International Journal of Innovations in Engineering and Technology (IJIET)
http://dx.doi.org/10.21172/ijiet.83.009

Long-term observations of Bright band characteristics over Kadapa (14.47°N; 78.82°E) Semi-arid-region of tropical India

K.Hemalatha and D. Punyaseshudu
Department of Physics, Rayaseema University, Kurnool

R.Suneetha
Silver Jubliee Degree College, Kurnool

Abstract- **Yogi Vemana University (YVU) established Semiarid zonal Atmospheric Research Centre (SARC) at Kadapa (14.47°N; 78.82°E) which often experiences thunderstorm activity with hailstorm/squall during pre-monsoon and monsoon. Hence, Kadapa is the bridge between 'wet' and 'dry' regions of Andhra Pradesh and hence, a natural laboratory to investigate vertical structure of various types of precipitating clouds and Raindrop Size Distribution (RSD) observed during different rainy/monsoon seasons. South-West (SW) and North East (NE) monsoon are the two important periodic winds, which show high impact on the rain. Hence, a detail observational modeling study was performed on microphysical/bright band properties during SW and NE monsoon over Kadapa, tropical semi-arid zone for two years from May 2009 to April 2011. We adapted melting-layer model, "Non-coalescence–Non-break up (N-N) model" proposed and rigorously detailed by Awaka et al. (1985). This paper examines the long-term bright band characteristics during SW and NE monsoon regimes and comparison with N-N Model.**
Keywords – Watermarking, Haar Wavelet, DWT, PSNR

I. Introduction

Knowledge of attenuation by the melting layer (is the transition region between snow and rain, it usually starts at the 0°C isotherm level and finishes at a few degrees above 0°C where all the snow particles have melted and become raindrops) will be crucial in order to estimate rainfall using short wavelength space borne radars [Smith 1986; Joss and Waldvogel 1990; Fabry and Zawadzki 1995; Reddy, 2003]. Hence, characteristics of the melting layer are not only important for understanding the microphysical processes involved in rainfall mechanism but also necessary for rain retrieval algorithms used for the present and future space-borne rain radars such as Tropical Rainfall Measuring Mission (TRMM) precipitating radar (PR) and future Global Precipitation Mission (GPM). With the Tropical Rainfall Measuring Mission (TRMM) satellite, more data about the melting layer have been available in tropics. The information regarding its height and thickness are vitally important to both remote sensing and radio wave communications research because it can lead to the total rain-cell height and the impact of melting particles. As active devices, radars have the potential to study the microphysical properties of the precipitating clouds [Cunningham ,1947; Battan 1973; Meneghini and Liao 2000]. The observation of the melting layer in radar parameters gives rise to bright band signatures, which are caused by a high concentration of particles of high index of refraction arising from the melting snow, with the additional factor of non-spherical shapes.(Battan 1973; Zawadzki et al. 2005).Bright band height (BBH) is the altitude of maximum radar reflectivity in the melting layer [Stewart et al. 1984; Klaassen 1988; Fabry and Zawadzki 1995; Houze 1997; Gray et al. 2001; White et al. 2002; Zawadzkiet al. 2005].

. Thurai et al. (2003) show that there is a significant variation of melting layer height with the latitude. Seasonal variability of zero-degree isotherm height for some tropical locations from local Radiosonde data are also reported [Mondal et al., 2001; Mandeep, 2009]. Although, TRMM provides a good amount of data, but its resolution is poor both spatially and temporally. Also measurements of melting layer height from radiosonde are limited to a few hours only. Thus, there is a need of continuous measurement of melting layer to estimate the actual variability of this layer. So, continuous measurements of bright band height (BBH) are required to overcome these limitations.

http://dx.doi.org/10.21172/ijiet.83.009

Weather radars can be used to detect bright bands by finding the minimum and maximum reflectivity levels (Kitchen et al., 1994). However, time and spatial resolutions are too low for detecting precise bright band information that is required for a detailed cloud microphysics study. Most of the studies on this subject have been conducted using an X-band Doppler radar (e.g., Fabry and Zawadzki, 1995). Recently, however, L¨offler-Mang and Kunz (1999) and Kunhikrishnan et al. (2006) demonstrated that a Micro Rain Radar (MRR), a vertically pointing Doppler radar, could be a very useful instrument to measure the vertical profiles of precipitation and the bright bands, with the advantage of a higher time resolution, a significantly lower cost than X-band radars, and the easiness of operation.

In addition to MRR and other weather radar observations, several models [Zawadzki et al. 2005; White et al. 2010] have been proposed to estimate the height/intensity of bright band. Minder and Kingsmill (2013) studied the lowering of snow line over Northern Sierra Nevada using Weather Research and Forecasting model. However, modeling of melting layer/bright band either obtains correct reflectivity enhancement or overestimate the intensity by considering the bright band enhancement to be caused by the melting of low density snowflakes along. The lack of agreement of model results with observations is also exacerbated by the fact that there are no extensive measurement records of the bright band. Information about melting layer height and thickness in tropical regions, especially in semi-arid region, has been particularly sparse due to the lack of experimental data. In the present study, BBH measurements are made with a ground based high resolution vertically profiling Micro Rain Radar (MRR). MRR is well suited for melting layer characterization because of no attenuation and also in the Rayleigh scattering regime. However, these measurements will allow us to derive the dependence of bright band characteristics on precipitation type and intensity.

Our main focus is to elucidate the fundamental differences of the bright band characteristics between the two monsoon regime. A literature search indicates that a detailed cloud microphysics study based on the MRR measured bright band characteristics has not been made yet over the SARC region. Long term data presented here justifies the climatological significance of this study.

.

II. EXPERIMENTAL SETUP & TESTBED

The overall research carried out at two experimental sites located at YVU Campus Kadapa (14.47° N; 78.82 ° E), a semiarid global site in Andhra Pradesh, India. Experimental setup 1 covered 3 acres' land, whereas experiment 2 carried out around 100 acres of land. We utilized Semi-arid-zonal Atmospheric Centre (SARC) observational and modelling facilities from Dept. of Physics, YVU Campus. The overall experimental setup and computing facilities presented in the *Fig.1, Fig.2 and Fig.3.*

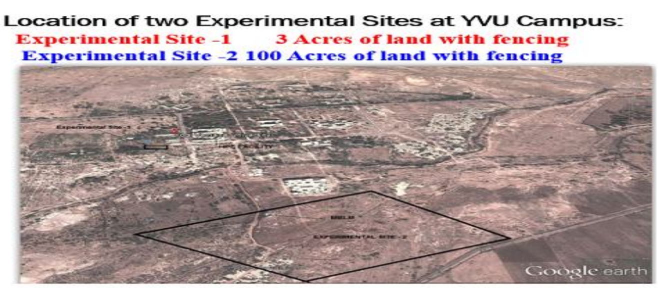

Fig.1. Experimental SetUP

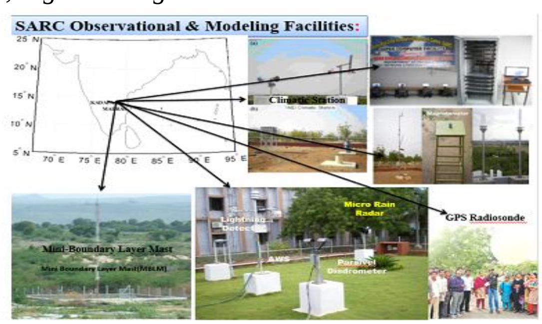

Fig.2.SARC Computing Facilities,YVU Campus Kadapa

Fig.3.Parsivel Disdrometer, MRR (Micro Rain Radar) and AWS (Automatic weather station) setup at YVU Campus

Aforesaid instruments were deployed in YVU campus to track both stratiform and convective precipitation and their characteristics over semi-arid region (Amrutha Kumari et al. 2014; Jayalaksmi and Reddy, 2014; Jayalaksmiet al., 2017*)*. In general, the South-West (SW) monsoon spread over the state from June to September and North-East(NE) monsoon from October to December. In this paper we measured the rain fall information with Micro Rain Radar (MRR) deployed at Kadapa (14.47° N; 78.82 ° E), a semiarid global site in Andhra Pradesh, India. We tracked and observed various microphysical parameters (Rain Reflectivity (Z), Rain Rate (RR), Liquid Water Content (LWC) of the rain with MRR, Disdrometer, AWS in these two monsoons.

In general, the South-West (SW) monsoon spread over the state from June to September and North-East(NE) monsoon from October to December. In this paper we measured the rain fall information with Micro Rain Radar (MRR) deployed at Kadapa (14.47° N; 78.82 ° E), a semiarid global site in Andhra Pradesh, India. For this purpose, we have utilized MRR, Disdrometer, GPS sonde and AWS. Observations with the MRR were carried out fairly continuously from 01st May 2009 to 30th April 2011. Data with a rainfall rate less than 0.1 mm/h are excluded from the analysis. Non-availability of the MRR data, mainly, is due to the power failure at the observational site and also due to the malfunctioning of the instrument.

The Micro Rain radar (MRR) is a vertically pointing FM-CW Doppler radar manufactured by Meteorological schemes TEchniK GmbH (METEK), a German company. The CW-operation makes optimum use of the available transmit power. Thus, a stable and reliable Gunn oscillator with only 50 mW output power can be used for the transmitter. The retrieval of range resolved Doppler spectra follows the method described by Strauch (1976). The specification of the MRR is listed in Table 1. In this study, the height resolution of the MRR was 150 m and the time resolution was 1 minute.

III OBSERVATIONAL STUDY ON MELTING LAYER CHARACTERISTICS

Various techniques have been developed for automated identification of bright band height from radar observations. Traditionally the bright band is depicted in vertical profile of reflectivity as a pronounced maximum or noise. In the present study we utilized the BBH retrieval algorithm given by Fabry and Zawadzki (1995) where the top of the melting layer as the height at which the curvature in log (Z) is maximum. A similar criterion is used to find the bottom of the melting layer. Once the melting layer boundaries are determined, the peak in the bright band reflectivity and its height can be determined. Freezing height (Zero-degree isotherm height) is also calculated from radiosonde data. As the radiosonde measurements are available at standard pressure levels only, the temperature profile is interpolated to get 0^oC isotherm. The height corresponding to 0^oC isotherm is considered as zero-degree isotherm height. In the case of 0^oC at multiple levels, the upper level was chosen. In situations where the entire profile is below freezing level, isentropic extrapolation using a lapse rate of -6.5^oC/km was applied to get the 0^oC level. This extrapolation is necessary to avoid biased statistics.

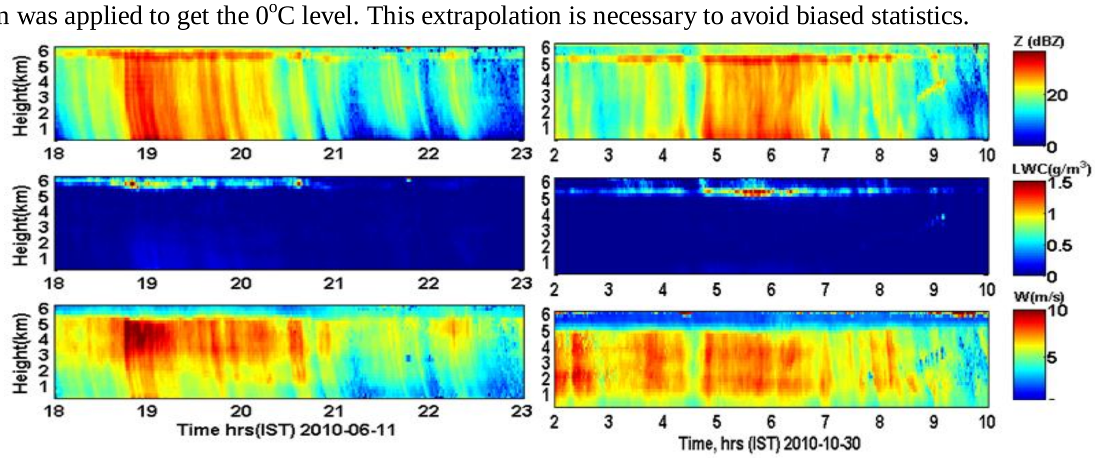

Fig. 4 Time-height cross-section of rain integral [rainrate(RR), radar reflectivity(Z), liquid water content(LWC) and fall velocity(W)] stratiform precipitating clouds observed during SW (on 11th June 2010) and NE (on 30th Oct. 2010) monsoon.

In ***Figure 4***, vertical sections of radar reflectivity (Z), liquid water content (LWC) and Doppler Velocity on 11th June 2010 and 30th Oct. 2010 are depicted. In Figure 4(a& d), MRR -derived radar reflectivity patterns show a prominent and continuous bright band signature whose height oscillated by ~ 250 m from a mean height of 4.3 km. Rainfall rates up to 23 mm/hr. and low-level *Z* maxima approaching 40 dBZ were measured within this rain band. Within the melting layer near 5.2 km msl, *Z* values exceeded 50 dBZ. These observations indicate that this was a relatively intense stratiform rain band. In Figure 54 (c& f), the larger W_{dop}regions reaching about 8m/s located particularly just below the stronger bright band, were well correlated with the regions of higher *Z* streaks.. A positive correlation between $W_{dop}$and *Z* and an increase in their magnitudes over several kilometers above the melting layer indicates a substantial increase in snow aggregation close to 0 ^{o}C level.

IV. Brief description of Non-coalescence-Non-break up (N-N) model

In the past years, different models of the melting process have been developed (Klassen 1988; Fabry and Szyrmer 1999; Olson et al. 2001). In order to address the various dyanmical processes in nature, these models usually apply different parameterizations for the microphysical properties that drive the melting process (see Pruppacher and Klett 1997, chapter 16). Scattering properties at microwave frequencies are usually computed by treating melting particles as a uniform mixture of ice, water, and air with an effective dielectric constant. In this context, a variety of different methodologies have been developed that result in large variability in the electromagnetic properties of melting particles.

In order to resolve the uncertainty of the bright band model, it is necessary to go back to experimental data that can provide some physical constraints. For example, using the Micro Rain Radar data of Kadapa, India during both monsoons, it is possible to retrieve the size distribution of rain below the bright band, and, from this, to draw upwardly both the reflectivity and the Doppler velocity profile in the melting particles region.

The characteristics of the melting layer are not only important for understanding the microphysical processes involved in rainfall mechanism but also necessary for rain retrieval algorithms used for the present and future space-borne rain radars such as Tropical Rainfall Measuring Mission (TRMM) precipitating radar (PR) and Global Precipitation Mission (GPM). The current version of the TRMM precipitation radar retrieval algorithm (version 6 of 2A25) uses the Non-coalescence–Non-break up (N-N) model described in Awaka et al. (1985).

Aforesaid N-N model is utilized for the present study. It assumes that the flux of the particles is preserved during the melting process, i.e. the equation.

$$N_S(D_S).v_S(D_S).dD_S = N_R(D_R).v_R(D_R).dD_R \quad \dots (1)$$

is assumed to hold during the entire melting process. Here, N represents the size distribution, v the fall velocity, D the particle diameter, with S and R representing snow and rain respectively. A full description is given in Awaka et al. (1985), hence only the salient points are given here.

For an assumed drop size distribution in rain, it becomes possible to derive the equivalent size distribution at any given stage in the melting process, provided we know the relationship between the fall velocity of the melting snowflake and its diameter. In this model, two different formulae are used to relate v_S and D_S, depending on the stage of melting. These are given by: -

$$v_S = 8.8\sqrt{(\rho_S - \rho_a)\, 0.1 D_S} \quad \text{m/s for } \rho_S \le 0.3 \text{ g/cm}^3 \quad \dots (2)$$

$$v_S = \frac{(v_R - v_S{}^0).(\rho_S{}^{1/3} - 0.3^{1/3})}{(1 - 0.3^{1/3})} + v_S^0 \quad \text{m/s for } \rho_S > 0.3 \text{ g/cm}^3 \quad \dots (3)$$

Where ρ_S and ρ_a represent the density of snow and air respectively and $v_S$is the fall speed of the melting particle when ρ_S= 0.3 g/m^3.

Using the approximations: -

$$D_S = \frac{D_R}{\rho_S^{1/3}} \quad \text{and} \quad \rho_S = \sqrt{P_W} \qquad \ldots (4)$$

Where P_W represents the volume content of water, the fall speed of each melting particle is determined. $P_W$is obtained from a predefined look-up table as a function of height with respect to the top of the melting layer. In the rain region, the velocity-diameter relationship given by Atlas and Ulbrich (1971) is used for $v_R(D_R)$ in equation (1).

Having derived the size distribution of the melting particles, the radar reflectivity is computed in a manner which is analogous to rain, i.e.: -

$$Z = \int_{D_{min}}^{D_{max}} \sigma_b(D_S).N_S(D_S).dD_S \qquad \ldots (5)$$

Where σb(D_s) is the backscatter cross section of the melting snow particle with diameter Ds. The dielectric constant is calculated from Wiener's theory and the backscatter coefficient σb(Ds) is obtained using Mie scattering (for further details, refer to Awaka et al., 1985). The Doppler spectrum S_s (vs) can be derived in an analogous way using:-

$$S_S(v_S)\,dv_S = N_S(D_S).\sigma_b(D_S).dD_S \qquad \ldots (6)$$

Where NS(DS) is calculated using equation (1). There is one other factor which needs to be taken into consideration, namely the correction term for the fall velocity due to air density change with height. In this study, a US standard atmosphere has been assumed.

The bright band is an important radar feature since changes in precipitation rate and raindrop size distribution (RSD) are closely related to bright band intensity and its dependence on aggregation and breakup. However, only a limited number of studies have used a vertically pointing wind profiler to examine the melting layer microphysics and dynamics within stratiform precipitation (Drummond et al. 1996; Fabry and Zawadzki 1995; Huggel et al. 1996; Zawadzki et al. 2005). To our knowledge, such studies in stratiform precipitation over Kadapa, semi-arid region of India have not been conducted.

4.1 N-N Model result comparison with MRR:

In order to resolve the uncertainty of the bright band model, it is necessary to go back to experimental data that can provide some physical constraints. For example, using the Micro Rain Radar during SW and NE monsoon, it is possible to retrieve the size distribution of rain below the bright band, and, from this, to draw upwardly both the reflectivity and the Doppler velocity profile in the melting particles region.

4.2 Reflectivity-height profiles

The model predictions of dBZ-height variations are given in Figure 5, SW *(on 11th June 2010) and NE (on 30th Oct. 2010) monsoon* (2-hr averaged radar reflectivity profiles are compared. These were obtained using the fitted parameters to the averaged drop size distribution as input to the model for the two cases.

$$N_R(D_R) = N_0 \; exp\left(-3.67\,\frac{D_R}{D_0}\right) \qquad \ldots \quad (6)$$

The surface- Parsivel disdrometer derived rainfall integral parameters are shown in ***Table 2***.

Parameter	11th June 2010 Case 1	30th Oct. 2010 Case 2
N_o	4440	6340
D_o, mm	1.02	0.98
Rain Rate, mm/hr	2.41	1.65

Table 2   DSD parameters from the Disdrometer data

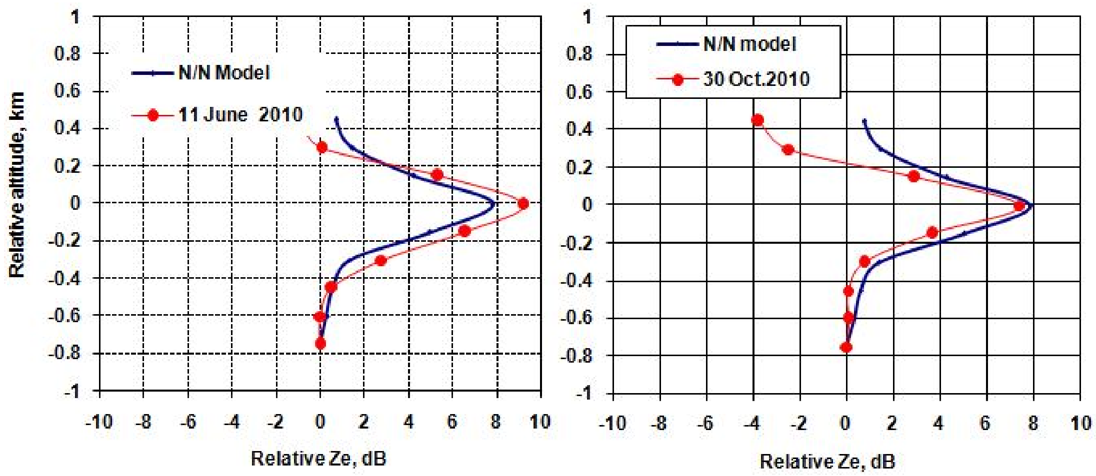

Fig.5: Vertical Profiles of Radar Reflectivity, dB. Comparison between N-N Model and MRR-derived Reflectivity.

The model prediction of dBZ-height variations is given in **Figure 5** These were obtained using the fitted parameters to the averaged drop size distribution as input to the model for the two SW (on 11th June 2010) and NE (on 30th Oct. 2010) monsoon regimes. The model predicted Radar Reflectivity do not show the same trend as was observed with the MRR measurements are depicted in ***Figures 5(a) and 5(b)*** for cases 11th June 2010 and on 30th Oct. 2010. For example, the bright band peak occurs at almost same height for the two days predicted curves and their thickness remains more or less the same. Furthermore, in both cases the model predicts thicker melting layer than the data. These dissimilarities perhaps some limitations of the N-N Model, at least for stratiform rain in tropical regions. It's worth noting again that the MRR radar reflectivity for 11th June 2010 and on 30th Oct. 2010 are consistent with the long-term characteristics of the melting layer in semi-arid region.

V. DISTRIBUTION OF BRIGHT BAND HEIGHT DURING SW AND NE MONSOON

30 minutes averaged BBH's during all the stratiform rain events in SW and NE monsoon periods. Probability distribution of BBH for all the stratiform rain events during both SW and NE monsoon period is given in ***Figure 6.4***. The bright band height varies from 4.8 km to 5.6 km for SW monsoon while it is varied from 4 km to 4.9 km during westerly monsoon period over the probability range 0.01–99.99%.

Firstly, we compare the bright band height obtained by the N-N model and the MRR. For the wind profiler, the bright band heights in each month are averaged using all available precipitation echo profiles obtained in that month.

Figure 6 shows time sequences of the monthly mean bright band height of the two [(a) N-N Model derived Bright Band and (b) MRR estimated Bright Band height. Color scale is for total number of occurrences Mean values are indicated by '+'] from April 2009 to March 2011. Good comparison of the wind profiler with the N-N model, suggests that N-N model output may be used as good surrogate of melting levels in absence of other information, on daily operations. There is very little benefit to using a static climatological vertical profile of reflectivity correction in our region. The large variations of the heights of the 0^oC levels and hence the melting levels would offset any gain due to bias reduction because of the large variances of the melting level heights.

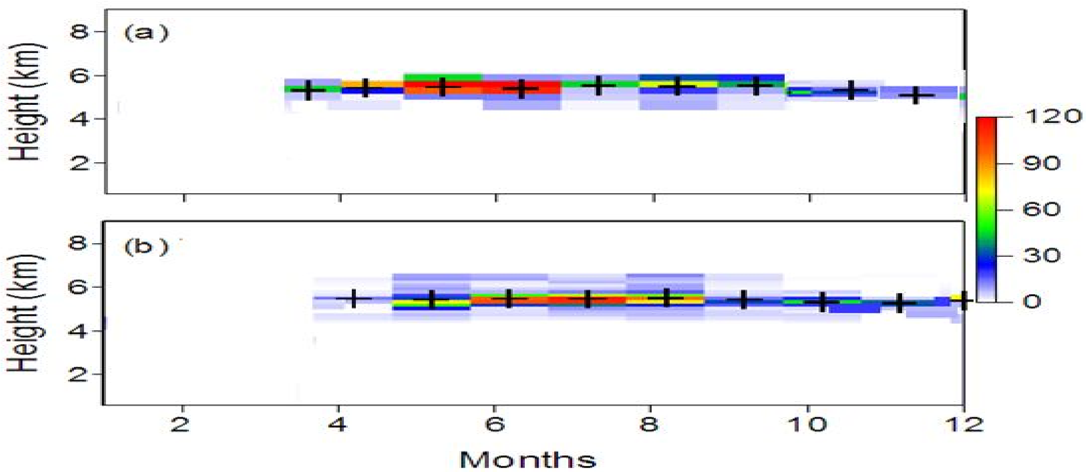

Fig.6 Monthly mean bright band height derived (a) N-N Model and (b) MRR observations from April 2009 to March 2010. Color scale is for total number of occurrences. Mean values are indicated by '+'.

VI.CONCLUSION

Three year of observations from the Micro Rain Radar and TRMM measurements have been analyzed to obtain the bright-band heights associated with the melting layer in stratiform precipitation over semi-arid regions of India. The observational results show that the constant rain height assumption is valid only for some tropical regions. However, it is inadequate to model for region like Kadapa where monthly variability of melting layer is quite significant. Micro rain radar can be used to study the melting layer/bright band height continuously overhead of the experimental site, Kadapa. Monthly variation of bright band height indicates that the SW monsoon months have less bright band height compared to NE monsoon months. However, the probability of occurrence of bright band height is 5.2 km in SW monsoon period and the probability of occurrence is more for extreme values in the NE monsoon period. Annual variability of bright band height shows that the median bright band height is maximum during SW monsoon period and minimum in the NE monsoon period. Hence, seasonal variation in the bright band height is more pronounced compared to monthly variations in the bright band height. We have examined the accuracy of the so-called non-coalescence – non-breakup (N-N) melting layer model by fitting the model predictions to the L-band wind profiler radar data taken in Palau. The comparisons are shown for two cases (i) the top of the melting layer, (ii) the bright-band peak region and (iii) the rain region just below the melting layer. From the observational results it noticed that the N-N model derived spectra agree well with the measurements. The current results give further evidence for the validity of the N-N model for retrieval algorithms for climates affected by monsoon seasons, at least at Rayleigh scattering frequencies.

Acknowledgement

We are very much thankful to **Proof. Krishna Reddy K**, Co-coordinator, Semi-arid zonal Atmospheric Research Centre (SARC), Yogi Vemana University, Kadapa for providing observational data and High Performance Computational Facility**.**

REFERENCE

[1] Amurtha Kumari, N.P., S.Balaji, J.Jayalakshmi and K.Krishna Reddy, 2014: Raindrop size distribution variations in JAL and NILAM cyclones induced precipitation observed over Kadapa (14.47o N, 78. 82o E), a Tropical semi-arid region of India, Indian Journal of Radio and Space Physics, 43, 57-66.

[2] Atlas D., Ulbrich C.W., Marks Jr F.D., Amitai E., Williams C.R. 1999: Systematic variation of drop size and radar rainfall relations. Journal of Geophysical Research, 104, 6155-6169.

[3] Awaka, J., Furuhama,Y., Hoshiyama, M., and Nishitsuji, A. 1985:, Model calculations of scattering properties of spherical bright-band particles made of composite dielectrics. *J. Radio Res. Lab*., 32, 73-87.

[4] Battan, L. J., 1973: Radar Observations of the Atmosphere. The University of the Chicago Press, pp-324.

[5] Cha, J.-W., K.-H. Chang, S. S. Yum, and Y.-J. Choi, 2009: Comparison of the bright band characteristics measured by Micro Rain Radar (MRR) at a mountain and a coastal site in South Korea. *Adv. Atmos. Sci.*, **26**(2), 211–221, doi: 10.1007/s00376-009-0211-0.

[6] Cunningham, R. M., 1947: A different explanation of the bright line. *J. Meteor*., **4**,163.

[7] Fabry, F., and Zawadzki, I., 1995: Long-term radar observations of the melting layer of precipitation and their interpretation. *J. Atmos. Sci*., **52(7)**, 838–851.

[8] Gray, W. R., Cluckie, I. D., and Griffith, R. J., 2001: Aspects of melting and the radar bright band. *Meteorol. Appl*., **8,** 371–379.

[9] Houze, R. A. Jr., 1997: Stratiform precipitation in regions of convection: A meteorological paradox?. *Bull. Am. Meteor. Soc.*, **78,** 2179–96.

[10] Jayalakshmi, J., and K.Krishna Reddy**, 2014:**Raindrop Size Distributions of South West and North East Monsoon Heavy Precipitations Observed over Kadapa (14^{o} 4' N, 78^{o} 82' E), a Semi Arid Region of India, ***Current Science*, 107**, 1312- 1320**.**

[11] Jayalakshmi, J., S.Balaji Kumar, M.Venkatarami Reddy, K Krishana Reddy, Pay Liam Lin, T Narayana Rao and Chian-Yi Liu, 2017: A study on Raindrop Size Distributions Variability in before and after Landfall Precipitation of Tropical Cyclones observed over Southern India, ***Journal of Atmospheric and Solar-Terrestrial Physics*,** 159, 23–40.

[12] Joss, J., Waldvogel, A., 1990: Precipitation measurement and hydrology. Radar in Meteorology,. *Soc*., 577-606.

[13] Klaassen, W., 1988: Radar observations and simulations of the melting layer of precipitation. *J. Atmos. Sci*., **45**, 3741–3753.

[14] Kunhikrishnan, P. K., B. R. Sivaraman, N. V. P. Kiran Kumar, and D. P. Alappattu, 2006: Rain observations with micro rain radar (MRR) over Thumba, *Optical Engineering*, **6408**, doi: 10.1117/12.694115.

[15] Lðffler-Mang, M., and M. Kunz, 1999: On the performance of a low-cost K-band Doppler radar for quantities rain measurements. *J. Atmos. Oceanic Technol*., **16**, 379–387.

[16] Mandeep, J. S., 2009: 0oC isotherm height for satellite communication in Malaysia. *Adv. Space Res*, **43**, 984-989.

[17] Marshall J.S., Palmer W.M. 1948: The distribution of raindrops with size. J. Meteor., 5, 165-166.

[18] Meneghini, R., and Liao, L., 2000: Effective dielectric constants of mixed-phasehydrometeors. *J. Atm. Ocean. Tech*., **17**, 628– 640.

[19] Minder, J. R., and Kingsmill, D. E., 2013: Mesoscale variations of the atmospheric snow line over the Northern Sierra Nevada: Multiyear statistics, case study, and mechanisms. *J. Atmos. Sci.*, **70**, 916-938.

[20] Mondal, N. C., Sarkar, S. K., Bhattacharya, A. B., and Mali, P., 2001: Rain height in relation to 0oC isotherm height over some Indian tropical locations and rain attenuation for an Indian south coastal location for microwave and millimeter wave communication systems. *Int. J. Infrared Millim Waves*, **22**, 495-503.

[21] Olson, W. S., Bauer, P., Viltard, N. F., Johnson, D. E., Tao, W. K., Meneghini, R., Liao,L., 2001: A melting-layer model for passive/active microwave remote sensing applications. Part I: Model formulation and comparison with observations. *J.Appl. Meteor.*, **40**, 1145-1163.

[22] Peters G., Fischer B., Münster H., Clemens M., Wagner A. 2005: Profiles of Raindrop Size Distributions as retrieved by Micro rain Radars, Journal of Applied Meteorology, 44, 1930–1949.

[23] Pruppacher, H. R. and Klett, J. D., 1978: Microphysics of clouds and precipitation.Reidel, Dordrecht. pp-714.

[24] Reddy, K.K., 2003: Diagnostic study on vertical structure of monsoon Precipitating cloud systems, *Indian Journal of Radio & Space Physics* , 32, 198-208.

[25] Smith, C. J., 1986: The reduction of errors caused by bright bands in quantitative rainfall measurements made using radar. *J. Atmos. Ocean. Tech*., **3**, 129-141.

[26] Stewart, R. J., Marwitz, J., Pace, 1984: Characteristics through the melting layer of stratiform clouds. *J. Atmos. Sci*., **41**, 3227–3237.

[27] Thurai, M., and H. Hanado, 2004: Melting layer model evaluation using fall velocity. *IEE Proc. Microw. Antennas Propag*., **151**, 465–472.

[28] Wexler, R., 1955: An evaluation of the physical effects in the melting layer. Preprints, *Fifth Weather Radar Conf.*, Fort Monmouth, NJ, Amer. Meteo. Soc., 329–334.

[29] White, A. B., and D. J. Gottas, E. T. Strem, F. M.Ralph, and P. J. Neiman, 2002: An automated bright band height detection algorithm for use with Doppler radar spectral moment. *J. Atmos. Oceanic Technol.*,**19**, 687–697.

[30] Zawadzki, I., W. Szyrmer, C. Bell, and F. Fabry, 2005: Modeling of the melting layer. Part III: The density effect. *J. Atmos. Sci.*, **62**, 3705–3723.