SATSA Mukhapatra - Annual Technical Issue **30** : 2026 ISSN 0971-975X

Satellite Remote Sensing for Tropical Cyclones : From Early Warning to Post-Flood Mapping (with a 2024 Remal Case Study)

Sunayan Saha[1], Tanuj Misra[2], Suman[3] and Debashis Chakraborty[3,4]*

(Received : December 02, 2025; Revised : December 28, 2025; Accepted : January 10, 2026)

ABSTRACT

Tropical cyclone (TC) is a recurrent phenomenon in the Bay of Bengal. The cyclones forming over the warm waters threaten millions of people living in the eastern coastal states of India, Bangladesh, Myanmar and Srilanka. This article explains the fundamentals of tropical cyclone formation, structure, classification, and life cycle, followed by an overview of the monitoring and forewarning methods, including the traditional Dvorak technique, the advanced Satellite observations, and emerging AI-based methods. This article explores the potential of the satellite remote sensing in tropical cyclone monitoring and disaster management in the Bay of Bengal. Historically, limited observational tools led to catastrophic loss of life, as seen during the 1970 Bhola cyclone. Today, integrated satellite systems comprising of Multispectral- visible/IR Imager, passive and active microwave radiometers and sounders, Ku-band Scatterometer, Radar Altimeter etc. from different Indian (ISRO) and foreign space agencies (e.g. NASA, European Space Agency, Japan Meteorological Agency etc.) enable early detection tropical cyclones, continuous tracking of their structure, development stages and intensity even under dense cloud cover. The satellite technology also enables rapid post-disaster impact assessment and mapping of vulnerable regions. India's significant achievements through ISRO and IMD towards effective forewarning and disaster management has also been discussed. A case study of Severe Cyclonic Storm Remal (May 2024) demonstrates the practical application of multi-source satellite data for real-time tracking, mass evacuation, flood mapping, and damage assessment in India and Bangladesh.

Keywords : Tropical cyclone, Cyclone structure, Remote Sensing, Cyclone forewarning, Disaster management, Remal

Introduction

The Bay of Bengal, with its shallow, funnel-shaped coastline and densely populated low-lying deltas, remains one of the most cyclone-prone regions of the world. Every year tropical cyclones that form over its warm waters threaten millions of people living in the eastern coastal states

[1]ICAR-Central Potato Research Institute, Regional Station, Jalandhar, Punjab, 144 026
[2]Rani Laxmi bai Central Agricultural University, College of Fisheries, Datia, 475661
[3]International Maize and Wheat Improvement Center, Gulshan-2, Dhaka, 1212
[4]ICAR-Indian Agricultural Research Institute, New Delhi, 110012
* Corresponding Author Email: debashisiari@gmail.com

and India and the neighbouring countries like Bangladesh and Myanmar. These storms not only bring destructive winds but also dangerous storm surges and widespread floods. In the past, conventional methods of cyclone monitoring, like surface observations, upper-air soundings, coastal radars, and occasional aircraft reconnaissance, struggled to keep pace, especially when thick clouds, heavy rains or nighttime intensification hid the storm. The devastating impact of Cyclone, Bhola (1970), which claimed an estimated 300,000 lives (Frank and Husain, 1971) largely due to lack of timely warning and communication, remains a stark reminder of the human cost of technological limitations in the face of natural hazards.

Today, satellite remote sensing supports almost every stage of cyclone management over the North Indian Ocean. Satellites help detect the first signs of a disturbance over the ocean, follow its path and intensity, and later map the floods and the consequent devastations after landfall. The recent severe Cyclonic Storm, Remal in May 2024 provides a perfect example of how the satellite-based monitoring system helped in real-time tracking of tropical cyclone, forecasting its path and landfall location, its possible intensity as well as identifying the vulnerable region. This made possible timely evacuation of more than 10 lakh people from vulnerable coastal areas of India and Bangladesh (UNICEF, 2024; UNOCHA, 2024). In this article, we present step-by-step methods to combine multi-source images and data from Indian and international space missions - India's INSAT weather satellites, Oceansat wind data, NASA's global rain products, as well as the European Union's Sentinel satellite data and data products to quickly map the inundation extent and affected farms and villages. We also discussed the scope and limitations of the satellite based technologies as well as the emerging role of and AI-based tools in cyclone studies.

Basics of Tropical Cyclone

Key drivers and life-cycle of tropical cyclone

Tropical cyclones are intense, rotating low-pressure systems that form over warm tropical oceans when a few key conditions come together. First, the sea surface temperature (SST) exceeds 26°C to a depth of nearly 50 m, providing enough heat and moisture to fuel deep convection. Second, there must be sufficient Coriolis force prevalent at about 5° away from the equator, so that the system can begin to rotate. Third, vertical wind shear (the change of wind with height) should be relatively low, so that the storm's vertical structure remains upright and organized. A pre-existing disturbance or low-pressure area acts as the 'seed' on which the cyclone can grow.

Over the North Indian Ocean, the most favourable periods for cyclone formation are the pre-monsoon (April-May) and post-monsoon (October-November) seasons. The Bay of Bengal's warm waters, large supply of moisture and funnel-shaped coastline make it particularly prone to powerful and damaging cyclones.

The life cycle of a cyclone generally progresses through four stages. It begins with *Formation*, when a low-pressure area develops with converging winds (often below 17 knots; 1 knot = 1.852 km/h) accompanied with disorganized cloud clusters without clear circulation. This can intensify into a *Depression* with sustained winds of 17-27 knots, where a more organized rotation appears. With further strengthening into a *Deep Depression* (~28-33 knots), the spiral rainbands become more prominent, and the central pressures continues to fall. As winds increase beyond this, the system develops into a *Cyclonic Storm* and into more intense categories, with tighter rotation, and in stronger cases, a visible eye. Finally, during *Dissipation*, the cyclone weakens as it moves over land or into cooler waters; increased friction and loss of heat supply gradually break down until it degenerates into a remnant low-pressure area.

Anatomy of a tropical cyclone

A mature tropical cyclone has a distinct internal structure (Figure 1) that regulates its intensification as well as the distribution of wind and rainfall. At the center lies the eye (Figure 2), a relatively calm, nearly cloud-free region with the lowest pressure. This is surrounded by the 'eyewall', a circular wall of tall, deep convective clouds where the strongest winds and heaviest rainfall occur. Curving outward from the eyewall are 'spiral rainbands', long arcs of clouds and thunderstorms that bring intermittent heavy rain and gusty winds far from the centre.

Air spirals inward (anticlockwise in the northern hemisphere and vice versa in southern hemisphere) near the surface, rises rapidly in the eyewall, and then spreads outward at high levels as an outflow layer atop. This outflow interacts with the surrounding environment and influences whether the storm intensifies or weakens. Tropical cyclones can vary greatly in size-from under 100 km to over 1000 km in diameter, but size alone does not determine strength. Understanding this internal structure is crucial because modern satellite and radar technologies monitor these features in real time to assess cyclone intensity, track movement, and provide timely warnings.

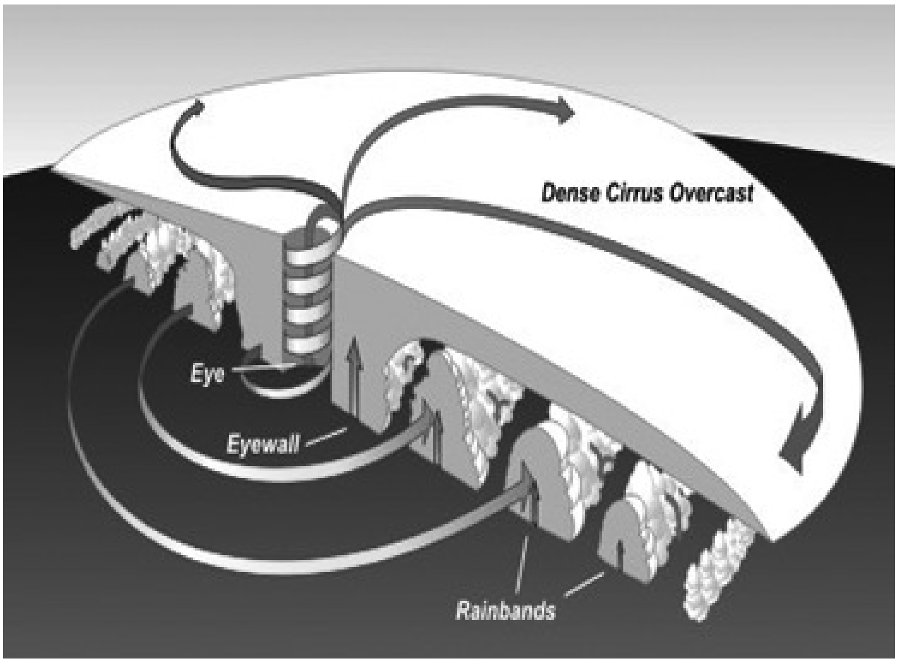


Figure 1. Cross-section of a typical tropical cyclone showing its structure (central eye surrounded by spiral bands of thunder clouds) and air-movement pattern (courtesy: NOAA)

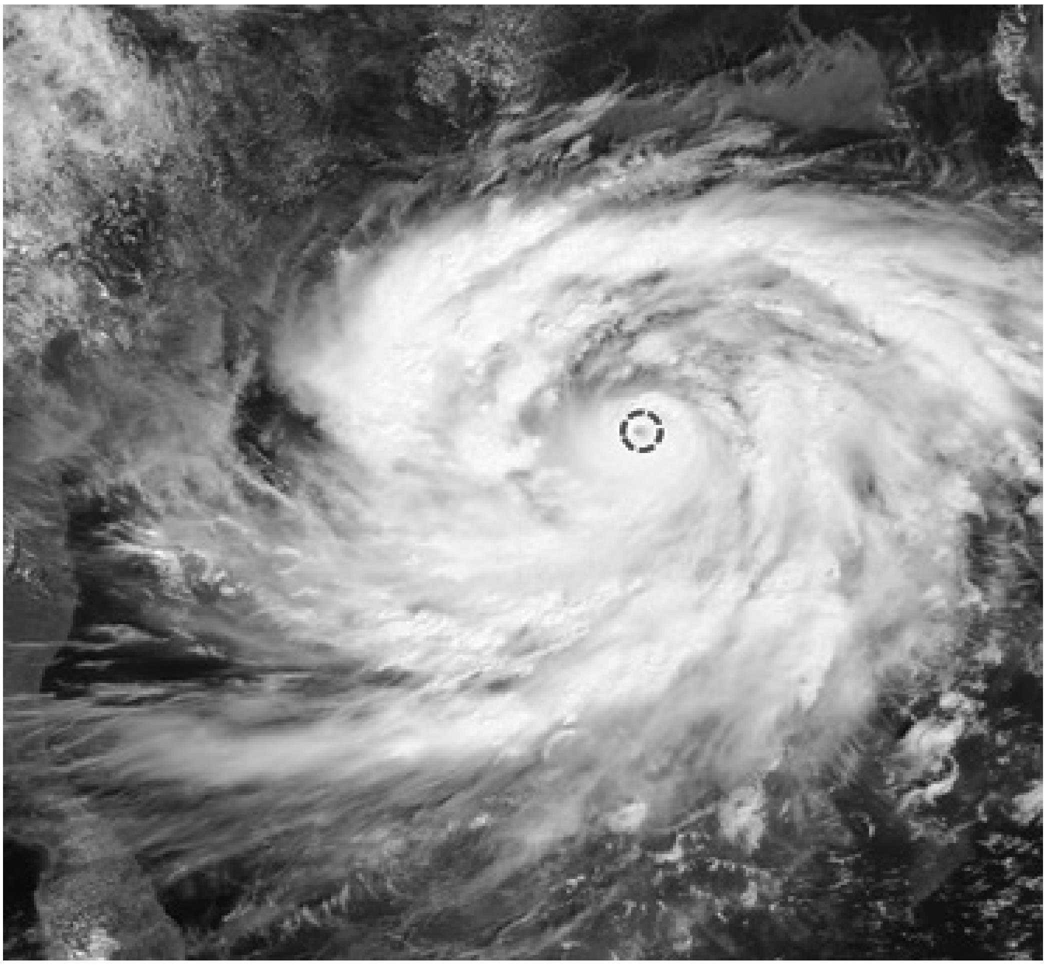


Figure 2. Satellite image of tropical cyclone Phailin (02B) over the Bay of Bengal on 11 October 2013. The black dot-like feature, indicated by a red dotted circle, at the centre of the swirling white cloud mass, marks the eye of the storm (courtesy: NASA)

Classification

The amount of pressure drop in the center of a cyclonic system and the associated maximum sustained wind speed determine the intensity of the system and strength of winds. Over the North Indian Ocean, the India Meteorological Department (IMD) and the World Meteorological Organization (WMO) use a standard classification to group cyclonic disturbances into categories such as Depression, Deep Depression, Cyclonic Storm, Severe Cyclonic Storm, Very Severe Cyclonic Storm, Extremely Severe Cyclonic Storm and Super Cyclonic Storm. Each category corresponds to a range of wind speeds and central pressure drop Classification is given below (Table 1).

Table 1. Cyclonic disturbances (IMD/WMO Standard for North Indian ocean, comprising the Bay of Bengal and Arabian sea)

Category	Associated maximum sustained wind speed (MSW)
Depression (L)	17-27 Knots (31–49 km h^{-1})
Deep Depression (DD)	28-33 Knots (50–61 km h^{-1})
Cyclonic Storm (CS)	34-47 Knots (62–87 km h^{-1})
Severe Cyclonic Storm (SCS)	48-63 Knots (88–117 km h^{-1})
Very Severe Cyclonic Storm (VSCS)	64-89 Knots (118–166 km h^{-1})
Extremely Severe Cyclonic Storm (ESCS)	90-119 Knots (167–221 km h^{-1})
Super Cyclonic Storm (SuCS)	≥120 Knots (≥222 km h^{-1})

This classification is used in official bulletins and warning messages to help disaster-management agencies and the public understanding of how dangerous a given system is likely to be.

Modern Technologies for Cyclone Monitoring

Cyclone monitoring has evolved dramatically over the last few decades. Earlier, short-range coastal radar systems, ship observations and sparse island stations were the primary tools for tracking storms. These radars usually had a range of only about 200-300 km, so cyclones could be monitored in detail only when they were already close to the coast, leaving limited time for evacuation and preparedness. Today's modern cyclone-monitoring system is truly multi-platform that integrates satellite data, numerical weather prediction (NWP) models, coastal radars, buoys and ground-based observations in a coordinated way. The combined system helps forecasters track a cyclone from its origin over the ocean to landfall and dissipation, while supporting both early warning and post-disaster assessment.

Satellite data products

Modern cyclone monitoring relies heavily on satellites placed in two broad types of orbits: Geostationary (GEO) and Low Earth orbit (LEO). The GEO satellites are placed about 36,000 km above the equator and move at the same angular velocity as Earth's rotation, so they appear fixed over one point on the globe making a 'permanent watchtower' for continuous scanning of the same region at small time interval. This continuous view facilitates spotting early signs of cyclone formation, following the build-up of cloud clusters, and tracking the storm's position and shape hour by hour. Instruments on GEO satellites mainly use visible and infrared channels to monitor cloud patterns and cloud-top temperatures, which are key indicators of storm organization and intensity. Some GEO satellites also carry sounders that provide temperature and humidity profiles at different heights, helping scientists understand the atmospheric environment around the cyclone.

The LEO satellites, on the other hand, orbit closer to Earth, typically at an altitudes of 700-800 km above, and move from pole to pole in Sun-synchronous orbits. They do not provide continuous coverage of a given location, but they offer high resolution images and carry advanced sensors that can 'see' through clouds, heavy rain, and even darkness. Passive microwave instruments on LEO satellites measure rainfall, water vapour and sea-surface temperature hidden beneath thick cloud layers. Active microwave sensors, such as scatterometers, altimeters and synthetic aperture radar (SAR), send out their own pulses and detect the back-scattered signal to measure surface wind speed and direction, sea-level changes, wave heights and areas of flooding. Under clear sky condition, optical and infrared imagers on LEO platforms help in coastline mapping, land-use and land-cover mapping, risk assessment and post-cyclone damage analysis.

The GEO and LEO satellite data products are complementary to each other. The GEO satellites provide the continuous "big picture" of a cyclone's evolution, while LEO satellites supply detailed snapshots of its inner structure, surface wind field, rainfall and impacts on land and ocean. This combined view is essential for improving track and intensity forecasts, issuing coastal storm-surge warnings and planning response measures before, during and after landfall. A summary of major geostationary and low-Earth-orbit satellite missions, their sensors, spatial and temporal resolution, and their role at different stages of cyclone monitoring is provided in Table 2.

Table 2. Major geostationary and low-earth-orbit satellite missions, their sensors, spatial/temoral resolution, and how each contributes to different stages of cyclone monitoring, from early detection and structure analysis to landfall assessment and post-cyclone damage mapping.

Satellite / Mission	Orbit Type	Sensor / Instrument	Spatial & Temporal Resolution	Role in Cyclone Monitoring (Information Provided)	Key Monitoring Stage(s)
INSAT-series	GEO	Multispectral VIS/IR Imager, IR Sounder	1-10 km; 30-15 min; ~5 min rapid scan	Cloud patterns, cloud-top temperature, convective growth, moisture profile, storm structure, continuous tracking	Detection, Intensification monitoring, Track forecasting, Landfall monitoring

Himawari-series	GEO	Advanced multispectral imager	0.5-2 km; 10-2.5 min	High-frequency cloud evolution, convection bursts, eyewall changes	Genesis, Intensification, Real-time tracking
Meteosat / GOES	GEO	VIS/IR/WV imagers	1-3 km; 15-10 min	Large-scale cloud systems, water vapour fields, temperature structure	Early monitoring, Continuous tracking
Oceansat / SCAT-series	LEO	Ku-band Scatterometer	12.5-25 km; ~2 days	Ocean surface winds (speed + direction), vorticity, wind convergence, low-level circulation	Genesis, Intensification assessment, Track guidance
SCATSAT	LEO	Scatterometer	25-50 km; ~2 days	Surface wind vectors, identifying closed circulation	Early detection, Track estimation
GPM / SSMIS / AMSR2 (Microwave)	LEO	Passive microwave radiometers & sounders	~5-20 km; 2-3 days	Rainbands, internal structure, latent heat release, moisture distribution, SST under clouds	Intensification, Structure analysis
NISAR / Sentinel-1 / RADAR-based missions	LEO	SAR (L/S/C-band)	3-20 m; 6-12 days (NISAR: 12 days)	Surface roughness, high-wind zones, inundation mapping, flood extent, post-landfall damage	Landfall impact, Post-cyclone assessment
Altimeter missions (Jason, Sentinel-6, SARAL-AltiKa)	LEO	Radar Altimeter	~0.3 m vertical; 10-35 days	Sea surface height, storm surge signal, wave height, coastal water rise	Intensification (OHC proxy), Storm surge prediction
Megha-Tropiques	LEO	Microwave humidity sounder, radiometer, radiation sensor	10-40 km; several observations/ day	Humidity profiles, rainfall distribution, cloud ice/water, atmospheric instability	Genesis environment, Moisture analysis
MODIS / VIIRS / AVHRR	LEO	Optical / IR Imager	250 m-1 km; daily	SST patterns, cloud properties, coastal changes, clear-sky mapping	Genesis environment, Coastal risk mapping

Methodologies

Existing Techniques

Dvorak Technique : The Dvorak Technique is one of the most widely used satellite-based method for estimating the tropical cyclone intensity. Developed by Vernon Dvorak in the 1970s, it provides an objective way to estimate cyclone strength over ocean areas where direct observations are limited. The method relies on pattern recognition using visible and infrared satellite images. Forecasters analyze the shape, symmetry and organization of cloud features, such as curved bands, central dense overcast (CDO, a thick cloud mass over the storm centre), and the presence of a clear eye.

Based on these patterns, the cyclone is assigned a T-number (1.0 to 8.0) which corresponds to a range of maximum sustained wind speeds and central pressure values. As the system intensifies, the cloud pattern becomes more organized and the T-number increases. A Current Intensity (CI) number provides an updated measure of the storm's present strength. By combining infrared temperature patterns with these empirically derived rules, the Dvorak Technique offers a systematic estimation of cyclone intensity from satellite imagery and still forms the backbone of real-time tropical cyclone monitoring worldwide (Figure 3).

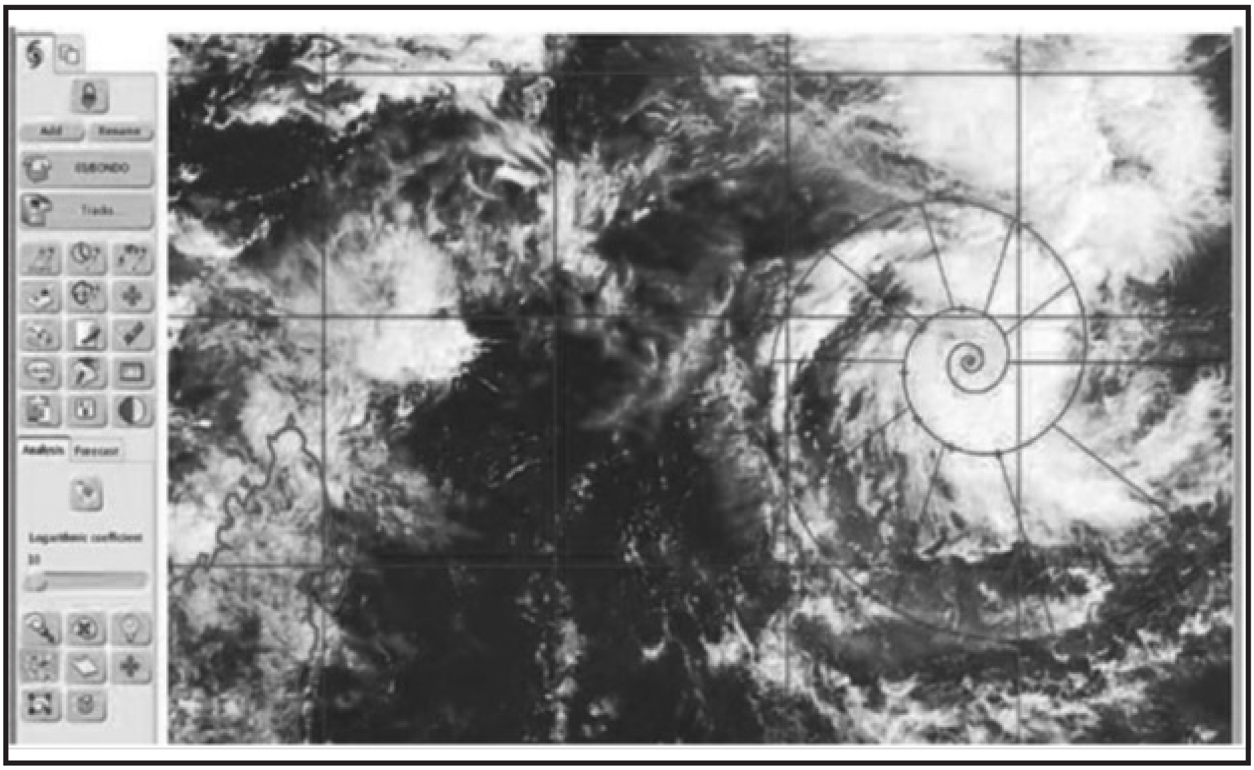


Figure 3. Position and intensity of a tropical cyclone derived using the Dvorak method (courtesy : IMD)

Object-based Image Analysis for Post-disaster Impact Mapping : With the availability of moderate- and high-resolution satellite imagery, object-based image analysis has become an important tool for cyclone-related risk assessment and post-disaster impact mapping. Instead of treating each pixel individually, object-based methods group neighbouring pixels into meaningful 'objects' such as patches of water, vegetation or built-up areas. Using multi-temporal images, these methods can detect which objects have changed between pre- and post-cyclone scenes. This helps classify damage to cropland and settlements, map flood extent, identify breached embankments, and generate practical risk maps for local-scale management. Such techniques have been successfully applied in coastal belts of the Bay of Bengal (Hoque, 2017; Hoque *et al.*, 2016) and elsewhere for accurate damage mapping, vulnerability assessment and targeted mitigation planning. They also support operational monitoring by helping with cloud and eyewall segmentation, cyclone-centre detection and identification of convective cores (Sieglaff *et al.*, 2013; Heikenfeld *et al.*, 2019; Carballo *et al.*, 2023).

Advanced Techniques

Although the Dvorak technique is still widely in operation, it has several limitations. As this technique is based on pattern recognition from visible and infrared images, its efficiency depends on human skill, it can be subjective, and it does not work efficiently to detect the storms with irregular shapes or embedded within larger cloud masses. At the same time, today's satellite constellations produce massive volumes of high-resolution, all-weather data including microwave and sounder data. Globally, scientists are therefore developing more automated, objective tools to extract information from this data and to feed it into high-fidelity forecast systems (Bai *et al.*, 2025; Kelkar, 2021).

Artificial Intelligence and Machine Learning (AI/ML) : AI and ML are rapidly transforming cyclone monitoring by providing faster, more objective, and often more accurate analysis of the huge volume of satellite observations. Techniques such as convolutional neural networks (CNNs), recurrent neural networks (including ConvLSTM) and newer architectures like YOLO-NAS, trained on long-term multispectral satellite archives have significantly advanced the cyclone detection, intensity estimation, and track prediction (Yang and Cossuth, 2016; Nandal *et al.,* 2025; Li *et al.,* 2024). Some advanced digital Dvorak techniques (ADT) perform comparably to, and often slightly better than, manual Dvorak estimates, reducing errors and allowing more frequent updates (Olander and Velden, 2019). Deep learning models trained on INSAT-3D multispectral infrared imagery are now becoming operationally feasible over the North Indian Ocean, offering near-real-time automated estimates of cyclone centre and intensity.

Complementary sensors, including microwave and SAR, provide high-resolution information on surface winds and precipitation even under dense cloud cover (Zhang and Perrie, 2024; Katsaros *et al.,* 2002), while GNSS-based approaches (Global Navigation Satellite Systems such as GPS, GLONASS, Galileo) offer useful atmospheric profiling and ocean-surface wind retrieval capabilities (Bai *et al.,* 2025; Esmaili *et al.,* 2022). For track prediction, recurrent neural network architectures such as ConvLSTM (Convolutional Long Short-Term Memory) have demonstrated up to ~25% improvement over conventional techniques by effectively learning the spatiotemporal evolution of cyclones and supporting more accurate forecasts up to 72 h ahead (Tao *et al.,* 2024).

Data Assimilation and Numerical Weather Prediction (NWP) : The accuracy of any forecast model, such as the Weather Research and Forecasting (WRF) model by IMD, depends critically on the quality of its initial conditions. Data Assimilation (DA) is the process by which observations (winds, temperature, humidity, and ocean surface parameters) from satellite sources (e.g., INSAT imagers, high resolution LEO sensors like EOS scatterometers, and GNSS radio occultation) are optimally combined with the model's previous forecast to produce the best possible estimate of the current atmospheric state. Satellite data plays a central role here. Temperature and humidity profiles from sounders, atmospheric motion vectors, scatterometer winds, altimeter-derived sea-level anomalies and microwave rainfall estimates are all assimilated into modern NWP systems. Improvements in DA have directly reduced errors in cyclone track and intensity forecasts and have helped quantify forecast uncertainty in probabilistic terms, which is crucial for decision-makers.

India's Achievements in Satellite-based Cyclone Monitoring

Few scientific achievements in India have had as much direct impact on saving lives as the country's advances in satellite-based cyclone-monitoring. Over the past two decades, India has made remarkable progress in this field, driven by the combined strengths of the Indian Space Research Organization (ISRO) and the India Meteorological Department (IMD).

A major strength is India's ability to generate regionally tailored, high temporal-resolution satellite data from its INSAT geostationary series. Instruments aboard INSAT-3D/3DR and the latest INSAT-3DS provide multispectral imagery every 15-30 min over the North Indian Ocean, with spatial resolution of the order of 1 km in the visible/short-wave infrared channels and 4-8 km in the middle/thermal infrared and water-vapour bands. Sounder-derived temperature-humidity profiles and Atmospheric Motion Vectors (AMVs) derived from these images form the backbone of real-time cyclone detection and intensity estimation. Recent studies show that INSAT multispectral and infrared imagery can be used combinedly with high accuracy for real-time intensity classification over the Indian Ocean, placing India at par with global best practices (Nandal *et al.*, 2025).

ISRO's polar-orbiting satellites complement this GEO view with detailed snapshots of the ocean surface and coastal land areas. Oceansat-3 (EOS-06), equipped with the Ku-band SCAT-3 (also referred as OSCAT-3) scatterometer, delivers wind vectors at ~25 km resolution with ~1.8 m/s RMS wind-speed accuracy (Figure 4), comparable to EUMETSAT's ASCAT. Such performance enables early detection of wind-field asymmetries, cyclone genesis signatures, and intensity changes. The

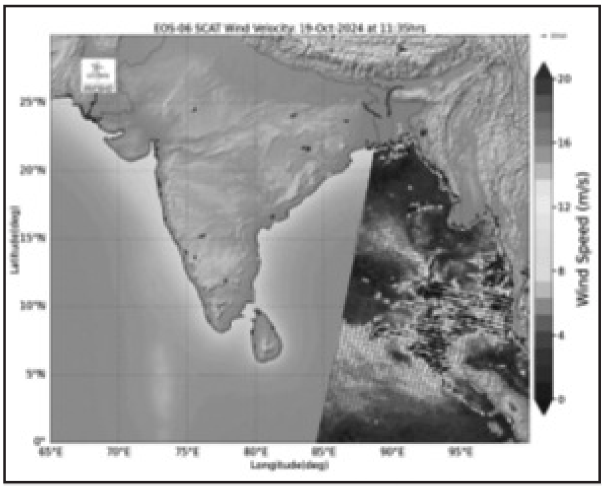
Indo-French missions (ISRO-CNES) such as SARAL–AltiKa provide precise altimeter measurements, strengthens storm-surge and coastal inundation assessments which is especially important for the North Indian Ocean basin. High-resolution optical sensors (such as Resourcesat, Cartosat and Sentinel-2) support pre-storm coastal mapping and post-storm damage assessment.

A unique Indian capability is the Megha-Tropiques mission, whose orbit allows up to six passes per day over the North Indian Ocean - far more frequent than typical polar-orbiting missions. Its microwave radiometer MADRAS/imager), Microwave sounder (SAPHIR/sounder) provide vertical humidity profiles, cloud water, and rainfall at ~10 km resolution that is highly valuable for tracking convective evolution in developing cyclones (Roca *et al.,* 2015). Near-real-time products derived from this mission have improved monitoring of tropical convention and rainfall systems. The recently launched NISAR (NASA–ISRO Synthetic Aperture Radar) mission, with its dual-frequency L- and S-band SAR operating at 2-8 m spatial resolution, is expected to further strengthen rapid flood mapping, coastal erosion and structural damage detection, even under heavy cloud cover.

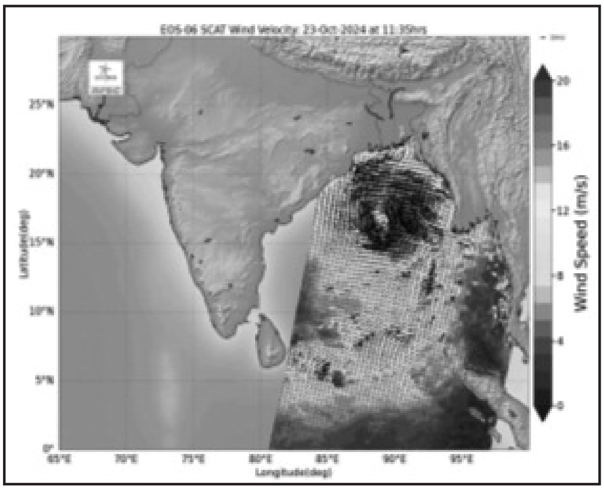
Most of the satellite data related to cyclone monitoring generated by ISRO are distributed in near real time through the Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) at Ahmedabad and other national data portals. The Data Relay Transponder (DRT) onboard INSAT satellites also plays a crucial role in collecting environmental information from remote Automatic Weather Stations, Automatic Rain Gauge Stations and ocean buoys, and relaying those to central receiving stations even during severe weather. The India Meteorological Department (IMD) integrates these satellite inputs with other observations and numerical model data and issues operational cyclone advisories every three hours. These warnings are disseminated through multiple channels, including the Cyclone Warning Dissemination System (CWDS) via INSAT and the Digital Meteorological Data Dissemination (DMDD) broadcast service. IMD also shares data and advisories with affected SAARC (South Asian Association for Regional Cooperation) countries, providing details on the cyclone’s location, intensity, movement, wind speed, sea condition and 72-hour forecasts, along with storm-surge guidance. More than 350 coastal stations receive automated alerts in regional languages, ensuring last-mile communication. Together, ISRO and IMD have established one of the world’s most effective regional cyclone-monitoring frameworks, greatly reducing loss of life in the vulnerable coastal zones of India and other South Asian countries.

Case Study : Monitoring Cyclone Remal in the Sundarbans, West Bengal

Severe Cyclonic Storm, Remal made landfall on May 26, 2024 (night) between Sagar Island (West Bengal) and Khepupara (Bangladesh). The storm brought very heavy rainfall, strong winds, high waves and storm surge to large parts of the Sundarbans and the adjoining coastal belt. Flights were suspended, Kolkata airport remained closed for about 21 hour, and



(A) Cyclone DANA - before intensification (20 Oct, 2024)



(B) Cyclone DANA - after intensification (23 Oct, 2024)

Figure 4. Scatterometry wind image (EOS-06) showing the genesis of cyclonic storm DANA over the Bay of Bengal on (courtesy : ISRO, https://www.isro.gov.in/ISROSatellitestrackCycloneDANA.html)

evacuations ran into the hundreds of thousands (IMD Tropical Cyclone Advisory No. 07). During the landfall the system was a Severe Cyclonic Storm, with gale-force winds typically in the range of about 89-117 km/h and higher gusts. A simplified methodology for monitoring such events and their impacts using multi-source satellite data is summarized in Figure 5.

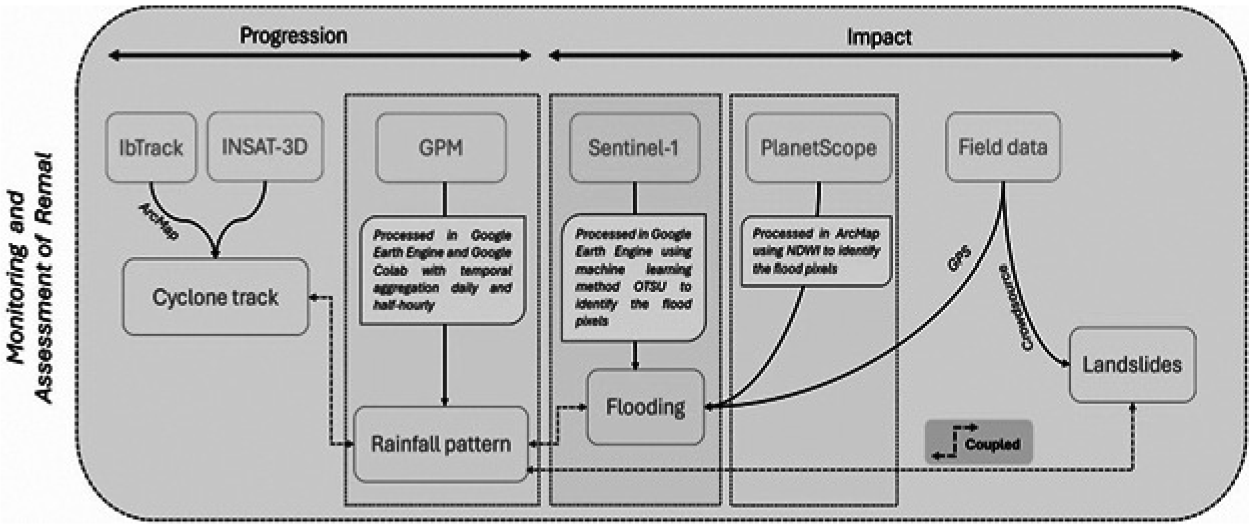


Figure 5. Methodology used for tracking the progression of Remal and its cascading impacts after landfall (courtesy : Ghosh *et al.*, 2025)

Cyclone Remal was originated from a low-pressure area formed over the central Bay of Bengal on 24 May 2024, under favorable oceanic and atmospheric conditions. By 25 May, the system had intensified into a depression and started moving northwards. As its winds strengthened and convection became more organized, the system further intensified into a deep depression and then into a cyclonic storm (Figure 6). During the night of 26 May, it reached a stage of 'Severe Cyclonic Storm' just before landfall, with its centre crossing the coast between Sagar Island in India and Khepupara in Bangladesh, accompanied by strong winds and heavy rainfall (Figure 7). After landfall, the system gradually weakened while moving inland towards Bangladesh and northeastern India, and by 28 May it had dissipated into a depression over Bangladesh and Meghalaya, marking the end of its life cycle (Figure 10).

Storm surge and intense rainfall breached embankments and flooded the coastal villages and agricultural fields, particularly in the low-lying islands of the Sundarbans and parts of in-land regions of coastal North and South 24-Parganas causing widespread damage across Bangladesh and parts of West Bengal. Here, satellite data played a dual role in monitoring the storm before and during landfall, as well as mapping the impacts afterwards. The impact of cyclone Remal as captured by the satellite platform is depicted in the panel (Figure 10 and 11). The public warnings issued by the IMD, India during Remal are presented in Figure 12 to 14.

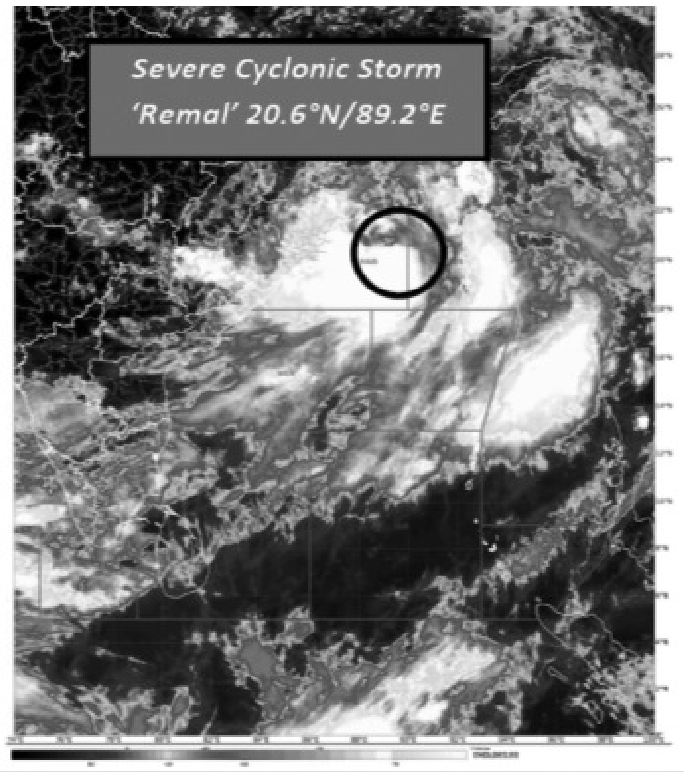


Figure 6. False-colour representation of surface-temperature derived from INSAT-3D satellite image (TIR 1 and 10.8 μm), acquired on 26 May 2024 (1500 and 1526 IST) capturing cyclone Remal. Bright white indicates deep, vertically developed convective clouds with low cloud top temperature, blue and black are indicate relatively warm ocean surface and inland areas. (image courtesy: IMD/ ISRO).

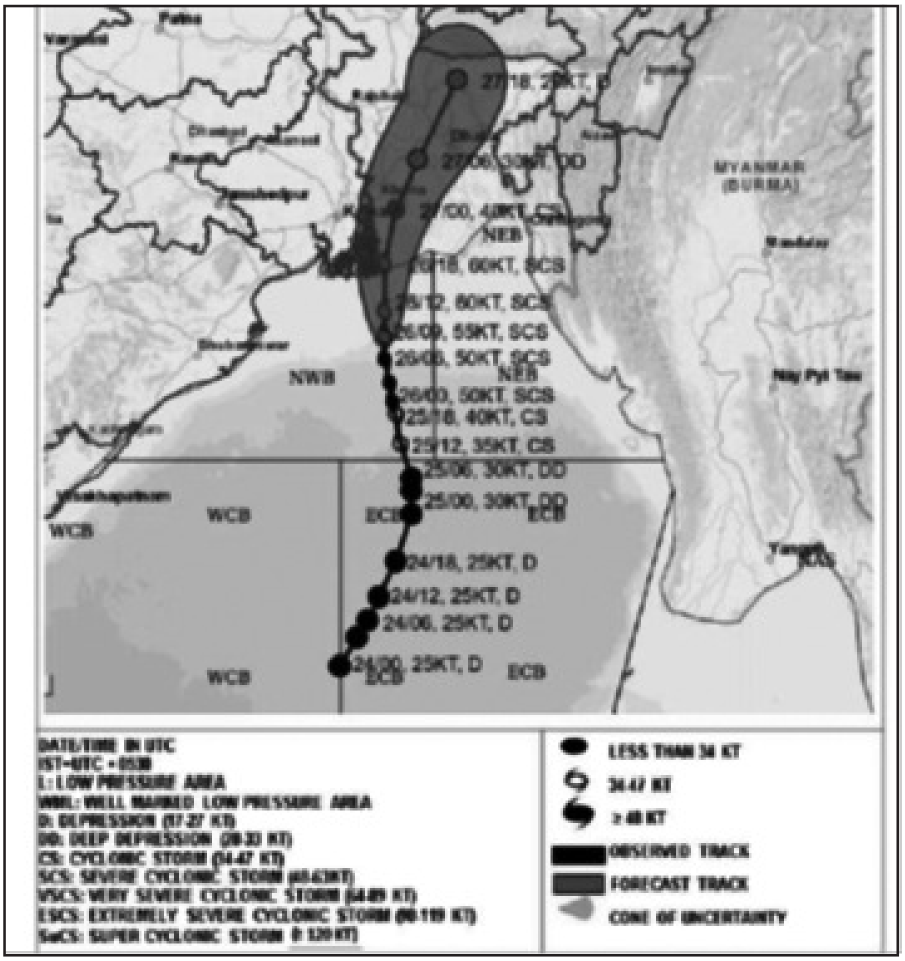


Figure 7. Observed (black dots) and forecast (red dots) trajectory of the eye of severe cyclonic storm Remal, with cone of uncertainty (green shaded band), based on 1430 IST of 26 May 2024, over the north Bay of Bengal and adjoining landmasses of India and Bangladesh using satellite-based technology (courtesy: IMD).

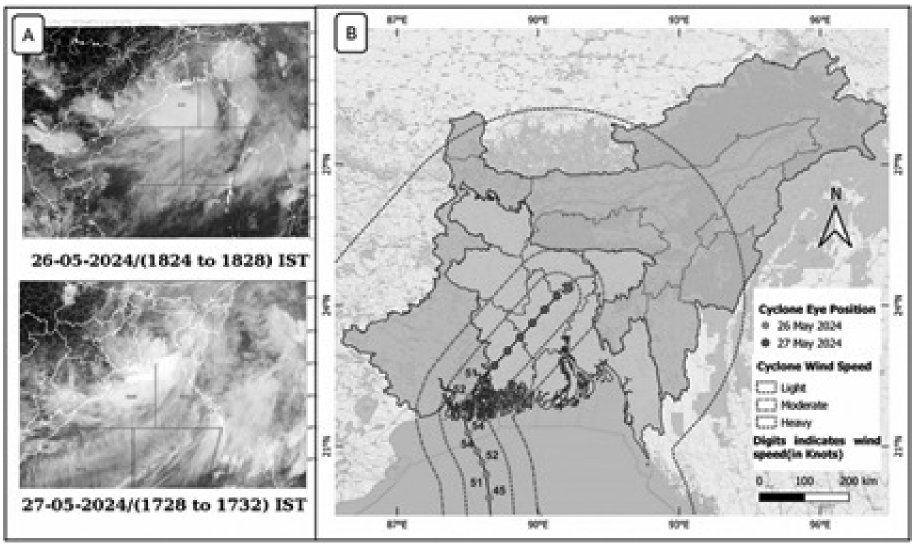


Figure 8. (a) INSAT-3D imageries and (b) actually observed track of the eye of cyclone Remal (Courtesy: Ghosh *et al.*, 2025; Source of image: IbTracks / https://www.ncei.noaa.gov/)

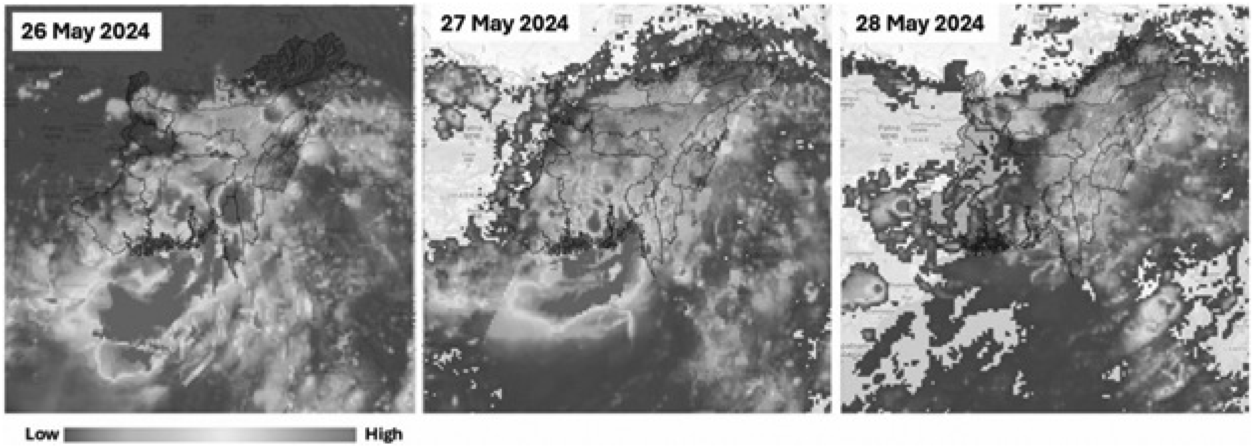
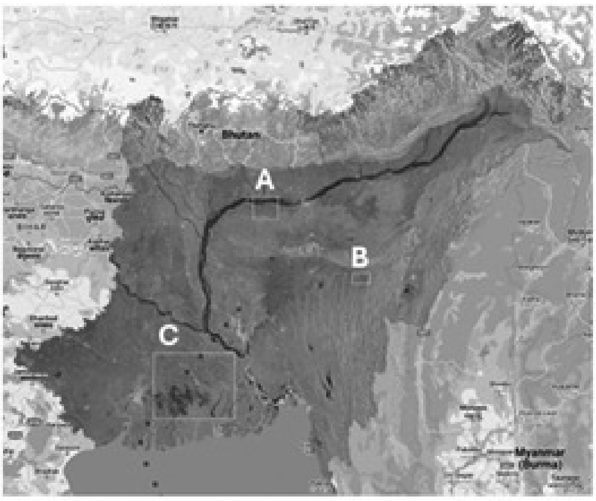
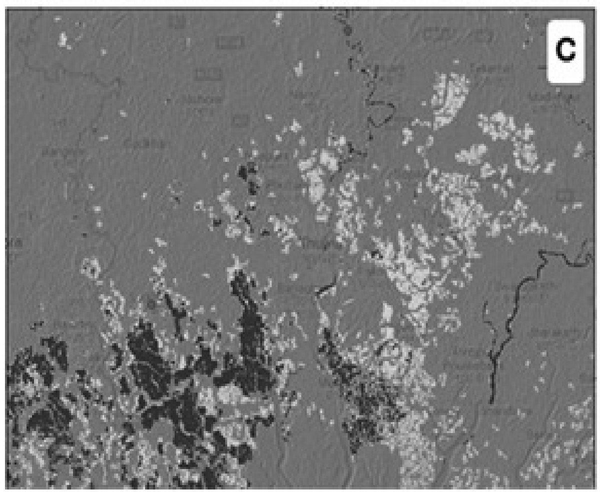


Figure 9. Daily maximum rainfall progression during 26–28 May 2024 captured from IMERG (Integrated Multi-satellitE Retrievals for GPM, NASA, USA) over the Remal-affected area. The sequence of images from left to right shows how the region of most intense rainfall shifted from the open sea to the West Bengal–Bangladesh border areas, in north-easterly track of the storm.



i) Study sites (A, B and C) and cyclone track in red dots



ii) Cyclone track (in red dots) and wetlands and permanent water bodies (blue colour) at WB–Bangladesh border with

Figure 10. Cyclone's path experienced more extensive and severe flooding than the left, following the cyclone's direction and associated wind

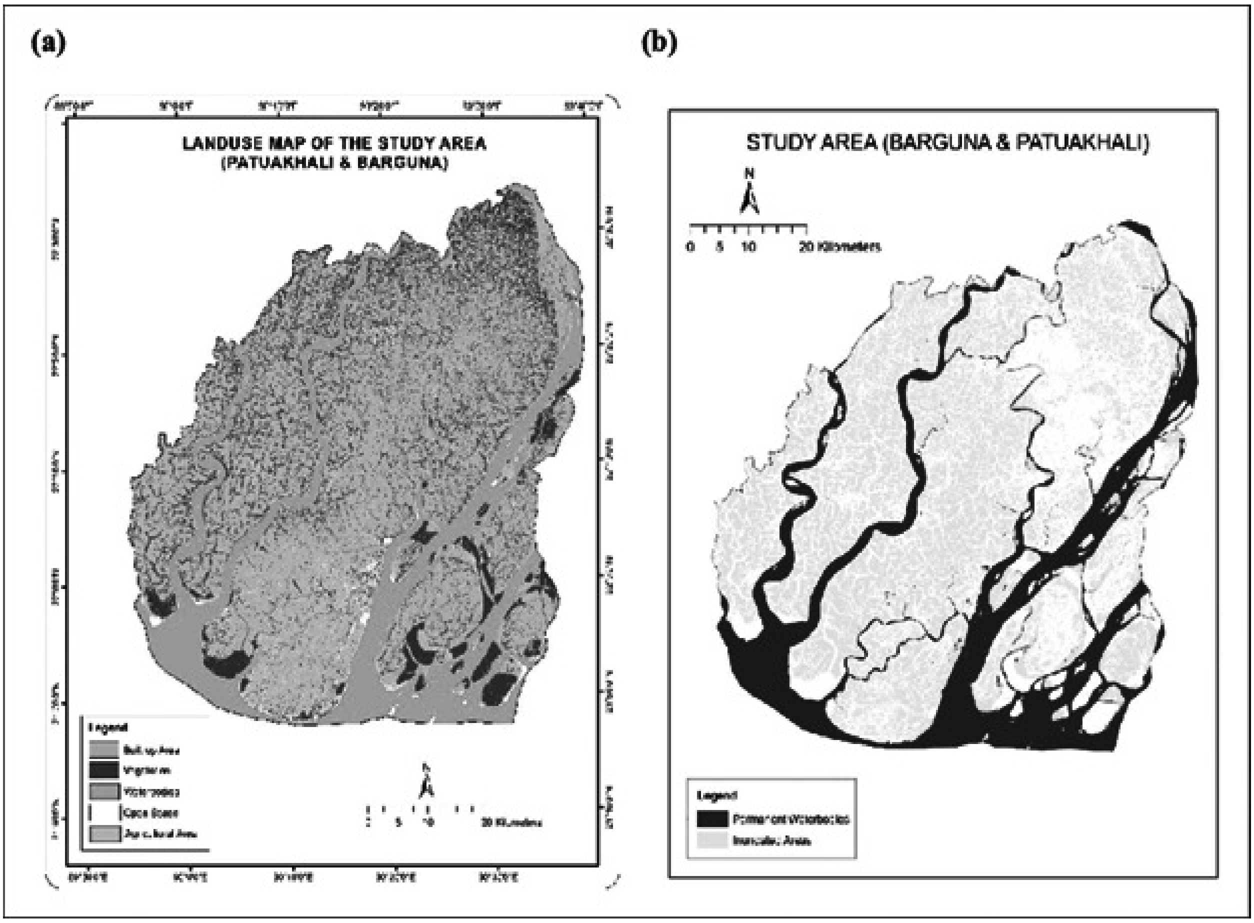


Figure 11. Pre-Remal (a) and post-Remal (b) inundation in Barguna and Patuakhali (coastal districts of Bangladesh). About 30% of study area was inundated (10 m X 10 m) - derived from Sentinel-1 and Sentinel-2 satellite data (courtesy: Hossen *et al.*, 2025).

A practical workflow for flood mapping after Remal used pre-event and post-event SAR images from Sentinel-1. Water surfaces appear dark in radar images, while land tends to be brighter. By comparing the backscatter values before and after the event, areas that shifted to a darker tone were identified as newly inundated. These flood-water masks were then overlaid on land-use/land-cover maps and administrative boundaries to estimate the area of affected cropland, settlements and other land-use classes. This type of analysis, as demonstrated by recent studies in the Sundarbans, helps identify critically affected villages, breached embankment stretches and zones of severe salinity intrusion.

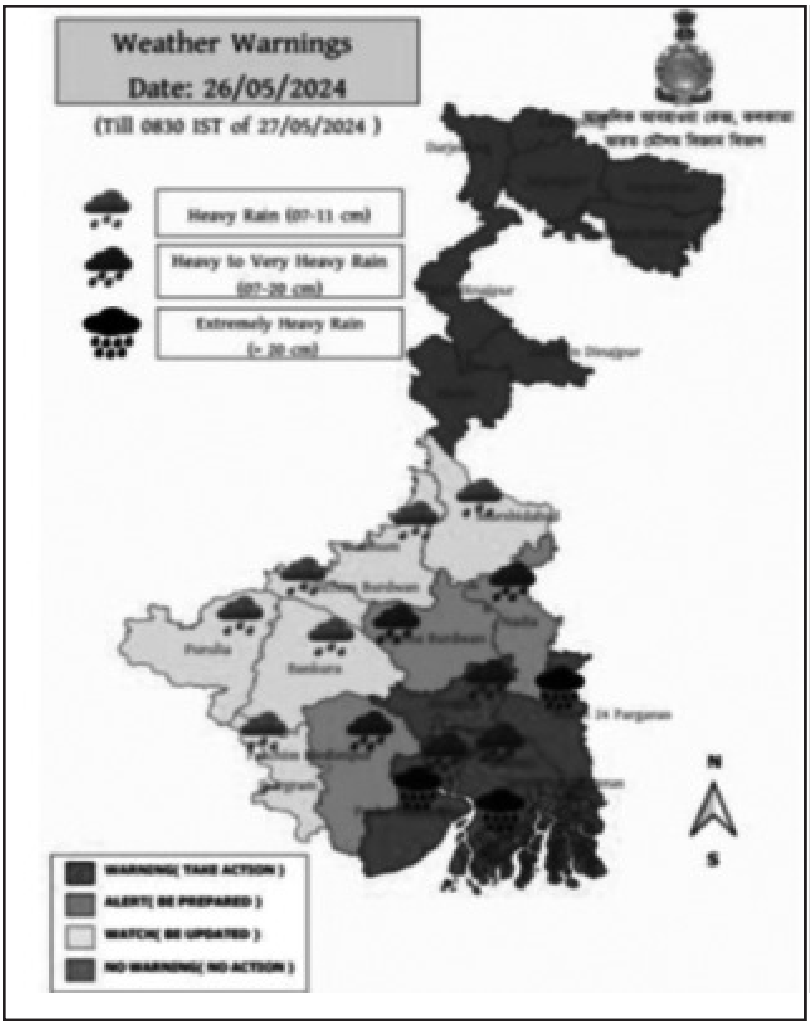


Figure 12. Weather warnings issued by IMD for land areas during cyclone Remal. Red-coloured areas represent 'Warning' (time to take appropriate action); Orange-coloured areas indicate "Alert" (be prepared to take action).

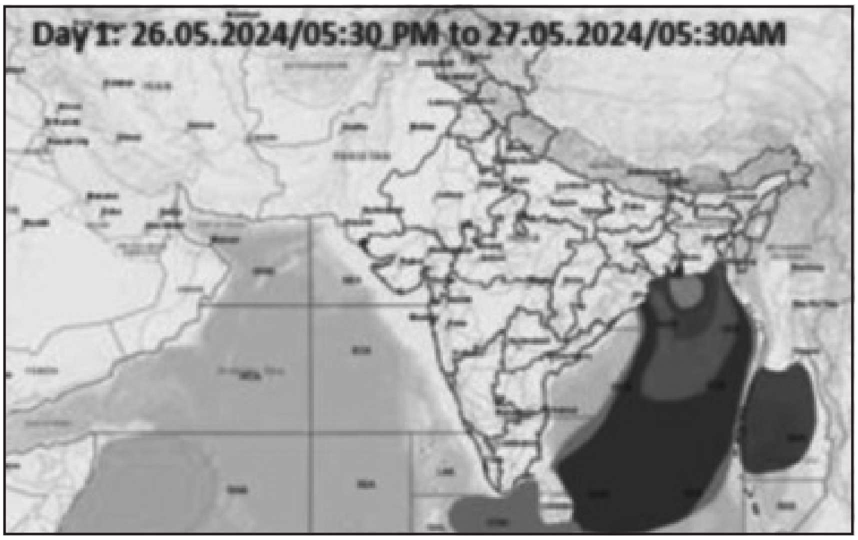


Figure 13. Warning graphics for fishermen during cyclone Remal (shaded region). Orange-colour indicates a "super cyclone" with gale-level wind speeds of 90–120 km h^{-1} and wind gusts reaching up to 135 km h^{-1} (source : IMD bulletin).

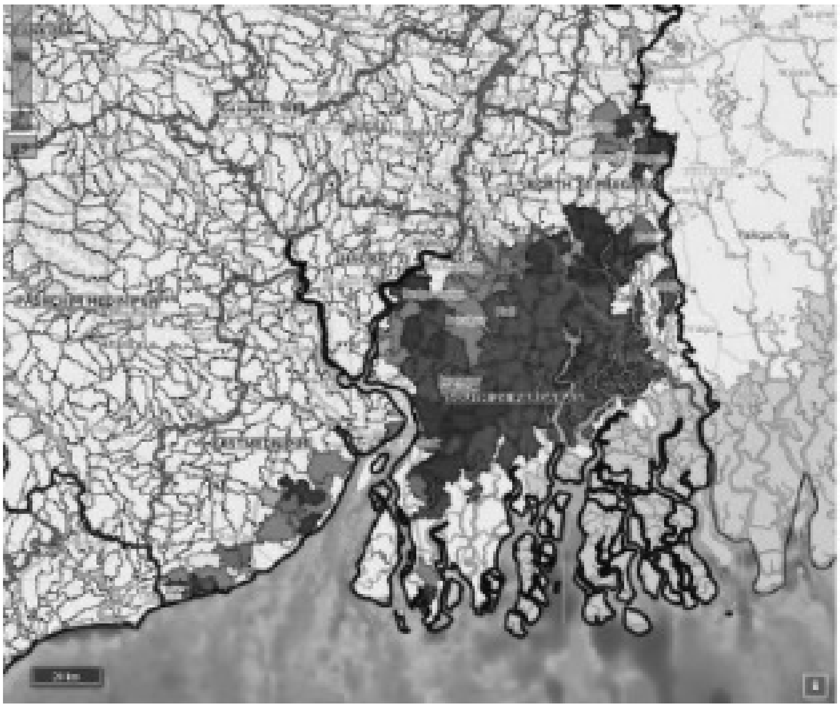


Figure 14. Flash-flood risk map depicting areas of high (red) and moderate (orange) threat in the South and North 24 Parganas districts of West Bengal and adjoining areas during cyclone Remal (issued on 26 May 2024 and valid till 11:30 AM on 27 May 2024) (source: IMD).

Salient Findings

- INSAT-3D/3DR imageries provided visible, infrared and water-vapour images at frequent interval showing the evolution of cloud structures, the formation of the eye and changes in storm symmetry.
- INSAT-derived surface temperature and wind products helped identify areas of deep convection and supported intensity estimation.
- Scatterometric winds from EOS-06 (Oceansat-3) and other missions captured the surface wind field, including asymmetries and bands of strongest winds near the eyewall.
- Rainfall products and daily rainfall analyses tracked the progression of heavy rainfall from the Bay of Bengal onto the eastern and northeastern states during 26–28 May.
- Synthetic Aperture Radar (SAR) and optical images from Sentinel-1 and Sentinel-2 were used in a "before and after" framework to map flood-inundated areas at high resolution.

At the same time, IMD's operational advisories and graphics (Figure 13-14) provided fishermen warnings, track forecasts and intensity guidance well before landfall. The combination of satellite-based early warning, on-ground preparedness and post-event impact mapping shows how modern remote sensing tools can support the full disaster-management cycle for cyclones such as Remal.

Conclusion

Satellite remote sensing today supports all phases of cyclone management: early detection, real-time monitoring, impact assessment and post-disaster recovery. For the densely populated coasts of the Bay of Bengal, it has become both a lifeline and a technological shield. From the continuous watch of indigenous INSAT satellites in geostationary orbit to the high-resolution wind vectors measured by EOS-06 scatterometer, Indian advances have turned a once largely unpredictable natural hazard into a better-managed risk. The experience of Cyclone Remal exemplifies this shift. Multi-source satellite data and timely IMD advisories enabled large-scale evacuations, effective flood mapping and targeted assessment of damage to agriculture and settlements within a short time window.

Looking ahead, cyclone monitoring and impact assessment sit at a vibrant intersection of atmospheric science, geospatial technology and public policy. Emerging deep learning tools, when combined with high-resolution Earth observation data, can provide faster and more objective estimates of cyclone intensity and track. Scatterometer winds are improving storm-surge models, and SAR missions such as NISAR promise rapid, cloud-independent mapping of floods, coastal erosion and structural damage. At the same time, micro-scale vulnerability studies—such as detailed coastal erosion mapping and monitoring of mangrove health in the Sundarbans—are essential to strengthen natural defences against future climate-related threats. These efforts must make full use of advanced optical, hyperspectral and radar data, particularly along the east coast of India.

Practical Takeaways for Disaster Management in West Bengal

Here are some practical actions where satellite data can directly support disaster management and planning in West Bengal and similar cyclone-prone regions:

- **Targeted embankment repair** : Use SAR-based flood and erosion maps to identify which embankment stretches were overtopped or breached, and prioritise repair of critically weakened segments.
- **Soil health and salinity management** : Map post-flood salinity zones using radar and optical imagery to guide precise soil-reclamation measures, such as gypsum application and improved drainage.
- **Transparent crop-damage compensation** : Deploy high-resolution flood-extent maps to validate crop losses at field or village level, enabling faster and fairer compensation to affected farmers.
- **Disaster-ready planning** : Integrate satellite-derived flood layers into district-level GIS maps to plan evacuation routes, locate relief centres and pre-position essential supplies before the next cyclone.
- **Restoration prioritization** : Use remote-sensing indicators such as inundation depth and duration to rank affected villages and blocks, guiding fair and efficient allocation of recovery resources.
- **Community advisories** : Convert satellite-based flood, rainfall and salinity information into simple advisories in local languages for farmers and coastal communities, supporting timely protective actions.

- **Cross-department synergy** : Encourage routine sharing and joint use of radar-derived flood and salinity data among Agriculture, Irrigation and Disaster Management departments so that all agencies act on a common, satellite-informed picture of the situation.

References

Bai, W., Wang, G., Huang, F., Sun, Y., Du, Q., Xia, J., Wang, X., Meng, X., Hu, P., Yin, C., Tan, G. and Wu, R. 2025. Review of Assimilating Spaceborne Global Navigation Satellite System Remote Sensing Data for Tropical Cyclone Forecasting. *Remote Sensing* **17**(8):118 https://doi.org/10.3390/rs17010118

CNES / ISRO. 2021. SARAL/AltiKa Products Handbook. Issue: 3 rev 1, Date: January 26th, 2021. Published by AVISO Altimetry.

Esmaili, R., Barnet, C., Dunion, J., Folmer, M. and Zawislak, J. 2022. Evaluating Satellite Sounders for Monitoring the Tropical Cyclone Environment in Operational Forecasting. *Remote Sensing* **14:** 3189. https://doi.org/10.3390/rs14133189

Frank, N. L. and Husain, S. A. 1971. The deadliest tropical cyclone in history? *Bulletin of the American Meteorological Society* **52**(6): 438–445.

Ghosh, S., Dawn, A., Kour, S., Mallick, A., Chowdhury, A., Kundu, K., ... & Shaw, R. (2025). Climate extremes walking together: Evidence from recent compounding climate hazards after Remal. *International Journal of Disaster Risk Reduction* **11:** 104974.

Hoque, M. 2017. Cyclone disaster mapping, monitoring and management using satellite remote sensing and spatial analysis. https://doi.org/10.14264/UQL.2017.908

Hoque, M., Phinn, S., Roelfsema, C. and Childs, I. 2016. Assessing tropical cyclone impacts using object-based moderate spatial resolution image analysis: a case study in Bangladesh. *International Journal of Remote Sensing* **37**: 5320-5343. https://doi.org/10.1080/01431161.2016.1239286

Hossen, Md., Ayon, M. A. and Jubayer, Radoan. 2025. Assessment of Tropical Cyclone Remal Induced Inundation in Patuakhali and Barguna Districts of Bangladesh Using Sentinel Satellite Images. *The Dhaka University Journal of Earth and Environmental Sciences* **14**: 1-17. 10.3329/dujees.v14i1.83012.

India Meteorological Department. 2024, May 26. *National Bulletin No. 16 (BOB/01/2024): Severe Cyclonic Storm "Remal" (pronounced as "Re-Mal") over North Bay of Bengal (Cyclone Warning for West Bengal Coast: Red Message).* Ministry of Earth Sciences.

Katsaros, K., Vachon, P., Liu, T. and Black, P. 2002. Microwave Remote Sensing of Tropical Cyclones from Space. *Journal of Oceanography* **58**: 137-151. https://doi.org/10.1023/A:1015884903180

Kattamanchi, V. K., Viswanadhapalli, Y., Dasari, H. P., Langodan, S., Vissa, N. K., Sanikommu, S. and Rao, S. V. B. 2021. Impact of assimilation of SCATSAT-1 data on coupled ocean-atmospheric simulations of tropical cyclones over Bay of Bengal. *Atmospheric Research* **261:** 105733.

Kelkar, R. 2021. Satellite-based monitoring and prediction of tropical cyclone intensity and movement. *MAUSAM.*

https://doi.org/10.54302/mausam.v48i2.3965

Li, T., Lai, M., Nie, S., Liu, H., Liang, Z. and Lv, W. 2024. Tropical cyclone trajectory based on satellite remote sensing prediction and time attention mechanism ConvLSTM model. *Big Data Research* **36:** 100439. https://doi.org/10.1016/j.bdr.2024.100439

Mohapatra, M., Mitra, A. K., Singh, V., Mukherjee, S. K., Navria, K., Prashar, V., Tyagi, A., Verma, A. K., Devi, S., Prasad, V. S., Ramesh, M. and Kumar, R. 2021. *INSAT-3DR-rapid scan operations for weather monitoring over India.* Current Science **120**(6): 1026–1034. https://doi.org/10.18520/cs/v120/i6/1026-1034.

Nandal, P., Mann, P., Bohra, N., Aldehim, G., Elnour, A. and Allafi, R. 2025. Tropical cyclone intensity estimation based on YOLO-NAS using satellite images in real time. *Alexandria Engineering Journal* **113:** 227-241. https://doi.org/10.1016/j.aej.2024.10.072

Ricciardulli, L., Howell, B., Jackson, C., Hawkins, J., Courtney, J., Stoffelen, A., Langlade, S., Fogarty, C., Mouche, A., Blackwell, W., Meissner, T., Heming, J., Candy, B., McNally, T., Kazumori, M., Khadke, C. and Escullar, M. 2023. Remote Sensing and Analysis of Tropical Cyclones: Current and Emerging Satellite Sensors. *Tropical Cyclone Research and Review* **12**(4): 267-293. https://doi.org/10.1016/j.tcrr.2023.12.003

Roca R., Brogniez H., Chambon P., Chomette O., Cloche, S., Gosset, M.E., Mahfouf, J.F., Roberanto, P. and Viltard, N. 2015. The Megha-Tropiques mission: a review after three years in orbit. *Frontiers in Earth Science* **3**:17. doi:10.3389/feart.2015.00017

Sankhala, D. K., Rani, S. I., Srinivas, D., Prasad, V. S. and George, J. P. 2025. Validation of OceanSat-3 sea surface winds for their utilization in the NCMRWF NWP assimilation systems. *Advances in Space Research* ***75***(2): 1945-1959.

Tao, C., Wang, Z., Tian, Y., Han, Y., Wang, K., Li, Q. and Zuo, J. 2024. Calibration of Typhoon Track Forecasts Based on Deep Learning Methods. *Atmosphere* **15**(9): 1125. https://doi.org/10.3390/atmos15091125.

UNICEF. 2024, May 30. *India: Humanitarian Situation Report – Cyclone Remal, SitRep #02 (West Bengal, India, 13:00 hrs IST).* UNICEF Office for West Bengal. https://www.unicef.org/india/

United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA). 2024. *Bangladesh: CERF Rapid Response – Severe Cyclonic Storm Remal (24-RR-BGD-63521).* United Nations Central Emergency Response Fund (CERF). https://cerf.un.org/sites/default/files/resources/24-RRBGD63521_Bangladesh_CERF_Report.pdf

Yang, S. and Cossuth, J. 2016. Satellite Remote Sensing of Tropical Cyclones. Chapter 7 of Recent Development in Tropical Cyclone Dynamics, Prediction, and Detection. *Intech.* pp. 138-170. https://doi.org/10.5772/64114

Zhang, B. and Perrie, W. 2024. Remote Sensing of Tropical Cyclones by Spaceborne Synthetic Aperture Radar: Past, present, and future. *IEEE Geoscience and Remote Sensing Magazine* **12**: 79-109. https://doi.org/10.1109/mgrs.2024.3405310