CHAPTER 5

Spatial Rainfall Patterns Associated with
Indian Northeast Monsoon Derived from High Resolution Rainfall Estimates of DWR Chennai

5.1. Introduction

In the preceding Chapters 2, 3 and 4, many new features of NEM were identified with INSAT based OLR data of 1° x 1° resolution. In this chapter, it is proposed to examine the spatial RF patterns associated with NEM to extract finer aspects of variability in NEM utilising further higher resolution (333m x 333m) estimates of RF from DWR Chennai. Digital DWR is a state-of-the-art modern remote sensing instrument system of the recent years widely used for weather surveillance, from which very advanced and sophisticated products are available compared to those from analog radars of yesteryears.

Meteorological radars are distinguished by the electromagnetic frequencies (like X, C or S bands) in which they operate and are deployed into the observational networks of the NWS depending upon the specific requirement and type of weather phenomena to be monitored. The analog radars inducted in 1952 by IMD into the weather monitoring network played a crucial role for several decades in service delivery in the areas of cyclone warning and aviation meteorology though they provided output in a very basic form of photographic images. In the early days, restrictions mainly imposed by technological constraints existed in the observational schedules for operating the analog radars on a full-time basis. The researchers who used data from analog radars as stated in Section 1.8 had to reconcile with limited data which was available only for the active periods of observations.

Advancements in radar technology paved the way for induction of digital DWRs in the NMS. Various aspects of the DWRs have been documented by pioneers, like Skolnik (1970), Doviak and Zrnic (1984), Atlas (1990), Rinehart (1991). Conventional weather radars can look deep into a weather system to provide information on intensity, rain rate, vertical extent, drop size distribution (DSD) etc. However, the capability to probe internal motion of hydrometeors and hence to derive
velocity and turbulence information has become available only after the advent of digital DWRs (Bhatnagar et al., 2003).

DWRs can be operated round the clock and throughout the year to map the time evolution of weather events in the neighbourhood of their installation. DWRs record high resolution data in digital form and generate sophisticated meteorological and hydrological products for off-line visualisation from multiple perspectives. Continuous weather surveillance enables estimation of the rate of precipitation and its accumulation. IMD network of DWRs is quite expansive, generating huge amount of data every day.

The base products from the DWR as mentioned in Section 1.9 are $Z$, $V$ and $W$. Innumerable derived by-products from these base products are utilised for real-time monitoring of weather events, like thunderstorms, squall lines and TCs. In view of this, DWR is a potential tool for nowcasting weather in general and RF in particular. The maximum range of the radar is 400 km. However, certain weather events can be tracked only up to short distances due to the effect of curvature of the earth. The DWR is able to provide point values of RERF every minute over a wider area, of places which have no RGs. Among the several products available from a DWR, PAC is an important output reliably providing RERF at a very high resolution for a distance of 100 km from the radar location. There is tremendous scope of using the PAC data available since 2002 from DWR Chennai to understand and unravel characteristic features of RF distribution during the NEM season which is associated with maximum RF activity over Chennai and surrounding areas.

Hence, in this chapter, it is proposed to utilise, the PAC product of DWR Chennai and study the RERF distribution within the 100 km range of the location of DWR Chennai during the NEM season for the 12 year period 2002-13. The present study is the first of its kind undertaken in India to study climatological features of NEM and to derive a few new results by utilising DWR products generated for over more than a decade. The daily RERF (DRERF) values for the above said period have been processed to derive monthly and seasonal RERF figures to identify various climatological features of NEM, some of them hitherto unknown.

In the forthcoming sections, the RERF pattern during the pre-NEM onset days of Oct, that during the duration of NEM from DO to DW (DW excluded), spatial variability during various phases of NEM, viz. dry, weak, normal, active and vigorous, influence of the days of CDs over BoB, illustration of variability in
RERF close to the coast and over the adjoining BoB, the mean RERF pattern in Dec after withdrawal of NEM are derived. The instrumental limitations and artifacts contributing to errors in RERF are elaborately discussed and the results have been summarised.

5.2. Installation of DWR at Chennai

Under IMD’s modernisation programme and upgradation of hardware, the old S-band radar of Madras (now, Chennai) was replaced with a new digital DWR operating in S-band (2875 MHz) with a wavelength $\lambda = 0.10428$ metres. This DWR which is sited atop the Port Trust building, Chennai at an altitude of 53 metres above M.S.L., was put into operational use on 20 Feb 2002 as mentioned in Section 1.8. Technical specifications and salient features of DWR Chennai have been described by Bhatnagar et al. (2003) and Rao et al. (2004). DWR Chennai has been in continuous operation since its installation generating a large quantum of weather data. The voluminous data generated by DWR Chennai have been systematically archived.

Chennai city with an area of 178 sq.km. lies within 80.20°-80.32°E and 12.15°-13.15°N stretching up to a distance of 25.6 km N-S along the BoB coast. Basic meteorological observations commenced as early as in 1793 in Nungambakkam (13.06°N / 80.25°E, NBK) which receives an annual RF of 139 cm with a major contribution of 88 cm from NEM season (IMD, 2010b). Chennai city experiences a tropical climate with Koppen climate classification Aw having maritime influence, due to its location on the BoB coast. An advantage of a DWR located on the sea coast like the DWR Chennai in comparison with a surface-based conventional RG is that reliable RF estimates are available on near-real time basis over the adjoining BoB also up to 100 km where obviously no conventional RG observations exist. Over land too, the DWR is superior in capturing the finer details of granularity of spatial variations in RF.

5.3. Radar as a Tool for Estimation of Rainfall

5.3.1. Principles of Radar based Rainfall Estimation

Before proceeding with the methodology of the present study using the DWR data, a conceptual understanding of $Z$ would help in correlating the contributions of various physical parameters in obtaining RERF. Representation of $Z$ from the hydrometeors in clouds at a specific altitude on a spatial and temporal scale
provides an aerial view of the extent of precipitation and so the RERF from Z product of DWR is one of the quantitatively valuable inputs for the forecasters.

Radar works by transmitting pulses of radio energy, which are focused by the antenna into a narrow beam. When the beam intercepts a target such as RF, some of its energy is scattered back to the antenna and detected by the radar receiver as echo power. Received echo power, which is a function of many factors, is converted into an independent characteristic of RF, viz. reflectivity factor Z, using the famous Probert-Jones Radar Equation (Jones, 1962). The parameter Z is converted to rain rate (R), through an empirical Z-R relationship. For a rain drop of diameter D, the echo power is proportional to \( D^6 \) whereas the water content is proportional to \( D^3 \). Z is converted to R as both are functions of D. Any type of RF contains millions of drops, tiny droplets to large ones, with highly varying Size versus Number-distribution. Hence, the Z-R relation \( Z = A R^b \) according to Marshall and Palmer (1948) is a varying function of DSD where Z is in mm\(^6\)/m\(^3\), R in mm/hour, A and b are numerical constants attaining values depending on the DSD. When the DSD details are unavailable and the type of precipitation is predominantly stratiform, \( A = 200 \) and \( b = 1.6 \) are the most commonly used values.

As stated in Section 1.8, validation studies using RGRF data of stations in the 100 km vicinity of DWR Chennai were first undertaken by Suresh et al., 2005, considering the variations in DSD of RF during the period 1 Mar to 31 Dec, 2003. A best fit regression equation was derived and new values of \( A = 267 \) and \( b = 1.345 \) in the Z-R relationship \( Z = A R^b \) were used in the computational software for deriving the RERF data. These values are used in DWR Chennai for operational generation and archival of base and derived products.

5.3.2. Radar Data Acquisition Sequence or Scan Strategy

Dual degree of freedom (both vertical and horizontal) for the antenna facilitates the radar beam to be swept around in different elevations angles. Present scan strategy of DWR Chennai consists of ten complete azimuth sweeps (on completion of each sweep the elevation angle is stepped up by a predetermined increment) lifting the elevation angle [Fig. 5.1(a)] from near horizontal to about 21°. Data thus acquired forms a quasi-cylindrical volume [Fig. 5.1(b)] of Z values, which are in turn converted into values of R using the Z-R relation. Due to the curvature of the earth, while looking away from the radar, even for the lowest sweep, access is denied below a certain height for rain events far away. Also, as the angle of the
highest elevation sweep is limited to around 21°, access to an overhead conical region is forbidden and so the data volume is quasi-cylindrical in shape. The data is acquired in polar (r, $\Theta$, $\Phi$) form.

In the direction of the range or distance from the DWR, the spatial resolution of data is set generally to values between 0.5 and 2 km. While sweeping in azimuth, the angular coverage is a function of radar beam width (1° for the DWR Chennai). Thus, the spatial resolution of the base data is say, $\sim$1 km $\times$ 1°. In the post-processing stage, the base data in polar form is mapped to a Cartesian Space. From the 3D volume data, $R$ pertaining to a surface layer (SL) of equal height from underlying surface is extracted and used as a derived product called Surface Rainfall Intensity (SRI). For SL height of 1 km, lowest and highest elevation angles 0.5° and 21° respectively, the farthest visible range is $\sim$100 km and the nearest visible range is $\sim$5 km. It takes about 10 minutes to acquire one full set of volume data. Thus, for a whole day there can be 144 SRI products. Time integration of these 144 sets of SRI data provides a new product called PAC.

In this study, PAC for the 24 hour period from 0300 UTC of previous day to 0300 UTC of the current day is used as the daily RERF data. Fig. 5.2 is a sample of the daily PAC image generated for the 24 hours period ending at 0300 UTC [0830 hours Indian Standard Time (IST)] of 13 Nov 2006.

5.4. PAC Configuration, Data Artifacts and Quality Control Measures opted for this Study

Details of the PAC configuration and artifacts in the data are explained in this section.

5.4.1. PAC Specifications

The PAC data from DWR Chennai is generated with configuration settings as given in Table 5.1. There is a limit to the minimum altitude that can be observed at longer ranges due to the curvature of the earth. Both the beam width and the size of the sampled volume increase as the range from the radar location increases. Hence the RERF at ground level are less reliable beyond 100 km range though they can be derived up to a range of 250 km albeit with reduced accuracy. Hence, SRI and PAC products generated up to a range of 100 km from the DWR location are considered as reliable and accurate.
5.4.2. Data Contaminants and Quality Control

As the RERF is prone to many forms of contamination and misrepresentation caused by echoes of non-precipitation origin and temporal variations in the radio propagation characteristics of the atmosphere, many grid points of the daily PAC product may contain spurious values of high or moderate RF values (Rao et al., 2004). Spurious echoes which occasionally contributed to very high RF rates were eliminated from the text data files by following a procedure of manually flagging such spurious values and removing them from the text data. The final quality controlled daily output files containing RF (in mm), almost bereft of such spurious values were used for further analysis.

5.4.3. Data Artifacts

5.4.3.1. Beam Blockage and Mirror Effect

A few wedge-shaped narrow sectors of distinctly different RF estimates visible in the PAC image (Fig. 5.2) on fairly widespread rainy days are due to blocking of the radar beam by solid objects like tall semi-permanent cranes of Chennai Port Trust (NE quadrant), TV tower (South of SW octant), Chimneys of thermal power plants (NW quadrant) and a few mobile communication towers. These distinct RF values are mostly underestimations and at times overestimations due to mirror effect wherein echoes of rain drops from diametrically opposite directions reach the receiver due to reflection of the transmitted pulse by these solid objects which act as obstructions. Care was taken to avoid or account for these artifacts while performing RERF analysis and drawing inferences from the patterns obtained.

5.4.3.2. Zero Isodop Effect

To get rid of spurious reflectivity and the resulting erroneous RERF values contributed by strong non-precipitation echoes mostly from stationary objects, their near-zero Doppler velocity is exploited to identify and eliminate or attenuate them significantly. When such a velocity based clutter filter technique is used for all data points indiscriminately, along with undesired echoes from static clutters, some real value echoes (from those rain drops moving tangential to the radar beam with near zero radial velocity) also would get filtered out or significantly attenuated. On days with preferred large-scale winds in the radar field, echoes in two diametrically opposite sectors orthogonal to the prevailing WD would continue to have near zero radial velocity and hence get attenuated repeatedly. At the end of the day when all such RF samples are integrated to build a PAC product, such an artifact due to zero
isodop effect (Nan and Ming, 2010) leading to subdued RF would emerge. An illustration of zero isodop effect when WNW winds prevailed on 21 Jul 2010 causing suppression of RERF in NNE-SSW sectors is provided in Fig. 5.3.

The same artifact could also build-up in a monthly or seasonal average PAC product, if a preferred WD existed for the month and the season. It is well known that during the active NEM season, the preferred WD over Chennai region is from NE. As DWR Chennai has been using the Doppler clutter filter all along, subdued RF values in the NW and SE sectors could be expected in daily, monthly or even seasonal average PAC images. This effect wherever manifested during data analysis is identified and mentioned in the relevant sections.

5.5. Data

In the present study, the following data have been used.

5.5.1. The DO and DW of NEM determined by Geetha and Raj (2015) for the period 2002-13 (Table 2.1).

5.5.2. Grid point data of the PAC product generated daily by DWR Chennai, for Oct, Nov and Dec for the 12 year period 2002-13 at a spatial resolution of 333 m per pixel in both directions.

5.5.3. Details of CDs that occurred during 2002-13 over BoB / NIO (IMD, 2011a) presented in Table 5.2 and Figs. 5.4a&b.

5.5.4. DRF data from 1 Oct to 31 Dec of the 12 year period of 2002-13, for 34 stations of CTN and SCAP located in the land region within the 100 km range of the DWR Chennai i.e. CDLR100. The spatial distribution of CDLR100, 34 stations and the geographical location of DWR Chennai are depicted in Fig. 5.5.

5.5.5. The long term DRF normals for the period 1951-2000, for 20 stations distinctly identified out of the 34 stations indicated in Fig. 5.5, were obtained from NDC, Pune (IMD, 2010a).

5.5.6. RF expressed as PDN for the NEM season (1 Oct-31 Dec) for TN (Table 2.1) obtained from RMC, Chennai. RF of CTN is generally taken as an index of NEM activity over TN and hence for the region of study.

5.6. Methodology of Computations, Analysis and Products Generated

The text data of the daily PAC product for the period of study were processed using Fortran and converted to GrADS compatible format for graphical analysis, visualisation and pattern recognition. Using the DRERF extracted from the PAC product, the mean RF distributions for the months of Oct, Nov and Dec and for the
NEM (OND) season of the period 2002-13, over the grid points in the area of consideration were computed and are presented in Figs. 5.6a-d. A large number of such maps on RERF were generated for various types of NEM activity also. The features observed are discussed in the following sub-sections.

5.6.1. Monthly Distribution of Mean RERF

Oct: In Fig. 5.6a the land area between 79.4°-79.8°E shows mean RERF of 20-30 cm except for patches in the NW sector with 10-20 cm. Areas closer to the coast, receive higher RF of 30-40 cm. Over the oceanic longitudes of 80.3° - 81.2°E, the NE sector 13°-14°N has significant areas of RF in the range of 40-50 cm while the rest of the areas are in 30-40 cm range. In the SE sector of BoB, RERF is 30-40 cm with few scattered patches of 20-30 cm. Underestimation of RERF is evident in certain sectors of Fig. 5.6a due to beam blockage as mentioned in Section 5.4.3.1.

Nov: The rainiest month over CTN is Nov and is representative of NEM season. The RERF distribution (Fig. 5.6b) reveals that over land the southern and SW sectors of DWR Chennai formed by 79.9°-80.1°E and 12.2°-13.2°N receive RF of 30-40 cm. Major portions of the land area westwards register RF of 20-30 cm. RF decreases to 10-20 cm from E-W of the DWR along 79.4°-79.6°E and 12.8°-13.8°N. Over the ocean, a tiny portion of the southern sector 79.8°-80.3°E up to 12.3°N along the BoB coast has a distinct patch of 40-50 cm RF while a vast area of BoB has RF of 30-40 cm in the SE / NE sectors with scattered zones of 20-30 cm RF in the eastern sector of the DWR Chennai.

The conical beams of underestimation of RF in the ocean are due to beam blockage as explained in Section 5.4.3.1. The clear-cut diagonal patch of low RF (20-30 cm) along NW-SE centered at the DWR location is due to the zero isodop effect which is described in Section 5.4.3.2.

Dec: The decrease in RERF marked by the withdrawal phase of NEM during Dec is evident from Fig. 5.6c. Over land, in the SW sector of the DWR, there is gradual decrease of RF from 12-15 cm close to the coast to 3-6 cm westwards. RERF close to the coast in the NW sector (9-12 cm) is less than that of the SW sector (12-15 cm). In most parts of the oceanic area, RERF > 9 cm is seen with zones of 12-15 cm and smaller patches of 15-18 cm. The conical beams of underestimation of RF as described earlier are seen in Dec also.
It is worthwhile to note that the isodop effect is observed for the distribution of Nov and Dec but absent for Oct where the first half of the month is characterised by prevalence of SW winds in the lower levels and NE winds set in much later.

5.6.2. Mean Seasonal Distribution of RERF

On a seasonal scale, RERF for OND for the entire area of consideration is depicted in Fig. 5.6d. Since this distribution is of very high resolution (333 m per grid point), it is possible to identify new features of NEM RF hitherto unknown. Some of the inferences drawn from Fig. 5.6d are as under:

5.6.2.1. Over the Land (CDLR100)

(i) The RERF is heavier over/closer to the coast.
(ii) Along a given latitude, the RERF by and large decreases from E-W over land.
(iii) Along a given longitude, the latitudes south of DWR receive 10-15% more RF than the northern latitudes.
(iv) RERF zones of 80-90 cm and smaller patches of 90-100 cm are observed in the SW sector of DWR location.
(v) The RERF decreases inland to 70-80 cm, then to 60-70 cm at 79.8°E and it reaches 50-60 cm roughly west of 79.7°E.

5.6.2.2. Over the Ocean

(i) The heaviest RERF zones of 80-90 cm and within that patches of 90-100 cm are seen in the NE sector of DWR location. Another heavy RERF zone is seen over the extreme south just east of the coastal belt.
(ii) East of 80.8°E the RERF over the ocean is lower than that adjacent to the coast. But the decrease further east is gradual and not uniform.
(iii) Lowest amount of RERF is 60-70 cm in small patches.

The OND seasonal RGRF is generally heavier over the coast and decreases westwards inland and this feature has been brought out in the mean RERF distribution very well. Features of the mean OND (NEM) RERF distribution over land derived in this study compare very well with that of RGRF distribution for OND based on long term climatology (IMD, 1973; Raj, 2012).

5.6.3. Mean RERF pre- and post-NEM Onset

By convention, the NEM seasonal RF total is accounted from 1 Oct to 31 Dec. However, the normal DO of NEM is 20 Oct with a SD of 7-8 days. During the period of analysis, onset of NEM took place in Oct in all the years with 19 Oct as the mean date for the 12 year period 2002-13 while the long term mean based on
1901-2000 is 20 Oct. The RF which is realised from 1 Oct up to the DO of NEM (DO excluded), associated with lower level SW winds not possessing NEM characteristics also gets included in the seasonal total RF. It is preferable to study separately and bring out distinct features of the variation of RERF during the pre-NEM phase in Oct and also the pattern of RF strictly during the duration of NEM, i.e. from DO to DW, named here as post-NEM onset.

5.6.3.1. Mean RERF Pattern during pre-NEM Days of Oct

To derive the quantum of RF that is realised during the pre-NEM onset phase, the days from 1 Oct to the day just prior to the DO during 2002-13 were identified and RERF was cumulated for each year and averaged over 12 years. There were 214 such days during the study period. The analysis was carried out for every grid point and the resulting spatial distribution of CRF is presented in Fig. 5.7. As seen, over most of the land area, the mean CRF is 4-8 cm with few smaller patches registering 8-12 cm. Over the ocean, the mean RERF in the NE sector is nearly 8-12 cm with regions of higher RF of 12-16 cm and 16-20 cm in the east-NE sector. In the SE sector around 40 km away from coast and over the ocean, RF is lower at 4-8 cm with a small zone receiving less than 4 cm. The high quantum of RF in the NE sector is probably due to the presence of feeble systems over BoB when the surface ET is on its southward progression during the first half of Oct. It is also worthwhile to note that the belt of relatively high RF over CTN observed during NEM is missing in the distribution of pre-NEM RERF.

5.6.3.2. Mean RERF Pattern during the Duration of NEM

To derive the average spatial CRF pattern during the duration of NEM viz. the period from DO to DW (DW excluded and was taken as 31 Dec if it was later) only was considered. Overall, 791 days of NEM were included in the analysis. The DRERF cumulated for each year was used to compute the 12 years mean CRF for each grid point. The spatial distribution of mean RERF for the duration of NEM is presented in Fig. 5.8.

Inferences drawn from an evaluation and comparison between the features of NEM observed in both Fig. 5.6d and Fig.5.8 are provided below:

Over Land

(i) Features related to seasonal OND total (Fig. 5.6d) RERF described in (i), (ii) and (iii) of Section 5.6.2 hold good for the CRF during DO-DW also.
Compared to CRF of OND [Fig. 5.6d] over both land and ocean, a reduction in RERF of 10-20 cm is observed in Fig. 5.8.

Maximum RERF of 80-90 cm is observed just 5-10 km away from the coast in the SW sector of DWR Chennai location.

Zero isodop effect as detailed in Section 5.4.3.2 is observed in Fig. 5.8.

Over the Ocean

(i) NE and SE sectors from the DWR location have higher RERF of 70-80 cm possibly caused by the influence of CDs of the BoB. RERF decreases to 60-70 cm beyond 80.7°E (Fig. 5.8).

(ii) There is a distinct patch of RERF > 90 cm in the NE sector, just a few km away from the coast between 80.3° and 80.5°E.

(iii) Higher RERF zone of 80-90 cm south of the DWR location extending up to the periphery of the area of consideration and a very small inner patch of RERF > 90 cm are observed.

(iv) A conspicuous difference in the RF pattern displayed by Figs. 5.6d and Fig. 5.8 is that the NE sector over ocean with reference to the DWR location is much less rainy in the latter compared to the former which takes into account all the 92 days of the season. That the NE sector received relatively more RF in the pre-NEM onset days of Oct (Fig. 5.8) is the obvious reason.

For further detailed analysis, the mean RERF distribution averaged over all the latitudes of the area under consideration for a given longitude was generated and is depicted in Fig. 5.9a. The RERF distribution at the latitude 13.1°N of DWR Chennai also has been extracted and presented in Fig. 5.9b.

Inferences drawn from Figs. 5.9a&b are as under:

(i) The peaking of RERF close to the coast, the sharp near-linear decrease of RF westwards into the land, the constant RERF profile for nearly 40 km eastwards from the coast into the ocean and the slow decrease of RERF further eastwards—these features have been captured and depicted with better clarity in Fig. 5.9a.

(ii) In the case of Fig. 5.9b, the area of the cone of silence is clearly seen and the RERF peaks at nearly 20 km west and east of the coast. The decrease of RERF over the ocean eastwards is sharper than the mean profile depicted in Fig. 5.9a and westwards in the land area also, the decrease in RERF is sharper, linear and similar to Fig. 5.9a.
5.6.4. Analysis of Mean RERF Pattern in Dec post-NEM Withdrawal

During the period 2002-13, NEM withdrew in Dec in 7 out of the 12 years and spilled over to Jan in 5 years (Table 2.2). The fixing of DW of NEM over CTN has been based on careful analysis of daily RGRF of several stations of south AP and CTN (Raj, 1998a; Geetha and Raj, 2015). However, even after the identified DW, some amount of RF might get realised over land itself which may not have been detected by the manual RG network. There has been no authentic study on the quantum of RF received over BoB after the retreat of NEM from land (i.e. CTN). To study the same, using the RERF of 99 post-NEM withdrawal days of Dec, the mean DRERF was computed and the spatial distribution is depicted in Fig. 5.10.

It is seen that the oceanic areas received more RF compared to land areas. Except for a small patch north of DWR Chennai, the land region is almost dry with no substantial contribution of RF to the seasonal NEM. The mean RERF shows increasing RF over BoB as one moves eastwards from the coast. It is well known that NEM prolongs into Jan over the eastern parts of Sri Lanka with stations like Baticaloa (7.7°N / 81.7°E at 3 m above M.S.L.) receiving NRF of 27 cm. The pattern of NEM withdrawal is by and large from N-S and west to east (W-E). The RERF distribution over BoB as shown in Fig. 5.10 conforms to the above pattern despite the fact that the data used in the analysis is only up to a distance of 100 km from Chennai DWR.

5.6.5. Mean RERF over Land and Oceanic Areas during NEM season, 2002-13

In the previous sections, the salient features of the spatial distributions of mean RERF for seven different periods were elaborated. Whereas conventional RGRF observations are not available over oceanic areas, RERF observations over BoB are available up to a distance of 100 km from DWR Chennai. Continuing the analysis further, the mean RERF over CDLR100 and that over ocean based on the grid point values were computed to facilitate ease of comparison. The BoB coast runs almost N-S and so the circular area of 100 km radius was approximately delineated into two semi-circles comprising areas of CDLR100 and ocean. The RERF values from the 600 × 600 matrix that belong to each semi-circle, numbering nearly 1.42 lakhs, were separately averaged to derive the mean RERF over land and ocean. Such computations were repeated for each of the seven periods and the mean RF values thus derived are presented in Table 5.3.
As shown, mean RERF over oceanic areas of BoB in the 100 km radius from the DWR Chennai is consistently more than that over CDLR100 for all the periods. Oct is the rainiest month over the oceanic area with a mean RERF of 357.1 mm when compared to Nov (299.6 mm) and Dec (107.8 mm). However, over land, RERF of Oct (273.3 mm) is almost equal to that of Nov (262.2 mm) while that of Dec is 92.5 mm. During the NEM season (OND) as a whole, oceanic areas (761.4 mm) are rainier than land (628.4 mm). The same pattern is observed during pre-NEM days of Oct with RERF of 83.0 mm and 66.4 mm over ocean and land respectively. During DO-DW, the mean RERF over ocean is 680.8 mm and that over land is 561.5 mm. In the case of post-withdrawal days of NEM, mean RERF over ocean is 1.9 mm while that over land is negligible (0.4 mm). It is seen from Fig. 5.10 that RERF over the eastern parts of BoB is higher. In all seven cases discussed above, RERF over ocean is higher than that over land. However, there is a deviation from this overall pattern observed, which will be presented in a subsequent section.

5.6.6. Mean RF Pattern during Days of CDs over BoB

It is well-known from the NEM RF climatology that CDs which form and move over BoB are major synoptic systems associated with active NEM conditions over TN and adjoining areas. Apart from these migratory systems, active NEM is also associated with occurrence of strong low level easterly winds. When CDs are present over the ocean, that substantial RF should occur over the oceanic areas affected by the CDs is obvious. As RERF is available over the area of concern in BoB, it is of interest to study the RERF pattern over the ocean vis-à-vis land when NEM is active over the land with or without CDs present over BoB. The spatial distribution of RERF discussed in Section 5.6.3.2 for DO-DW of NEM includes CD days also. During Oct-Dec (2002-2013), as many as 36 systems formed or moved over BoB. In the case of the duration of NEM, 26 days associated with 17 CDs which originated / moved / crossed in the 400 km distance from DWR Chennai, as listed in Table 5.2 have been identified as causing normal or higher level of NEM RF activity over land. The tracks of the 17 CDs are displayed in Figs. 5.4a&b. The spatial distribution of mean DRERF averaged over the 26 CD days in BoB during DO-DW for each grid point was generated and is presented in Fig. 5.11.

Mean DRERF > 4 cm on CD days is observed over large parts of the ocean. Land areas close to the coast have DRERF of the order of 3.0-3.5 cm while few patches of RF 4-4.5 cm just a few km away from the coastline are observed. The
mean DRERF values computed for the semi-circular areas of both the ocean and land are 4.4 cm and 2.2 cm respectively indicating that during CD days, oceanic areas of BoB over the region of study receive approximately twice more RF than CDLR100. A rapid decrease in RF over land from coast to inland is evident from Fig. 5.9. Further, it is inferred from Figs. 5.8 & 5.11 that when RF due to CDs is excluded, the mean DRERF realised during DO-DW is lesser approximately by 2 cm over land and by 4 cm over ocean.

5.6.7. Spatial Variation of RERF during Various Phases of NEM

The NEM season is generally interspersed with 4-5 active spells of RF with dry spells in between. Some of the dry spells could last for a prolonged duration. The seasonal RF realised is largely dependent upon the number of active spells of RF. When high resolution data is available from DWR, it is possible to analyse the RF estimates over the region of study to understand the mesoscale variations in RF during the various phases of NEM activity. In order to determine the strength and spatial distribution of NEM within CDLR100, the DRF recorded by 34 RG stations have been used (Fig. 5.5).

IMD describes the spatial DRF distribution over a region as per nomenclature and classifications which are defined in Table 2.3. Using the long term (1951-2000) normals of DRF (NDRF) of 20 stations (IMD, 2010a), the NDRF values for the remaining 14 stations were interpolated. The NDRF for the NEM season 1 Oct-31 Dec computed as a mean of RGRF data of 34 stations in the CDLR100 region is presented in Fig. 5.12. The mean RGRF of a day was computed based on the number of stations for which RF data was available. The ratio of actual RF to NDRF was calculated for each day. The strength and spatial distribution of NEM were determined for each day and year to identify the days of various types of NEM activity. During the 12 year period 2002-13 of the NEM season, PAC data from DWR Chennai was available for 1079 out of 1104 days save for 25 days of missing data. The numbers of days of dry, weak, normal, active and vigorous phases of NEM are 309, 399, 206, 99 and 66 respectively (Table 5.4). The daily RERF values of the days falling under dry, weak and normal NEM activity were averaged to generate the categorywise spatial mean RERF patterns that are depicted in Figs. 5.13a-c.
The features are described below:

**Dry :** In the case of dry days (Fig. 5.13a) almost the entire area in the 100 km range of the DWR is rain-free except for a patch of mean DRERF < 1 mm in the southern sector over the ocean, close to the coast.

**Weak :** During weak NEM days (Fig. 5.13b), mean DRERF up to 2 mm near the coast decreases to 1 mm westwards. The oceanic areas have DRERF of 2-7 mm.

**Normal :** In the case of normal NEM days (Fig. 5.13c), an increase in DRERF in the range 9-12 mm along the entire coast of BoB is observed. A gradual decrease in DRERF from coast to inland up to 3 mm is discernible over land, whereas over ocean the RF activity is spatially widespread with southern and easternmost patches indicating DRERF up to 18 mm.

**Active :** During active NEM days (Fig. 5.14a), an almost uniform distribution of DRERF in the range 1.5-2 cm over both land and ocean is observed except for significant patches of 2-2.5 cm in the SW (over land) and NE (over ocean) sectors between 79.8 - 80.6°E and 12.8-13.2°N. The southern sector also has a zone of DRERF of 2-2.5 cm with a small patch of 2.5-3 cm along the periphery of the DWR range. The SW sector also has a distinct high RF patch of 2.5-3 cm located a few km inland from the coast.

**Vigorous :** In the case of vigorous days of NEM (Fig. 5.14b), a spatially uniform mean DRERF of 4-5 cm is realised over larger areas of both land and ocean. Distinct patches of higher RF of 5-6 cm are observed both over land in the SW sector of the DWR location and over ocean in the SSE sector. Decrease in DRERF up to 2 cm further westwards inland is noticed.

It is well-established that presence of CDs in BoB for 2-3 days increases the RF over the coastal areas drastically and so identifying the influence of CDs on the RF activity during NEM season becomes important. Hence, the analysis was further continued by excluding 14 CD days (out of which 8 are in active and 6 in vigorous phase) from the active (99) and vigorous (66) NEM days and averaging 151 [(99 + 66) – (8 + 6)] days of DRERF for which data was available, to generate a mean RERF distribution as given in Fig. 5.14c.

After removal of RF due to CD days, it is observed that DRERF due to active and vigorous (AV) NEM days is conspicuously higher (4-5 cm) over or close to the coast and adjoining land areas than that over ocean. RERF of 4-5 cm extends up to 30 km west of the coast inland but decreases sharply further westwards. Over the ocean,
the DRERF of 4-5 cm extends up to only around 15 km eastwards that too predominantly in southern latitudes. In northern latitudes, DRF is 3-4 cm only even over the ocean but further decrease is gradual. Clearly and expectedly, removal of RF due to CD days has reduced the RF over ocean.

Some of the other salient results of this analysis are:

(i) The mode in DRERF occurs 5-10 km SW of DWR Chennai near BoB coast with the presence of a very high RF patch of 5-6 cm which is clear from both Figs. 5.14b&c. The patch of higher RF is not exactly over the coast during AV NEM days.

(ii) During AV NEM days without CDs, land areas have received comparatively more RF than ocean.

In all the phases viz. normal, active, vigorous and AV minus CD days of NEM activity, isodop effect (Section 5.4.3.2) of varying dimensions and scales and underestimation of RERF due to obstructions manifested as conical beams as explained in Section 5.4.3.1 have been observed.

The high RERF pattern in the SW sector of the DWR is seen in Fig. 5.8 (DO-DW) as well but the extent to which such a signature would be present if the zero isodop effect were nullified is a bit obscure. However, for vigorous and AV NEM days (Figs. 5.14b&c), the pattern is clearly defined and would be so despite the isodop effect. If such a feature of higher RERF observed in the SW sector of the DWR location is not an artifact of DWR system, a plausible physical reasoning could be that the SW sector of Chennai city is highly urbanised with a large number of high rise buildings compared to north or NW sectors. The resulting contribution of higher roughness parameter to increased frictional convergence and hence slightly higher RF appears as a reasonable explanation.

5.6.8. Region of Heaviest NEM RF over BoB - Comparison with Satellite Data based Findings

It is well-known from NEM climatology that RF during NEM is higher over coast and decreases inland. This feature which can be appraised from the NRF pattern is also frequently observed during active NEM conditions [IMD (1973) and Raj (2012)]. In this study based on RERF, it has been possible to bring out the sharp decrease of RF inland (Fig. 5.6d) during NEM. It is of tremendous interest and scientific curiosity to get an insight on the quantum of RF realised over the oceanic areas adjacent to CTN during the NEM and its various phases. In the absence of
RGRF data over oceans, remote sensing methods which provide RF directly or through some proxy parameter are the other options available. Suresh and Raj (2001) based on 3 years (1996-98) of OLR data of resolution 80 km × 80 km obtained from NOAA polar orbiting satellites showed that the RF profile during active NEM conditions displayed a maximum over CTN, decreasing sharply inland and gradually eastwards over ocean. The analysis in Chapter 3, using 13 years (2000-12) of INSAT OLR data of 1°×1° resolution reiterates the same result. In both the studies, OLR was taken as a proxy for RF.

It is important to examine whether the above feature of NEM RF as derived from OLR observations emerges when analysis is based on RERF data of very high resolution, i.e. 333m×333m. The mean RERF distributions presented in Figs. 5.6b-d, 5.8, 5.9a, 5.14a-c were critically evaluated to detect such a pattern, if any. A mosaic of the above figures (excluding Figs. 5.6d and Fig. 5.9a) clearly demarcating through isohyets, the higher RERF regions is presented in Fig.5.15. For colour coding and finer details, original figures may be referred.

The inferences drawn from the above figures are described below:

It is seen from the RERF distribution for Nov and Dec that over the ocean, the heaviest RERF values are observed within 40 km from the coast with some decrease further eastwards. Almost similar pattern is seen in the normal RERF distribution for the NEM (OND) season. Figures depicting the normal RERF distribution for DO-DW and Fig. 5.9a which displays the mean longitudinal distribution also clearly illustrate this feature. In Fig. 5.9a, the highest RF during DO-DW of NEM occurs in the stretch which extends nearly 30 km west of the coast into the land (65-72 cm) and 40 km east of the coast into the ocean (67-68 cm) beyond which RF decreases (62-65 cm). Overall, the quantum of RERF decrease in the ocean in the eastern region compared to coastal regions is only around 8% but the pattern is well-defined and clearly marked. Further, reiteration is clear from Figs. 5.14a-c depicting the spatial distribution of mean DRERF on active, vigorous and AV days excluding RERF due to CDs.

In view of the high resolution of the data used and the well-known property that RF varies considerably in space and can have discontinuities even if averaged, sometimes the spatial distributions which are presented do not give a smooth profile and there might be patches of RF which deviate from the conceptual pattern described as above. However, the overall feature that RF is heaviest over CTN and
neighbourhood stands reiterated. Yet another authentic evidence of the above characteristic is provided by the comparison of the mean RERF during DO-DW (Table 5.3) over the semi-circular region of the ocean and the mean coastal RERF computed from the data of several representative points along the coast (Fig. 5.8). The former is 68 cm and the latter 75 cm. These figures clearly indicate that the quantum of RF realised over eastern parts of the semi-circular oceanic region is lower when compared to that along the coast.

The study by Suresh and Raj (2001) and results presented in Chapter 3 based on OLR data could not precisely delineate the extent of high RF closer to CTN based they are of comparatively lower resolution when compared to the resolution of RERF (333 m x 333 m). With higher resolution RERF data, it has become possible to delineate the high RF zone which approximately extends 25-30 km west of the coast into land and around 30-40 km east of the coast over the ocean as deduced from the various figures and elaborations in the previous sections. It must be stated that the analysis based on OLR data covered almost the entire BoB and extended up to southern latitudes whereas reliable RERF data is available only up to 100 km from the DWR Chennai location and for lesser distances in other latitudes of the area of consideration. Notwithstanding such a limitation, both the reiteration of the OLR based features and the delineation of high RF zone based on RERF analysis are interesting results emerging from this study.

5.7. Remarks

While analysing the RF characteristics of NEM extracted from RERF and arriving at conclusions as elaborately discussed above, various aspects of DWR instrumental configurations and calibration procedures have been taken into account. Huge volume of data has been processed by carefully eliminating noise in the data though few artifacts as mentioned in Section 5.4.3 could not be eliminated totally. In spite of the advantage of using Doppler clutter filters during the sampling which outweighs its disadvantages, high intensity echoes do creep in which cannot be totally avoided as observed from the data used in the analysis.

Both spatially and temporally, RF is a highly variable parameter. Climatologically, 30-50 years of continuous data is needed to derive normals representative of the behaviour of a meteorological parameter over the specific location of study. The present analysis pertaining to the 12 year period, 2002-13 is too short a period to derive inferences which can be taken as general features. In
addition, this period had a historically high positive epoch of RF years 2004-11 for TN and for the region of consideration which possibly could have induced some amount of bias in the results derived. Despite such limitations, it is remarkable that seemingly consistent results have emerged from this study. Needless to say that there is tremendous scope to pursue more research based on the voluminous and wide spectrum of DWR data. The results of this chapter have been published [Amudha et.al. (2016c)].

To understand further the extent of reliability of the results presented in this chapter on monthly and seasonal scales, it is preferable to perform a validation of the RERF data with ground truth RGRF. Hence, in the next chapter the comparison of RERF with RGRF on monthly and seasonal basis has been undertaken using various methodologies and results are presented.


**TABLE 5.1**

**Configuration and processing details of the PAC product generated by DWR Chennai**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displayed parameter</td>
<td>Rain accumulation from PAC product of DWR for 24 hours ending at 0830 hours IST (0300 UTC)</td>
</tr>
<tr>
<td>Data domain :</td>
<td></td>
</tr>
<tr>
<td>(a) Centre</td>
<td>DWR Chennai (Long. 80.2899° E Lat.13.0838° N)</td>
</tr>
<tr>
<td>(b) Areal extent</td>
<td>Region bounded by a circle of radius 100 km with its centre at DWR Chennai</td>
</tr>
<tr>
<td>(c) Surface layer</td>
<td>A curvilinear surface 1 km above the ground right below. As the earth’s surface undulates, the surface layer too undulates keeping 1 km height always</td>
</tr>
<tr>
<td>(d) Spatial resolution</td>
<td>200 km represented by 600 pixels in both East-West and North-South directions (333 m × 333 m)</td>
</tr>
<tr>
<td>Number of data points per PAC</td>
<td>(\pi \times \left(\frac{100000 \text{ m}}{333 \text{ m} \times 333 \text{ m}}\right)^2 = \sim 283310) (Nearly half lie over the oceanic area of BoB)</td>
</tr>
<tr>
<td>Number of PAC products processed</td>
<td>1 PAC/day × 92 OND days/year × 12 years = 1104</td>
</tr>
<tr>
<td>Total data points processed</td>
<td>1104 × 2.83 lakhs = \sim 312 million</td>
</tr>
</tbody>
</table>

(Source : IMD, DWR Chennai)
### TABLE 5.2

CDs over BoB contributing to various phases of NEM during 2002-13

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Year</th>
<th>CD</th>
<th>Duration</th>
<th>NEM activity</th>
<th>Dates</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2002</td>
<td>SCS</td>
<td>10-12 Nov</td>
<td>10, 11</td>
<td>A, N</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>2005</td>
<td>DD</td>
<td>26-29 Oct</td>
<td>26, 27, 28</td>
<td>A, V</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td>D</td>
<td>20-22 Nov</td>
<td>21</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td></td>
<td>CS Bazz</td>
<td>28 Nov - 2 Dec</td>
<td>2</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td>CS Fanoos</td>
<td>6-10 Dec</td>
<td>10</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td>DD</td>
<td>15-21 Dec</td>
<td>17</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>2006</td>
<td>CS Ogni</td>
<td>29-30 Oct</td>
<td>29, 30</td>
<td>V, A</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>2008</td>
<td>CS Khai-Muk</td>
<td>13-16 Nov</td>
<td>16</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td></td>
<td>CS Nisha</td>
<td>25-27 Nov</td>
<td>26</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>2010</td>
<td>SCS Jal</td>
<td>4-8 Nov</td>
<td>7, 8</td>
<td>N, V</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td></td>
<td>DD</td>
<td>7-8 Dec</td>
<td>7</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>2011</td>
<td>VSCS Thane</td>
<td>25-31 Dec</td>
<td>30</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>2013</td>
<td>D</td>
<td>13-16 Nov</td>
<td>16, 18</td>
<td>N, A</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td></td>
<td>VSCS Lehar</td>
<td>23-28 Nov</td>
<td>23-25</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td></td>
<td>VSCS Madi</td>
<td>6-13 Dec</td>
<td>12</td>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>

**Total days** 26

(Source : IMD, http://www.rmcchennaieatlas.tn.nic.in)

CD : Cyclonic Disturbances,  BoB : Bay of Bengal.  
D : Depression,  DD : Deep Depression,  CS : Cyclonic Storm,  
SCS : Severe CS,  VSCS : Very SCS.  
Phases of NEM : N : Normal, A : Active, V : Vigorous  
N, A, V defined for the CDLR100 region
TABLE 5.3
Mean RERF (in mm) over land and ocean during the NEM season of 2002-13

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Category</th>
<th>Land</th>
<th>Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Oct</td>
<td>273.3</td>
<td>357.1</td>
</tr>
<tr>
<td>2.</td>
<td>Nov</td>
<td>262.2</td>
<td>299.6</td>
</tr>
<tr>
<td>3.</td>
<td>Dec</td>
<td>92.5</td>
<td>107.6</td>
</tr>
<tr>
<td>4.</td>
<td>NEM season (OND)</td>
<td>628.4</td>
<td>761.4</td>
</tr>
<tr>
<td>5.</td>
<td>Pre-NEM days of Oct</td>
<td>66.4</td>
<td>83.0</td>
</tr>
<tr>
<td>6.</td>
<td>Duration of NEM (DO-DW)</td>
<td>561.5</td>
<td>680.8</td>
</tr>
<tr>
<td>7.</td>
<td>Post-withdrawal days of Dec</td>
<td>0.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>

DO : Date of Onset; DW : Date of Withdrawal

TABLE 5.4
Number of days of DWR data availability for the various phases of NEM activity during 2002-13

<table>
<thead>
<tr>
<th>Activity →</th>
<th>Dry</th>
<th>Weak</th>
<th>Normal</th>
<th>Active</th>
<th>Vigorous</th>
<th>Total data used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month↓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>33</td>
<td>162</td>
<td>100</td>
<td>51</td>
<td>19</td>
<td>365</td>
</tr>
<tr>
<td>Nov</td>
<td>93</td>
<td>147</td>
<td>59</td>
<td>37</td>
<td>23</td>
<td>359</td>
</tr>
<tr>
<td>Dec</td>
<td>183</td>
<td>90</td>
<td>47</td>
<td>11</td>
<td>24</td>
<td>355</td>
</tr>
<tr>
<td>Total</td>
<td>309</td>
<td>399</td>
<td>206</td>
<td>99</td>
<td>66</td>
<td>1079</td>
</tr>
</tbody>
</table>

Missing data : 25 days
Total : 1079 + 25 = 1104 days
Fig. 5.1a & b (a) Stepping up of elevation angles of the DWR antenna in volume scan strategy and (b) the quasi-cylindrical shape of the volume of data scanned.
Fig. 5.2 A sample image of the 24 hours PAC product (in dBA) for the period ending at 0300 UTC of 13 Nov 2006 generated by DWR Chennai
(Source : IMD, DWR Chennai)

Fig. 5.3 Illustration of zero isodop effect along NNE-SSW direction with DWR Chennai as centre
(Source : IMD, DWR Chennai)
Figs. 5.4a&b  Tracks of 17 CDs which originated over BoB / Sri Lanka and contributed to higher RF activity near DWR Chennai during the NEM season, 2002-13
(a) 2002-07 (CDs : 8) and (b) 2008-13 (CDs : 9)
(Source, IMD, http://www.rmcchennaieatlas.tn.nic.in)
Fig. 5.5 Spatial distribution of the 34 RG stations over land within 100 km radius of DWR Chennai (CDLR100) ('■' indicates stations with long term normals)
Figs. 5.6a-d  Distribution of mean RERF (in cm) for 
(a) Oct, (b) Nov and (c) Dec, d) Oct-Dec (NEM), 2002-13
Fig. 5.7  Distribution of cumulative mean RF (in cm) for pre-NEM onset days of Oct, 2002-13

Fig. 5.8  Distribution of cumulative mean RERF (in cm) during DO-DW (Dates of onset and withdrawal), 2002-13
Figs. 5.9a&b Longitudinal variability of mean RERF (in cm) over land and ocean during DO-DW of NEM, 2002-13 (a) averaged across all latitudes, (b) at 13.1° N
(The space between the arrows in the above figures indicates areas in and around the coastline)
Fig. 5.10  Mean daily RERF (in mm) of post-NEM withdrawal days of Dec, 2002-13

Fig. 5.11  Mean daily RERF (in cm) within 100 km of DWR Chennai under the influence of CDs of BoB during DO-DW of NEM, 2002-13
Fig. 5.12 Normal daily RGRF (in mm) over land within 100 km of DWR Chennai based on data of 34 stations, for 1 Oct - 31 Dec

Figs. 5.13a-c Mean daily RERF (in mm) associated with (a) dry (b) weak and (c) normal NEM activity during 2002-13
Figs. 5.14a-c  Mean daily RERF (in cm) associated with (a) active (b) vigorous NEM activity (c) both active and vigorous days combined excluding 14 CD days
Figs. 5.15a-f  Mosaic of cumulated mean RERF (in cm) of (a) Nov, (b) Dec, (c) the period between DO-DW and daily mean RERF (in cm) associated with (d) active (e) vigorous and (f) active and vigorous NEM days excluding CD days.