Intensification of tropical cyclone FANI observed by INSAT-3DR rapid scan data

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Abstract
Geo-stationary satellite images are one of the primary tools for real-time monitoring and intensity analysis of tropical cyclones (TCs) in spite of other complimentary remote sensing sensors like scatterometers, microwave imagers and sounders, mounted on the polar orbiting satellites. The weather activities over the Indian region are continuously monitored by two Indian geostationary satellites, viz. INSAT-3D and INSAT-3DR, for every 15 min in staggered mode. During extreme weather events like TCs, INSAT-3DR is operated in rapid scan operation mode by taking observations over the system in every 4-min interval. These observations are highly useful in understanding the instantaneous structural changes during evolution, intensification and landfall of TC. In this study, an attempt has been made to present the salient observations over the cloud systems by visible, thermal infrared (TIR1) and water vapour imageries of INSAT-3DR satellite during the life cycle of the TC FANI. The rapidly evolving small-scale features inside the inner core of TC FANI in high temporal resolution images are examined. The relationship between TC intensity and inner core TIR1 brightness temperature (BT) and the number of overshooting top clouds in the difference images of TIR1-WV BT have been presented by analysing the sequence of INSAT-3DR imageries. The strong correlation ($r^2 = 0.74$) is obtained between the TC eye temperature and radial distance of the first overshooting cloud top. The 1 km × 1 km visible images of TC were found to have the presence of small-scale mesovortices in the eye region, which are a typical characteristic of intense TC system. Usefulness of high temporal satellite images generated using rapid scan mode is demonstrated for identifying the signatures of TC intensification.

1 Introduction

The rapid scan images from geostationary satellites have been proven to be a useful tool in weather applications like the derivation of atmospheric motion winds, analysis of wildfires, convective initiation nowcasting and identification of overshooting convective cloud tops (Schmidt et al. 2014; Bedka et al. 2015; Line et al. 2016; Mohapatra et al. 2021; Sankhala et al. 2021). These images are useful for monitoring the convective features of storms that evolve on shorter time scales, i.e. less than 15 or 30 min (Dworak et al. 2012; Cintineo et al. 2013). Earlier studies have shown the identification of several unique signatures within satellite imagery of severe convective storm tops, which include rapid cloud-top cooling (Cintineo et al. 2013), overshooting tops (Dworak et al. 2012), above-anvil cirrus plumes (Levizzani and Setvák 1996) and the cold ring (Setvák et al. 2010). Bedka et al. (2015) have shown the relationships between the different properties of deep convective storms observed by high temporal resolution satellite imageries and radar. One-minute interval images of GOES-12 have been used to feature the mesovortices inside the eye of a tropical cyclone (Kossin and Schubert 2004).

Tropical cyclones (TCs) are the weather event with complex multi-scale processes and non-linear interactions. The high temporal frequency satellite images are very useful for extreme weather events like TCs because monitoring the significant changes in the atmosphere during a short interval is possible (Sun et al. 2019) using these images. Moreover, the spatial resolution of the imaging system determines the detail of the observed textures, which is very important for fine-scale target tracking. Researchers have shown that convective scale processes within the hurricane core might have played a crucial role in influencing rapid changes in TC intensity and structure (Rogers 2010). The strong
relationship between the satellite measured brightness temperature (BT) of cloud tops near the core of TCs and its current and future intensity has been well demonstrated (Gentry et al. 1980; Dvorak 1975). Past observational studies have documented that intensifying TCs have outflow that links to synoptic scale upper tropospheric flow features, while non-intensifying TCs have no such link. Outflow tends to develop in regions where upper tropospheric inertial stability is low and stronger outflow tends to be associated with intensifying TCs. The data provided by geostationary satellites in high temporal sampling mode may give insight into the upper level outflow and rapidly changing structural features of TCs, which in turn may be used as a guidance of TC intensification processes. The satellite-derived features of inner core can be used as an indicator of TC rapid intensification (Callaghan 2017). In the past few years, due to the advance developments in in situ and satellite-based measurements, there have been a significant improvement in the TC inner core observations. The observations from the advanced sensors like GPS dropsonde, step frequency microwave radiometer (SFMR), aircraft reconnaissance, weather radar systems, satellite microwave sensors, radiometers, sounders, rapid-scan satellite imagers and scatterometers have provided a huge amount of data for studying the TC inner core dynamics (Kepert 2010).

India’s two meteorological geostationary satellites, viz. INSAT-3D and INSAT-3DR, provide coverage over India and the surrounding regions including the oceans. INSAT-3D and INSAT-3DR both have two meteorological payloads, an Imager (with 6 channels) and a Sounder (with 18 infrared channels and a visible channel for daytime cloud detection). The Imager has capability of taking observations of full earth disk from geostationary orbit in one visible channel (VIS, 0.55–0.75 µm) and five infrared (IR) channels: short-wave infrared (SWIR, 1.55–170 µm), mid-wave infrared (MIR, 3.8–4.0 µm), water vapour absorption channel (WV, 6.5–7.1 µm) and two split-window thermal infrared channels (TIR1, 10.2–11.2 µm, and TIR2, 11.5 to 12.5 µm). The observations from VIS and SWIR channels are available at 1 km x 1 km ground resolution at nadir, whereas MIR, TIR1 and TIR2 have resolution of 4 km x 4 km, respectively. The WV channel has coarser resolution of 8 km x 8 km at nadir. The sub-satellite points of INSAT-3D and INSAT-3DR are at 82°E and 74°E, respectively.

The Indian geostationary satellite INSAT-3DR is being operated in rapid scan mode during high-impact weather activities like TCs to capture the images every 4-min interval. These satellite observations may be helpful in observing the rapidly changing features over TCs, and thus determining its movement, structure and intensity. During the extremely severe TC FANI, in the Bay of Bengal during 26 April–04 May 2019, the INSAT-3DR satellite was operated in the rapid scan mode. This TC was developed near the equator, which is very rare, and made landfall at the Odisha coast after achieving extremely severe TC category. The present work aims to discuss the fine-scale short-lived features within TC FANI, i.e. eye-eyewall mesovortices, double eyewall and overshooting cloud top, and its association with TC intensification by analysing rapid scan satellite images from INSAT-3D satellite. The visual animations of TIR1, WV, visible and differenced “TIR1–WV” imageries over TC were also extensively analysed to observe the deep convective cloud-top movement, outflow characteristics and other structural features.

### 1.1 Overview of tropical cyclone FANI (26 April–03 May 2019)

TC “FANI” was classified by India Meteorological Department (IMD) as an extremely severe cyclonic storm. It originated from a tropical depression, and formed west of Sumatra in the North Indian Ocean on 26 April 2019. Vertical wind shear at first hindered the storm’s development, but conditions became more favourable on 30 April. TC FANI rapidly intensified into an extremely severe cyclonic storm and reached its peak intensity on 02 May, as a high-end extremely severe cyclonic storm, and the equivalent of a high-end Category 4 major hurricane on the Saffir-Simpson scale. FANI made landfall as extremely severe cyclone category on 03 May morning hours, and its convective structure rapidly degraded thereafter, dissipating on 05 May. Prior to its landfall, authorities in India and Bangladesh evacuated at least a million people each from FANI’s predicted path onto higher ground and into cyclone shelters, which is thought to have reduced the resultant death toll. The best track of the cyclone from IMD is shown in Fig. 1. The cyclone intensity stages are shown in the figure with different colours based on IMD intensity classification criterion.

### 2 Data used and methodology

The INSAT-3DR satellite data during evolution and active period of TC FANI, i.e. 26 April–04 May 2019, have been used in the present work. During this period, satellite was scanning in the Rapid Scan Operation mode, with satellite images produced in 4- and 9-min intervals. Gridded satellite data over TC FANI used in the present work have been taken from the MOSDAC server (www.mosdac.gov.in). The three hourly best track data for TC FANI is obtained from the Regional Specialized Meteorological Centre (RSMC), IMD, Delhi, for tropical cyclones over the North Indian Ocean. This also includes the different intensity stages of TC FANI, from cyclonic storm to extremely severe cyclonic storm category as per the IMD criterion of cyclone intensity classification. Intensity units are presented in nautical miles per
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hour, i.e. knots (1 knot = 0.51 m/s). Out of total 971 satellite observations, 74 (7.6%) were made over cyclonic storm stage (34–47 knots), 147 (15.2%, SCS) over severe cyclonic storm intensity stage (48–63 knots), 192 (19.8%, VSCS) over very severe cyclonic storm intensity stage (64–85 knots), and 558 (57.5%, ESCS) over extremely severe cyclonic storm intensity stage (86–119 knots). Cooperative Institute of Meteorological Satellite Studies (CIMSS) provides the half-hourly intensity estimation using the Advanced Dvorak Technique (ADT), which has been used in the present work. For rapid scan (4-min interval) images, the intensity values were obtained from the interpolation of half-hourly ADT intensity estimates of CIMSS. The time series of intensity values of TC FANI during its lifetime from satellite-based estimation of CIMSS and best track estimates of IMD are presented in Fig. 2a. The histogram of intensity stages of TC FANI observed by INSAT-3DR is shown in Fig. 2b.

The present study includes visual analysis of images of TC FANI generated from the high scanning rate (~ 4 min) data captured by imager channels of INSAT-3DR satellite. The short-lived features (< 15 min) observed by visible, TIR1 and water vapour (WV) channel data have been discussed in this study. The differenced images of TIR1 and WV channel are also analysed to examine the overshooting clouds and its association with TC intensification.

3 Results and discussions

3.1 TC FANI observed by INSAT-3DR TIR1 imageries

The visual animations of TIR1 imageries from INSAT-3DR satellite over TC are monitored to observe the deep convective cloud-top movement over TC at high temporal resolution. The 4-km spatial resolution TIR1 imageries are analysed to identify the short-lived features and its association with TC intensity. The images show a well-defined eye with an annular of axisymmetric eyewall structure. A blow-up of convection can be clearly seen near the centre of circulation. A sample image of TC FANI from TIR1 channel valid at 1515 UTC 02 May 2019 is shown in Fig. 3. The colour-enhanced image is also presented. The red shades in the colour-enhanced image represent the area with regions colder than −30 °C grading through to white colour, which represents an area colder than −70 °C. The warm eye can be seen in the images with temperatures greater than +10 °C.
Fig. 2  a Time series of intensity of TC FANI during its lifetime from IMD best track and ADT estimates by CIMSS. Different intensity classification stages of cyclone are presented by horizontal lines. Durations of satellite images with clear eye scenes, which are used in the present study, are marked with dotted vertical lines. b Histogram of intensity associated with the scenes of TC FANI provided by INSAT-3DR during 29 April–02 May 2019

Fig. 3  TIR1 channel image from INSAT-3DR satellite over TC FANI valid at 1515 UTC 02 May 2019 (left). The colour-enhanced TIR-1 image (right) with red area making regions colder than $-30 \, ^\circ C$ grading through to white colder than $-70 \, ^\circ C$. The eye of the TC is shown with a region of temperature greater than $+10 \, ^\circ C$. The eye of the TC is shown with a region of temperature greater than $+10 \, ^\circ C$. The eye of the TC is shown with a region of temperature greater than $+10 \, ^\circ C$. The eye of the TC is shown with a region of temperature greater than $+10 \, ^\circ C$.
All the archived TIR1 images of TC over open ocean areas with eye conditions during 01 May–02 May 2019 are examined for the warmest TIR1 BT in the eye of TC. The time series plots of BT in TC eye and corresponding intensity have been shown in Fig. 4. TIR1 BT in the eye of TC is found increasing with the increasing intensity values. Thus, the higher values of TIR1 BT in TC eye can be used as an indicator of TC intensification. The warmest temperature in the eye of TC by TIR1 channels is observed as 293.78 K on 1232 UTC 02 May 2019. During this hour, TC achieved its peak intensity of 115 knots and was categorised as an extremely severe TC as per the IMD intensity classification criterion.

The variability of TIR1 BT in the inner core of TC during its intensification is investigated by computing the standard deviation of TIR1 BT. The TIR1 observed BT values of the inner core region, i.e. area within 2 degrees from TC centre was used to compute the standard deviation in each image. The centre of the cyclone was manually identified for each image by identifying the warmest pixel in the centre of circulation. The TIR1 BT standard deviation (STD) is then plotted with the corresponding intensity of TC as shown in Fig. 5. The STD values are found to be decreasing during intensification of TC. The values of STD are minimum during high-intensity stages. The minimum value of inner core TIR1 STD is found as 9.51 K during its peak intensity of 115 knots.

### 3.2 INSAT-3DR differenced “TIR1-WV” imageries

The weighting function is a factor used to provide a weight to the plank function in the atmospheric component of the emitted radiation while deriving the BT values.
corresponding to different satellite channels. The weighting values change based on different atmospheric conditions and channel characteristics. The WV spectral response peak is about 350 mb, whereas the IR peak is at or near the surface. Due to this weighting function characteristic, during clear sky conditions, the TIR1 BT is always warmer than WV BT values as TIR1 BT represents temperature near surface and WV BT represents temperature above the surface. However, during the presence of deep clouds, the weighting functions shift further and the BT measured by WV becomes warmer than IR. The pixels with warmer WV BT than IR show the deep convective clouds. Thus, in opaque cloud conditions associated with intense active convection penetrating the tropopause, the sign of the measured difference between the two channels can reverse due to the re-emitted absorbed radiation from upper-tropospheric–lower-stratospheric (UTLS) water vapour (Schmetz et al. 1997). The sequence of differenced TIR1-WV BT images for TC FANI has been generated and analysed for the existence of any short-lived features during the TC life period.

One of the sample images representing INSAT-3DR observed TIR1, WV and differenced (TIR1-WV) BT of TC FANI during 1453 UTC 02 May 2019 is shown in Fig. 6. The distinguishable, warm and intense eye can be seen in the given image for both the channels. The regions with deep clouds can be seen warmer in the water vapour image than the TIR image. These regions are shown by the negative values in the differenced image. One can see that eye temperature observed in TIR1 is warmer than the WV channel; this reflects the presence of clear eye with low levels or no clouds. In the differenced image, the BT in the eye region is positive and has been shown in white colour. However, the negative BT of greater than 20° can be seen in the inner core region of TC surrounding the eye area, near the eyewall region.

The images of differenced BT (TIR1-WV) values of two channels during the entire life of cyclone are computed and analysed. These images well represent the asymmetric clouds within the eyewall and inner core region of TC. The presence of overshooting clouds at some locations is found rapidly changing as it alters in the next 4-min imageries. The deep overshooting clouds (blue in colour, with differenced BT < −20 °C) are observed in the southern part of the eyewall, whereas the low clouds (red in colour, with differenced BT close to 0 °C) are present in the northern part. The extent of differenced BT is found to be changing in every 4-min images.

The correlations between the total number of negative pixels in the inner core region of TC and its current and future intensity are investigated further. The time series plot of the number of negative TIR1-WV pixels in TC inner core region and intensity is shown in Fig. 7. Figure 7 shows that there is a lag between the number of negative pixels and the intensity changes. This result can be utilised to address the future intensification of TC.

3.3 TC eyewall mesovortices observed in the visible images of INSAT-3DR satellite

An eyewall mesovortex is a small-scale rotational feature found in an eyewall of an intense TC. Many theories have been proposed in the literature to explain the eye-eyewall process within the mature TC. Wang and Wu (2004) argued that mesoscale vortices might be convectively generated in the eyewall region and then sheared and damped by the axisymmetrization process followed by intensification of storm. Montogomery et al. (2002) have presented
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Fig. 7 The time series plot of the number of negative TIR1-WV pixels in TC inner core region and its corresponding intensity values (knots).

Fig. 8 The low-level mesovortices and hot towers depicted by the INSAT-3DR visible channel image valid at 0906 UTC 02 May 2019. The mesovortices are circled in yellow colour, and hot towers are circled in red colour.

an experimental study on the mesovortices within the eye of TC, and their experiment supported the hypothesis that the eyewall region of intense storms contains mesovortices that have higher horizontal wind speeds locally than the parent TC. However, there are very few theories that explain whether the eyewall mesovortices play a significant positive or negative role in determining the intensification rate of a TC (Wang and Wu 2004). The study of Eastin et al. (2002a, b) has shown that maximum moist entropy exists at low levels in the eye. Mesovortices in the eye may serve as efficient transporters of this high moist entropy air back into the eyewall, re-strengthening the deep convection and causing intensification (as cited in Hendricks 2012). The visible imageries of 1 km × 1 km resolution of TC FANI are also analysed to identify some characteristic features.

In the eyewall of intense TCs, tornado-scale rotational features, i.e. mesovortices, have been speculated since the last two decades. Due to their small horizontal scale, fast movement and associated severe turbulence, it is often found difficult to observe them directly (Wu et al. 2018). In these vortices, wind speed can be up to 10% higher than in the rest of the eyewall. These are the characteristic features of intense TCs typically observed during the periods of intensification.

The numerical simulations of hurricane models run at a horizontal grid spacing of 2–3 km have demonstrated the occurrence of mesovortices or small-scale cores of rotating deep clouds, which are called vertical hot towers (Montgomery et al. 2006; Hendricks et al. 2004; Hendricks and Montgomery 2006). These features within the eye of intense TC have also been reported from the visible images from the rapid scan high spatial resolution observations of other geostationary satellites like visible imageries (0.64 µm) of Himawari-8 satellite for typhoon Jebi (30 AUG 2018) and 1-min GOES-16 visible data for hurricane Florence (11 September 2018) and GOES-15 visible data for hurricane Hector (06 August 2018). The animation of visible images (1-km resolution) obtained from INSAT-3DR rapid scan provides the signatures of transient low-level cloud swirls in eye of TC FANI during its intensification stage on 01–02 May. These small-scale regions of vorticity are known as mesovortices, and their presence in the TC eye and eyewall is widely documented (Kossin et al. 2002). The visible image of INSAT-3DR showing the mesovortices (yellow circled) and hot towers (red circles) is given in Fig. 8.

The closer look of the inner core of TC FANI taken from 1-km-resolution visible imageries of INSAT-3DR during the
period 0800–1000 UTC 02 May 2019 has been analysed. These visible channel images show a distinct eye and eyewall with the surface mesovortex features within the eye of TC. In every 4-min images, these features of multiple mesovortices are found rapidly evolving and dissipating. The moat of clear air at the edge of eye represents strong subsidence (Schubert et al. 2007). These observations along with the numerical simulations can give better insight of TC intensification. The details of eye structure in terms of its temperature, size and shape may also be helpful in TC intensity estimation.

### 3.4 Radial location of first overshooting top

TC core has been defined as a region within 200 km from the TC centre. The near zero or negative TIR1 minus water vapour BT difference values indicate the presence of vigorous convection in the atmosphere, which is termed as overshooting tops (Olander and Velden 2009). As the convective intensity decreases, the magnitude and coverage of negative “TIR1-WV” BT difference decrease, while the only TIR1 signatures may remain. Thus, “TIR1-WV” BT difference data provides stronger signals of TC intensity changes than TIR1 BT alone. Radial location of the first overshooting top (FOT) is also identified using “TIR1-WV” BT differences. The FOT is determined by locating the radial point closest to the TC centre (i.e. minimum radial distance), where a negative “TIR1-WV” BT difference is found at any azimuthal direction. The relation between radial distance of first overshooting top and pressure drop at eye is investigated by plotting the scatter diagram between FOT and TIR1 BT of the TC eye. The scatter plot is presented in Fig. 9. It can be seen from the figure that there has been a strong correlation ($R^2 = 0.74$) between TIR1 BT of the TC eye and FOT. This is computed for only clear eye cases (317) during 01 May–02 May 2019. This shows that as the temperature in eye is increasing, the size of the eye is also expanding resulting in the increased values of FOT.

During the analysis, the warmest TIR1 BT was found at 1232 UTC 02 May 2019 for TC FANI, before its landfall. The 40-km-diameter eye is observed during this time. The diameter of the eye in this case is approximated by the positive number of “TIR1-WV” differenced BT image pixels in the centre of circulation. The TIR1-WV BT during TC intensification is shown in Fig. 10. The figure shows increase in the size of TC eye as the cyclone is being intensified.

### 4 Conclusions and future work

TCs formed in the North Indian Ocean (NIO) are monitored by geostationary satellites, viz. INSAT-3D and INSAT-3DR, in addition to the polar satellite-based microwave instruments like scatterometer (SCATSAT) and humidity sounder (SAPHIR). During active TC period in NIO, INSAT-3DR satellite is operated in rapid scan mode, providing data over TC latitudes every 4 min. This data has been utilized in this study to address the structural changes in the inner core of TC FANI during its intensification.

The rapid scan data from INSAT-3DR imager channels, i.e. TIR1, WV, visible and differenced “TIR1-WV”, are analysed to investigate the fine-scale short-lived features within the TC. The BT measured by TIR1 channel in the eye of a TC is examined and found to be maximum (293.78 K) during its peak intensity. The increasing BT in the eye of a TC is a good indicator of TC intensification. The TC inner core mean TIR1 BT and standard deviation are also analysed and its minimum is found as 9.51 K during peak intensity value. The 4 km $\times$ 4 km differenced images of “TIR1-WV” BT are examined and a systematic lag of approximately 12 h is found between the number of negative pixels and the intensity changes. These images are found very useful to identify the short-lived changes in the TC asymmetric eyewall cloud structure and can be utilised to address the intensification of TC. These images are further utilised to examine the relation between radial distance of the first overshooting top from the TC centre and TIR1 BT in the TC eye. Results show a strong correlation ($R^2 = 0.74$) between TIR1 BT in the eye and radial distance of the first overshooting cloud top from the TC centre. Furthermore, the 1 km $\times$ 1 km resolution visible channel images of INSAT-3DR are investigated to identify the rapidly evolving and dissipating surface mesovortex features within the eye of the TC. These mesovortices are the characteristic features of intense TCs, which are typically observed during periods of intensification. The rapid scan images from INSAT-3DR provide insight into fine-scale TC structure, which can be utilized in real-time to track the system every 4 min and for the guidance of TC intensification.
TC observations, analysis and prediction have improved significantly due to advancements of observations (in situ, satellite and radar), computational systems and numerical models. In the future, simultaneous observations from satellites and coastal radar can be used to identify the occurrence of hot towers. The further way forward is to include artificial intelligence-based advanced emerging technologies in addition to the development of more advanced satellite sensors to observe the 3D structure of convective systems.

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**Author contribution** NJ conceived the idea and performed maximum computations. NJ and SKD analysed the results from the computations and wrote the manuscript. CMK added his expertise in the analysed results and overhauled it in the present form.

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**Data availability** The satellite data used in this study are available at www.mosdac.gov.in.

**Code availability** The analysis of results used for the current study is available from the corresponding author upon reasonable request.

**Declarations**

**Ethics approval** All procedures performed in this study involving human participants were in accordance with the ethical standards of the institution.

**Consent to participate** All the authors mutually agreed for communicating this manuscript in the present form.

**Consent for publication** All the authors give consent for publication of this manuscript at Theoretical and Applied Climatology upon successful completion of the review process.

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