution issues, and the highly dynamic nature of tropical cyclones.[2] The subjectivity inherent in some traditional eye definition methods, such as manual Dvorak analysis, also impacts the consistency and reliability of eye size estimates.[32] These factors contribute to the uncertainty in identifying and tracking extreme eye sizes in real-time, which is crucial for timely warnings.

6.3. Recommendations for Advancing Tropical Cyclone Eye Dynamics Research

To overcome the identified limitations and advance the understanding and prediction of tropical cyclone eye and RMW characteristics, several key research directions are recommended:

1. **Model Expansion and Generalization**: A critical next step is to extend the applicability of models like Yadav and Das (2024) to a wider range of storm intensities. This involves developing methodologies for pressure drops exceeding the current 12 hPa limit, thereby enabling RMW prediction for the most intense tropical cyclones.[1] Furthermore, validating and adapting such models for additional ocean basins, including the North Pacific and South Pacific, would enhance their global utility.[1]

2. **Integration of Multi-Source High-Resolution Data:** Future research should prioritize the seamless integration of high-resolution data from diverse observational platforms. This includes combining data from aircraft reconnaissance (providing direct measurements), Synthetic Aperture Radar (SAR) (offering cloud-penetrating surface wind fields), and advanced satellite imagery (providing broad coverage and detailed cloud-top information).[18] Such a multi-sensor approach is essential to overcome the individual limitations of each platform and provide a more comprehensive and accurate characterization of inner-core features, especially for extreme eye sizes.
3. **Development of Advanced Machine Learning and Deep Learning Techniques**: The complexity of tropical cyclone inner-core dynamics, coupled with the vast amounts of observational data, presents an ideal opportunity for advanced computational methods. Exploring and refining deep learning models can help overcome the limitations of traditional approaches, particularly in handling blurring and background noise in satellite imagery and in effectively integrating multisource observation data for more accurate RMW and eye size estimation.[36] This represents a paradigm shift towards more data-driven, AI-assisted forecasting.
4. **Dedicated Eye Radius Models**: While RMW is crucial, there is a clear need to develop and refine models specifically for predicting tropical cyclone eye radius, rather than solely inferring it from RMW. Such models could explicitly incorporate factors like eyewall replacement cycles (ERCs), diurnal cycles, and detailed inner- core thermodynamic and kinematic processes that directly influence eye expansion and contraction.[14] This would provide a more direct answer to the user's query about maximum eye radius.
5. **Enhanced Understanding of Eyewall Replacement Cycles**: Given their profound impact on eye size and intensity fluctuations, further research into the mechanisms, triggers, and predictability of eyewall replacement cycles is crucial.[16] Improving the ability to forecast the onset, duration, and outcome of ERCs would significantly enhance predictions of eye evolution and maximum size.
6. **Expanded Climatological Studies of Extreme Events**: Continuing and expanding climatological studies of exceptionally large and small eye events is vital. This research

should aim to better understand their frequency, geographical distribution, and the specific environmental conditions that foster their formation and maintenance.[52] Such studies provide valuable context for understanding the upper limits of eye size and their potential changes in a warming climate.

7. **Improved Real-time Operational Algorithms**: A strong emphasis must be placed on developing more robust and automated algorithms for real-time eye and RMW detection and sizing. These algorithms should aim to minimize subjective biases and improve the timeliness of information for operational forecasting.[36] Bridging the gap between cutting-edge research and operational needs is essential for ensuring that scientific advancements translate into tangible improvements in public safety and disaster mitigation. This means that future research must maintain a strong link to operational requirements, ensuring that models and techniques are not only scientifically sound but also practically implementable.

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