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Use of SWIRLS nowcasting system for quantitative precipitation forecast using Indian DWR data

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सार – स्थानीय प्रचंड तूफाने, चरम मौसम की ऐसी घटनाएँ होती हैं जो कुछ घंटों के लिए रहती हैं और तेजी से फैल जाती हैं। इन स्थानीय प्रचंड तूफानों से संबंद्ध मेसोस्केल के लक्ष्ण सिनाप्टिक रूप से अक्सर सही प्राप्त नहीं होते हैं। पूर्वानुमानकर्ताओं को अद्यतन प्रेक्षणों के आधार पर आगामी 0–6 घंटों में परिवर्तनशील मौसम की स्थिति का पूर्वानुमान करना होता है। आगामी 0–6 घंटों में मौसम का पूर्वानुमान करने की प्रचालनात्मक प्रक्रिया को ''तात्कालिक'' पूर्वानुमान नाम से जाना जाता है। तात्कालिक पूर्वानुमान के लिए विशिष्ट रूप से मेल खाते प्रेक्षणात्मक आँकड़ों में डॉप्लर मौसम रेडार (डी. डब्ल्यू. आर.), पवन प्रोफाइलर, सूक्ष्म तरंग साउंडर और उपग्रह विकिरण शामिल हैं। मौसम सूचना का पूर्वानुमान करने के लिए पूर्वानुमानकर्ताओं को सहयोग देने हेतु और चेतावनी देने का निर्णय लेने के लिए हाल ही के वर्षों में विभिन्न देशों द्वारा विविध तात्कालिक प्रणालियाँ विकसित की गई हैं। कुछ उल्लेखनीय उदाहरण इस प्रकार हैं– ऑटो–नॉवकास्टर (संयुक्त राज्य अमेरिका), बी. जे.–ए. एन. सी. (चीन–संयुक्त राज्य अमेरिका) सी. ए. आर. डी. एस. (कनाडा), ग्रेपस–स्विफ्ट (चीन), मैपल (कनाडा) निमरोड (यू. के.), नीवोट (संयुक्त राज्य अमेरिका), स्टेपस (आस्ट्रेलिया), स्विरलस (हांगकांग, चीन), टीफस (आस्ट्रेलिया), टाइटन (संयुक्त राज्य अमेरिका), (डिक्सान और वाइनर, 1993) और डब्ल्यू. डी. एस. एस. (संयुक्त राज्य अमेरिका)। इनमें से कुछ प्रणालियों का उपयोग विश्व मौसम संगठन द्वारा आयोजित दो पूर्वानुमान प्रदर्शन परियोजनाओं, सिडनी 2000 और बीजिंग 2008 ओलम्पिक के लिए किया गया है। इन सभी प्रणालियों की सामान्य विशेषता है कि ये सभी तेजी से अद्यतन किए गए रेडार के आँकड़ों का उपयोग विशेष रूप से प्रत्येक छह मिनट में एक बार करते हैं।

तात्कालिक प्रणाली स्विरलस (स्थानीकृत प्रणालियों में तीव्र वर्षा के तूफान की अल्प अवधि चेतावनी) हांग कांग वेधशाला (एच.के.ओ.) द्वारा विकसित की गई है और वर्ष 1999 में हांग कांग में इसे प्रचालन में लाया गया। उस समय से अब तक इस प्रणाली को कई बार उन्नत किया गया है, नवीनतम प्रणाली को ''स्विरलस–2'' के नाम से जाना जाता है जिसने बीजिंग 2008 के ओलम्पिक खेलों में सहयोग दिया। एच.के.ओ. के सहयोग से नई दिल्ली में आयोजित राष्ट्रमंडल खेलों 2010 के दौरान उपयोग करने और जाँच करने के लिए भारत मौसम विज्ञान विभाग (आई. एम. डी.) ने स्विरलस–2 को अपनाया। स्विरलस–2 में आकाश से भूमि तक बिजली के चमकने, प्रचंड चंडवातें और ओलावृष्टि तथा वर्षा की संभावना सहित गर्ज के साथ तूफान के पथ और इससे संबंध प्रचंड मौसम के साथ–साथ परावर्तकता , रेडार प्रतिध्वनि की गति, क्यू. पी. ई., क्यू. पी. एफ. का पूर्वानुमान लगाने और विश्लेषण करने के लिए सिगमेट/आइ. आर. आइ. एस. डी. डब्ल्यू. आर. रेडार उत्पाद वर्षा के आँकड़ों, रेडियोसौंदे के आँकड़ों, बिजली चमकने के आँकड़ों सहित प्रेक्षणात्मक आँकड़ों की श्रंखलाएँ निहित हैं। स्विरलस–2 तूफान गति सदिशों को उत्पन्न करने के लिए कई एलगॉरिथ्मस का उपयोग करता है। इसमें टी. आर. ई. सी. (सहसंबंध द्वारा रेडार प्रतिध्वनियों का पता लगाना) जी. ट्रेक (रेडार प्रतिध्वनियों का ग्रुप ट्रैकिंग, संपूर्ण प्रभुत्व के रूप में तूफान की गति का पता लगाने के लिए वस्तुपरक तकनीक) और बाद में एम. ओ. वी. ए. (विविधात्मक विशलेषण द्वारा बहु मान प्रकाशीय प्रवाह) शामिल है। इस नवीनतम एलगॉरिथ्मस में प्रकाशीय प्रवाह का उपयोग किया जाता है, ऐसी तकनीक जो सामान्यतः चित्र संसाधन में गति का पता लगाने और गति सदिश क्षेत्र को प्राप्त करने के लिए विविधात्मक विश्लेषण करने हेतु उपयोग में लाई जाती है। मापक्रमों की श्रंखलाओं के माध्यम से सोपान पात द्वारा टी.आर.ई.सी. और जी. ट्रेक के साथ तुलना करने कार वास्तविक तूफान गति सदिश क्षेत्र को एम. ओ. वी. ए. द्वारा बेहतर ढंग से बता सकते हैं जो क्रमशः अल्प मापक्रम के लक्ष्णों और तूफान के प्रभाव को सही रूप से बताते है। इस शोध पत्र में भारतीय डी. डब्ल्यू. आर आँकड़ों का उपयोग करते हुए तूफान गति सदिश, परावर्तकता और क्यू. पी. एफ. को प्राप्त करने के लिए टी. आर. ई. सी. और एम. ओ. वी. ए. का अनुप्रयोग कोलकता और नई दिल्ली में गर्ज के साथ तूफानों की घटनाओं के लिए किया गया है। राष्ट्रमंडल खेलों 2010 के दौरान दिल्ली और निकटवर्ती क्षेत्रों में इस प्रणाली को सफलतापूर्वक प्रचालन में लाया गया है। वास्तविक समय उत्माद भारत मौसम विज्ञान विभाग की वेबसाईट पर उपलब्ध है।

ABSTRACT. Local severe storms are extreme weather events that last only for a few hours and evolve rapidly. Very often the mesoscale features associated these local severe storms are not well-captured synoptically. Forecasters have to predict the changing weather situation in the next 0-6 hrs based on latest observations. The operational process to predict the weather in the next 0-6 hrs is known as "nowcast". Observational data that are typically suited for nowcasting includes Doppler Weather Radar (DWR), wind profiler, microwave sounder and satellite radiance. To assist forecasters, in predicting the weather information and making warning decisions, various nowcasting systems have been developed by various countries in recent years. Notable examples are Auto-Nowcaster (U.S.), BJ-ANC (China-U.S.), CARDS (Canada), GRAPES-SWIFT (China), MAPLE (Canada), NIMROD (U.K.), NIWOT (U.S.), STEPS (Australia), SWIRLS (Hong Kong, China), TIFS (Australia), TITAN (U.S.) (Dixon and Wiener, 1993) and WDSS (U.S.). Some of these systems were used in the two forecast demonstration projects organized by WMO for the Sydney 2000 and Beijing 2008 Olympic. A common feature of these systems is that they all use rapidly updated radar data, typically once every 6 minutes.

The nowcasting system SWIRLS ("Short-range Warning of Intense Rainstorms in Localized Systems") has been developed by the Hong Kong Observatory (HKO) and was put into operation in Hong Kong in 1999. Since then system has undergone several upgrades, the latest known as "SWIRLS-2" to support the Beijing 2008 Olympic Games. SWIRLS-2 is being adapted by India Meteorological Department (IMD) for use and test for the Commonwealth Games 2010 at New Delhi with assistance from HKO. SWIRLS-2 ingests a range of observation data including SIGMET/IRIS DWR radar product, raingauge data, radiosonde data, lightning data to analyze and predict reflectivity, radar-echo motion, QPE, QPF, as well as track of thunderstorm and its associated severe weather, including cloud-to-ground lightning, severe squalls and hail, and probability of precipitation. SWIRLS-2 uses a number of algorithms to derive the storm motion vectors. These include TREC ("Tracking of Radar Echoes by Correlation"), GTrack (Group tracking of radar echoes, an object-oriented technique for tracking the movement of a storm as a whole entity) and lately MOVA ("Multi-scale Optical flow by Variational Analysis"). This latest algorithm uses optical flow, a technique commonly used in motion detection in image processing, and variational analysis to derive the motion vector field. By cascading through a range of scales, MOVA can better depict the actual storm motion vector field as compared with TREC and GTrack which does well in tracking small scales features and storm entity respectively. In this paper the application of TREC and MOVA to derive the storm motion vector, reflectivity and QPF using Indian DWR data has been demonstrated for the thunderstorm events over Kolkata and New Delhi. The system has been successfully operationalized for Delhi and neighborhood area for commonwealth games 2010. Real time products are available on IMD website.

Key words – SWIRLS, TREC, MOVA, storm motion vector, QPF, Thunderstorm.

1. Introduction

Convective heavy rainfall event is one of the most disastrous weather phenomena affecting a large population and of common interest to tropical countries. Accurate forecast of these events are crucial for early warning of potential hazard to minimize loss of life and property. For the realistic prediction of these events, there is a need for a very high resolution nowcasting system with sophisticated strategies for ingesting data of high temporal and spatial density.

For nowcasting any meso-scale system, the most important source of information in the current operational observing system is the Doppler Weather Radar (DWR). The installation of four GEMATRONIC METEOR 1500S model DWRs (Chennai (2002), Kolkata (2003), Machilipattanam (2004) and Vishakhapattnam (2006)] and two METSTAR built DWRs (New Delhi (2010) and New Hyderabad (2010)) has heightened the prospects for the operational implementation of nowcasting system to explicitly predict the evolution of mesoscale phenomena. The DWR scans with beam width of 1o create 360 beams radials of information per elevation angle. A full volume scan takes about 15 minutes for GEMATRONIC METEOR 1500S model DWRs and 10 minutes for METSTAR built DWRs. This provides high resolution measurement of radial velocity and velocity spectrum width to ranges of 250 km and of reflectivity to ranges of 500 km.

The Hong Kong Observatory nowcasting system SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems) has been in operation since 1999 [Lai & Li 1999, 2000]. Its second-generation version (referred to as SWIRLS-2) has been under development and real-time testing in Hong Kong since 2007. To support the 2008 Beijing Olympic Games, a special version of SWIRLS-2 [Yeung *et al*. 2009] was deployed for the Beijing 2008 Forecast Demonstration Project (B08FDP) under the auspices of the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO). SWIRLS-2 has become operational in Hong Kong since 2010.

The original SWIRLS focused primarily on rainstorm and storm track predictions. The much enhanced SWIRLS-2 comprises a family of sub-systems, responsible respectively for ingestion of conventional and remote-sensing observation data, execution of nowcasting algorithms, as well as generation, dissemination and visualization of products *via* different channels. It embraces new nowcasting techniques, namely : (a) blending and combined use of radar-based nowcast and high-resolution NWP model analysis and forecast (Wong *et al*. 2009); (b) detection and nowcasting of high-impact weather including lightning, severe squalls and hail based on conceptual models; (c) grid-based, multi-scale storm-tracking method; and (d) probabilistic representation of nowcast uncertainties arising from storm tracking, growth and decay.

In this study, capabilities of TREC and MOVA techniques of SWIRLS in depicting the storm motion vector using Indian DWR data is discussed. The motion vector field so derived can be applied to forecast the future position of the storm cells or individual reflectivity and QPF forecast. Section 2 provides a brief overview of TREC and MOVA techniques of SWIRLS nowcasting system. The data used in this study and the adaptation of SWIRLS to the Indian data set is described in section 3. In Section 4 the performance of TREC and MOVA to depict storm motion vector, predicted reflectivity and QPF for thunderstorm event over Kolkata is discussed. In section 5 the performance of TREC and MOVA to depict storm motion vector, predicted reflectivity and QPF for thunderstorm event over New Delhi is discussed. The summary and conclusions are presented in section 6.

2. SWIRLS implementation for TREC and MOVA

2.1. *TREC (Tracking of Radar Echoes by Correlation)*

Movement of individual radar echoes between two consecutive CAPPI scans at 6-minute interval is derived by maximizing the cross-correlation. The whole domain is divided into a number of equally sized "boxes". For each box, the cross-correlation with all possible boxes in the previous 6-minutes is derived to determine which box results in the highest correlation. The vector joining these 2 boxes then represents the motion vector. To reduce computation time, a search radius, which should tally with the maximum possible speed of rainfall systems, centred on the box is prescribed. The final output field will be smoothed by Cressman analysis. In SWIRLS, the reflectivity field has a resolution of 480 × 480 pixels. The boxes are spaced 5 pixels apart, giving a TREC vector field on a 93 × 93 grid. The equivalent spatial resolution is of the order of 1 to 5 km depending on the range of the scan. Further technical details can be found in Lai & Li [1999] and Li & Lai [2004].

2.2. *MOVA ("Multi-scale Optical flow by Variational Analysis")*

MOVA is a new storm tracking algorithm added in SWIRLS-2 [Yeung *et al.* 2009]. Gridded echo-motion field is retrieved from successive CAPPI scans at 6-minute interval by solving the optical flow equation using variational minimization technique. The smoothness of the motion vector field is prescribed as a constraint in the minimization process. In contrast to correlation method such as TREC, MOVA or optical flow in general does not capture similarity but instead aims at minimizing the difference or variance between two image patterns. The domain is divided into equally sized box(es). To bestow MOVA with the capability to track storm motion at different scales, a multi-level cascade with decreasing box size (*i.e*., increasing spatial resolution), was carried out. In SWIRLS, a 7-level cascade with box size ranging from full domain (256 km) to around 3 km is implemented. More technical details can be found in Wong & Lai [2006, 2009].

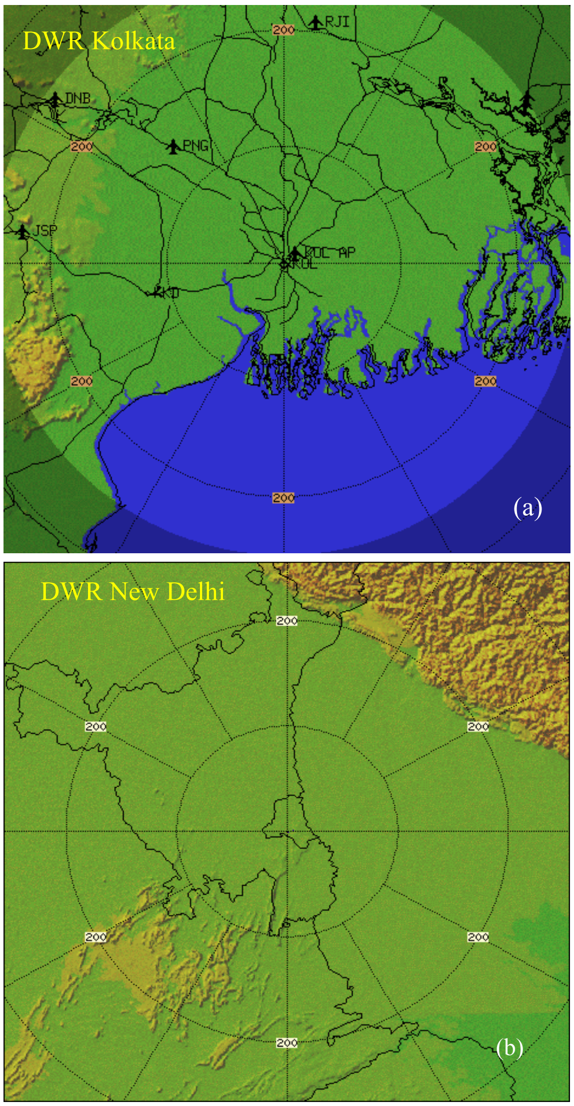
3. Data Sources and SWIRLS Customization

3.1. *Data*

Two case studies were carried out using radar reflectivity data from the DWR Kolkata (Lat. 22.5° N and Long. 88.4° E) and New Delhi (Lat. 28.56° N and Long. 77.07° E). The Kolkata radar has a 1° beam width and a volume scan takes around 15 minutes while New Delhi has a 1° beam width and volume scan takes around 10 minutes. This scan strategy was optimized by IMD to take into account the limitations of the radar hardware and the meteorological requirement of sampling frequency for convective events over the Indian region. This study made use of the reflectivity CAPPI data generated at 3-km altitude. Beyond 150 km range, reflectivity values were filled in by vertical interpolation out to 256 km. The volume scan data for generating the CAPPI product were not quality controlled.

3.2. *SWIRLS customization*

The Kolkata DWR raw data files, in VOL format (a proprietary RAINBOW format of GEMATRONIK Corporation) were converted to IRIS/SIGMET format for ingestion into SWIRLS using interface software developed by METSTAR. While New Delhi DWR data is already in IRIS/SIGMET format so it was directly used in SWIRLS. The domain selected for the SWIRLS run covers a range of 256 km with Kolkata and New Delhi at the center of the domain as shown in Figs. 1(a&b).



Figs. 1(a&b). Nowcast domain of SWIRLS centred at (a) Kolkata (b) New Delhi

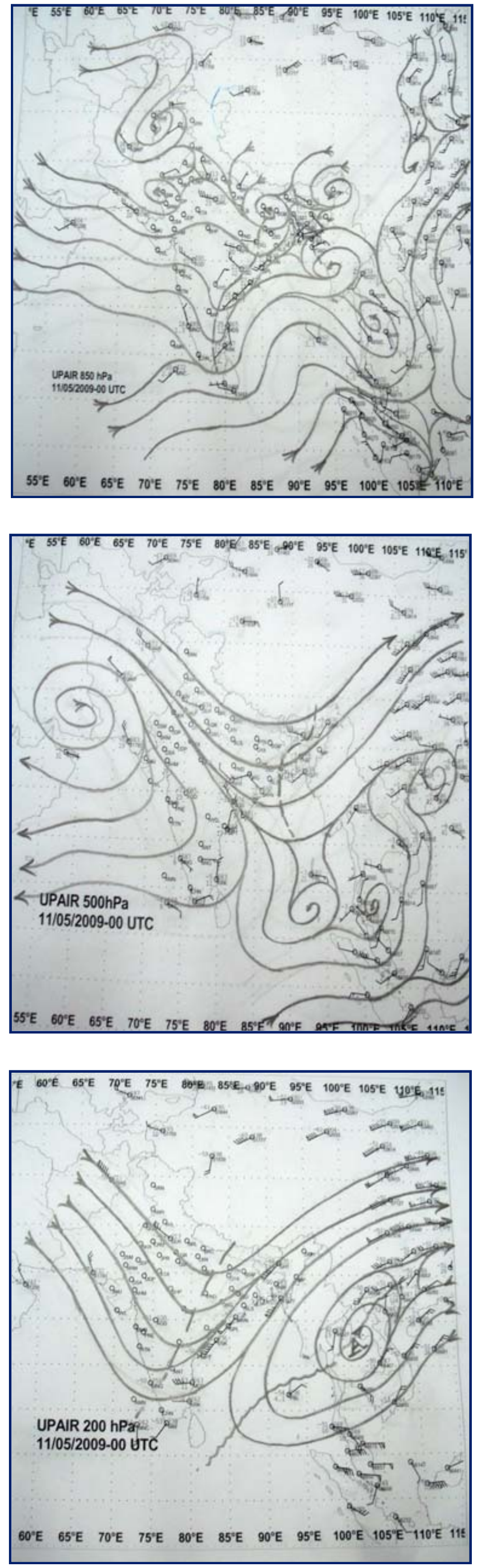
(a) *TREC*

Successive CAPPI scans of the Kolkata DWR are separated by 15-minutes and for New Delhi Successive CAPPI scans are separated by 10-minutes. Since a radar echo would have moved much further during next period, the search radius was increased from 19 km (equivalent to a motion speed of about 90 km/hr) implemented in Hong Kong to 38.4 km (equivalent to about 154 km/hr) in this study for both the cases. As the original search radius was tuned mainly for monsoonal and tropical cyclone rainfall events over Southern China, further tuning of this search radius based on convective storms in India might be required for best results.

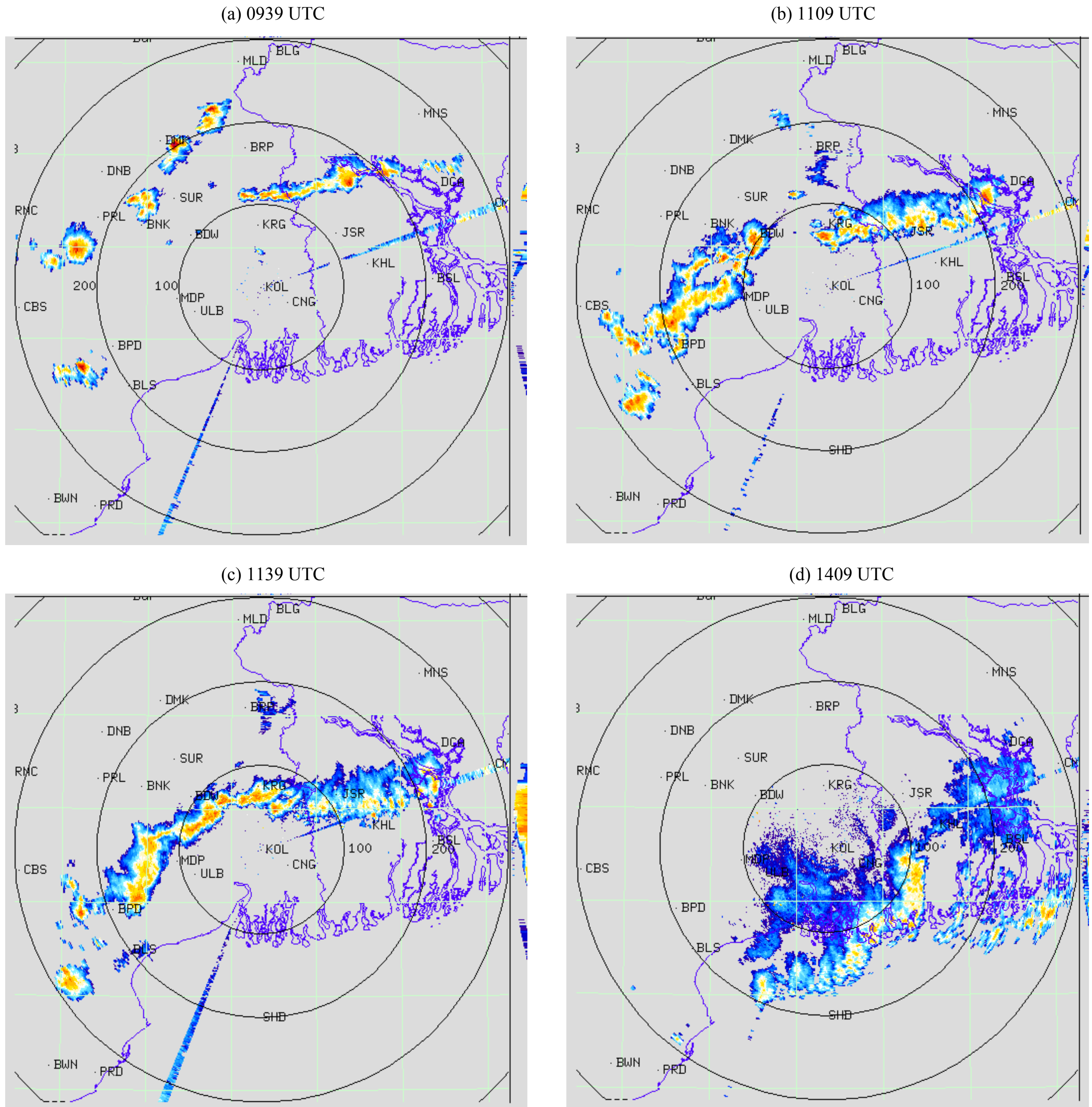
(a) 850 hPa

(b) 500 hPa

(c) 200 hPa



Figs. 2(a-c). Streamline analysis over Indian region on 11 May 2009



Figs. 3(a-d). Radar reflectivity ("MAX" product) as observed by DWR Kolkata on 11 May 2009

(b) *MOVA*

Two basic assumptions of optical flow are (a) constancy of brightness of pixels; and (b) small displacement. Since in these studies, successive CAPPI scans are different from Hong Kong scans, these 2 assumptions no longer hold true. In particular, for fast moving localized storms, there is practically no overlapping in the storm positions between 2 consecutive CAPPI scans, making tracking by optical flow impossible. To partly address this, fast Fourier transform (FFT) was implemented to replace the first level (full domain) of optical flow tracking.

4. Case study of Kolkata thunderstorm event

4.1. *Synoptic observation*

Case selected for this study is the thunderstorm event of 11 May 2009 over West Bengal. On 11 May 2009 there

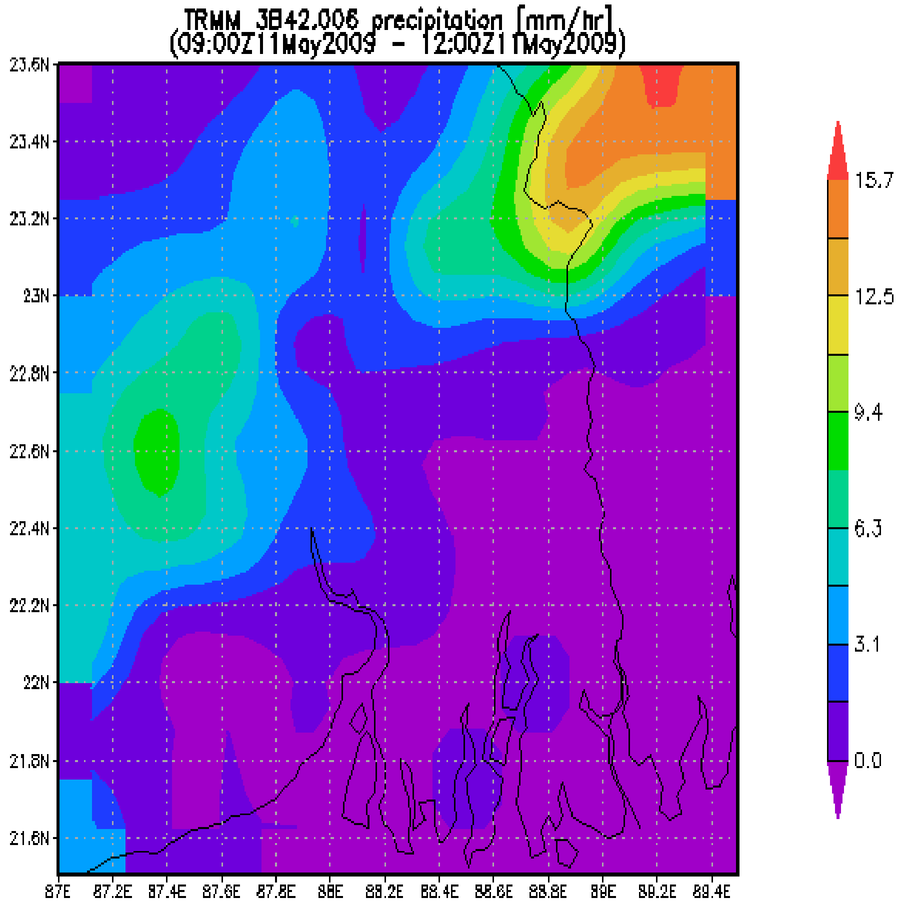


Fig. 4. Observed 3-hour precipitation between (0900 UTC - 1200 UTC) over east and northeast India on 11 May 2009

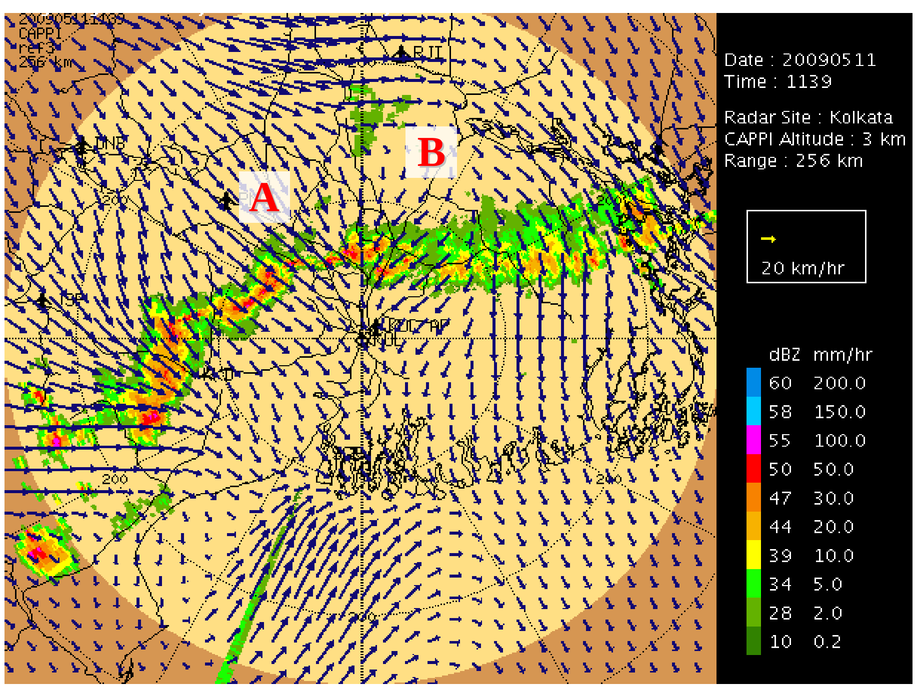


Fig. 5. SWIRLS TREC motion vector fields at 1139 UTC on 11 May 2009

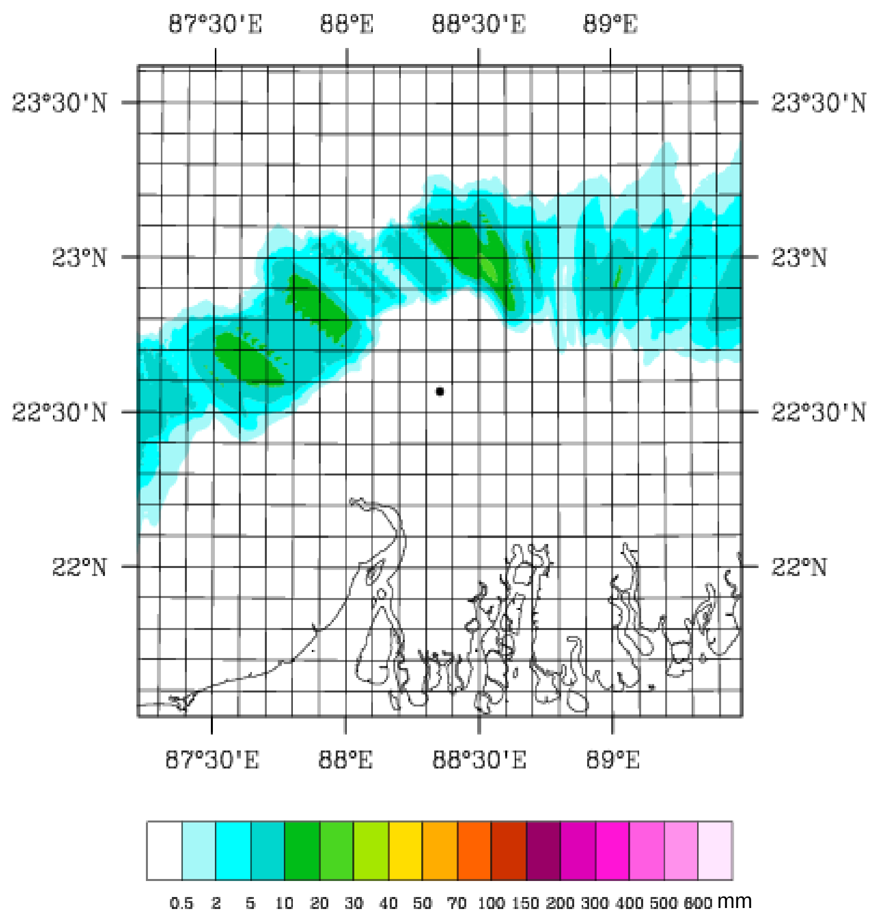


Fig. 6. SWIRLS 3-hour QPF derived from TREC motion vector fields at 11:39 UTC on 11 May 2009

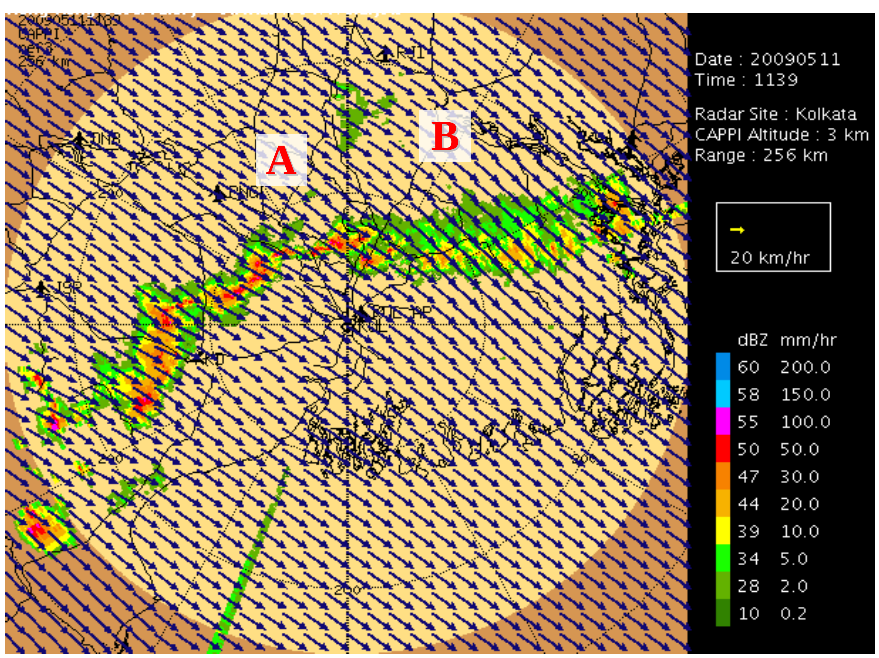


Fig. 7. SWIRLS MOVA motion vector fields at 1139 UTC on 11 May 2009

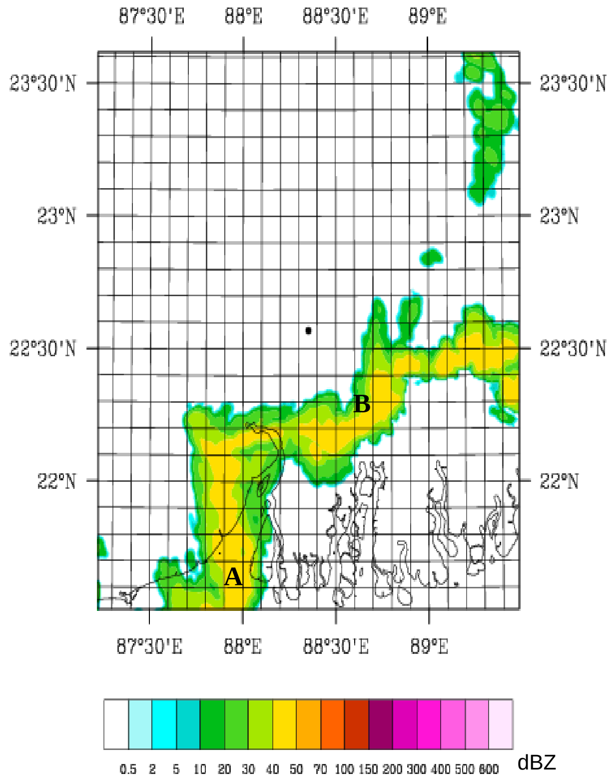


Fig. 8. Forecast reflectivity valid for 1409 UTC derived from MOVA motion vector fields at 1139 UTC on 11 May 2009

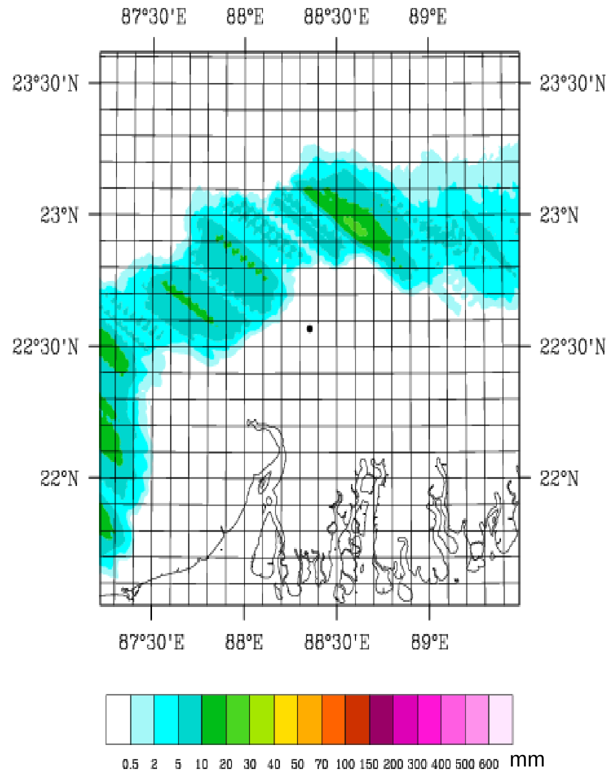


Fig. 9. SWIRLS 3-hour QPF derived from MOVA motion vector fields at 1139 UTC on 11 May 2009

was cyclonic circulation in lower levels over Bihar & neighbourhood. Trough from this circulation extended upto extreme south peninsula across Chhattisgarh, Talengana and Rayalaseema. Another cyclonic circulation lies over Arunachal Pradesh and adjoining Assam & Meghalaya [Fig. 2(a)]. These led to significant moisture incursion at low level over the area. Meanwhile, a trough extended from Arunachal Pradesh to NW Bay of Bengal in middle troposphere [Fig. 2(b)]. At 200 hPa, a significant westerly trough with jet maxima over the region resulted in strong upper-level divergence Fig. 2(c).

4.2. *Radar observation*

On 11 May 2009 Kolkata DWR observed that thunderstorms started developing at 0939 UTC with six small meso cells [labeled "A" in Fig. 3(b)] in the north-west region about 200 km from Kolkata. At the same time, another line of echo [labeled "B" in Fig. 3(b)] was observed about 100 km to north of Kolkata. By 11:09 UTC, the six meso cells moved southeastwards and merged as one large cell about 100 km northwest of Kolkata. Meanwhile the line of echo moved south to about 80 km north of Kolkata. At 1139 UTC, these cells merged and can be seen as one organized east-west band of convections. At 1409 UTC, the echoes move southeastwards and started dissipating over Bay of Bengal about 100 km southeast of Kolkata. Corresponding radar images of Maximum Reflectivity (Z) are shown in Fig. 3.

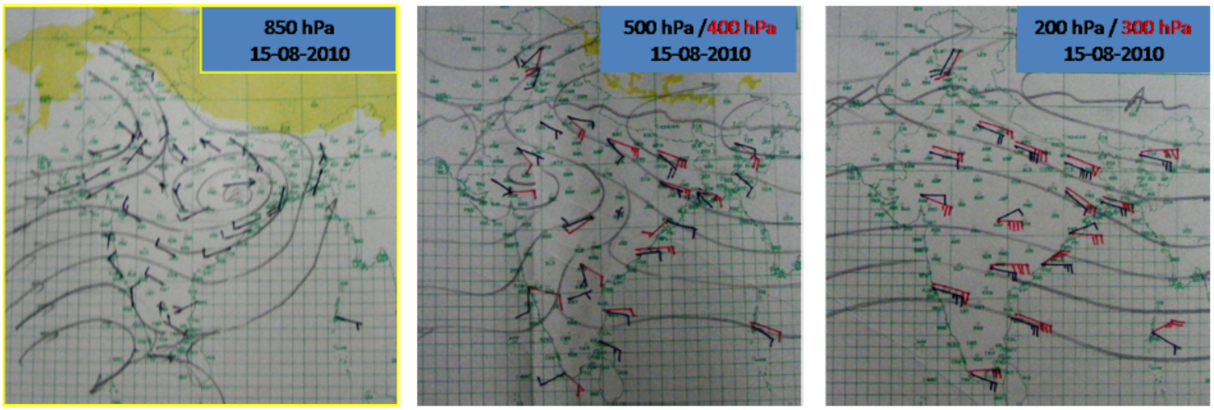
4.3. *Observed rainfall*

The 3-hour accumulated rainfall between 09 - 12 UTC, due to the thunderstorm on 11 May 2009 as observed by TRMM satellite, is shown in the Fig. 4. The highest rainfall was recorded at Barrackpur (West Bengal) surface observatory, totaling 40 mm from this episode.

4.4. *SWIRLS TREC motion vector and QPF*

Fig. 5 shows the TREC motion vector at 1139 UTC. The southeastward motion of the storm cells to northwest of Kolkata [labeled "A" in Fig. 3(b) and Fig. 5] is well captured by TREC. The speed of motion, around 40 km/hr, also agreed reasonably well with the actual observation (about 50 km/hr). TREC also correctly depicted the south to southwest ward motion of the line of echo to north of Kolkata (labeled "B" in Fig. 3(b) and

(a) 850 hPa (b) 500 hPa (c) 200 hPa



Figs. 10(a-c). Streamline analysis over Indian region at 0000 UTC on 15 August 2010

Fig. 5]. The southeast motion vector associated with storm cell “A” and the southwest motion vector near the western end of storm cell “B” comes handy in depicting the merging of storm cell “A” and “B”.

While the storm motion vector field depicted in Fig. 5 looks generally reasonable, a region of erroneous storm motion vectors was observed near the spike to the southwest. The spike remained more or less stationary. As the intensity of individual pixel varied from scan to scan, the highest cross-correlation between successive scans of each pixel was not with itself. This results in erroneous storm motion vectors. This shows the importance of quality controlling the raw radar data before ingesting into SWIRLS.

The 3-hour accumulated QPF from 1139 UTC, obtained by applying the Semi-Lagrangian advection technique using the TREC storm motion vector obtained above, is given in Fig. 6. The 3-hour accumulated QPF was forecast to be between 20-30 mm to the northeast of Kolkata.

4.5. *SWIRLS MOVA motion vector and QPF*

Fig. 7 shows the result of MOVA with the first-level (domain wide) tracking supplemented with FFT analyzed displacement vectors as discussed in section 3.2(b). Comparing to the TREC motion vectors, the most prominent difference is the “uniformity” of the MOVA field due to the enforcement of smoothness constraint. Due to this reason, the erroneous tracking due to the interference spike echoes was avoided naturally. The important point here is that the smaller scale motions, namely the convergence of storm cell “A” and “B”, was lost. Further tuning of the smoothness constraint is required for MOVA to reveal the smaller scale features.

In terms of motion speed, MOVA tracked cell “A” to be travelling at about 55 km/h. Comparing to TREC’s estimate of about 40 km/h and the observed speed of 50 km/h, MOVA in this case provides a better speed for the storm cell as a whole.

Fig. 8 shows the 150-minute forecast reflectivity based on the MOVA motion vector fields at 1139 UTC. The main body of the echo associated with storm cell “A” had already moved offshore while that associated with storm cell “B” still lying along the coast. This compared well with the actual radar observations given in Fig. 3, suggesting that MOVA was indeed capable of capturing the large scale storm motion.

Obtained by applying the same Semi-Lagrangian advection technique, the 3-hour accumulated QPF based on the MOVA storm motion vector at 1139 UTC is given in Fig. 9. The pattern in general was very similar to that based on TREC motion vector (Fig. 6) though with a higher motion vector speed, the affected area was larger and closer to Kolkata.

4.6. *Discussion on the Kolkata case*

Although SWIRLS radar tracking modules were successfully implemented in IMD, the current study revealed two major issues: one is the importance of quality controlling the data before ingestion to SWIRLS; the other is the need for rapidly updated radar data.

As discussed in section 4.4, erroneous motion vectors could be introduced due to spurious data. Although such spurious data usually occurs over rain free

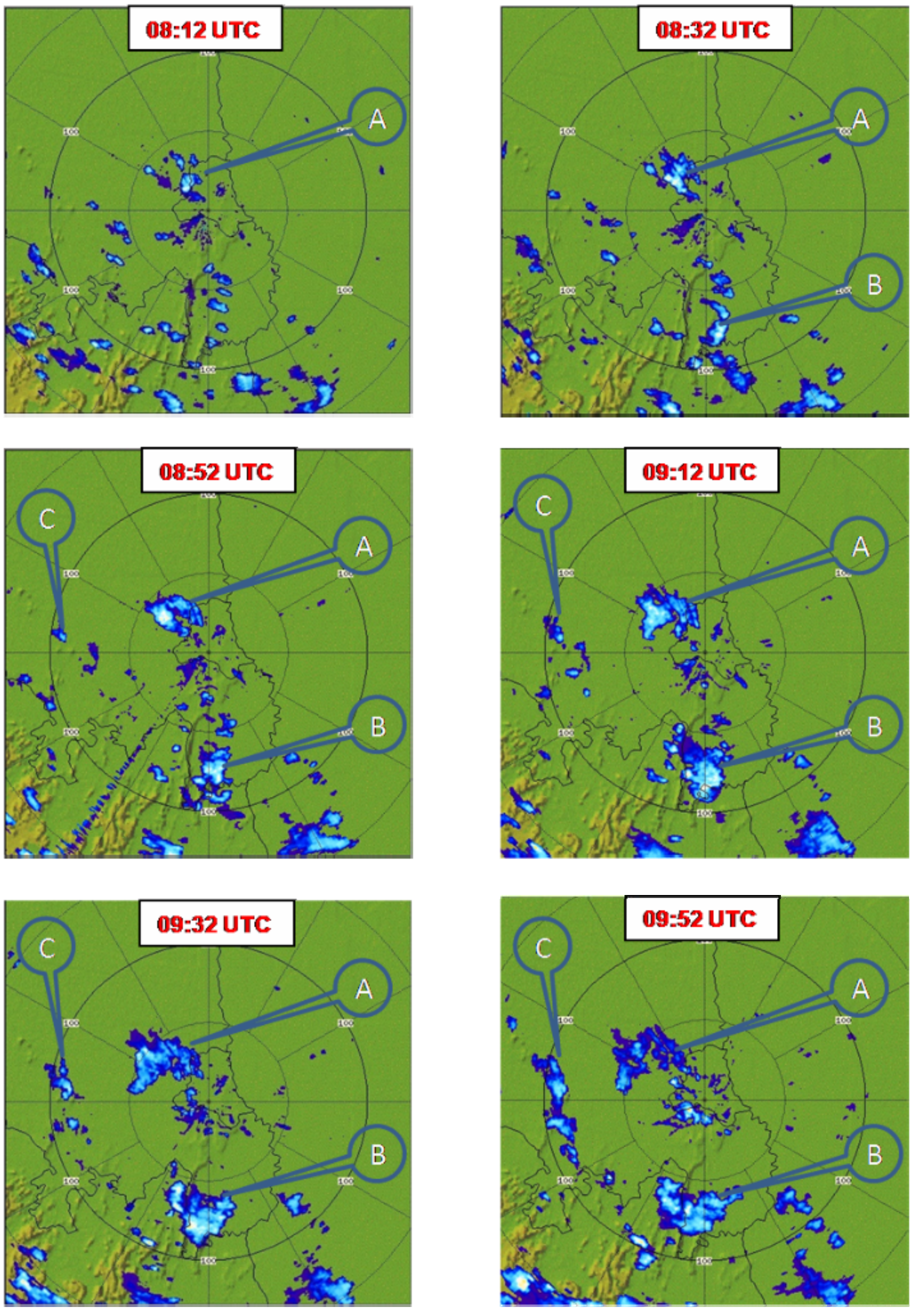


Fig. 11. Radar reflectivity ("MAX" product) as observed by DWR New Delhi on 15 August 2010

areas, the distorted motion vectors could still impact the QPF of SWIRLS, especially at long time integration, due to its use of backward semi-Lagrangian advection scheme [Staniforth & Cote 1991].

The lengthening of the time interval between successive CAPPI scans from 6 to 15 minutes posed an even greater challenge to the two tracking algorithms. With the much longer time interval, the shape and intensity of the radar echoes could have changed significantly, making it more difficult to track the echoes whether by maximizing the cross-correlation or minimizing the difference between successive CAPPI scans. Moreover for TREC, with the increase in the time interval between successive CAPPI scans, the search radius has to be increased. With a much larger search area,

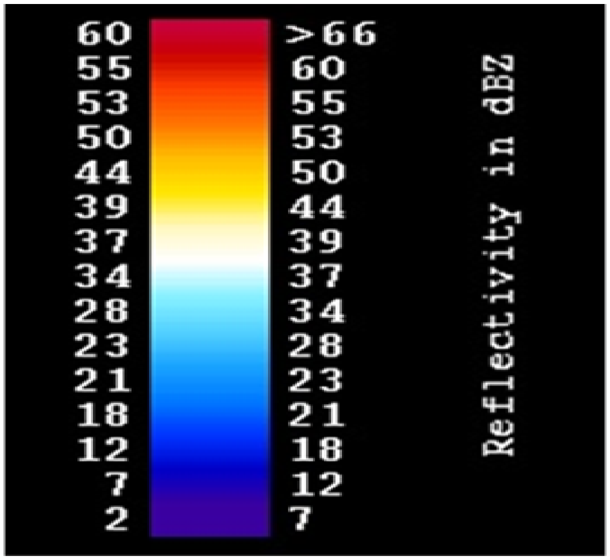


Fig. 12. Scale bar corresponding to images in Fig. 11

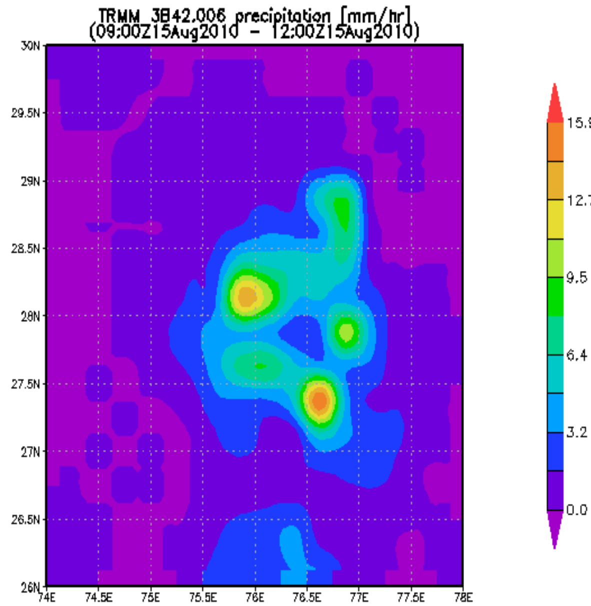


Fig. 13. Observed 3-hour precipitation between (0900 UTC – 1200 UTC) over New Delhi and neighborhood area on 15 August 2010

apart from much increased processing time, there is higher chance that a wrong echo be picked up to be correlated with the echo concerned, leading to wrong storm motion vectors. For MOVA, the issue due to the lengthening of time interval is even more serious as it undermines the fundamental assumption of optical flow: the displacement between successive images is small. Although the use of FFT to supplement the top level (full domain) optical flow was able to reasonably capture the large scale speed, as discussed in section 4.5, the MOVA motion vector field is very uniform. The feasibility to apply MOVA to other levels under these settings needs to be evaluated. Further testing and tuning of MOVA algorithm is required before deployment. Having said that, the 150-minute forecast reflectivity compared reasonably well with the actual radar observation, suggesting that MOVA in general was capable of tracking the large scale storm motion.

5. Case study of New Delhi thunderstorm event

5.1. *Synoptic observation*

Another case selected for this study is the thunderstorm event of 15 August 2010 over Delhi and West Uttar Pradesh. On 15 August 2010 the axis of monsoon trough passes through Anupgarh, Pilani, Mathura, Kanpur, Varanasi, Hazaribagh, Digha and thence southeastwards it east-central Bay of Bengal. It is important to note that in Figs. 10(a-c) streamline analysis has been done at 850 hPa, 500 hPa and 200 hPa. There was upper air cyclonic circulation in lower levels over northwest Rajasthan and neighborhood [seen as cyclonic flow in Fig. 10 (a)]. These led to significant moisture incursion at low level over the area from Arabian Sea [Fig.10 (a)]. Another cyclonic circulation lies over Orissa and adjoining Chhattisgarh extending up to mid-tropospheric levels [Fig. 10 (b)]. At 200-300 hPa, the position of ridge line is around 32 degree North, this resulting in upper-level divergence over the region covering New Delhi [Fig. 10(c)].

5.2. *Radar observation*

On 15 August 2010 New Delhi DWR observed that many small mesoscale cells started developing at 0812 UTC in and around Delhi. There were three main cells [labeled “A”, “B”, “C” in Fig. 11] in the region.

Cell “A” started developing at 0812 UTC at north-west boundary of Delhi. It intensified and broadened horizontally till 0852 UTC. During this period this cell “A” moved slightly north-west ward. After that cell started weakening and moved west north-west ward and dissipated around 0952 UTC.

Cell “B” started developing around 0832 UTC over a location approximately 75 km south of Delhi. Its intensification as well as horizontal broadening continued till 0932 UTC. During this period this cell “B” moved slightly west ward (*i.e.*, remains practically stationary). After that the cell weakened significantly.

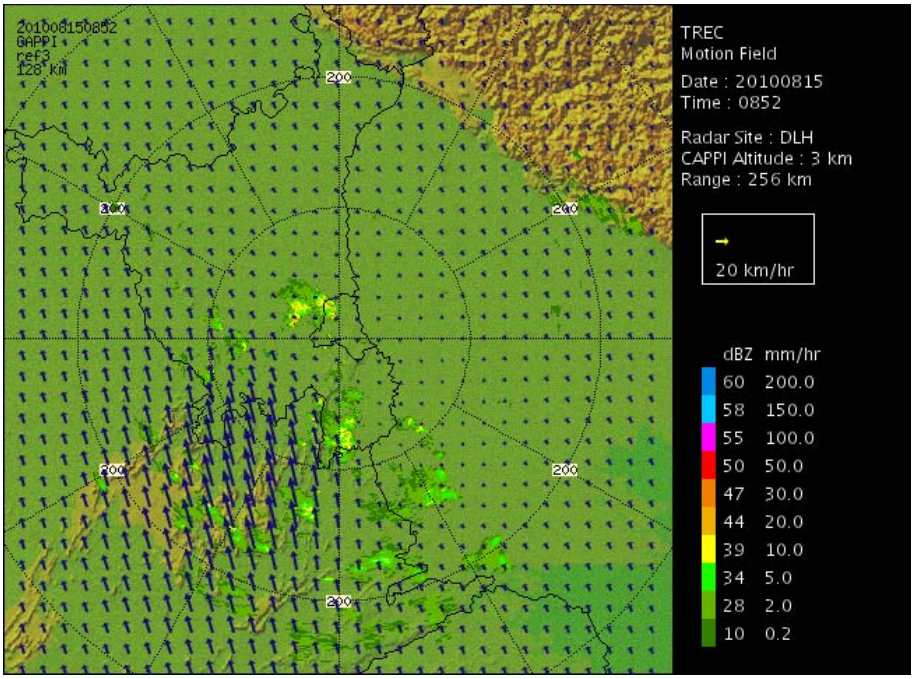


Fig. 14. SWIRLS TREC motion vector fields at 0852 UTC on 15 August 2010

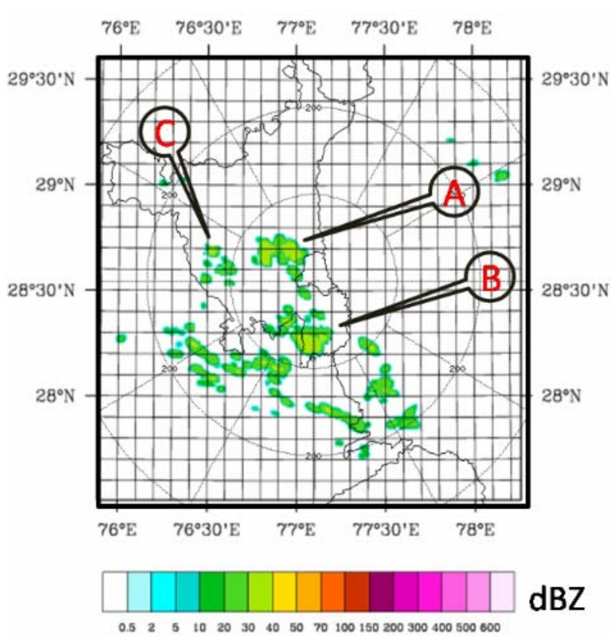


Fig. 15. Forecast reflectivity valid for 0952 UTC derived from TREC motion vector fields at 0852 UTC on 15 August 2010

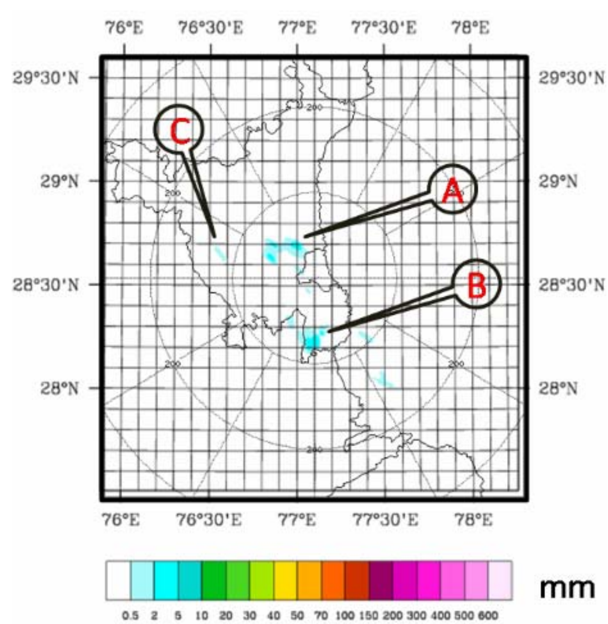


Fig. 16. SWIRLS 1-hour QPF valid for 0952 UTC derived from TREC motion vector fields at 0852 UTC on 15 August 2010

Cell "C", located approximately 95 km west of Delhi, started developing since around 0852 UTC. It intensified and evolved into a north-south oriented rain band in the subsequent one hour and forty minutes. There was not much translational motion.

Corresponding radar images (Maximum Reflectivity) are shown in Fig. 11 and scale bar corresponding to these images is given in Fig. 12.

5.3. *Observed rainfall*

The 3-hour accumulated rainfall between (0900 UTC - 1200 UTC) on 15 August 2010 due to the thunderstorm as observed by TRMM satellite is shown in the Fig. 13.

5.4. *SWIRLS TREC motion vector and QPF*

Fig. 14 shows the TREC motion vector at 0852 UTC. The slow west north-west ward motion of the storm cells at northwest boundary of Delhi (labeled "A" in Fig. 11) was well captured by TREC. The speed of motion, around 5-10 km/hr, also agreed reasonably well with the actual observation (about 10 km/hr). TREC depicted the north-west motion of the Cell "B" (labeled "B" in Fig. 11). The observation shows the cell "B" moved slightly west ward.

While the storm motion vector field depicted in Fig. 14 looks generally reasonable, similar to Kolkata case, a region of erroneous storm motion vectors was observed near the spike to the southwest. This is due to erroneous linear echo appeared southwest of Delhi at 0852 UTC (Fig. 11). This shows the importance of quality controlling the raw radar data before ingesting into SWIRLS system.

Fig. 15 shows the 60-minute forecast reflectivity based on the TREC motion vector fields at 0852 UTC. The echo associated with storm cell "A" had moved slightly west north-west ward of Delhi, echo associated with storm cell "B" has also moved and while that with "C" is at the same place. This compared well with the actual radar observations given in Fig. 11, suggesting that TREC was capable of capturing the small scale storm motion. Simultaneously it is able to depict echo corresponding to very small cells.

The 1-hour accumulated QPF from 0852 UTC, obtained by applying the Semi-Lagrangian advection technique using the TREC storm motion vector obtained above, is given in Fig. 16. The 1-hour accumulated QPF was forecast to be between 5-10 mm for the three cells A, B and C. However it was not producing significant precipitation associated with all the small meso cells. This may be due to the reason that TREC is moving the echoes too quickly.

5.5. *SWIRLS MOVA motion vector and QPF*

Fig. 17 shows the result of MOVA vectors as discussed in section 3.2(b). Similar to Kolkata case on comparing to the TREC motion vectors, the most prominent difference is the "uniformity" of the MOVA field due to the enforcement of smoothness constraint. As in Kolkata case, erroneous tracking due the sudden appearance of the interference line was avoided. All cells are showing uniform motion.

In terms of motion speed, MOVA tracked cell "A", "B" and "C" to be travelling at about 5-15 km/h, MOVA in this case provides a better speed for the storm cell as a whole.

Fig. 18 shows the 60-minute forecast reflectivity based on the MOVA motion vector fields at 0852 UTC. Similar to TREC forecast, movement of the echo associated with storm cell "A", "B" and "C" compared well with the actual radar observations. While echo corresponding to cell in the south-west of Delhi has moved more north-west ward using TREC motion vector fields as compared to MOVA motion vector fields. This may be due to strong north-west ward motion in south west of Delhi, as seen in TREC motion vector fields (Fig. 14).

The 1-hour accumulated QPF from 0852 UTC, obtained by applying the Semi-Lagrangian advection technique using the MOVA storm motion vector obtained above, is given in Fig. 19. The 1-hour accumulated QPF is forecast in between 5-10 mm for the three cells A, B and C. Note that in this case it is able to produce precipitation associated with all the small meso cells while TREC vector has produced precipitation corresponding to three main cells only.

5.6. *Discussion of results (New Delhi Case)*

Similar to Kolkata case, SWIRLS radar tracking modules for Delhi were also successfully implemented.

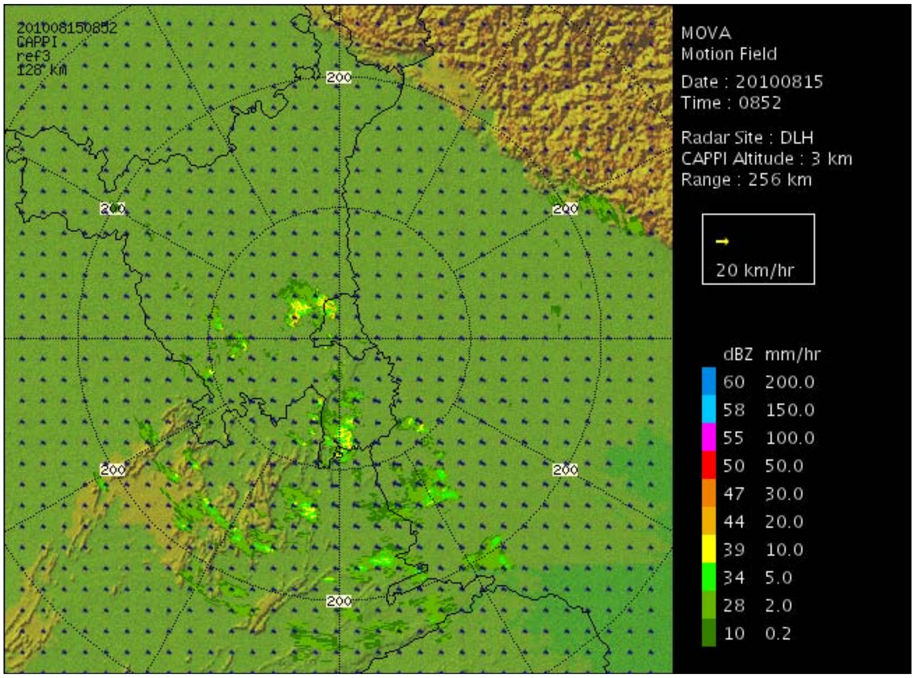


Fig. 17. SWIRLS MOVA motion vector fields at 0852 UTC on 15 August 2010

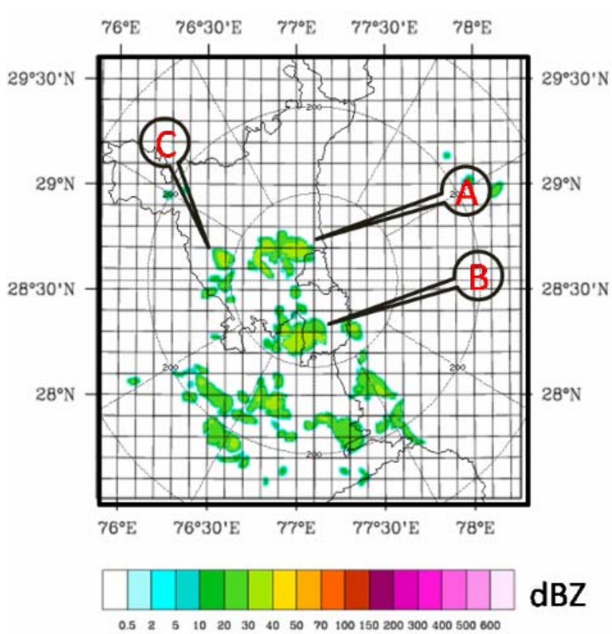


Fig. 18. Forecast reflectivity valid for 0952 UTC derived from MOVA motion vector fields at 0852 UTC on 15 August 2010

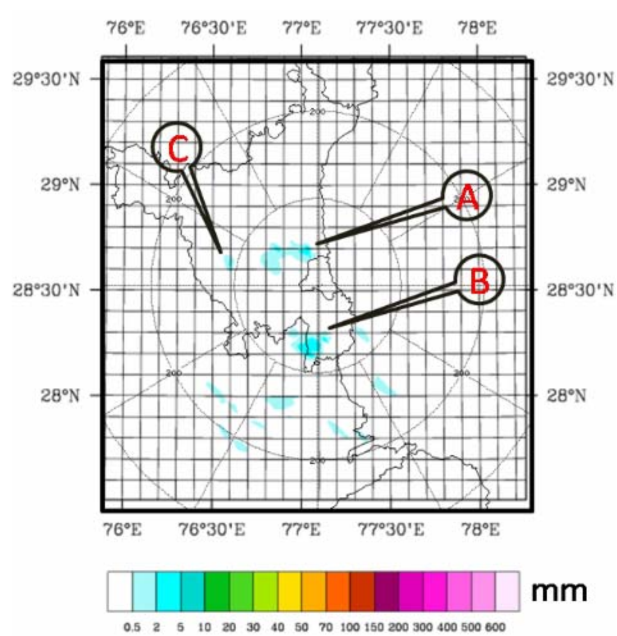


Fig. 19. SWIRLS 1-hour QPF valid for 0952 UTC derived from MOVA motion vector fields at 0852 UTC on 15 August 2010

As discussed in section 3.1 for Delhi case Radar data is updated at 10 minute interval while this software is most suitable for 6 min interval.

For real time implementation of SWIRLS for Delhi, DWR data available at 10 minute interval is preprocessed in real time in IRIS format. After that the data is transmitted to SYNERGY system from DWR server at IMD, New Delhi. Finally SYNERGY system sends the data to SWIRLS nowcasting server for real time nowcasting. SWIRLS nowcasting system takes around two minutes for processing and website updating. Whole process takes approximately 15 minutes. This cycle runs at every 10 minutes interval round the clock. Real time run of SWIRLS started before common wealth Games-2010. Real time products are available on IMD website.

Both TREC and MOVA based QPF and Reflectivity forecast are capable of tracking small scale storm motion. But MOVA technique is able to predict QPF and Reflectivity forecast corresponding to all the cells. While using TREC technique, QPF corresponding to bigger cell are captured. But the QPF corresponding to smaller cell are not captured because TREC moved smaller cells quickly. In case of storm motion vector MOVA technique cells are showing uniform motion. This is due to the enforcement of smoothness constraint due to which echoes of the fast moving small meso were avoided naturally. However more cases need to be studied.

6. Conclusions

The main objective of this study was to ingest the Indian DWR into SWIRLS nowcasting system for nowcasting of severe convective events over the Indian region. This task has been successfully accomplished. Preliminary result suggests that SWIRLS has the potential to be useful for providing nowcast guidance in India.

The other objective was to operationalize and real time nowcasting during commonwealth games 2010.The system has been successfully operationalize before commonwealth games. Real time products are available on IMD website.

QPF and Reflectivity forecast based on MOVA in general are capable of tracking both the large and small scale storm motion reasonably well. While in case of storm motion vector MOVA technique cells are showing uniform motion. This is due to the enforcement of smoothness constraint due to which echoes of the fast moving small meso ware avoided naturally.

Future work includes further tuning and testing of the TREC and MOVA algorithms; tuning of the smoothness constraint; tuning of the Marshall-Palmer relationship using DWR and rain gauge data in India. Finally is the compilation of verification statistics.

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