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Evolution of radar meteorology in India and the latest trends

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सार – उष्णकटिबंधीय चक्रवातों और तूफानों सहित चरम घटनाओं की निरंतर निगरानी और चेतावनी में मौसम रडार एक अनिवार्य उपकरण है। भारत मौसम विज्ञान विभाग (IMD) 1949 से रडार का संचालन कर रहा है। भारत में रडार मौसम विज्ञान के विकास को तीन व्यापक चरणों में विभाजित किया जा सकता है, अर्थात् 1950 के दशक (चरण-I), फिर वर्ष 2000 तक (चरण-II) , और उसके बाद (चरण-III)। चरण-I के दौरान, विमान संचालन में सहायता के लिए राडार आयात किए गए और शहरों में स्थापित किए गए। देश के विभिन्न हिस्सों और मौसमों में अवक्षेपित बादलों के अस्थायी विकास और स्थानिक सीमा की व्यापक समझ प्रदान करने के लिए रडार स्कोप की तस्वीरों का विश्लेषण किया गया। चरण- II के दौरान, अधिक शक्ति और रेंज वाले तूफान चेतावनी (एक्स-बैंड) और चक्रवात चेतावनी (एस-बैंड) रडार स्थापित किए गए थे, और उनमें से कुछ स्वदेशी थे। चरण-III ने भारत में डिजिटल डॉपलर मौसम रडार के युग की शुरुआत की। चरण-III में संख्यात्मक मॉडल और राडार के बीच इंटरफेसिंग शुरू हुई जिसमें राडार हवाओं को आत्मसात करना और मॉडल सत्यापन शामिल है। आईएमडी के बाहर मौसम राडार की स्थापना और संचालन भी चरण-III में शुरू हुआ। महत्वपूर्ण क्षेत्र जहां अधिक काम करने की आवश्यकता है, उनमें रडार मौसम विज्ञान, रडार अंशांकन और डेटा मानकीकरण, रडार क्षेत्र कवरेज और नेटवर्किंग, पोलारिमेट्रिक उत्पादों का उपयोग करके मात्रात्मक वर्षा अनुमान के लिए एल्गोरिदम, संख्यात्मक मॉडल में रडार उत्पादों को आत्मसात करना, अनुसंधान में एक अच्छी तरह से प्रशिक्षित कार्यबल शामिल है। क्लाउड भौतिकी और गतिशीलता, तूफान और गंभीर मौसम में एआई/एमएल के अनुप्रयोग।

ABSTRACT. Weather radar is an indispensable tool in the continuous monitoring and warning of extreme events including tropical cyclones and thunderstorms. The India Meteorological Department (IMD) has been operating radars since 1949. The evolution of radar meteorology in India may be divided into three broad phases, namely, the 1950s (phase-I), then up to the year 2000 (phase-II), and thereafter (phase-III). During phase-I, radars were imported and installed in cities to aid aircraft operations. Photographs of radar scopes were analysed to provide a broad understanding of temporal evolution and spatial extent of precipitating clouds in different parts of the country and seasons. During phase-II, storm warning (X-band) and cyclone warning (S-band) radars with more power and range were installed, and some of them were indigenous. Phase-III ushered in the era of digital Doppler weather radars in India. Interfacing between numerical models and radars started in phase-III including assimilation of radar winds and model verification. Installation and operation of weather radars outside IMD also started in phase-III. Important areas where more work needs to be done include a well-trained workforce in radar meteorology, radar calibration and data standardization, radar area coverage and networking, algorithms for quantitative precipitation estimation using polarimetric products, assimilation of radar products in numerical models, research on cloud physics and dynamics, applications of AI/ML in storm and severe weather nowcasting.

Key words – Weather radar, Precipitation, Convection.

1. Introduction

Guglielmo Marconi, the inventor of radio, showed in 1899 that ships could be detected even under dense fog using radio waves. In the following four decades, efforts were made in the USA, Europe, and Japan to use the method to remotely detect and locate enemy aircraft (and preferably destroy it as well). A group led by Sir Robert Watson-Watt in the UK argued (in 1935) that the power needed to destroy an aircraft is too high (so an impractical task), however, pulsed radio waves can be used to detect an aircraft-sized object and determine its position miles ahead (online materials). A working radar based on radio waves (hence the name RAdio Detection and Ranging for radar) was in place in the UK by 1939; however, the details were kept a top secret because it was wartime. The accuracy of this instrument was not that great, and the size was too bulky. A compact "Cavity Magnetron" that was developed around this time in the UK and the design shared with the USA and Canada, could produce high power at microwave wavelengths, considerably reducing the size and weight of a radar. Now, it is history that magnetron-based radars played a vital role in deciding the outcome of World War-II in Europe.

1.1. *Global scenario*

In the radars of the 1940s, returned signals were displayed on scopes [plan position indicator (PPI) and range height indicator (RHI)] and photographed for further analysis. A grid in the radar scope was illuminated white if the returned signal was above the noise level, otherwise, it remained dark. Scales in the radar scopes enabled reading the position of the detected object on the radar. The earliest community with access to radar images were scientists (meteorologists) working for military projects and personnel. They observed that precipitating clouds produced detectable signals/echoes in magnetron-based radars and were a major nuisance in aircraft detection. Soon it dawned upon that radar echoes are helpful to infer precipitation structure hidden inside clouds and radar became a new powerful tool in identifying and tracking thunderstorms that threatened aircraft operations (Maynard 1945). Thus, weather radar is an unintended product of military research.

Parallel independent developments in the theory of scattering of microwave radiation by liquid drops and ice particles (Ryde 1941) showed that the returned power depended on the total number of scattering particles in the measuring volume and the 6th power of particle diameter. Some defence radars were passed on to Universities for further research in the mid-1940s. For example, MIT(Massachusetts Institute of Technology) got two radars, namely a 10 cm (SCR-615-B) and a 3 cm (AN/TPS-10A) (Bemis 1947). [Here, cm refers to the wavelength (in cm) of radiation transmitted by the radar, and radar type is often identified by its wavelength.] This decade also saw the radar equation and the nature of the relation between radar reflectivity factor (Z) and rain rate (R) (Marshall et al. 1947), known as the Z-R relation and expressed in the form,

$$Z = aR^b \qquad (1)$$

where a and b are some constants.

A major field campaign on thunderstorms, namely, *The Thunderstorm Project* (Byers and Braham 1949), carried out during 1946-47 in the USA, extensively employed radars. Radars enabled the unravelling of the three-dimensional structure of thunderstorms. Thus, we may conclude that the field" of "Radar Meteorology", which deals with the application of radar to observe weather phenomena, was born in the 1940s. At that time, the radar product available was Z. Radar became not only an operational tool, but it had the potential to provide rich information on cloud microphysics and dynamics over a spatial scale that bridged the gap between the synoptic and the local scales, *i.e.*, mesoscale. Since the beginning of the Thunderstorm Project, radars have significantly advanced our understanding of convective systems, including severe storms.

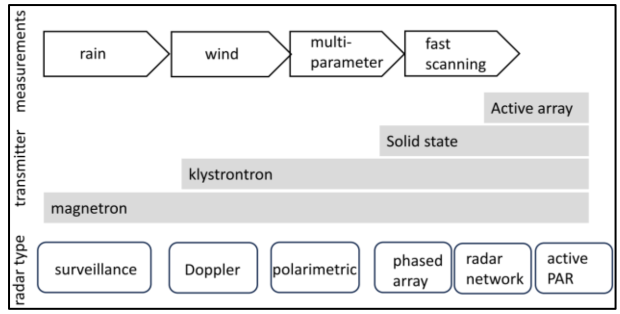

Fig. 1. Evolution of radar technology & products(*Courtesy*: Dusan Zrnic)

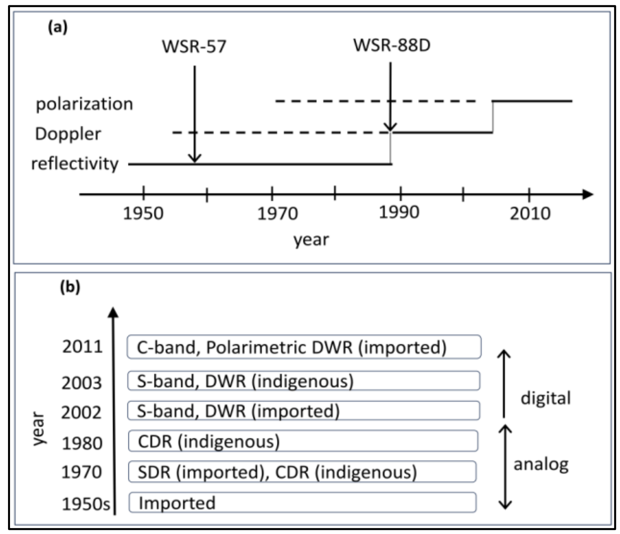

Fig. 2. (a). A schematic of the history of deployment of different types of weather radars in the US Weather Service. X-axis shows time. Dashed line indicates the time span during which the concept to product development and field trials of the technology took place. Start of the solid line its induction into the Weather Service's operational network and the corresponding radar models are shown at the top (Courtesy: Dusan Zrnic). (b) Major milestones in the deployment of radars in IMD. SDR – storm detection radar (X-band); CDR – cyclone detection radar (S-band); DWR – Doppler weather radar.

With time, radars evolved as technology advanced (Fig. 1). It takes time to go from a successful research idea to a regular operational mode. For example, progress in adapting radar technology from concept to operational use in the US Weather Service is shown in Fig. 2a. The first major advancement is the incorporation of the Doppler velocity feature that could provide the radial component of velocity and turbulence in the measuring volume. The next breakthrough is the polarimetric capability to detect and characterize the target (Bringi and Chandrasekar 2001). Important polarimetric variables include differential reflectivity (Z_{DR}), copolar correlation coefficient (ρ_{hv}) and differential propagation phase (ϕ_{DP}). Each dual-polarization variable has specific properties/characteristics about different weather or nonweather radar echoes and together with Z, they reveal the microphysical properties of clouds and precipitation. Z_{DR} measures the reflectivity-weighted shape of the scatterers and tends to increase for more oblate scatterers (within the Rayleigh regime). ρ_{hv} represents the similarity between the horizontal and vertical polarization signals, and it is reduced when there is increased randomness and diversity between the horizontally and vertically polarized backscattered waves, especially for non-Rayleigh scattering. Φ_{DP} is the difference in phase shift between horizontally and vertically polarized waves, including the differential scattering phase (δ). ϕ_{DP} increases rapidly for heavy rain because the horizontally polarized wave propagates slower than the vertically polarized wave, as its polarization is in the direction of the larger dimension of oblate particles.

2. Indian scenario

The radar meteorology scenario in India followed the developments in the USA, Europe, and elsewhere, but with a time lag (Fig. 2b). The India Meteorological Department (IMD) has been operating radars since 1949. The first set of radars, having a wavelength of 150 cm and 90 kW power, were installed in New Delhi, Poona, Madras and Calcutta (Mausam Editorial) for wind profiling using tracking of balloons. For the first time, upper-level winds could be measured under monsoonal cloudy conditions, which was not possible with theodolite-based pilot-balloon observation (Venkiteshwaran and Yegnanarayana 1951). Observations taken at Poona showed the existence of a low-level jet around 2 km and an upper-level jet around 12 km (both asl), mainly during July (Venkiteshwaran and Yegnanarayana 1951). While the exact chronology of the installations of precipitation measuring radars in IMD is not available, editorial and papers published in the *Mausam* journal reveal that the first installation was in New Delhi in 1950-51 with the addition of a 3 cm (model AN/APQ-13) and a 10 cm (model SCR-717C) radars (Mull et al. 1962). The next one was in IMD Pune where a SCR-717C radar with 40 kW peak power and 1.25 ms pulse duration was set up on a truck (Fig. 3, Gupta *et al*., 1955). Then, the activity spread to other cities with airports, *e.g*., Kolkata, Mumbai, Chennai, Guwahati, Nagpur, *etc*. We believe their primary purpose was aiding aircraft operations near the airports.

We may divide the developments in weather radar activity in India into three broad phases, namely, the 1950s, then up to the year 2000, and thereafter. During the early phase, radars were imported, primarily installed in cities with airports aiding aircraft operations & were operated by IMD. During the second phase, cyclone warning radars with more power & range were installed along the coasts & some radars were made in India as well. They continued to be analog type and data remained mainly with IMD. In the third phase, starting in the early 2000s, four M/s Gamatronic GmbH made Doppler weather radars (DWRs) were installed along the East coast of India (Chennai, Kolkata, Machlipatnam and Vishakhapatnam). These were digital radars, data could be archived as well as transmitted for further usage. Digitization and archival of DWR data enabled IMD to share its data. Access to and use of weather radar data by other organizations and academic institutes/universities commenced in the third phase. For the Commonwealth Games 2010, IMD got two C-band polarimetric radars (Vaisala make) installed in New Delhi and Jaipur. DWR coverage over India got further boosted with several Chinese M/s Beijing Metstar Radars installed starting in 2010. The third phase also saw the installation and operation of weather radars outside IMD. For example, IITM (Indian Institute of Tropical Meteorology) Pune got polarimetric X-band and K_a-band radars for cloud physics research in the year 2012 installed in Mandradev near Mahabaleshwar in Maharastra. Subsequently, IITM also got two polarimetric C-band polarimetric Doppler radars, one at Sholapur (for the CAIPEEX program, Prabhakaran *et al*., 2023) and another at the Atmospheric Research Testbed at Silkheda near Bhopal. The Aerostat observing system, a defence weather monitoring system, has Rockwell Collins DWRs (Arora and Srivastava, 2010). Further, its DWR observations and MM5 modelling were used to understand the structure and short-term forecasting of convective systems (Arora and Srivastava, 2010). The third phase also saw the development of indigenous DWR (S, C, and X-band) led by the Radar Development group in ISRO, whose first S-band radar was installed at SHAR, Sriharikota in 2003. An indigenous polarimetric X-band DWR was installed at NARL in Gadanki.

In addition to conventional weather radars, India has indigenously developed other radars for atmospheric observations, *e.g*., MST (mesosphere, stratosphere and troposphere) radar (at National Atmospheric Research Laboratory, Gadanki) and three ST (stratosphere and troposphere) radars (at Cochin University of Science and Technology, Cochin, ARIES Nainital and University of Calcutta, Haringhata field station) which are capable of measuring three-dimensional wind field around the respective location. An important feature of these radars is that they can continuously measure 3-D vertical profile. velocity under clear sky and convective conditions, much needed to understand atmospheric dynamical processes (*e.g*., Rao *et al*., 2001; Mohankumar *et al*., 2017).

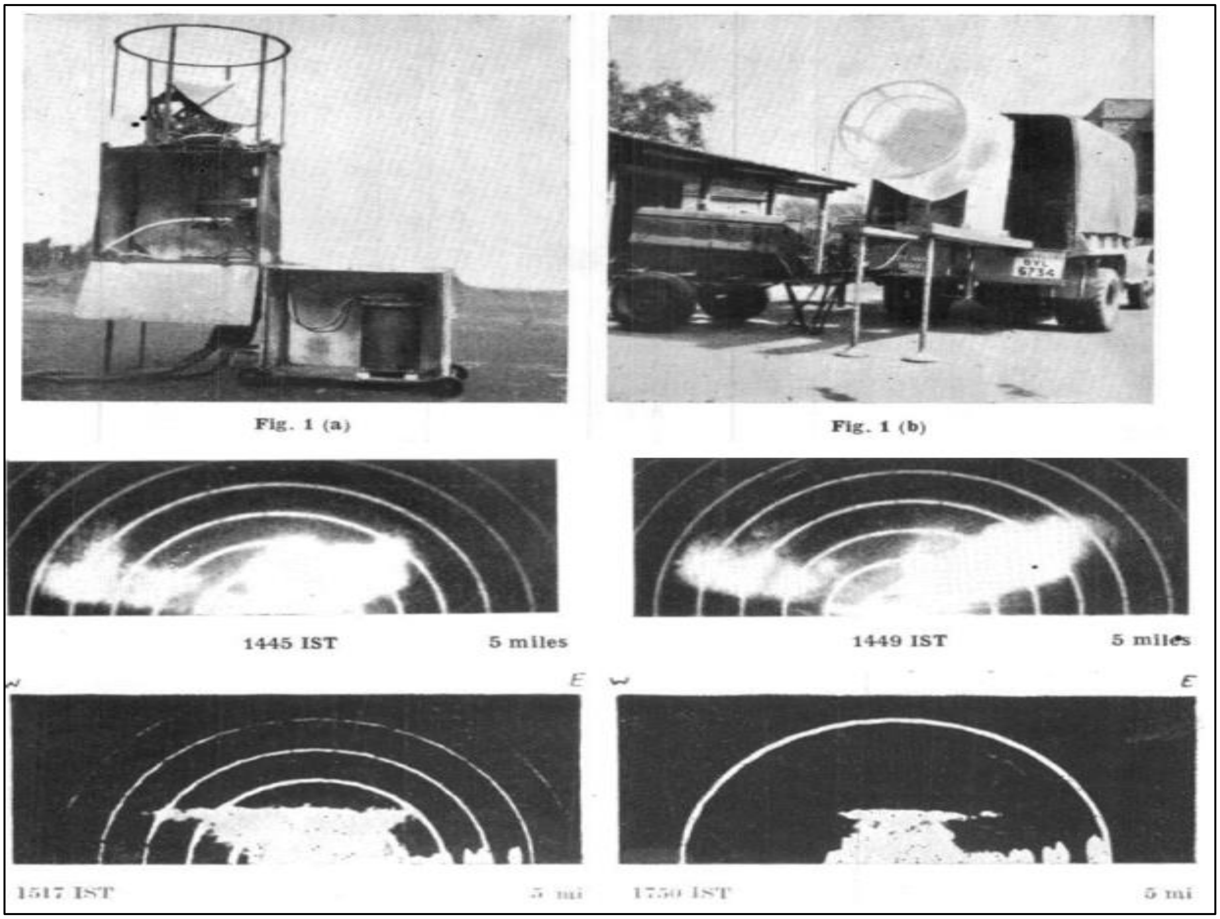

Fig. 3. Top panels: SCR-717C radar at Pune on a mobile platform. Mid panel: PPI images of a thunderstorm observed on 18 Sep 1953. Bottom panel: RHI display of the bright band of a thunderstorm observed on 07 Sep 1953. (Gupta *et al*. 1955).

3. Research

There is a close relation between radar capabilities and the kind of research carried out with the data. Precipitating clouds appeared as a white patch against the radarscope's dark background (Fig. 3), display photographs were taken for record-keeping; however, returned power intensity was unavailable. IMD Scientists who had access to the radar display photographs researched precipitating clouds. From the PPI and RHI displays (Fig. 3), the spatial and vertical extents of clouds (precipitation) and their evolution with time could be inferred. De and Rakshit (1961) measured the heights of isolated cumulus and Cb clouds, duration of precipitation, the time interval between the first formation of radar echo and precipitation reaching the ground, maximum echo top height, *etc*., at Calcutta. During the monsoon period, the first echo appeared in the height range below the freezing level, *i.e*., by warm rain processes. They also noted that radar-measured cloud top height was about 3000 feet less than that inferred from the theodolite (*i.e*., visual). The dominance of warm rain during the monsoon season was also observed at Poona (Gupta *et al*., 1955). Kulshreshtha (1962) reported the seasonal variation of Cb cloud tops around Delhi from December 1957 to June 1960. About 9% of Cb clouds extended beyond 50000 feet; in 63% of cases, tops were below 40000 ft. Another property studied was the rate of ascent and descent of echoes. For example, the echo ascent rate varied from 2 to 22 m/s, and the decent rate varied from 4 to 14 m/s at Poona (Mani and Venkiteswaran, 1961). Based on the nature of radar echo structure and the season, Mull *et al*. (1963) classified the thunderstorms around New Delhi into three types: cold front, air mass and Nor'wester.

Monsoonal clouds forming in the neighborhood of the west coast were also investigated. Narayanan (1967) reported that radar echoes of rain squalls over Mumbai were typically 6-8 km in height. Narayanan (1970) observed that radar echoes approaching Trivandrum from the Arabian Sea side were 60-120 km long and 10-20 km wide about 100 km off the coast and broke up into individual cells after moving inland. Two to three bands about 100 km long were generally noticed simultaneously with a spacing of 15 km. Echoes moved at 30-40 kmph.

These early studies brought out the nature of precipitating clouds in different parts of India during the monsoon and other seasons, documenting their differences and some arguments about the underlying cloud microphysical processes.

Cyclone warning radars were installed at some coastal stations in India in 1970, facilitating inferring the position, movement, intensity and structure of storms over the Bay of Bengal (*e.g*., Raghavan *et al*. 1980). The first cyclonic system tracked with a DWR is the 12th November 2002 cyclonic storm in the Bay of Bengal that moved within the range of the DWR at Kolkata (Banerjee *et al*. 2004). The cyclone track, intensity, and wind structures were monitored over the Bay to landfall. As in other countries, severe weather early warning is a primary operational use of DWR in India (Ray *et al*., 2015). IMD has developed an automated early warning system, the R-ALERT system that analyses DWR data and automatically sends messages to disaster managers when a potentially hazardous event is detected (Bibraj *et al*., 2021).

Polarimetric DWR provided information on the intensity, vertical variation in the type of hydrometeors, their spatio-temporal changes, vertical extent, *etc*., for storms over the New Delhi region (Singh *et al*., 2021). It is reported that max Z exceeded 55 dBZ, reaching as high as 60 dBZ. Singh *et al*., (2021) also reported the spatial distribution of polarimetric variables for three storms in the summer of 2018. One crucial missing parameter in these studies is the spatial distribution of radar-derived precipitation and its comparison with ground observations on these occasions.

3.1. *Quantitative precipitation estimation (QPE)*

Measuring rainfall over an area is an important problem in meteorology. Instantaneous R (rain rate) varies spatially and temporally and obtaining a spatial rainfall map is challenging. Weather radars can provide information on areal R, which, when integrated over a time interval, gives rainfall amounts. Following Marshall et al. (1947), R (mm h^{-1}) is derived from Z (mm^6 m^{-3}) from Eqn. (1). Values of a and b depend on the nature of the hydrometeors in the sampling volume, and change with time even within a rain spell (Atlas *et al.,* 1999; Bringi *et al.,* 2003). Das *et al.* (2017) investigated the characteristics of drop size distribution (DSD). They estimated Z-R relationships for different cloud types at the High Altitude Cloud Physics Laboratory (HACPL) at Mahabaleshwar using disdrometer and micro-rain radar measurements. For HACPL, they classified the precipitation types into four categories, namely, shallow-convective, convective, stratiform, and mixed convective-stratiform and the corresponding relations are $Z=144R^{1.31}$, $Z=96R^{1.61}$, $Z=272R^{1.26}$ and $Z=218R^{1.36}$, respectively.

Despite many studies addressing appropriate Z-R relations for different types of precipitation, geographic location, climate conditions, etc., consensus on appropriate Z-R relations is missing. The use of polarimetric variables improves QPE (Bringi *et al*. 2001). Using the data collected with the polarimetric DWR at New Delhi, Sindhu and Bhat (2019) showed that it is not the vertical extent of a storm but its area-time integral that correlates better with the total precipitation amount. Around the New Delhi area, daily accumulated precipitation derived from relations incorporating polarimetric variables is in better agreement with the rain gauge measurements than that obtained solely from Z-R relations which underestimated precipitation.

3.2. *Precipitating cloud systems*

Mukhopadhyay *et al*. (2009) used Kolkata DWR data to study the spatio-temporal evolution of two Nor'westers of 12 March and 22 May 2003 over the West Bengal region. The DWR observations suggested that the systems move at a speed of 20-25 m/s. The DWR estimated precipitation shows a detailed spatial distribution around Kolkata with several localized zones of heavy rain, which was well supported by the observations of nearby stations.

IMD DWR data were provided to the Indian research community for the CTCZ (Continental Tropical Convergence Programme, CTCZ, 2008)) and Indo-UK joint research program INCOMPASS (Turner *et al*., 2019), using which properties of mesoscale convective systems have been carried out (Sindhu and Bhat 2018, Sindhu and Bhat 2021). Sindhu and Bhat (2018) show that a convective area within a mesoscale convective system (MCS) contains intense convective cells or storms that could be made of a single cumulonimbus cloud or several joined together. (In the study, a storm is defined as a set of contiguous radar pixels in three-dimensional space with a reflectivity threshold of 30 dBZ and the threshold criterion is satisfied in a volume of at least 50 km^3.) Depending on geographic location and MCS life stage, monsoonal MCSs contain a few to more than 20 storms. Storms occupy 30-70% of the convective area within an MCS and contribute 90-97% of the convective precipitation at any given instant. Thus, a few to several cumulonimbus clouds grouped in a contiguous manner matter most for convective precipitation, making storm scale an important scale in the hierarchy of scales in tropical deep convective cloud systems. This has implications for cumulus parametrization as well as planning satellite payloads for observing precipitation.

Analyses of data collected with a C-band polarimetric radar at Sholapur of a cloud cluster (CC) during the Indian summer monsoon, which contributed more than 70 mm of rainfall, revealed size sorting of falling raindrops, growth

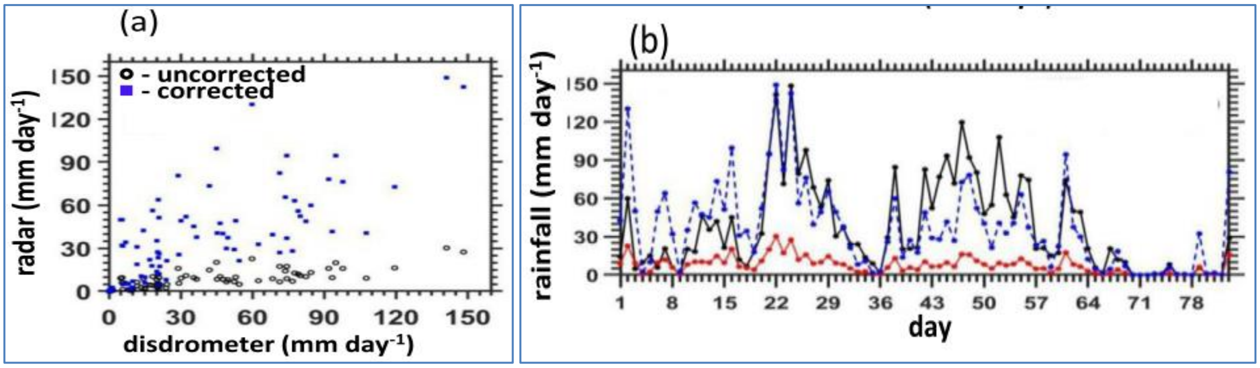

Fig. 4. Daily rainfall derived from disdrometer and estimated from IITM's Mandradev X-band radar using uncorrected and corrected radar reflectivity factors. (a) Scatter plot of JWD versus radar estimated rainfall. (b) Daily rainfall timeseries for 83 days having continuous radar coverage. Line color legend: black – disdrometer; red – uncorrected; blue – corrected. (source: Jha *et al*. 2023).

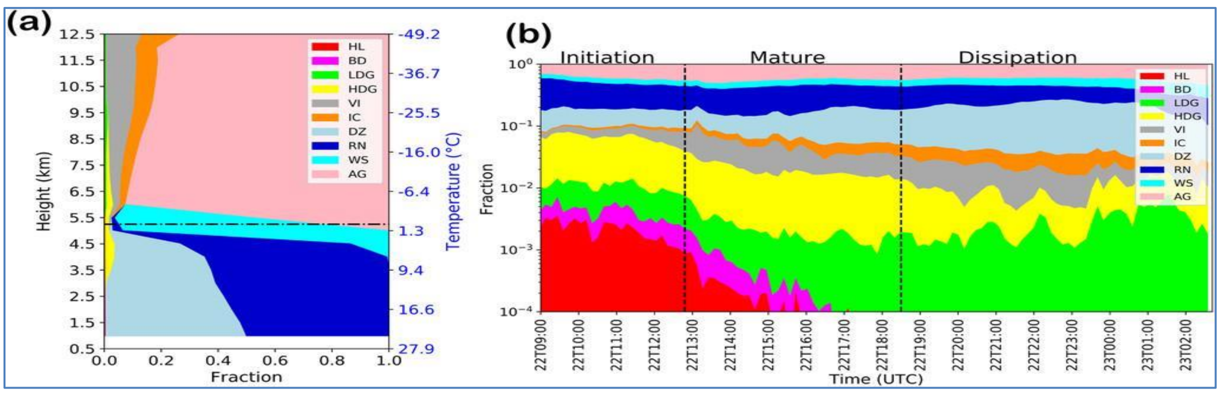

Fig. 5. a) Vertical (dotted line indicates the 0°C isotherm) and (b) temporal distribution of the relative proportion of dominant hydrometeors throughout the lifetime of the CC (between 0900 UTC 22 Jun 2018 and 0244 UTC 23 Jun 2018) as identified by the hydrometeor identification algorithm (Dolan et al. 2013). Vertical dotted lines in (b) separate the different phases of the life cycle of the CC. Hydrometeor types: drizzle (DZ < rain rate < 2.5 mm hr^{-1}), rain (RN; 2.5 mm hr^{-1} < rain rate < 300 mm hr^{-1}), ice crystals (IC), aggregates (AG), wet snow (WS), vertical ice (VI), low-density graupel (LDG; density: 0.25–0.55 g cm^{-3}), high-density graupel (HDG; density: 0.55–0.9 g cm^{-3}), hail (HL), and big drops (BD)/melting hail (>0.5 mm). (source: Samanta *et al*. 2021).

of dendritic particles, riming, aggregation, the occurrence of a saggy bright band, *etc*. (Samanta *et al*. 2021). The formation of big raindrops is observed during the initial convective rain associated with hail melting (Fig. 5). The stratiform counterpart is primarily associated with aggregates, ice crystals, and melting snow, resulting in surface rainfall. Aggregates are found to be the spatially dominant hydrometeor followed by ice crystals. Vertically oriented ice crystals indicate active cloud electrification processes during the spatial aggregation of convective clouds. The dominant microphysical processes and precipitation pathways are illustrated. This study forms a benchmark case for model intercomparisons and evaluations.

3.3. *Radar data assimilation and model verification*

DWR data has applications in modelling: for assimilation to improve model initial conditions and for verifying model prediction. Some mesoscale models have provision to assimilate a DWR wind field. Abhilash *et al*. (2007) assimilated IMD DWR data in the mesoscale model MM5 (version 3.5.6) to study convective events around Chennai and Kolkata. The study shows the positive impact of the assimilation of Doppler radar wind on short-range QPE forecast and a need to assimilate the reflectivity data for further improvements. Chaterjee *et al*. (2015) used DWR data at Kolkata to verify MM5 model predictions of wind squalls. The study shows that the model predicts strong convective cells better than weak ones. Though broad spatial distribution patterns appear similar, spatial and temporal shifts in model-simulated storms compared to the observed are common shortcomings.

3.4. *Radar data fidelity*

A critical component of DWR operation is its calibration since the error in Z propagates to other derived quantities. For example, a 1 dB bias in Z can lead to a 15 % uncertainty in rainfall (Fabry 2015). Radar reflectivity data quality improves when regular radar calibration procedures are followed. We believe that standard operational calibration procedures (*e.g*., Sun calibration, frequency, transmitted power, *etc*.) are being followed in all DWR facilities in India. IITM's X-band band radar at Mandradev, where calibrations were regularly carried out, was investigated as a case study (Jha *et al*., 2023). This work shows that even with a well-calibrated radar, there could still be large errors, which can be estimated using a disdrometer and GPM (Global Precipitation Measurement, Hou *et al*. 2014) radar data. Jha *et al*. (2023) show a mean bias of -8.3 dB in the Z of Mandradev X-band radar, correcting for which gives good agreement of derived rainfall with disdrometer (Fig. 4) and other rain gauge measurements.

4. Future

When looking at the future, there is a long shopping list, for example, national requirements from an operational point of view, exploiting the potential of the existing radar network and their data, adapting new technologies, research on cloud physics and dynamics, to name a few. The need for monitoring local weather will increase as India's economy grows. Higher incidences of lightning activity and severe rainfall events are expected in a warmer climate. Urban flooding due to extreme rain is a major concern now and will become more serious in the coming decades. In addition to the existing megacities, the smart cities will require near real-time information on severe weather. From the societal point of view, increasing lead time and accuracy of forecasts of severe weather, lightening, flooding, *etc*., are always in demand. For the near-real time and short-term forecasting of local severe weather, polarimetric DWRs are powerful tools. Further, radar data go into numerical models of the atmosphere that help improve short-term forecasts. An improved numerical model, in turn, provides a robust dependable platform for understanding different convective processes.

Considering the importance of the IMD's mandate and the need to augment the network, two committees were set up after the formation of the Ministry of Earth Sciences (MoES) in 2005. The Director-General of Meteorology constituted "National Committee to give recommendations on the proposal of establishing a National Weather Radar Operation Centre" (NWROC) in 2009 under the Chairmanship of Shri S. Raghavan. MoES constituted another committee in October 2012, namely, "High-Level Committee of experts for IMD DWR network under Modernization Phase-II and Integrated Himalayan Project" which was Co-Chaired by Dr. (AVM) Ajit Tyagi and Shri. G. Viswanathan. Both Committees gave several recommendations and suggestions, including the future of radar meteorology in India. We will not discuss them here in detail owing to page constraints, however, their relevance continues to hold. Important points include a roadmap for radar network area coverage of the country as a whole that consists of a mix of S, C, and S-band radars, maintenance, calibration, centralized data archival and sharing, improved QPE and future outlook. One important recommendation was that all future DWRs in the country be polarimetric. Radars are expensive, need suitable sites and infrastructure, trained workforce, quality 24 x 7 power supply, etc. Therefore, it is not a trivial task to install, operate and maintain them. Some of the recommendations of the two Committees are being implemented, but there is still a long way to go.

One important area requiring more work in the Indian context is appropriate algorithms for QPE in different seasons using ordinary and polarimetric radar data. This also calls for proper calibration of radars. Tracking storm track, intensity, and forecast requires more work and validation. Measured as well as derived quantities will feed to flood forecast and model data assimilation. Presently, IMD has 39 DWRs (22, 5 and 12, S, C and X-band radars, respectively). Operating them and utilizing their data requires a well-trained workforce. The country lacks a training program in radar meteorology, which requires attention.

4.1. *Emerging technologies*

The application of machine learning and artificial intelligence (AI/ML) to address/solve practical problems is becoming increasingly popular. Radar applications can benefit from AI/ML. A single radar can provide a limited amount of information. An important development in recent years is the Multi-Radar-Multi-Sensor (MRMS) approach. More reliable products and forecasts are achieved by merging radar observations, numerical models, and other sensors (*e.g*., rain gauges).

4.1.1. *Dual-wavelength & dual-polarimetric radar: Cloud and precipitation microphysics*

S, C and X-band radars, whose wavelengths are in the 3 to 10 cm range, are sensitive to precipitation-sized hydrometeors and not to cloud droplets which are less than 50 micrometer in size. One attractive feature of millimeter (mm) wavelength radar systems (*e.g*., Ka and W band) is their ability to detect micron-sized particles that constitute liquid and ice clouds. Another advantage of mm wavelength radars for airborne deployments is that the radar antenna is much smaller in size than the cm-wavelength antenna for a specified angular beam resolution, and the overall radar size is more compact. Therefore, achieving finer beam resolution < 1^0 and range resolution on the order of tens of meters is easier. Lower sidelobes and the larger signal-to-clutter ratio at mm wavelength band radars significantly enhance their detection capability, particularly close to the

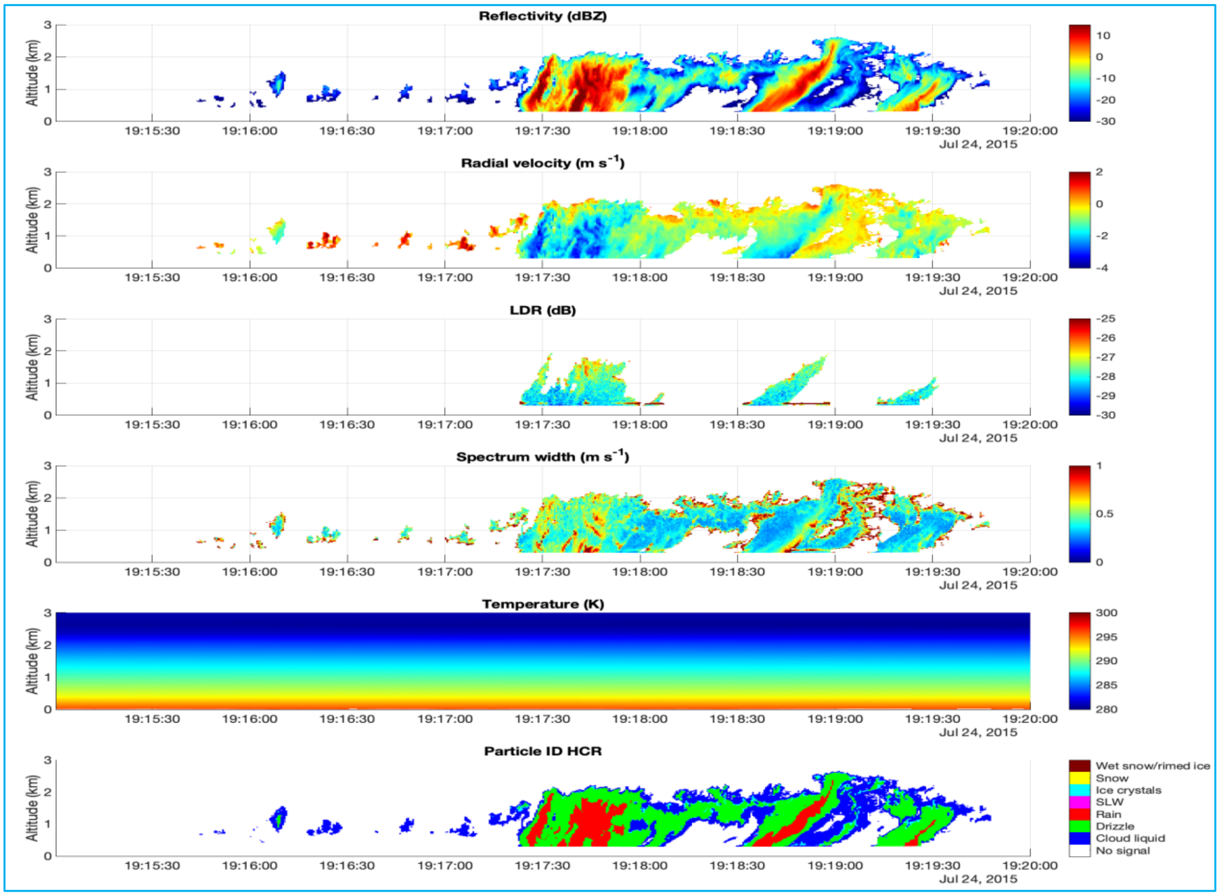

Fig. 6. The data were collected in zenith pointing from GV on 24 July 2015 between 19:15 and 19:20 UTC during CSET. The horizontal axis designates the time the aircraft traveled. The five-minute duration of the observation corresponds to a 42 km swath. The top four panels show HCR Gulfstream V High-Performance Instrumented Airborne Platform for Environmental Research (HIAPER) Cloud Radar (HCR; Vivekanandan et al. 2015) reflectivity, radial velocity, linear depolarization ratio, and Doppler spectrum width. ERA5 temperatures (TEMP, European Centre for Medium-Range Weather Forecasts, 2018) are shown in the fifth panel. The bottommost panel shows hydrometeor types using the HCR and temperature fields. (source: Romatschke and Vivekanandan, 2022).

radar (Kropfli and Kelly, 1996). However, mm-wavelength radar signals are more susceptible to attenuation. The amount of attenuation is proportional to the intensity of the precipitation and gaseous absorption (Ellis and Vivekanandan, 2010, 2011). As a result, they are not suitable for observing even moderate precipitation.

The scientific requirements of mm wavelength radar are mainly driven by climate and cloud process studies. Millimeter wavelength radar with dual-Doppler and dual-polarization capability is highly desirable for concurrently estimating dynamical and microphysical properties. A polarization Doppler radar with dual-wavelength and dual-beams can retrieve microphysical properties and two-dimensional winds. An example of a dataset collected during the CSET (Cloud System Evolution in the Trades) field deployment during the summer of 2015 (Romatschke and Vivekanandan, 2022) is shown in Fig. 6. The data were collected from the National Center for Atmospheric Research Gulfstream V (GV) on 24 July 2015 between 19:15 and 19:20 UTC. The horizontal axis designates the time the aircraft travelled. The aircraft altitude was 100 m MSL. The five-minute duration of the observation corresponds to a 42 km swath. The maximum altitude of the stratocumulus clouds is less than three kilometres, and they are all warm clouds.

4.1.2. *Phased array radar*

Phased array radar (PAR) has the potential mapping of storms and precipitation at unprecedented temporal and spatial resolution in a relatively short duration than a mechanically scanning radar. The backscatter signal from precipitation is a random variable due to hydrometeors' random location and random size distribution. The averaging of backscattered signals reduces statistical fluctuation in weather radar signals. PAR capitalizes on Active Electronic Scanning Array (AESA) technology for the beam multiplexing (BMX) mode of operation for recording independent samples of backscattered signals for more accurate radar measurements in less time than a mechanically scanning radar. One of the undesired features of the AESA is that the gain and beamwidth of the antenna change as the beam is steered away from the broadside.

4.1.3. *Open-source toolkits for analyzing radar data*

In recent years, several open-source software toolkits are available for reading, visualizing, and analyzing weather radar measurements. They were composed in Python, C, C++ and FORTRAN. The toolkits handle various radar data format conversions, merge fields from CfRadial files, radar data calibration, clutter detection and removal, nowcasting, hydrometeor identification, rain rate estimation, and dual Doppler analysis (Helmus and Collis, 2016). These toolkits are available for Linux, OS X, and Windows. The developers of the open-source software encourage the research community to contribute to collaborating on improvements to the software and composing new tools.

5. Conclusions

This article presented how radar meteorology evolved in India after giving a brief perspective of the global scenario. It is seen that developments in India closely followed that in developed countries in the initial stages, the gap was at best a few years. With available radar data in the form of photographs, considerable work on the nature of precipitating clouds, including spatial features, vertical extent, propagation, and seasonal differences was carried out covering different parts of the country. Hypotheses on precipitation processes in monsoon clouds were also tested and the dominance of the warm rain process emerged. This was phase-I, *i.e.*, in the 1950s. In phase-II from 1960 to 2000, radar activity spread, including installing storm (X-band) and cyclone (S-band) detection and warning radars and indigenous design and production. However, there was a long gap in introducing digital radars in India including the Doppler weather radars and polarimetric radars during phase-II. Starting in the early 2000s, Phase-III ushered in digital Doppler radars and radar-related activities in organizations outside IMD. The need for radar observations and products will increase in a warming climate and urbanization, and the radar meteorology program needs further boost in the coming decade.

The future of radar meteorology offers exciting research investigation and operational opportunities due to the combination of numerical weather prediction models, multiparameter cm and mm wave radar technology, and in-situ measurements. These advancements have significantly improved our understanding of mesoscale and cloud physics and enhanced operational meteorology by enabling better monitoring of rainfall, hydrometeor classification, and nowcasting. Advancement in supercomputing provides a leap to run models at very high horizontal and vertical resolutions to represent small-scale processes better (*e.g.*, convective scales). Furthermore, higher spatial and temporal measurements using polarimetric Doppler measurements, cloud radars, phased array radars, and leveraging artificial intelligence and machine learning techniques in analyzing observations can significantly advance the current understanding of monsoon rainfall climatology.

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