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NETWORK OF WIND PROFILERS TO UNDERSTAND BOUNDARY LAYER EVOLUTION AND PRECIPITATING CLOUDS OVER ASIA MONSOON

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1. INTRODUCTION

The occurrence of deep convection in the Asian regions play an important role in the global circulation, since it transports heat, water vapor, and so on, from the convective boundary layer (CBL) to the upper troposphere. The vertical distribution of diabatic heating depends on the vertical structure of the convective system; hence it is important to study the CBL evolution and vertical structure of the precipitating clouds occurring in the tropics. Previously, most of the studies carried out in and around Pacific Ocean using VHF/UHF wind profiler network [Gage et a., 2002]. In the Asia region, Wind profiler radar remote sensing of the tropical monsoon cloud systems and also studies on convective boundary layer are very limited. Comprehensive investigations are required to understand the Asia monsoon precipitating cloud systems. Also, since mid 1980's Doppler radars have been recognized as a useful tool to estimate vertical raindrop size distribution (DSD) profiles to study microphysical processes of precipitation and to develop DSD models for space borne rain radar algorithms.

2. RESEARCH PLAN

To understand the structure and behavior of monsoon cloud systems is a prerequisite for accurate representation of diabatic processes in large-scale numerical simulation and prediction of monsoons and of the global circulation. Therefore, our group at IORGC initiated collaborative research activity with several Institutes/ Universities (Fig.1& Table 1) to understand *'Asia monsoon convection'* using VHF/UHF wind profiler (WP) network and other collocated instruments for the next five years:

1. To understand key issues in the Asia monsoon convection processes including PBL, cloud systems (microphysical and DSD), land-atmosphere interactions, ocean-atmosphere interactions with diurnal, intra-seasonal (MJO) and seasonal time scales.
2. Investigate the role of the convective boundary layer in driving diurnal, intra-seasonal and spatial variability of the precipitating cloud systems.
3. UHF/VHF radars are optimum tools to investigate the development of overhead convection. We utilize VHF/UHF and Doppler radar data to study of convection processes in the boundary layer and prepare climatology of potentially different convection events in different environment and climatological conditions over the maritime continent region.
4. What is the probability density function (PDF) of vertical motions in tropical convection and how does this depend on the regime (e.g. monsoon vs. Open Ocean vs. continental). Where there are large variations in both the forcing and large scale environment? How do these variations reflect in the amount of cloud cover associated with individual mesoscale precipitating cloud systems? Are there systematic variations of Rain drop size distribution (DSD) associated with these different regimes?
5. To elucidate the global climate change, focusing on the ENSO (El Nino Southern Oscillation) event around the Asia and Western Tropical Pacific
6. We also utilize the PSU/NCAR mesoscale model (known as MM5), Weather Research and Forecast (WRF) and other climatological model to understand monsoon convection processes.

Some of these studies will be carried out, if possible, in cooperation and collaboration with the

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recently established "International Network of Tropical Atmosphere Radars (INTAR)" research program. In this presentation, 2 and some extent 1, 3 and 4 are documented.

3. OBSERVATIONAL SITES AND DATA-BASE

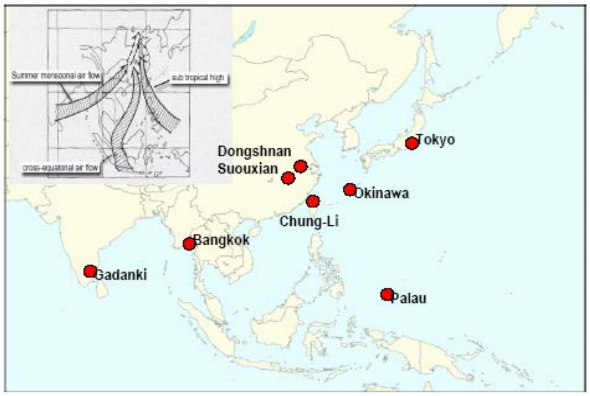

Fig.1. The map showing location of the wind profilers in the Asia Monsoon region. (Inset: Summer monsoonal flow from three different regions)

profiler (WP) data. GD-WP is situated in a rural environment about 120 km to northwest of Chennai (Madras) on the east coast of the southern India peninsula. The local and general topography is rather complex with a number of hills and a very irregular mix of agricultural, small-scale industrial, and rural population centers. Observations with the GD-WP were carried out fairly continuously from 01 October 1997 to 30 September 2000.

Whereas AI-WP is located in the high island of Babeldaob (in the Palau (508 Sq. km) archipelago), which is one of the largest islands in the western Pacific Ocean. Babeldaob Island is partly elevated limestone and partly volcanic. The vegetation in this island varies from the mangrove swamps of the coast, with trees often from 10 – 16 meters high; to the savannah type grasslands of the near interior which support palms and pandanus, and the densely forested valleys further inland. AI-WP is in continuous operation since 08 March 2003. For the present study from 15 March 2003 to 14 March 2004 data has been utilized. For detailed Gadanki and Palau wind profiler description, data

Table 1: Location of Wind profilers and other collocated instruments in Asia for the monsoon study

Parameter	Aimeliik PALAU	Gadanki INDIA	Bangkok THAILAND	Chung-Li TAIWAN	Okinawa JAPAN	Shouxian CHINA	Dongshan CHINA	Tokyo JAPAN
Location	07.4°N, 134.5°E	13.5°N, 79.2°E	13.7°N, 100.8°E	25.2°N, 121.4°E	26.6°N, 128.24°E	32.55°N, 116.78°E	35.7°N, 139.5°E	35.7°N, 139.5°E
VHF/ UHF Wind Profiler	1290 MHz	53/1357 MHz	1357 MHz	50/915 MHz	443/1357 MHz	1290 MHz	1290 MHz	1357 MHz
RASS	Yes	—	—	Yes	Yes	Yes	Yes	Yes
Doppler Radar	Yes	Yes	—	Yes	Yes	—	Yes	—
JW Disdrometer	Yes	Yes	—	Yes	Yes	Yes	Yes	Yes
μ Rain Radar	Yes	—	—	—	—	—	Yes	—
Optical Rain Gage	—	Yes	—	Yes	Yes	—	—	—
Celiometer/Lidar	Yes	Yes	—	—	—	—	—	—
μ Radiometer	Yes	Yes	—	Yes	—	—	—	Yes
AWS	Yes	Yes	—	Yes	Yes	Yes	Yes	Yes
Operating Institute	IORGC, Japan	NMRF, India	NICT, Japan	NCU, Taiwan	NICT, Japan	HyARC, Japan	IORGC, Japan	NICT, Japan
Observations started	March 2003	1991/1997	January 1994	1984/1987	January 1997	May 2003	May 2001	January 1993

IORGC : Institute of Observational Research for Global Change, Japan
NMRF : National MST Radar Facility, India
NICT : National Institute of Information and Communications Technology, India
NCU : National Central University, Taiwan
HyARC : Hydrospheric Atmospheric Research Center, Nagoya University, Japan

We have just started collecting data from different locations (as shown in Fig.1) and also due to incompletion data analysis, present paper shows boundary layer evolution and its influence on precipitating cloud systems in the continental region and also in the oceanic region i.e., form the Gadanki (GD) and Aimeliik (AI) L-band wind profiler (WP) data. collection and operation strategy, refer to Krishna Reddy et al. (2002 and 2004).

In this presentation, we also show some results of vertical DSD profiles estimated from VHF wind profiler operated at Gadanki, India and Chung-Li, Taiwan to study the DSD properties of tropical precipitation and typhoon.

4. CONVECTIVE BOUNDARY LAYER EVOLUTION DURING DIFFERENT SEASONS

Wind profiler offers the unique ability to directly measure vertical motion profiles through precipitating and non-precipitating cloud systems.

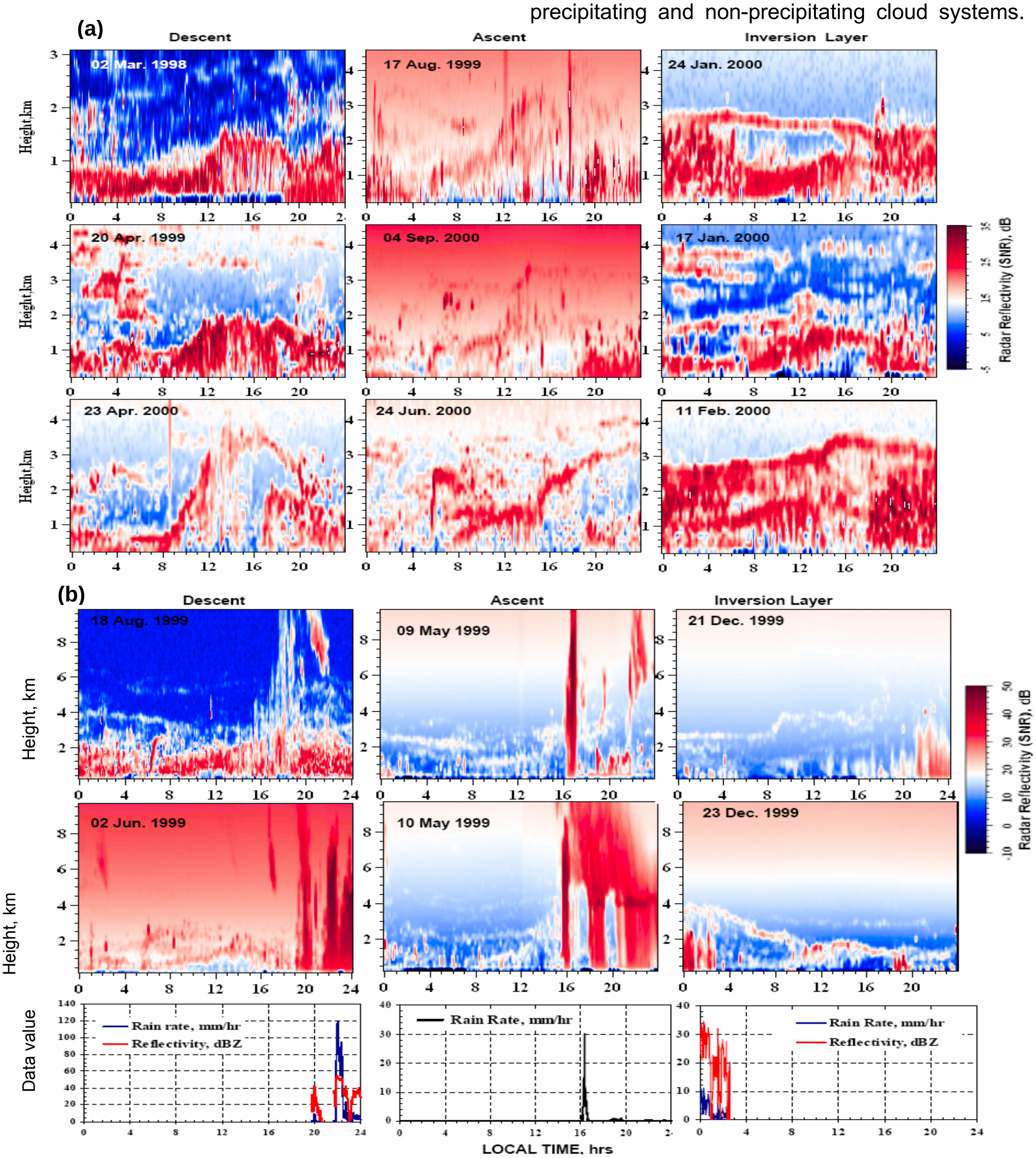

Fig.2 Time-height cross section of the Gadanki wind profiler (vertical beam) range-corrected reflectivity (SNR) during (a) 'dry' and (b) 'wet' convection days during different seasons.

Figure 2 and 3 show the time-height cross-section reflectivity observed with GD and AI wind profiler during different seasons. Strong reflectivity

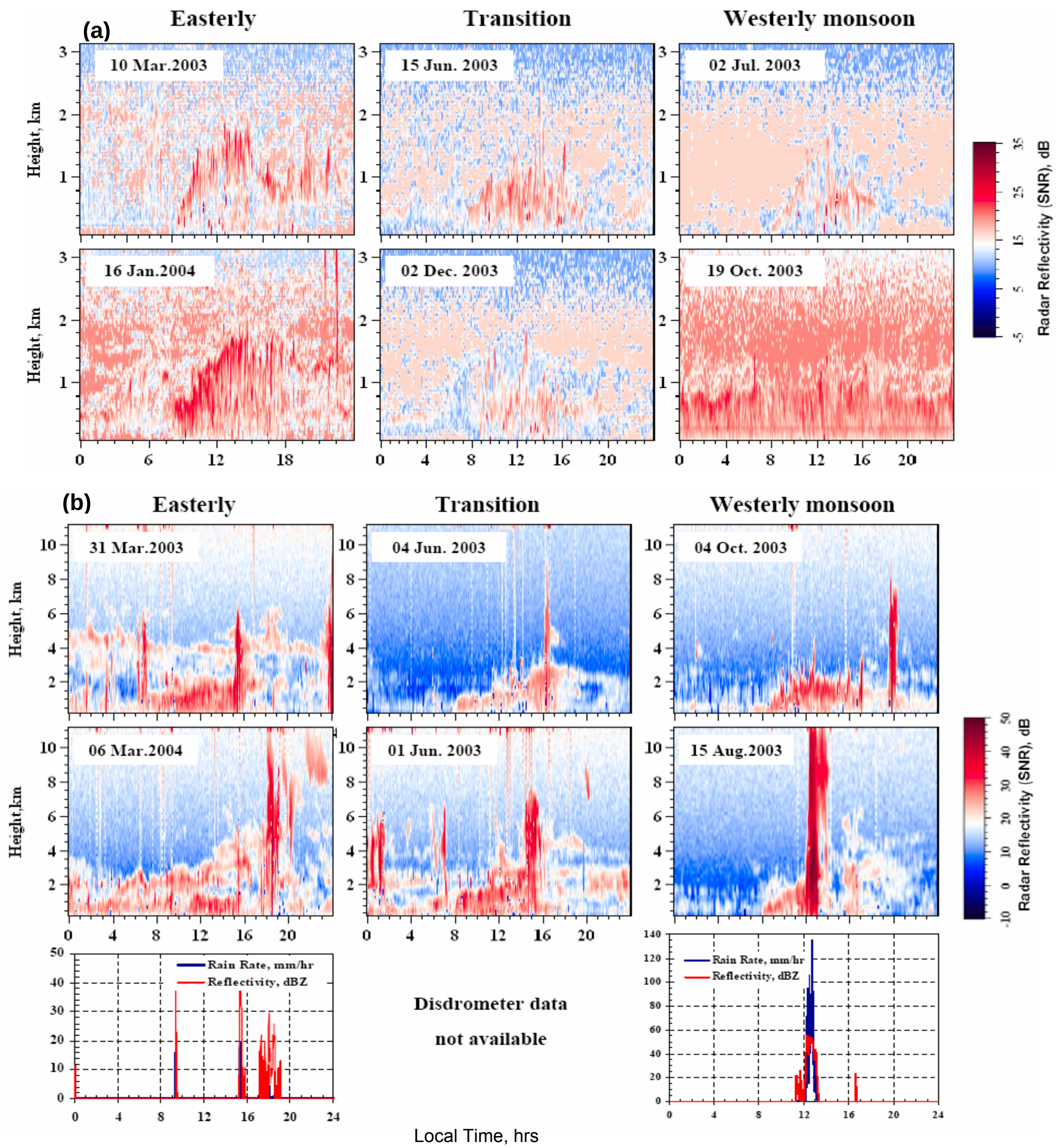

Fig.3 Time-height cross section of the Aimeliik wind profiler (vertical beam) range-corrected reflectivity (SNR) during (a) 'dry' and (b) 'wet' convection days during different seasons.

observed during morning hours corresponds to the morning transition or the morning rise of the inversion. The significant echo region appears in the lowest observational heights and ascends gradually, reaching a maximum height in the afternoon hours. This strong echo region marks the height of the daytime boundary layer or convective boundary layer (CBL). These features can be used for understanding the triggering of convection.

The WP reflectivity provides a detailed record of the evolution of CBL throughout the day. We adopted similar scheme proposed by Grimsdell and Angevine (2002) and also added another category of the CBL evolution based on GD-WP long-term data. In the present study CBL evolution during precipitating period also included. However,

those data was excluded when estimating the CBL depth. We established the following conditions that had to meet for inclusion in the CBL study.
The reflectivity pattern shows growth of the CBL during the morning transition that indicated the presence and growth of boundary layer thermals.
During the afternoon, a discernible and coherent pattern could be seen in the reflectivity figure. The spectral width (not shown here) shows a similar pattern, indicating that the reflectivity is related to turbulent activity within the CBL.

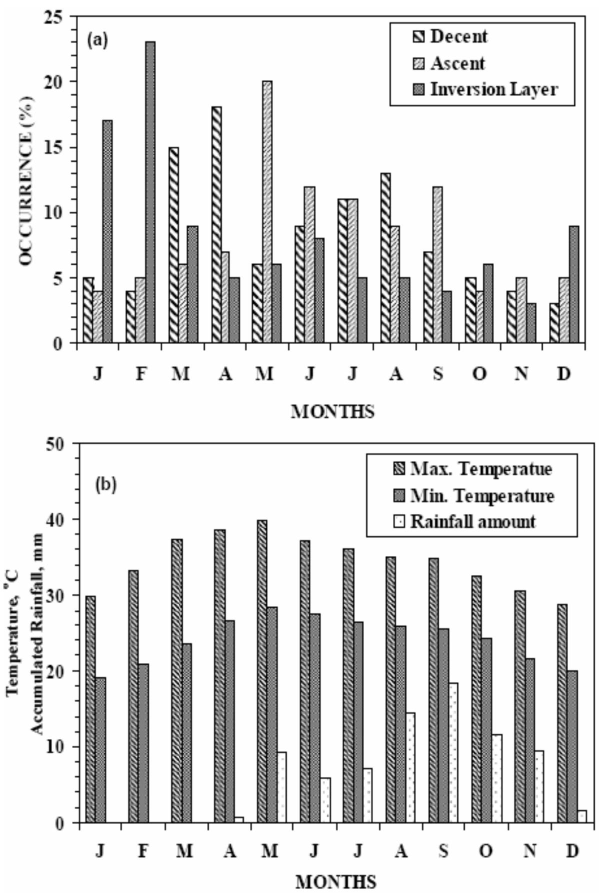

Fig.4. (a) Monthly variation of Decent, Ascent and Inversion Layer observed over Gadanki. (b) Monthly variation of minimum and maximum temperature and also rainfall observed over Gadanki using Automatic Weather station data

As was previously mentioned, much variation was observed in the behavior of the CBL during the morning, afternoon and early evening, in contrast with the consistency seen during the night time. The definition of three categories and the assignment of particular days to those categories based on two-dimensional patterns were necessarily subjective. Although it may be possible to describe these patterns with a small number of objective parameters, we did no do so; such pattern recognition is a notoriously difficult problem.

The three categories were named descent, ascent and inversion layer (IL)) based on the behavior of the profiler reflectivity in each category. The defining characteristics of the categories are as follows.

1. Descent:

The reflectivity pattern shows growth of the CBL during the morning transition that indicated the presence and growth of boundary layer thermals. The reflectivity is strong throughout the CBL depth during the morning and evening transition hours, with correspondingly large spectral width (not shown here), implying the presence of strong convection. From late afternoon to evening (i.e. in the evening transitions hours – between 1600 to 1800 hrs LT), the maximum height reached by the strong reflectivity steadily decreased while the signal strength remained constant and the spectral width remained small.

2. Ascent:

During the morning the reflectivity pattern shows CBL growth similar to that on the descent days. Moreover, CBL is continuously ascended after midday also. During the evening transition hours mostly CBL will be ascended or disappeared. However, despite this strong reflectivity, the spectral width was smaller, indicating weaker turbulence.

3. Inversion layer (IL):

WP reflectivity pattern shows CBL evolution similar to the descent days but through out the day persistence of an inversion layer between 1.5 to 3.5 km with strong reflectivity and also existence of the nocturnal multiple elevated layers (sometimes in the day time also).

Information from the surface weather maps (issued by India Meteorological Department), disdrometer, optical rain rage and Automatic weather station data is examined to see weather there any differences in the measured variables that could explain the observed differences in reflectivity between the three categories. Difference in temperature and humidity affect energy partitioning within CBL. In moist conditions, more energy is partitioned into latent heat flux, leading to weaker convection. This effect is consistent with the formation of a weak capping inversion that was present in the descent case, usually its occurrence is maximum in SW monsoon period [Fig. 4 and Table 2(b)]. It is also the fact that the average CBL depth of descent days was low [max. occurrence in monsoon (average CBL height ~1.4 km)] in comparison with ILS [max. occurrence pre monsoon (~2.6 km)].

The overall marine boundary layer (MBL) structure as observed by the AI-WP, Ceilometer, radiosonde, and various surface meteorological sensors was fairly uniform over the analysis period (Reddy et al., 2004). From these studies we found that MBL evolution is distinctly different from the CBL evolution over GD. The detailed analysis is in progress.

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Ventilation Coefficient (VC) represents the rate at which the air within the CBL is transported. This parameter plays an important role in the formation of CBL patterns.

Ventilation Coefficient (m^2/s^{-1}), VC can be defined as (Praveena and Kunhikrishnan, 2004)

$$VC = Z_i \, U$$

Where Z_i is the CBL height and U the averaged wind velocity

$$U = \sum_{i=1}^{i=Z_i} u_i$$

The seasonal variation of VC revealed low values during winter and high values during monsoon season. The analysis showed that VC is strongly influenced by wind speed during monsoon; whereas both CBL height and wind speed determine the value of VC during the other seasons over GD. The VC values are very less over AI compared to GD may due to northern hemisphere trade wind inversions.

Table 2 (a): Seasonal variation of Convective Boundary Layer (CBL) depth/height and Ventillation Coefficient (VC) at Gadanki (Oct.'97 to Sep'. 00)

Season/Climate	Months	No. of days CBL evolution	Mean noontime CBL height (km)	VC m^2S^{-1}
Summer/Pre-monsoon	March to May	143	2.68 ± 0.52	9467
Dry to Wet transition	May	47	2.38 ± 0.42	10565
South-West Monsoon	June to September	97	1.42 ± 0.33	13491
SW to NE monsoon transition	October	20	1.49 ± 0.35	11115
North-East Monsoon	October to Early December	36	1.51 ± 0.39	10015
Winter	Late December to February	119	1.68 ± 0.37	8305

Table 2 (b): Seasonal variation of Marine Boundary Layer (MBL) depth/height and Ventillation Coefficient (VC) at Aimeliik (Mar.'03 to Mar'. 04)

Season/Climate	Months	No. of days CBL evolution	Mean noontime CBL height (km)	VC m^2S^{-1}
Easterly monsoon	Late December to April	51	1.28 ± 0.26	6467
Easterly to Westerly monsoon Transition	May and June	18	1.11 ± 0.17	5463
Westerly Monsoon	July to October	36	1.22 ± 0.21	8765
Westerly to Easterly monsoon Transition	November to Early December	11	0.97 ± 0.16	4893

5. DIURNAL AND SEASONAL VARIATION OF PRECIPITATING CLOUDS OVER GADANKI AND PALAU

Wind profiler observations yield time height cross-section of reflectivity, Doppler velocity, and spectral width that illustrate the evolution of precipitating clouds. The vertical structure of these parameters has been used to classify the precipitating cloud systems into three different categories: Convective, Transition (mixed convection-stratiform) and Stratiform) [based on modified version of the classification of Williams et al. (1995)] at Palau and Gadanki. These observations document the prevalence of deep anvil cloud systems over the western pacific warm pool region and also Gadanki before (during May month) onset of the South-west monsoon. Rao et al. (2002) showed that during mid May frequent thunderstorms activity over this region because of

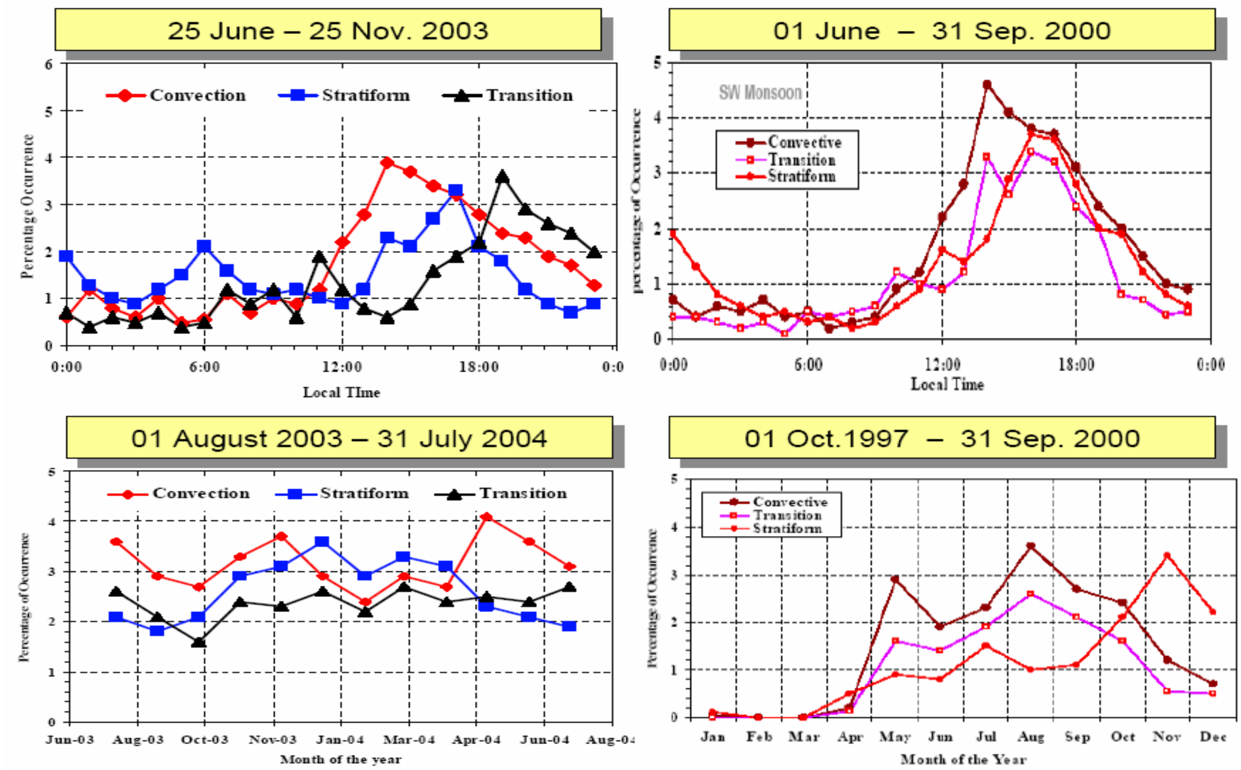

Fig. 5: Diurnal & Seasonal variation of precipitating clouds over Aimeliik & Gadanki

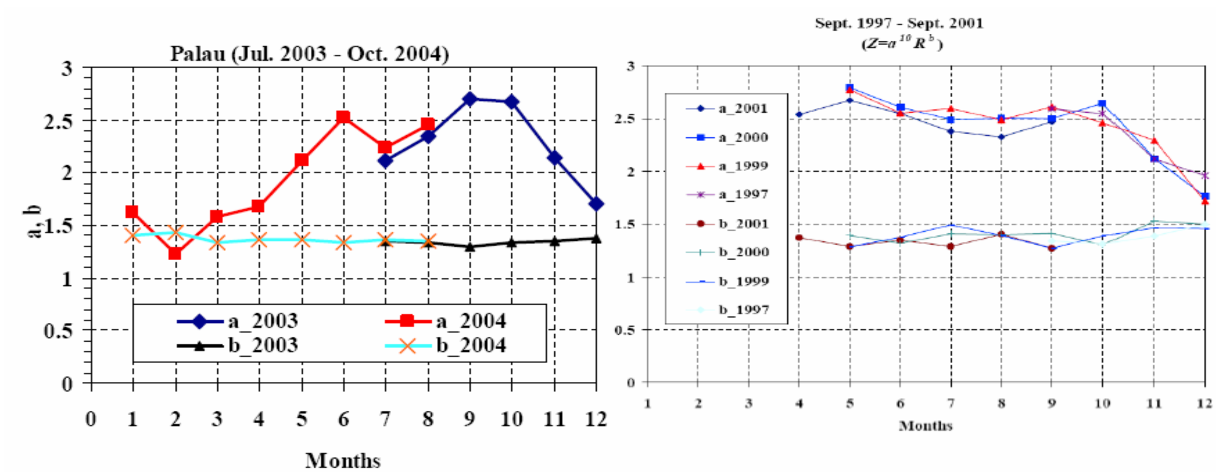

Fig. 6: Seasonal variation of the coefficient “a” and exponent “b” of $Z = 10^{a}R^{b}$ at Aimeliik and Gadanki.

dry to wet transition that is favorable for the “local convection”. Figure 5 shows the observation results of the precipitating cloud systems over AI and GD. Both sites the occurrence of precipitating clouds reaches a maximum in the SW monsoon compared with the NE monsoon. Diurnal variation of convection seems to occur within 1300–1700 LT over GD. However, during (westerly or southwesterly) monsoon period, occurrence of convective clouds are pre-dominant over Gadanki whereas mixing (Convective/ stratiform) clouds are observed over Aimeliik.

We have also utilized GD and AI Disdrometer data analysis to characterize Rain drop size Distribution (DSD) [rain rate (R) and Z factor] with “macro-scale” environmental factors. We define “macro-scale” properties here those having gradual space and/or temporal variabilities, e.g., diurnal and seasonal variations and their climatological dependences. Figures 6 [(a) and (b)] show the seasonal dependence of the coefficient "*a*" and exponent "*b*" in the *Z–R* relation. It is seen from Fig.6 during summer/westerly monsoon periods, "*a*" (the usual coefficient in *Z–R* relation) ranges between about 250 and 500, while during easterly monsoon, "*a*" decreases drastically. The exponent "*b*" also changes somewhat, which may be related to seasonal changes of light and heavy rains in NE monsoon and SW monsoons.

6. CHARACTERISTICS OF VERTICAL PROFILES OF RAINDROP SIZE DISTRIBUTION (DSD) DERIVED FROM VHF WIND PROFILER

The methodology of DSD estimation is a non-linear least square-based parametric estimation that have been employed by many researchers (e.g. Wakasugi et al., 1987; Gossard, 1988). Most importance of this paper is to describe a new form of Gamma DSD model (Kozu et al., 1987) that employs two arbitrary moments as free DSD parameters is proposed to enhance the flexibility in studying the characteristics of Gamma DSD model to fit the Doppler radar spectrum. Stabilized Gauss-Newton method is used to obtain the solution to the non-linear least squared (NLLS) problem. The goodness of a DSD model is evaluated in terms of the stability in solving NLLS problem and the accuracy in DSD moment estimates.

6.1 Indian MST Radar Observations of Stratiform Precipitation during Northeast Monsoon

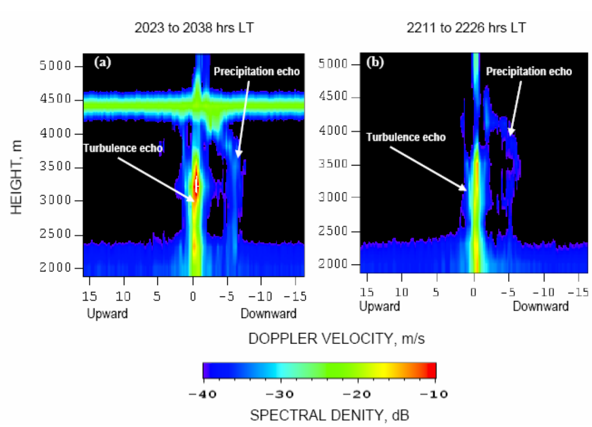

Fig.7 Vertical profile of echo power densities [dB/(ms-1)] observed on 23 Oct. 1997 (8 incoherent Integrations) [Upward motions are to the left of the zero value]

Doppler spectra obtained with the vertical beam observed on 23 Oct.1997. The vertical resolution is 150 m. Figure 7 [(a) and (b)] clearly demonstrates the existence of two spectral peaks in the Doppler spectra. The peak at the zero Doppler frequency shifts is coming from the refractive index fluctuations through Bragg scattering and the other peak, in the negative side of Doppler spectrum, is coming from the hydrometeors through Rayleigh scattering. Since these inhomogeneous structures are advected with the mean wind, the turbulent peak represents the vertical air motion. Wind profiler radar operating at 53 MHz is more sensitive to Bragg scattering. Consequently, the precipitation echo can be identified along with the clear air echoes during moderate to heavy rain.

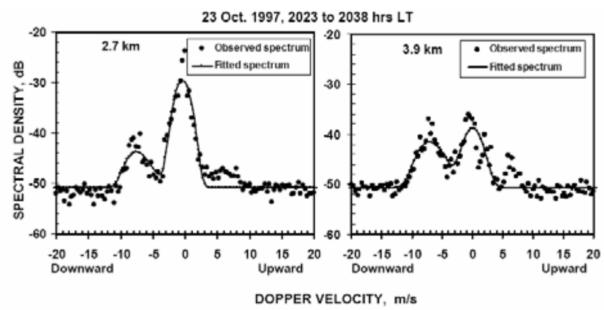

Fig.8. 15-min averaged spectra collected between 2023 to 2226 hrs LT on 23 Oct.1997 at (a) 2.7 km and (b) 3.9 km

Figure 8 [(a) μ=0 and (b) μ= 6] shows a typical example of the VHF radar spectra and fitted spectra (smoothed at two altitudes). From Fig.8 it can be noticed that the fitted and measured spectra for precipitation echo are in reasonably good agreement. Some difference in turbulence echo may be due to the non-Gaussain targets in the vertical incidence.

Figure 9(a) shows the drop concentration *N*(*D*) [m^{-3} mm^{-1}] derived from the wind profiler radar measurements (using gamma model with μ = 0), disdrometer and also from Marshall-Palmer (M-P) distribution. The shape of *N*(*D*) derived from radar observations, particularly, at 2.1 km, is very closely followed as M-P distribution[2] and also has reasonably good agreement with disdrometer estimated *N*(*D*) on the ground. To validate the present model, a relative comparison has been made with the exiting lognormal Indian climate model. Wind profiler radar derived DSD parameters [Fig.9(b) with μ =6] agree closely with lognormal model as compared to M-P distribution. The present results suggest that gamma model is also useful for the estimation of DSD parameters in the tropics, especially, from VHF wind profiler radar observations.

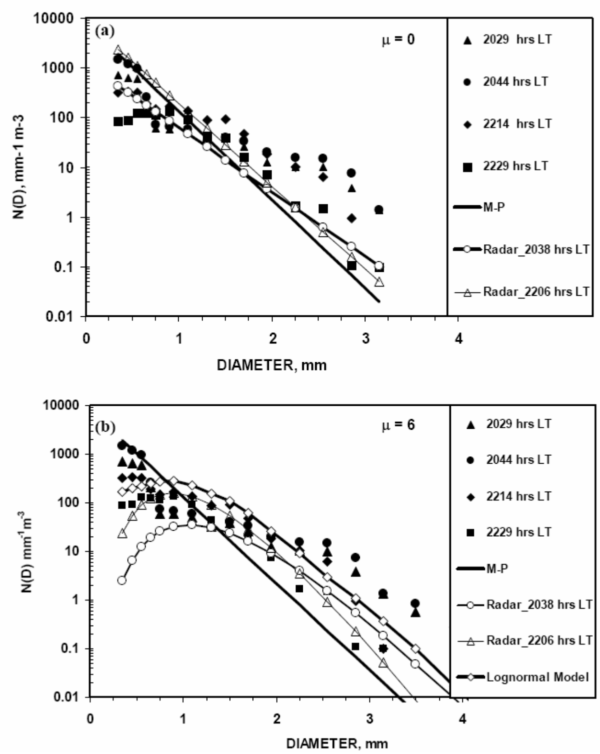

Fig.9. 15-min integrated DSD measured by the VHF radar (at altitude of 2.1 km) and Disdrometer [To estimate DSD parameters gamma model is used when (a) μ = 0 and (b) μ = 6]

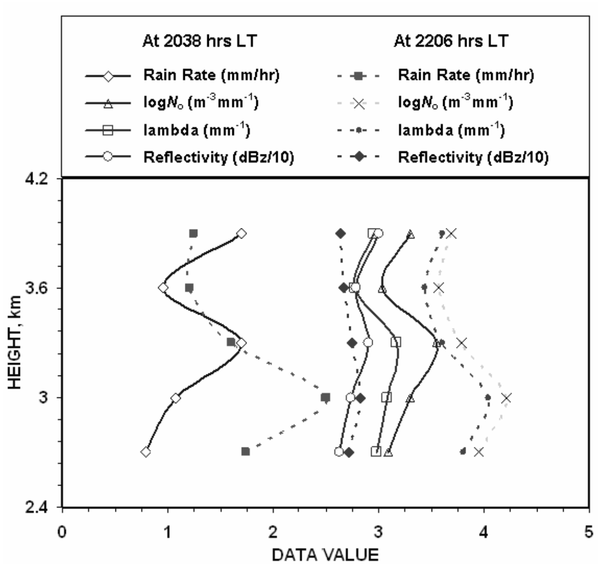

Fig.10. Altitude variations of DSD parameters [rain rate (mm/hr), reflectivity (dBz), scaling parameter, N_o ($m^{-3}mm^{-1}$ and slope, $\Lambda(mm^{-1})$] retrieved for μ = 6 on 23 Oct. 1997 [Each Doppler spectrum is average of 15 min (2023 to 2038 hrs LT & 2211 to 2226 hrs LT).

Vertical profiles of the DSD parameters estimated from the wind profiler radar observation are shown in Fig.10. These results are verified with previous DSD parameters estimated in the tropics and found that these values are within the limit of the stratiform precipitation.

6.2 Chung-Li VHF Radar Observations of typhoon Lekima

We used our DSD algorithm to estimate the microphysical (i.e., drop size distributions) properties of precipitating systems associated with typhoon Lekima (September 26-28, 2001) using Chung-Li VHF radar.

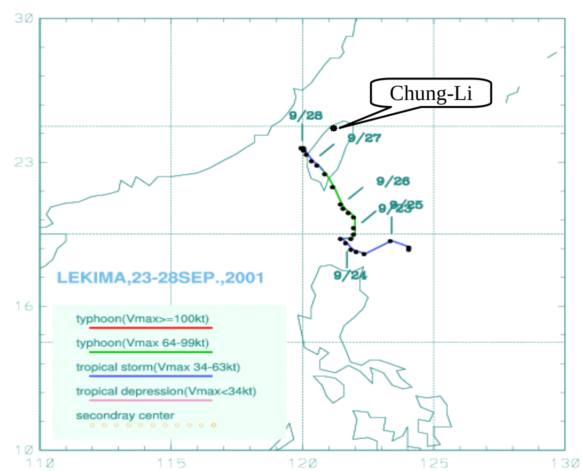

Fig.11. Movement of typhoon Lekima from 23 - 28 September 2001

Figure 12 (a) and (b) shows Height normalized profile of sample power spectra plots with fitting during a stratiform and convective event, respectively. The fluctuating line is the observed power spectra and smooth-solid line is that of spectra deduced using model.

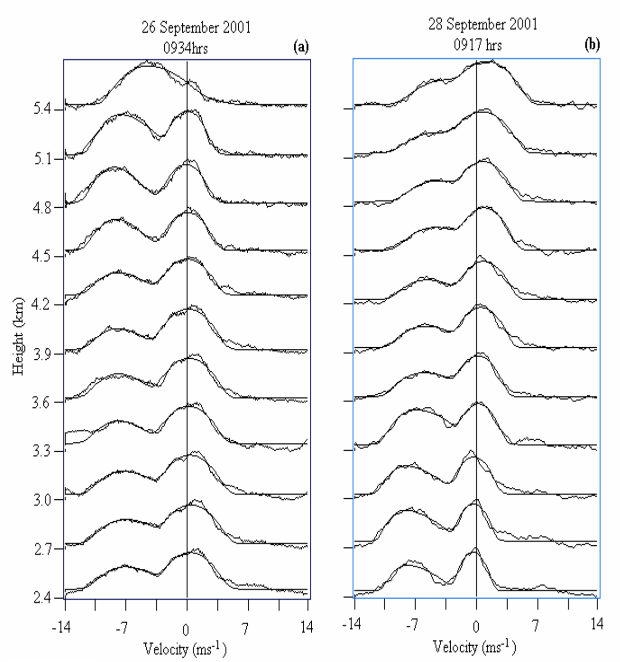

Fig.12. Height normalized profile of power spectrum observed (fluctuating line) and fitted (smooth line) during (a) stratiform event on 26 September 2001 and (b) convective event on 28 September 2001.

Figure 13 [(a), (b), (c)] shows radar reflectivity (dBZ), rain rate and drop concentration observed at 0906 –0920 LT on September 28, respectively. This event is classified as convective and maximum rain intensity observed is 6.6 mm/hr, which is the maximum reported rain rate during all the events in the typhoon. The other convective events observed on September 27, 1025-1109 LT is weak with a maximum rain arte of 2.7 mm/hr [not shown here]. The shallow convective case reported at 1400-1445 LT has a maximum rain rate 1.8 mm/hr [not shown here]. Remaining time of precipitation events, which radar could detect shows moderate rain with maximum value of rain rate varies from 1.0 to 2.8 mm/hr. For both convective case reported the DSD are comparable but gives different rain rate. The stratiform event on September 26 is comparable in DSD to that of strongest convective case reported even though it has different microphysical process. The convective event reported has duration about 10-15 minutes. This may be a characteristic feature of the convective phenomena within the cells of the rain-bands that move with the typhoon. Therefore, the 10-15 minutes duration may indicate the horizontal dimension of the convective cells in the typhoon. In the case of stratiform precipitation, most of the time rain gauge recorded value is

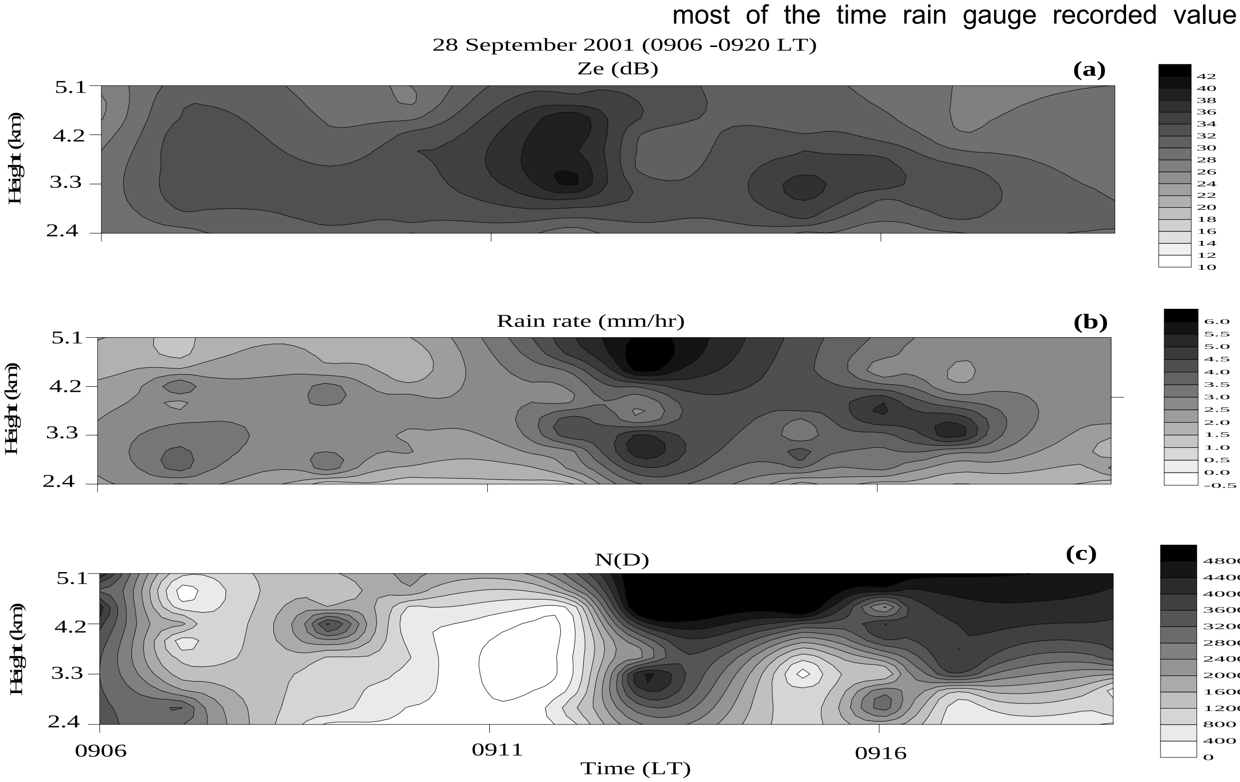

Fig. 13. Drop-size distribution estimated on 28 September 2001, 0906 – 0920 hrs

lower than the values estimated. In the convective case the rain gauge recorded value is higher than the values estimated. This clearly shows that in the case of stratiform type while rain-drops falls down may get partially evaporated and reformed as clouds depends on the meteorological condition prevailing and there by reduced rain rate at ground level, where as in the case of convective case the aggregation is taking place even below the radar observation region there by increase in rain rate. It suggest that to derive the complete information about the process such as classification of rain type, Z-R relation and other rain parameters it is essential to take in to account the profiles of reflectivity, velocity and velocity width along with DSD.

7. CONCLUSIONS

i. Extensive observations of the CBL revealed that well-distinguishable features over Gadanki in winter, pre-monsoon, pre-SW, SW, pre-NE and NE monsoon. Whereas Aimeliik observations shows that the marine boundary layer evolutions is somewhat different.

ii. From a wide variety of observed patterns from Gadanki-WP, three categories are identified: (i) Decent, (ii) Ascent, and (iii) Inversion Layer. WP results showed that the descent days to be warmer and moister than ILS days, with a weaker capping inversion. Dry convection during descent days was less vigorous, which led to fewer clouds, a lower CBL depth, and earlier fading of the CBL. Since the intermountain region is quite dry, it frequently features a deep and dry convective boundary layer.

iii. Over GD, the strength of the low-level jet is indicated as VC that shows higher values during monsoon season and low values during winter. However, VC values less in comparison with GD observations.

iv. Wind profiler and Disdrometer (at GD & AI) analysis show clear diurnal and seasonal dependence raindrop size distribution characteristics in westerly monsoon. During the westerly monsoon often the precipitating systems are associated with convection activities and also short duration with high intensity of rainfall. Whereas easterly Monsoon cloud systems are cyclonic in nature and occurrence of stratiform precipitation is dominant.

v. Wind Profiler observations of the precipitating clouds over AI and GD shows some similarity during summer monsoon but their characteristics are distinctly different during easterly monsoon. Moreover, Disdrometer observational results suggest that DSD characteristics are also different during two monsoon seasons.

vi. The estimated DSD parameters from the Indian MST Radar (stratiform precipitation) spectrum data collected on 23 Oct. 1997 show reasonably good agreement with disdrometer derived DSD. Relative comparison with tropical lognormal model also demonstrates fairly good agreement. Results indicate that the wind profiler radar - retrieved DSD closely match as the independent DSD measurements by disdrometer at Gadanki, suggesting that the wind profiler radar technique could be useful to calibrate scanning radar estimates of rainfall (i.e., *Z-R* techniques).

vii. During the passage of Lekima typhoon, a detailed analysis is carried out using Chung-Li VHF radar. There are two convective and one shallow convective event observed in three-day observation and remaining time precipitation shows the characteristics of stratiform type. The convective event reported has duration about 15 minutes. This may be a characteristic feature of the convective phenomena within the cells of the rain-bands that move with the typhoon. In the case of stratiform precipitation, most of the time rain gauge recorded value is lower than the values estimated and reverse is the case for convective events. The features of the bright band during convective and stratiform rain are in well agreement with the cases reported elsewhere. DSD parameters were deduced for all the events and shows reasonably good agreement with the observations.

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