CALIBRATION OF RADAR RAIN RATE WITH GROUND TRUTH DATA IN SYLHET

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Certification of Thesis Work

The thesis titled **"Calibration of radar rain rate with ground truth data in Sylhet"** Submitted by Asma Sabin, Roll No. 9514017 F, Session: 1994-95-96 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Philosophy** in Physics on August 20, 2001.

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It is hereby declared that this Thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

Weather radar collects data to detect reflectivity and reflectivity is usually used to estimate rain rate. Conventional weather radar collects data in a format that calculate reflectivity in a continuous pattern of 1 dBZ interval. Bangladesh Meteorological Department (BMD) has 4 radars installed at Dhaka, Rangpur, Cox's Bazar and Khepupara. These radars collect data individually and in composite way. BMD radar data format is different from conventional radar data and not very useful to estimate rain rate. The data format is different in the sense that BMD radar collects data in six different patterns viz; (a) Status 1 = 1 ~ 4 mm/h, (b) Status 2 = 4 ~ 16 mm/h, (c) Status 3= 16 ~ 32 mm/h, (d) Status 4 = 32 ~ 64 mm/h, (e) Status 5 = 64 ~ 128 mm/h and (f) Status 6 = more than 128 mm/h. In each Status there is a wide range of rain rate and it is very difficult to extract rain rate for a particular instant from these wide range. No method has yet been developed to determine particular rain rate from BMD radar data, which is essential for practical and for different research purpose. To overcome this problem initiative has been taken to calibrate BMD radar data with 1-minute interval raingauge data collected in a dense raingauge network in Sylhet.

In this work it is found that frequency in Status 1 is most dominant for all the stations Amalshid (24.877°N, 92.476°E), Chhatak (25.041°N, 91.673°E) and Netro Haor (25.035°N, 92.083°E). Rain rate is calculated from the matching events of radar images and raingauge rainfall. Calibrating radar Status with raingauge rainfall it is found that Status 1 = 0.5 mm/min to 0.618 mm/min, Status 2 = 0.5 mm/min to 0.785 mm/min and Status 3 = 3 mm/min. On average it is found that rain rate is 0.5325 mm/min for Status 1, 0.564 mm/min for Status 2 and 3 mm/min for Status 3. Investigating 28 events we found that rain rate lies between 10.47 mm/h to 17.02 mm/h and in average rain rate is 15.84 mm/h in Sylhet.

CONTENTS

CHAPTER 1

INTRODUCTION

Chapter 1 Introduction

1.1 Introduction:

Rainfall is one of the most important source of the water resources. It is vitally important to quantify it accurately. Determination of the spatial and temporal depth of rainfall input to the Earth is necessary for everyday management of water resources such as rivers and reservoirs, irrigation, and weather forecasting. It is also an essential component of scientific investigation of the hydrologic cycle, the global water balance and large-scale global atmospheric modeling.

In Bangladesh the onset of the summer monsoon starts in the southeastern tip of the country at the beginning of the June, progress toward the northwest and reaches the northwestern part by middle of June. The heavy rainfall during monsoon season often causes floods and disasters, which are serious problems for Bangladesh. The seasonal increase in the water level of the major rivers coming from vast monsoon areas causes floods in a wide area in Bangladesh. About one fourth to one third of Bangladesh is flooded every year for a relatively long term during the monsoon season [Rahman et.al, 1997]. Rainfall is one of the major components of floodwater. To quantify the floodwater, estimation of rainfall for a large coverage is essential [Islam et.al, 1998]. On the average, more than the 70% of annual rainfall in Bangladesh is concentrated in the four monsoon months, namely June, July, August and September.

Historically the estimation of rainfall has been accomplished by relatively simple instrumentation that samples the rain by capturing a volume over a continuous or fixed time interval. This instrumentation commonly referred to as a rain gauge provides a fairly accurate measure of point rates and depths of rainfall. The major shortcoming of this instrumentation is that the measurement is only at certain points. It has been well documented that rainfall on the Earth's surface varies greatly in both time and space. Although there are a vast number of rainfall gauges worldwide, they are not adequate to define the rainfall input for the most needs. The result of this is that rainfall can be measured relatively accurately for small areas with a network of rain gauges, but this approach is not practical for large areas, remote land areas of the globe and for oceans.

Recognizing the practical limitations of rain gauges, scientists have increasingly turned to remote sensing as a possible means for quantifying the rainfall input to the globe. It should be stressed, however, that remote sensing is at present, and will continue a supplement to, rather than a replacement for, more traditional methods of rainfall assessment. The measurement of rainfall by rain gauges is fraught with some problems, but that relatively simple instrumentation will long continue to provide the data against which rainfall assessments by other means must be adjusted [Quanwei, 1996].

1.2 Objectives of the Research

There are 4 radars belong to Bangladesh Meteorological Department (BMD) installed at Dhaka, Rangpur, Cox's Bazar and Khepupara. These radars collect data individually and in composite way. BMD radar data format is different from conventional radar and not very useful in calculating particular rain rate. The data format is different in the sense that BMD radar collects data in six different patterns viz; a) Status 1 is equal to 1-4 mm/h, b) Status 2 is equal to 4-16 mm/h, c) Status 3 is equal to 16-32 mm/h, d) Status 4 is equal to 32-64 mm/h, e) Status 5 is equal to 64-128 mm/h and f) Status 6 is more than 128 mm/h. In each Status there is a wide range and it is very difficult to decide the particular rain rate from the wide range. No method has yet been developed to determine particular rain rate from BMD radar which is necessary for different research purpose. To overcome this problem initiative has been taken to calibrate BMD radar data with 1-minute interval raingauge data collected in a dense raingauge network in Sylhet.

The objectives of the present work are:

a) Identification of radar Status from BMD radar data.
b) Determination of particular rain rate corresponding to each radar Status.
c) Use of rain rate in calculating rainfall from radar PPI scan.

1.3 Benefits of the Study

The coverage of 600x600 km^2 for individual radar data and 800x1200 km^2 for composite radar data will be useful to know the actual rainfall distribution over the country. Undoubtedly rainfall distribution is necessary for agriculture, flood, storage of surface water, communication and infrastructure of the country. For quantification of rainfall, assignment of rain rate is very important.

CHAPTER 2

RAINFALL AND RAINFALL MEASUREMENTS

Chapter 2 Rainfall and Rainfall Measurements

2.1. Rainfall:

Rainfall is the main source of water that is most vital for human life. Thus, rainfall studies are essential in order to co-relate the supply and demand of water. Precipitation varies in its frequency, duration, intensity and spatial distribution and hence requires accurate observations [Barrett and Martin, 1981]. Tropical rainfall is mainly convective and thus it is more localized and its spatial and temporal distribution as well as the intensity of rainfall is highly variable. The highly variable rainfall in tropics directly and / or indirectly affects different socioeconomic sectors namely agriculture, water resources, transport, construction and so on. Therefore, it is essential to measure areal rainfall on real time basis in order to see the influence of the variable rainfall on such sectors. Different instruments are used to measure and / or estimate rainfall over a place and these are discussed in the following sections.

2.2. Rainfall Measurements:

There are different procedures to measure rainfall which are described in this section.

2.2.1. Rain gauge

A rain gauge is a cylindrical funnel with a graduated cylinder used for collecting and measuring rainfall at a point. It is a widely used standard measuring device. The measurement is read once every day and this gives a total rainfall over a place during 24 hours of time. The raingauge has the following advantages and disadvantages:

- Advantages:

a. It is cheap and easy to maintain and read;
b. Gauge data are available for many years and hence it is possible to do climatologically analysis using long period gauge data; and
c. Comparison between gauge data from different region is possible.

- Disadvantages:

a. It measures point data. Thus, even having a high density of gauge network area estimate of rainfall with reasonable accuracy is difficult to achieve. Moreover, it is impractical and not-cost effective to have a dense network that can measure the highly variable spatial distribution of rainfall like that in tropics.

b. Since gauges are read once every day to get real time information they should be located in places where there is easy access for an observer. However, there are remote areas of interest that are difficult to be accessed every day. Therefore, gauge networks cannot cover all area of interest to make a real time observation.

c. Source of errors in the reading can easily be occurred due to:

   i. Airflow;

   ii. Unrepresentative orientation and exposure of the gauge;

   iii. Human Observation and transmission; and

   iv. Evaporation from within the cylinder; gauge leaks and overflow.

d. Sometimes there might be time delay in getting the gauge data due to communication problem between the observer and the main center.

Thus, the above limitations lead to the use of radar and satellite estimation that augment the rain gauge data.

2.2.2. Radar

Radar is used to estimate rainfall over a given area about 200 km – 500 km in radius by observing the backscatter of electromagnetic radiation from liquid water drops. Radar has an advantage over rain gauge for providing a spatially continuous image (Barrett and Martin, 1981).

- Advantages of Radar:

a. With Radar real time data acquisition is possible – the data can be viewed every few minutes;

b. Radar provides area estimate of rainfall, which cannot be attained by rain gauge;

c. The estimated rainfall from radar is computerized thus ready for further analysis; and
d. By animating the images it is easy to monitor the development, progress and motion of the rain producing systems.

- Disadvantages of Radar:

a. It is expensive and requires sophisticated technical and engineering support;
b. Buildings, nearby weathers, mountains etc. contaminate the radar signal and thereby the rainfall estimate;
c. Low level precipitation may be overlooked by radar signal;
d. Since radar covers a limited area many radar are needed to cover a large area of interest; and
e. Needs calibration with ground measured data

However, satellite is inexpensive, covers more area and also does not require sophisticated technical and engineering support. Therefore, for Bangladesh the use of satellite is more advantageous than radar.

2.2.3. Satellite

A Satellite is a spacecraft that orbits the earth and returns images of the earth and the atmosphere back to the receiving station on the ground. Satellites are used to estimate rainfall using radiation signals reflected or emitted from the ground and atmosphere and observed by it. The following are advantages and disadvantages of satellite based areal rainfall estimation.

- Advantages:

a. Real time estimate is possible and once the satellite is in orbit it is inexpensive;
b. Provide large area coverage;
c. Area estimate is possible; and
d. Animation of the images to observe the development, progress and motion of the weather system is possible.

- Disadvantages:

a. Needs calibration with ground measured data;

b. Since the estimates are indirect in nature contamination (over estimate and/or underestimate) occurs; and

c. Different techniques of rainfall estimations have their own limitations that are to be discussed later.

CHAPTER 3

OVERVIEW OF RADAR

Chapter 3 Overview of Radar

3.1 Introduction

Radar has been defined as "the art of detecting by means of radio echoes the presence of objects, determining their direction and range, recognizing their character and employing the data thus obtained". In radar meteorology the term 'object' is construed to mean anything in the atmosphere, which returns to a receiver a detectable amount of power. Thus, in the study of radar meteorology one must consider the reflections by raindrops, cloud droplets, ice particles, snowflakes, atmospheric nuclei, insects, birds, and regions of large index of refraction gradients.

Radar is based on the principle that an electromagnetic wave is propagated through space at the speed of light, $3x10^8$m/sec and travel along straight lines. Thus, by means of an antenna producing a narrow beam, one can scan with the antenna until a reflection is obtained and determine the direction to the reflecting object. Also, by measuring the time interval between the transmission of the radio energy and the reception of the reflected signal, one can easily calculate the distance to the object.

For many purposes, radar set can be considered to consist essentially of a transmitter, which produces power at the radar frequency; an antenna, which radiates the power and intercepts the reflected signals; a receiver, which detects, amplifies, and transforms the received signals into video form; and an indicator on which the returned signals can be displayed. The operation of simple radar set is illustrated in figure 3.1. Most weather-radar sets employ a single antenna for both transmission and reception.

With most radar sets, the frequency of operation is fixed, and generally, the source of the microwave is a special tube called a "magnetron". For the system to operate properly, the radar receiver must be tuned to the magnetron frequency.

A radar set such as the one blocked out in figure 3.1 is called a "non coherent radar". In such equipment, no account is taken of the phase of the returning radar wave with respect to the phase of the transmitted wave. Most radar sets now in use for weather observations are of this type and therefore non-coherent radars are sometimes called "conventional radars".

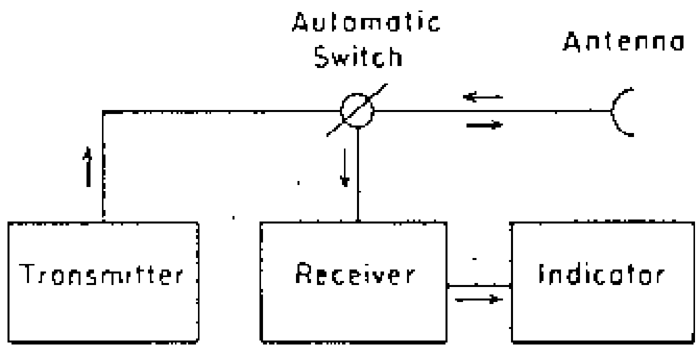

Fig. 3.1: Block diagram of radar set.

A class of radar sets referred to as "coherent" or "Doppler" radars makes use of the Doppler principle. These instruments, in addition to obtaining the data collected by non-coherent radar, also measure the velocity of the targets along the radar beam axis. The velocity measurements are made by noting the rate of change of the difference in phase between the outgoing and received signals. As a target moves, the phase changes at a rate proportional to the velocity of the target toward or away from the radar.

In most radar sets, the transmitted power is in the form of pulses of radio waves of short duration (e.g. 1 μsec). The frequency at which pulses are emitted is known as the "pulse-repetition frequency (PRF)", whose typical value is 1000 per second. The maximum range of radar set is specified by half the interval between pulses multiplied by the speed of light.

3.2 Radar Indicators:

The type of indicator used in weather radar depends on the information desired. Most indicators consist of a cathode-ray tube in which the beam of electrons is caused to scan across the tube, starting when the transmitter pulse is started and making a discernible indication on the tube when a signal is detected by the receiver. In conception, one of the most elementary indicators is the A-scope, or R-scope. It operates like the test oscilloscopes used in physics or electronics laboratories. The beam of electrons scans horizontally across the face of the tube at a fixed speed, and vertical deflections are produced when signals are received. The distance from the start of the sweep to the deflections gives the range of the target. It can be seen that the transmitted pulse also appears on the trace. This is produced by power, which leaks through the automatic switch shown in figure 3.1. The magnitude of the deflections is a measure of the strength of the signal received. It is obvious that signals from many targets can be displayed on an A-scope at any one time. In weather radar the A-scope is generally used to identify the source of the backscattered energy, to assist in the tuning of the radar and to make quantitative measurements of returned power.

3.2.1 Plan Position Indicator (PPI):

The most extensively used indicator on weather radars is the plan-position indicator, usually designated as PPI (fig-3.2.1). This display presents a plan view of the received signals on a polar coordinate system. It is used on radar sets with antennas, which scan azimuthally. In this presentation, the electron beam scans at a fixed speed from the center of the oscilloscope to the outer edge, then returns rapidly to the center of the tube and scans outward again. The beam rotates around the scope in synchronism with the rotation of the antenna. From the PPI display one can immediately read the range and bearing to the target.

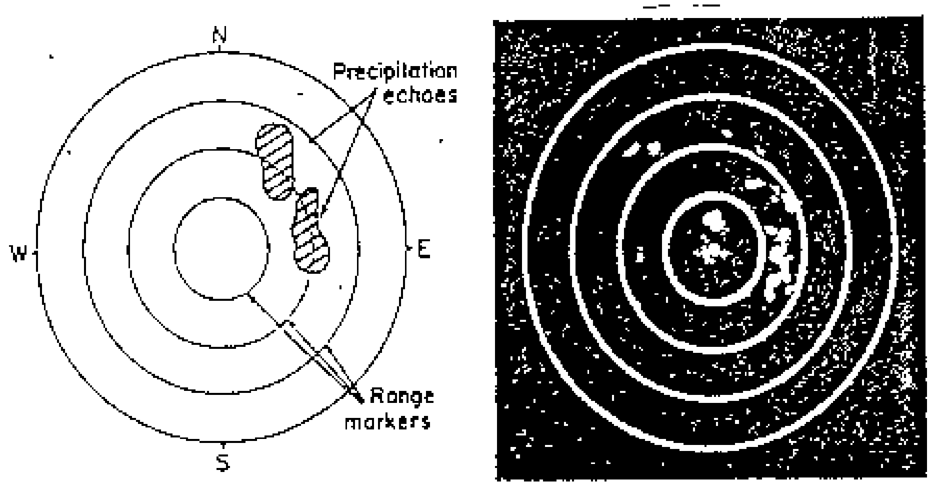

Fig. 3.2.1: Plane-position indicator (PPI).

The PPI scope is "intensity modulated". This means that the intensity of the bright spot corresponding to the returned signal depends on the strength of the return signal. A strong "echo" on the scope represents a large amount of returned power. Radar sets with PPI presentations have great application for observations of severe storms and are widely used in weather stations.

3.2.2 Range Height Indicator (RHI):

Another common radar display is the range-height indicator, usually designated as RHI (Fig. 3.2.2). This type of presentation is used with radar sets whose antennas scan vertically. In this scope the beam scans outward at a particular vertical angle, returns rapidly to the origin, and scans again at a different angle. The vertical angle of the beam is controlled by the vertical angle of the antenna. As can be seen in Fig. 3.2.2, the scope presents the position of the echo on a coordinate system with range as the abscissa and height as the ordinate.

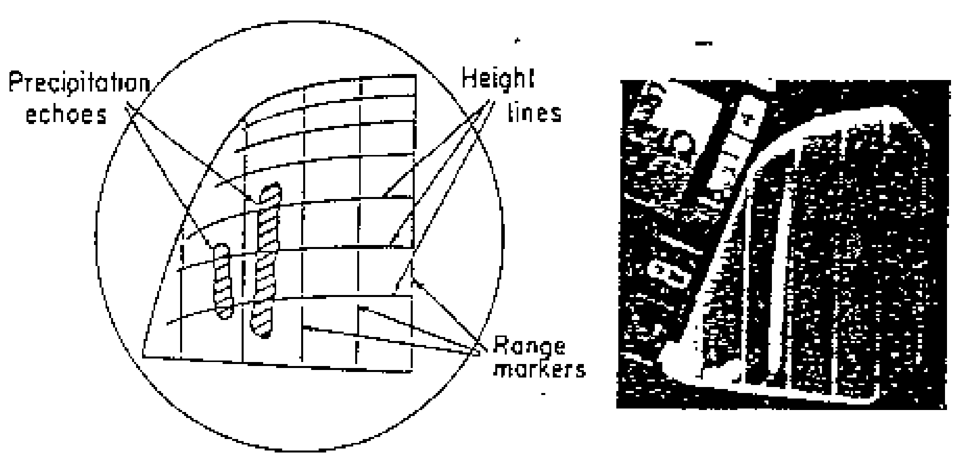

Fig. 3.2.2: Range-height indicator (RHI).

3.2.3 Height Time Section (HTI):

Many radar observations of clouds and precipitation have been made by fixing the antenna's position and allowing the weather phenomena to pass through the radar beam. When the antenna points vertically, the data may be displayed in the form of an intensity-modulated height-time section, as shown in Fig. 3.2.3. Such a presentation is called an HTI.

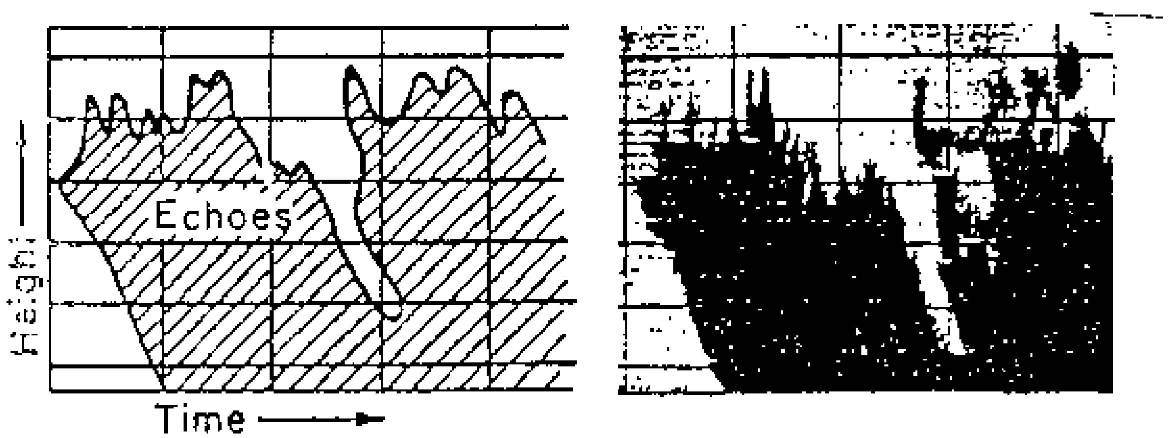

Fig. 3.2.3: Height-time indicator (HTI).

3.2.4 Range Time Indicator (RTI):

The same type of recording system may be used with the antenna pointing horizontally. In this case, the display might be called "range time indicator (RTI)".

CHAPTER 4

METHODOLOGY

Chapter 4 Methodology

4.1. Introduction:

In order to analyze radar data collected by Bangladesh Meteorological Department the methodology is discussed in this section.

4.2. Radar equation:

Radar sets employ antennas which are highly directional, in order to concentrate the power into a narrow beam. Let us consider a transmitter, which radiates isotropically. The power will spread equally in all directions, and, at a range r, the power per unit area on the surface of a sphere of radius r is $P_t/4\pi r^2$, where P_t is the power during the brief period that the transmitter is operating. The ratio of power per unit area along the axis of the radar beam to the isotropic value is a measure of the gain, G, of the antenna. It should be noted that, if the radar set uses one antenna for transmission and another for reception, the value of G would have to be replaced by G_t, the gain of the transmitting antenna.

If there is a target at range r with a cross-sectional area A_t, it will intercept an amonnt of power P_σ, given by

$$P_\sigma = \frac{P_t G A_t}{4\pi r^2} \quad \text{----------------(4.1)}$$

If it is assumed that the target does not absorb any power, but reradiates it all isotropically, the power intercepted by the radar antenna, P_r, will be given by

$$P_r = \frac{P_t G A_t A_e}{(4\pi)^2 r^4} \quad \text{----------------(4.2)}$$

Where A_e is the effective cross-section of the antenna. It can also be written $A_e=\rho A_p$, where A_p is the cross-sectional area of the antenna and ρ is the antenna efficiency whose value depends on the efficiency of the feed and the antenna illumination.

It was shown by Silver (1951) [Coton] from theoretical considerations that $A_e=G\lambda^2/4\pi$. Also, when an antenna employs a circular, paraboloidal reflector the gain is given approximately by $G=8\pi\, A_p/3\lambda^2$. In this instance $A_e=\frac{2}{3}A_p$. Substituting A_e and G in eq (4.2), we get

$$P_r = \frac{P_t G^2 \lambda^2 A_t}{(4\pi)^3 r^4} \approx \frac{P_t A_p{}^2 A_t}{9\pi \lambda^2 r^4} \quad \text{--------------(4.3)}$$

It was assumed earlier that the target had a cross-section A_t and that it scattered isotropically. In practice, there are no targets-certainly no meteorological ones-which scatter isotropically. Nevertheless, it has been found convenient to introduce a function, σ, called the "back-scattering cross-section", which is defined as "the area intercepting that amount of power, which, if scattered isotropically, would return to the receiver an amount of power equal to that actually received. The function σ may also be defined as "the area which, when multiplied by the incident intensity, gives the total power radiated by an isotropic source which radiates the same power in the backward direction as the scatterer". This can be written as

$$\sigma P_i = 4\pi r^2 S \quad \text{--------------------------------(4.4)}$$

where P_i is the power per unit area incident on the target at a range r, and S is the backscattered power per unit area at the antenna.

For a single scatterer, eq (4.3) becomes

$$P_r = \frac{P_t G^2 \lambda^2 \sigma_i}{(4\pi)^3 r^4} \quad \text{----------------------(4.5)}$$

This equation is perfectly general up to this point and can be applied whether the target be the moon, an airplane, or a raindrop. The problem for the meteorologist is to determine the form of σ_i for the meteorological elements he wishes to detect.

In eq (4.5) σ_i is given as the backscattering cross-section of a single scatterer. In practice, the radar beam illuminates a large group of scatterers-e.g. raindrops-at the same time; the number is equal to that within a volume defined by the beam widths and pulse length of the radar set. In this case, it is necessary to consider the power reflected from a large number of drops. The backscattered signal voltage from a volume of randomly distributed scatterers is the sum of the signals scattered by each of the scatterers, with the phase of each signal taken into account. It has been found to vary from one reflected pulse to the next because of the movement of the particles with respect to one another. After a period of the order of 10^{-2} sec, a random array of scattering particles changes into an essentially independent one. If the received power is averaged over a large number of independent arrays, we can write

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 r^4} \sum_{i=0}^{n} \sigma_i \quad \text{--------------(4.6)}$$

where the summation is carried out over the entire volume V_m from which power is scattered back to the receiver at any instant.

If the particles are uniformly distributed throughout V_m, the total back-scattering cross-section can be written as the backscattering per unit volume multiplied by V_m. The quantity V_m is given approximately by

$$V_m = \pi \left(r\frac{\theta}{2}\right)\left(r\frac{\phi}{2}\right)\frac{h}{2} \quad \text{---------(4.7)}$$

Where θ and φ are the horizontal and vertical widths of the beam in radians.

In calculating the volume illuminated, a depth of h/2 is used instead of h because the equations involved refer only to the scattered power, which returns to the radar receiver at the same instant of time. The power backscattered by particles at a range r from the rear of the outgoing pulse of length h.

By substituting in eq (4.6), we obtain

$$P_r = \frac{P_t G^2 \lambda^2 \theta \phi h}{512 \pi^2 r^2} \sum_{vol} \sigma_i \quad \text{-------------------(4.8)}$$

The factor $\sum_{vol} \sigma_i$ represents a summation of σ over a unit volume. It is called the radar reflectivity (η), and is commonly expressed in units of centimeters square per cubic meter or per centimeter.

It should be noted that the transmitted power is maximum along the beam axis and decreases to half the maximum value at the angles corresponding to half the beam widths.

4.3. Calculation of radar constant:

Assume that radar is observing rain and that the rain consists of spherical water drops small enough to permit the Rayleigh approximation to apply. If 10-cm radar is used, all rains will meet this requirement. Also under these conditions, attenuation can be neglected. The average power received by the radar when the entire beam is intercepted is given by

$$P_r = \left(\frac{\pi^3}{1024\ln 2}\frac{P_t G^2 \theta\phi h}{\lambda^2}\right)\left|\frac{m^2-1}{m^2+2}\right|\frac{Z}{r^2} \quad \text{-------(4.9)}$$

For any particular radar set, the term inside the parentheses of equation (4.9) can be considered to be a constant for that radar. The value of P_t can vary with time, but over periods of a few hours, changes should be negligibly small. Radar constant can be calculated by knowing the radar characteristics. A more precise procedure is to determine it empirically by making careful measurements of the power backscattered from a target of known cross-section such as a metal sphere. Equation (4.9) reduces to

$$P_r = \frac{C|K|^2 Z}{r^2} \quad \text{--------------------(4.10)}$$

To use equation (4.10) for calculating precipitation rates, it is necessary to know the relation between Z and the precipitation rate, R.

4.4. Particle-size distributions in the atmosphere:

For a wide range of rain and snow conditions, we can write

$$N_D = N_O\, e^{-\lambda D} \quad \text{---------------------(4.11)}$$

where D is the drop diameter and N_DdD is the number of drops per unit of air volume in the size range D to D+dD. When snow is involved, the value of D refers to the diameter of a sphere of water having the same mass as the original particle (Marshall and Palmer 1948). In precipitation from Stratiform clouds, N_O has been found to be equal to 0.08 cm^{-4} for rain, when N_D is the number of drops per cubic centimeter per centimeter of size range. Sekhon and Srivastava (1970) [Coton] have reported that, for snow, N_O=0.025 $R^{-0.94}cm^{-4}$, which compares with the quantity 0.038 $R^{-0.87}cm^{-4}$ reported by Gunn and Marshall (1958) [Coton].

The parameter λ depends on the rain intensity, and, when expressed in units of per millimeter,

$$\lambda = 4.1\ R^{-0.21} \text{ (rain)} \quad \text{---------------------4.12(a)}$$

$$\lambda = 2.29\ R^{-0.45} \text{ (snow)} \quad \text{---------------------4.12(b)}$$

Where R is expressed in millimeters per hour.

When precipitation size spectra are obtained by collecting the particles on a horizontal surface at the ground, it is necessary to correct for differing fall speeds in order to obtain particle concentrations in the free atmosphere. For example, if the sampling time were 1 sec, all drops with a fall speed of 10 m/sec in a 10 m column could be captured. In the case of drops with fall speeds of 1 m/sec, only those in a 1-m column would fall to the surface during the 1-second collection time. For any diameter D,

$$N_{D_t} = \frac{N_{D_0}}{AW_t \Delta t} \quad \text{--------------------(4.13)}$$

Where N_{D_t} is the number of drops per unit volume, of diameter D and terminal velocity W_t, and N_{D_0} is the number of drops of diameter D collected on surface area A during time interval Δt.

When raindrops are involved, it is common to use terminal-velocity data of Gunn and Kinzer (1949) [Coton], which applies at sea level. At greater altitudes more precise data are given by Foote and DuToit (1969) [Coton]. Spilhaus (1948) [Coton] showed that over the diameter range 1-4 mm the rain drop data of laws (1941) yield

$$W_t = 1.42 \times 10^3 D^{1/2} \quad \text{----------------(4.14)}$$

Where D is in centimeters and W_t in centimeters per second.

For calculating the size spectra of aggregate snowflakes Gunn and Marshall (1958)[Coton] used the expression

$$W_t = 2 \times 10^2 D^{0.31} \quad \text{-----------------(4.15)}$$

Where the nnits are the same as in equation (4.14).

Mueller and Jones (1960) [Coton] reported that raindrops from convective clouds in Miami, Florida exhibit a distinct frequency maximum at diameters of about 1.5 mm. Over the range of drop sizes smaller than those of maximum frequency, Λ (= - d (ln N)/dD) average about – 4.3 over large drop sizes Λ averages about 3.5.

It should be recognized that a distribution curve such as equation (4.11) is an empirical expression based on an accumulation of highly variable samples. Any small sample can vary substantially. Even large samples may do so. Geotis (1968) [Coton] examined raindrop spectra in all types of rainfall over a two-year period. He found that, at diameters greater than 0.6 mm, the smallest drops he could measure, the drop concentration was exponentially distributed. Geotis reported that the coefficient in equation (4.11) varied with rainfall in an unsystematic manner.

It has been demonstrated that in the case of rain, Λ can be expressed in terms of the median-volume diameter. Equation (4.11) can be written

$$N_D = N_O\, e^{-3.67D/D_0} \qquad \text{------------------(4.16)}$$

According to Atlas (1964) [Coton]. The median-volume diameter, D_o, is defined as that drop diameter, which divides the drop distribution in such a fashion, that half water content is contained in drops greater than D_o. Geotis (1968) [Coton] also found that $\Lambda = -3.7\ D_o$ gave a good fit to the slope of the observed raindrop-distribution curve. He implied that D_o would be a better indicator of the slope of the drop-size curves than R, but, as he noted, D_o cannot be measured directly.

According to Donaldson (1955a) [Coton], the drop size distribution in drizzle is given by equation (4.16) if $N_o = 70\ cm^{-4}$.

There is little reliable data on hail distribution in drizzle distribution aloft, but according to Douglas (1964) [Coton] the average spectrum of Hailstones in Alberta, Canada, was

$$N_D = N_O\, e^{-3.09D} \qquad \text{--------------------------(4.17)}$$

Where N_o and N_D are in units of per cubic meter per centimeter.

4.5. Z-R relationship:

In order to use radar for measuring rainfall intensity, most investigators have employed an empirical expression of the form

$$Z = BR^b \qquad \text{------------------------------------(4.18)}$$

The figure below shows the curves for the following equations, considered to be fairly typical for the indicated type of rain:

Stratiform rain: $Z = 200\ R^{1.6}$

(Marshall and Palmer 1948) --------(4.19)

Orographic rain: $Z = 31\ R^{1.71}$

(Blanchard 1953) [Coton] --------(4.20)

Thunderstorm rain: $Z = 486\ R^{1.37}$

(Jones 1956) [Coton] ------------------(4.21)

Where Z is in millimeters to the sixth power per cubic meter and R in millimeters per hour.

These three Z-R expressions were obtained by measuring raindrop spectra. Rainfall intensity was either calculated from the raindrop data or observed directly. Radar reflectivity factor Z was obtained by computing $\sum \mathbf{D}^6$ in a unit volume. This implies that the expression is valid only when the radar wavelength is much longer than the diameter of the largest drops.

When this is not the case, it is necessary to replace Z with Z_e, the effective radar reflectivity factor. The relationship of Z_e to R can be obtained by direct measurements of P_r and R. Here P_r is the average power received by the radar. It should be recognized that there are a number of distinct difficulties in obtaining Z_e versus R directly. For example P_r corresponds to the backscattering from a volume above the ground, while r is measured at the ground. The scattering volume has a much larger horizontal area than that sampled by rain gauges.

Coton (1964) measured R by means of a rain gauge at the same time that vertically pointing 3-cm pulsed-Doppler radar set was used to determine raindrop spectrum. This analysis yielded $Z = 240\ R^{1.3}$, which changed very little between the cloud base and the melting level. By means of the same procedure Gorelik et al. (1967) calculated an average expression $Z = 263\ R^{1.30}$.

The Z_e-R relationships for specific drop-size distributions and wavelengths were calculated by Wexler and Atlas (1963) [Coton] from Mie backscattering cross sections published by Herman, Browning, and Battan (1961) [Coton]. At wavelengths below 3.2 cm, the discrepancies between Z and Z_e are quite large, but such wavelengths are seldom used to measure radar reflectivity because they are heavily attenuated by rain.

There have been few measurements of the radar reflectivity of snow as a function of the precipitation intensity. One reason is that it is more difficult to obtain accurate particle size distributions and precipitation rates.

On the basis of the published results an appropriate expression appears to be

$$Z = 2000\ R^2 \quad \text{-------------------------}(4.22)$$

Where Z and R are in the usual units and R refers to the precipitation rates when the snow is melted.

It should be noted from a comparison of equation (4.19) and (4.22) that when the precipitation rates exceeds about 0.16 mm/hr, the value of Z is greater for snow than for rain.

Since snowflakes fall slowly (about 1 m/sec), while raindrops fall five to ten times faster, the concentration of snowflakes must be larger than that of raindrops in order to yield the same R. Also, the heavier the rainfall rate and the larger the raindrops, the greater the difference (Z_{snow} - Z_{rain}).

In this analysis radar raw Plan Position Indicator (PPI) scan digital data is collected in a 240x240 matrix with a 2.5 km grid mesh for Dhaka, Rangpur, Cox's Bazar and Khulna radar. For complex PPI scan four radar is used to collected data in a 320x480 matrix with the same 2.5 km grid mesh. The raw data is to be processed for GrADS and GMT formats. Then programming is to be developed for Status calculation using Reflectivity-Rain-rate (Z-R) relationship. The Z-R relationship is given in the form

$Z = B\ R^b$

Where Z is the radar reflectivity factor in mm^6m^{-3}, and R is rain rate in mm h^{-1}, and B and b are positive numbers determined empirically. In this analysis B and b are to be considered as 200 and 1.6 respectively [Battan 1973]. Different values of B and b are used by different researchers [Calheiros, R. V. and Zawadski,I,1987, Hadid, S. Z. and Rosenfeld, D., 1997, Woodly, W, L., 1970, Stiner, M and Houze, R.A.jr.,1993, Stiner, M and Houze, R. A. jr. and Yuter, S.E.,1995].

CHAPTER 5

RESULTS AND DISCUSSION

Chapter 5 Results and Discussion

5.1 Introduction:

Bangladesh Meteorological Department has four radars installed at Dhaka, Rangpur, Cox's Bazar and Khepupara. These radars collected data in a special format that Status 0 = no rain, Status 1 = 1~4 mm/h, Status 2 = 4 ~16 mm/h, Status 3 = 16~32 mm/h, Status 4 = 32~64 mm/h, Status 5 = 64~128 mm/h and Status 6 = more than 128 mm/h. From this wide range of rain rate in each Status it is difficult to get the exact rain rate. Rain rate is very important for research purpose. To get rain rate from radar data, in this work we employed raingauge rainfall for assignment of rain rate.

Rain rate is to be assigned from radar data. Over the country, Bangladesh Meteorological Department has a raingauge network using 33 raingauges. However, the data are 3 hourly or daily. To calibrate radar data we used the data from a dense raingauge network in Sylhet (Fig.1). These raingauges are installed by JICA (Japan International Cooperation Agency) project which are collecting continuous data round the clock.

5.2 Rain Rate - Amalshid

At station Amalshid the analysis is performed on the radar data for the months May, June and July 2000. The results for station Amalshid are discussed here.

5.2.1 *May 2000:* In May 2000 we have to analyze 161 radar images and 882-raingauge indications of raingauge (GR) at Amalshid. Among 161 radar images and 882 GR indications, we found 15 matched indications between radar and GR data, which is shown in Fig. 2. Out of 15 data matching there are 13 matched for Status 1 and 2 matched for Status 2 (Fig. 3). Among 13 matched in Status 1 radar indicates all corresponding to GR=0.5 mm/min. In Status 2 radar indicates all corresponding to GR=0.5 mm/min. It is found that at Amalshid for the month of May 2000, GR is 0.5 mm/min corresponds to both Status 1 and Status 2 i.e., Status 1 $\cong$ 0.5 mm/min and Status 2 $\cong$ 0.5 mm/min (Fig. 3).

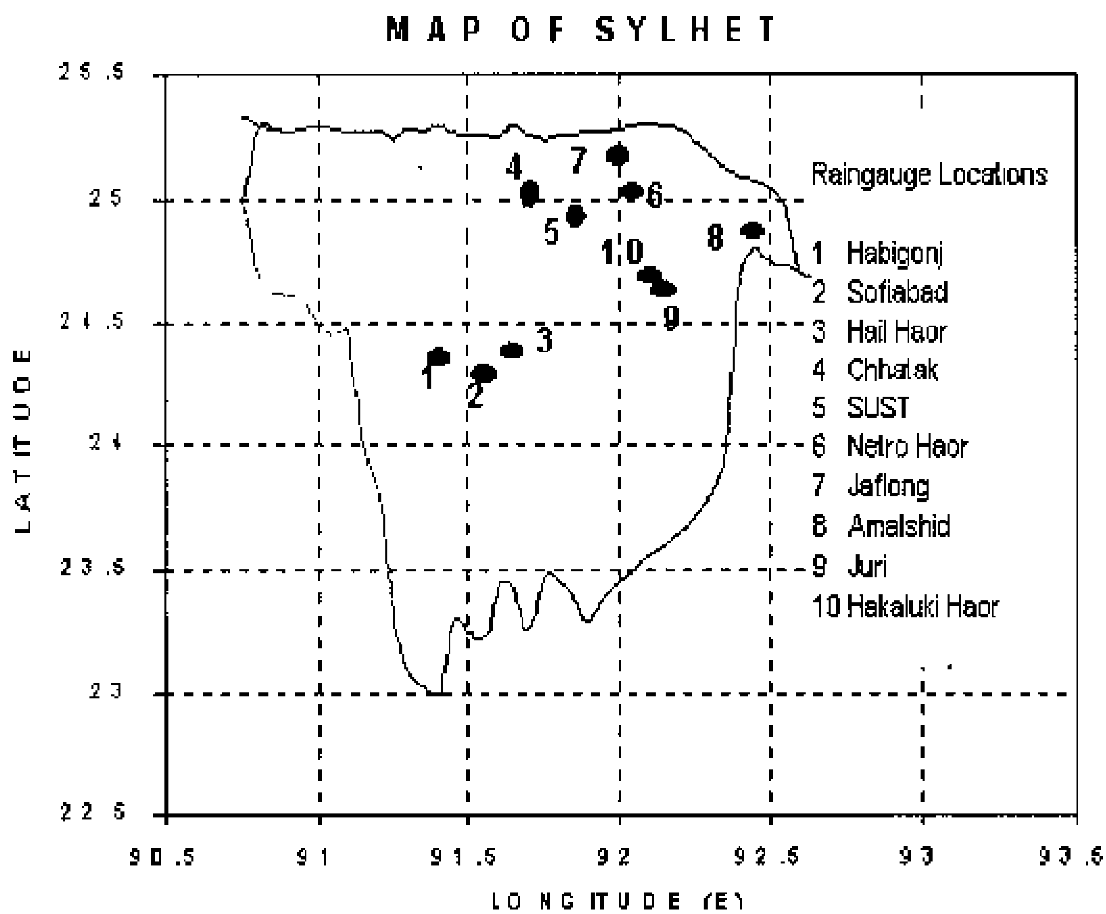

Fig.1. JICA raingauge location in Sylhet.

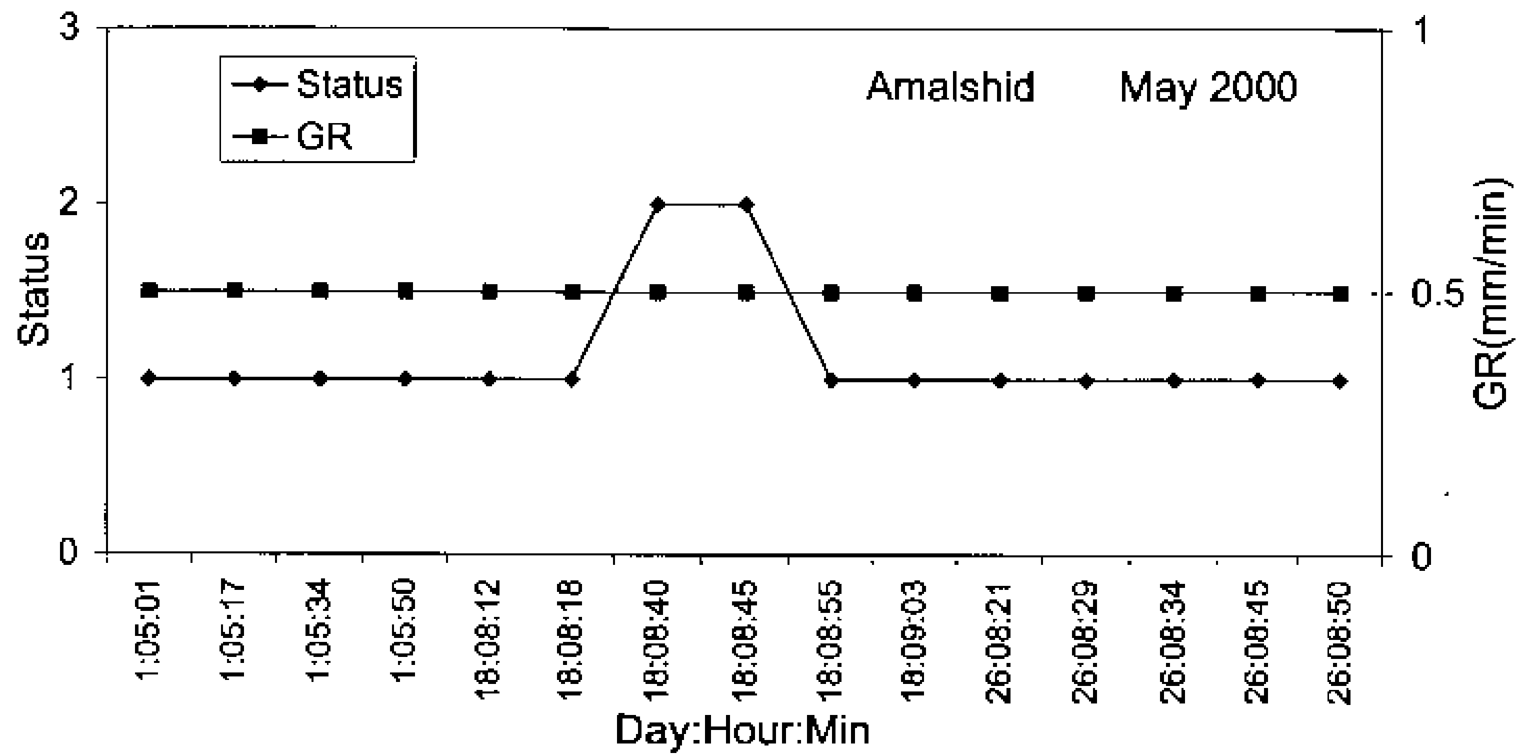

Fig. 2. Radar Status and rain gauge rain rate (GR) for May 2000 at Amalshid.

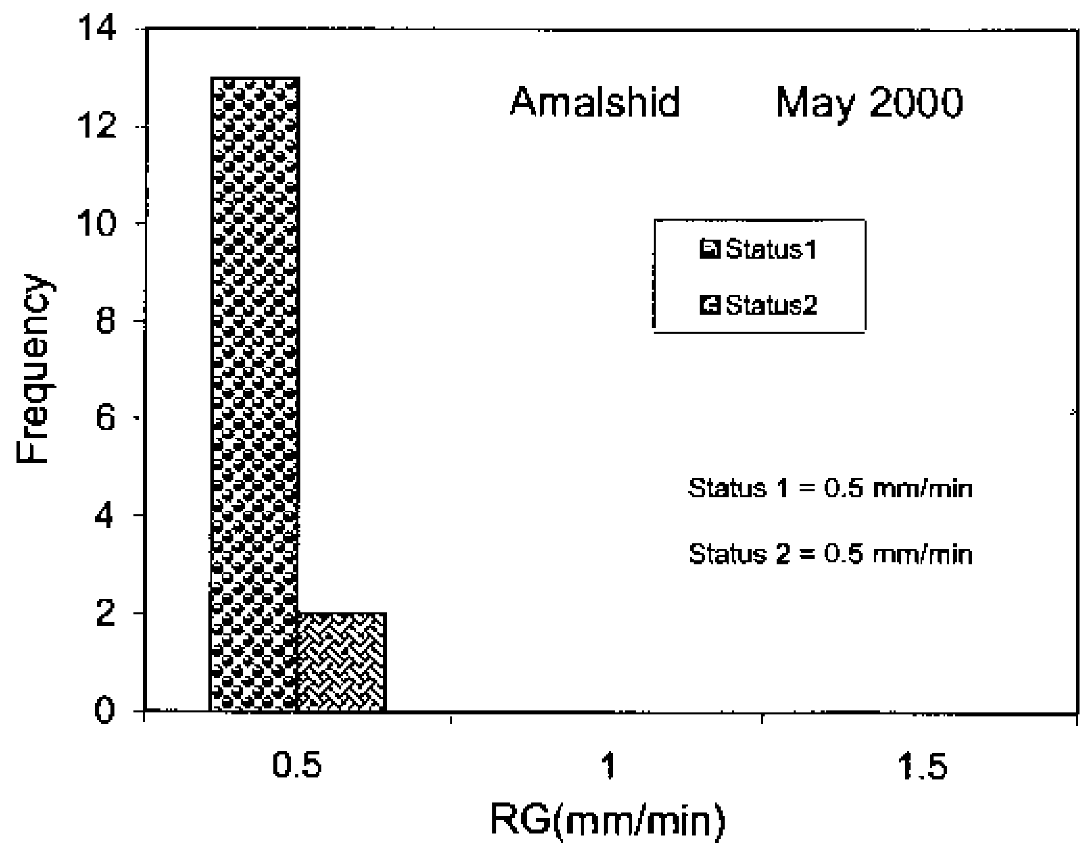

Fig. 3. Radar frequency and rain gauge rain rate (RG) for May 2000 at Amalshid.

5.2.2 *June 2000:* In June 2000 we have to analyze 124 radar images and 1180 rain gauge indications of rain gauge (GR) at Amalshid. Among 124 radar images and 1180 GR indications, we found only 8 matched indications between radar and GR data, which is shown in Fig. 4. Out of 8 data matching there are 6 matched for Status 1 and 2 matched for Status 2 (Fig. 5). Among 6 matched in Status 1 radar indicates all corresponding to GR=0.5 mm/min. In Status 2 radar indicates all corresponding to GR=0.5 mm/min. It is found that at Amalshid for the month of June 2000, GR is 0.5 mm/min corresponds to both Status 1 and Status 2 i.e. Status 1 $\cong$ 0.5 mm/min and Status 2 $\cong$ 0.5 mm/min (Fig. 5).

5.2.3 *July 2000:* In July 2000 we have to analyze 63 radar images and 489 rain gauge indications of rain gauge (GR) at Amalshid. Among 63 radar images and 489 GR indications, we found 2 matched indications between radar and GR data. Out of 2 data matching there are 2 matched for Status 1 and none matched for Statns 2. Among 2 in Status 1 radar indicates all corresponding to GR=0.5 mm/min. It is found that at Amalshid for the month of Jnly 2000, GR is 0.5 mm/min corresponds to Status 1 i.e., Status 1 $\cong$ 0.5 mm/min (Fig.6).

5.3 Rain Rate - Chhatak

At station Chhatak the analysis is performed on the radar data for the months May, June and July 2000. The results for station Chhatak are discussed here.

5.3.1 *May 2000:* In May 2000 we have to analyze 288 radar images and 1055 rain gauge indications of rain gauge (GR) at Chhatak. Among 288 radar images and 1055 GR indications, we found 36 matched indications between radar and GR data, which is shown in (Fig. 7). Out of 36 data matching there are 20 matched for Status 1 and 16 matched for Status 2 (Fig. 8). Among 20 matched in Status 1 radar indicates all corresponding to GR=0.5 mm/min. In Status 2 radar indicates all corresponding to GR=0.53 mm/min. It is found that at Chhatak for the month of May 2000, GR is 0.5 mm/min corresponds to status 1 and 0.53 mm/min corresponds to status 2 i.e., Status 1 $\cong$ 0.5 mm/min and Status 2 $\cong$ 0.53 mm/min (Fig. 8).

5.3.2 ***June 2000:*** In June 2000 we have to analyze 249 radar images and 1826 rain gauge indications of rain gauge (GR) at Chhatak. Among 161 radar images and 882 GR indications, we found 18 matched indications between radar and GR data, which is shown in (Fig. 9). Out of 18 all matched for Status 1 (Fig. 10). Among 18 matched in Status 1 radar indicates all corresponding to GR=0.5 mm/min. It is found that at Chhatak for the month of June 2000, GR is 0.5 mm/min corresponds to Status 1 i.e., Status 1 ≅ 0.5 mm/min (Fig. 10).

5.3.3 ***July 2000:*** In July 2000 we have to analyze 107 radar images and 976 rain gauge indications of rain gauge (GR) at Chhatak. Among 107 radar images and 976 GR indications, we found 4 matched indications between radar and GR data, which is shown in (Fig. 11). Out of 4 data matching there are 4 matched for Status 1 and none matched for Status 2 (Fig.13). Among 4 matched in Status 1 radar indicates all corresponding to GR=0.5 mm/min. It is found that at Chhatak for the month of July 2000, GR is 0.5 mm/min corresponds to Status 1 i.e., Status 1 ≅ 0.5 mm/min (Fig.12).

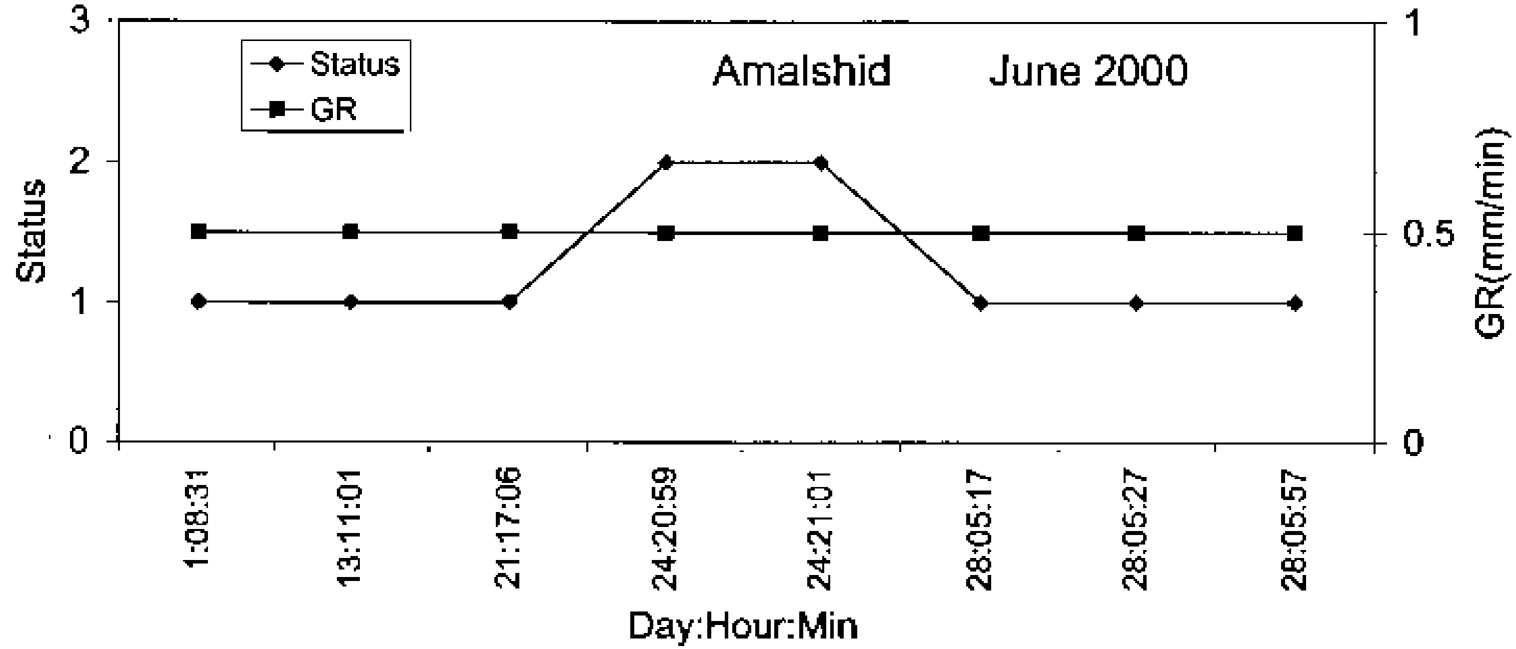

Fig. 4. Radar Status and rain gauge rain rate (GR) for June 2000 at Amalshid.

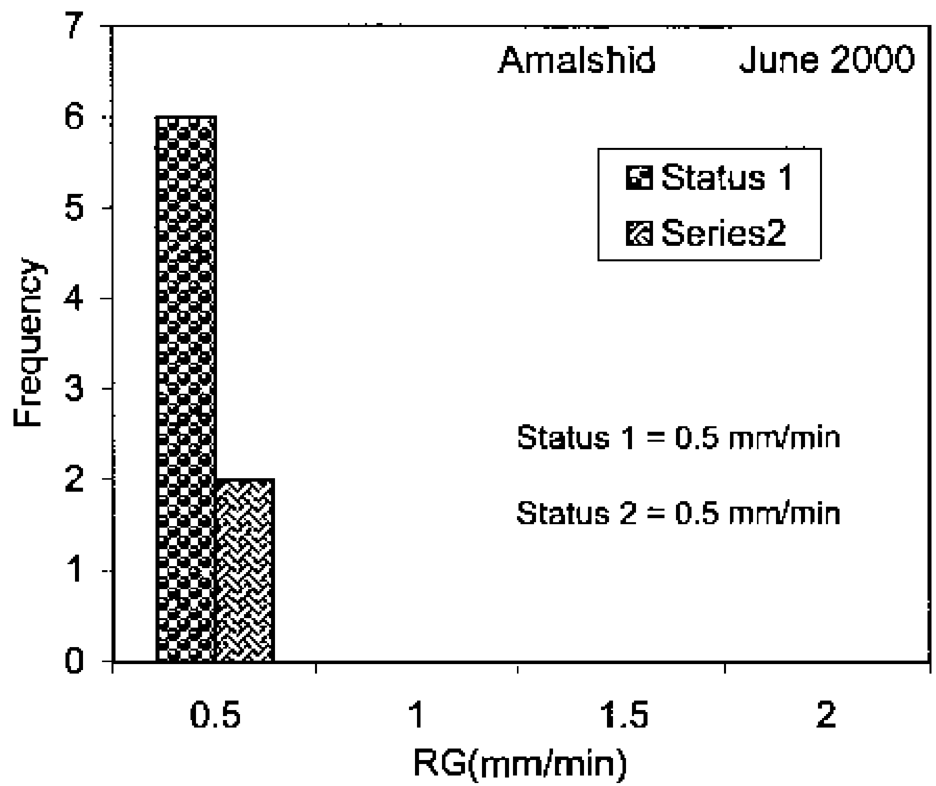

Fig. 5. Radar frequency and rain gauge rain rate (RG) for June 2000 at Amalshid.

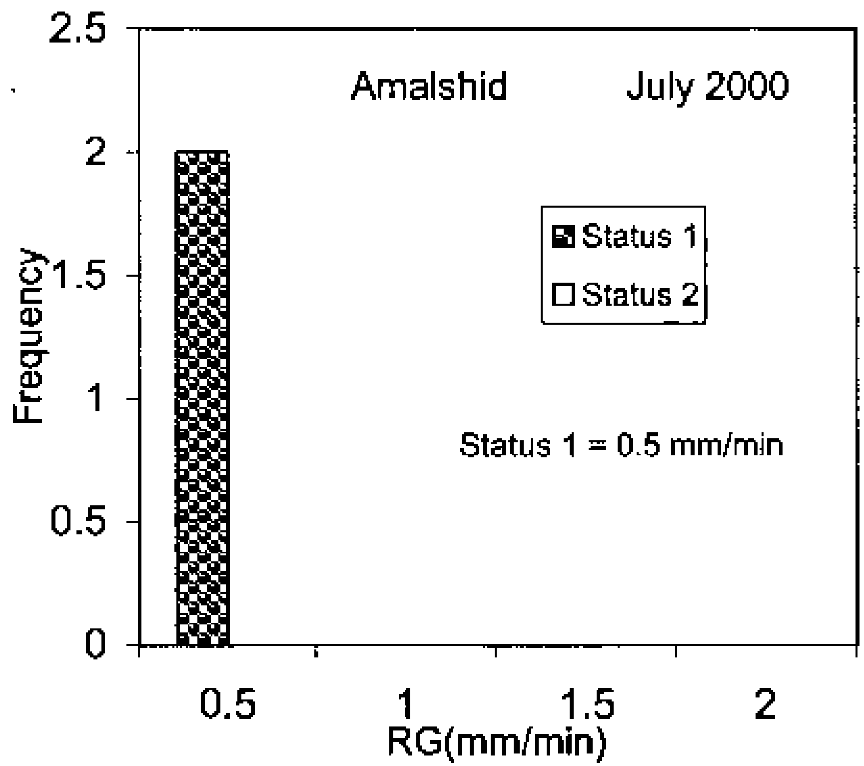

Fig. 6. Radar frequency and rain gauge rain rate (RG) for July 2000 at Amalshid.

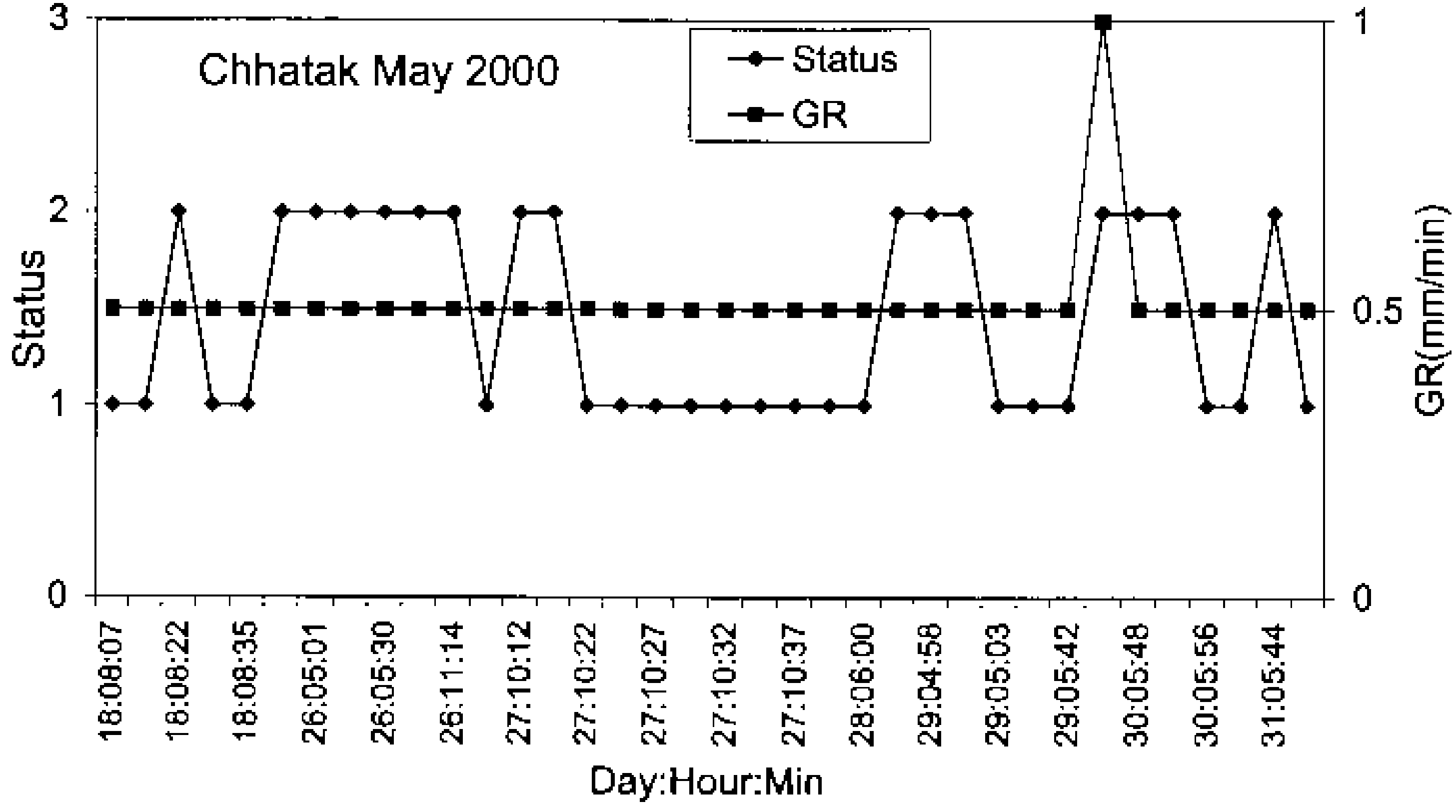

Fig. 7. Radar Status and rain gauge rain rate (GR) for May 2000 at Chhatak.

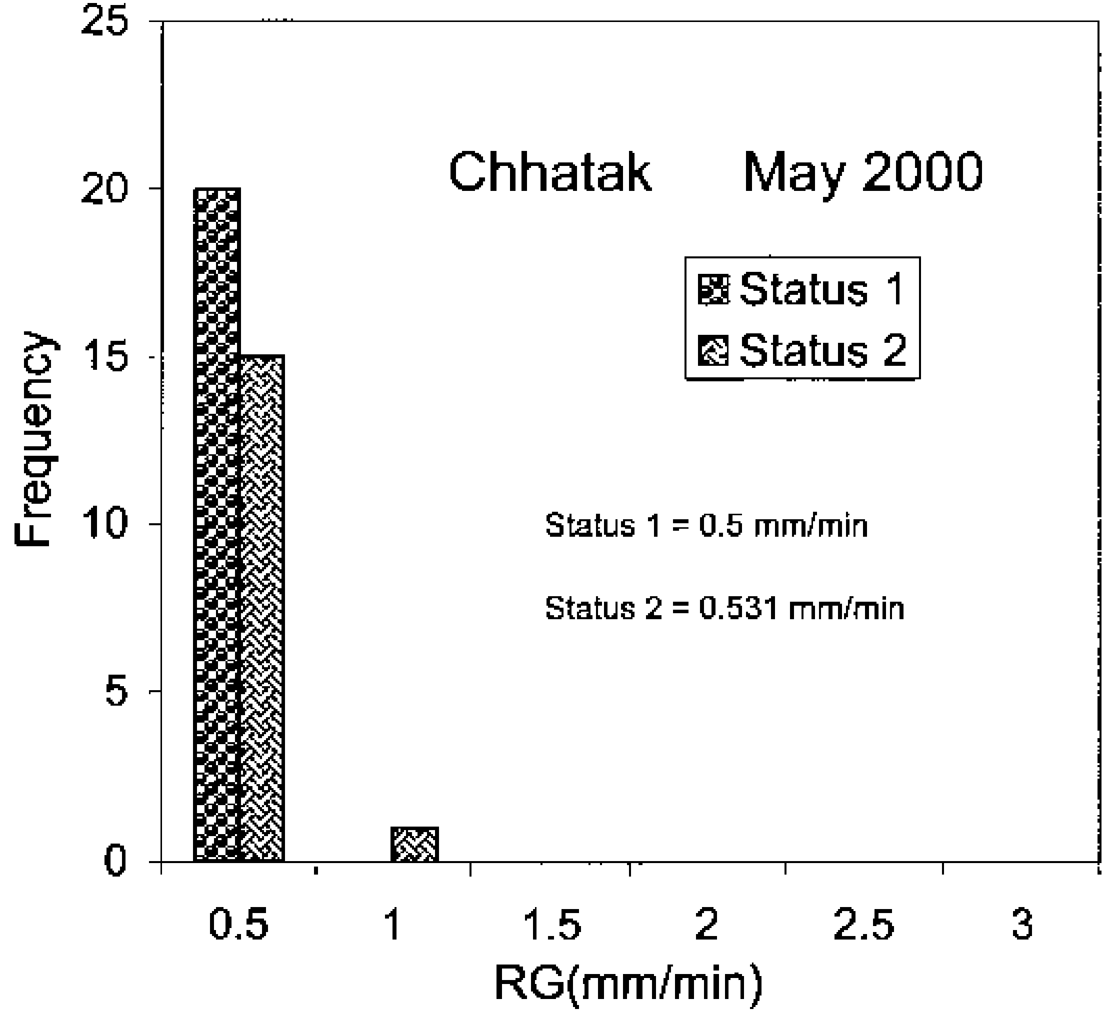

Fig. 8. Radar frequency and rain gauge rain rate (RG) for May 2000 at Chhatak.

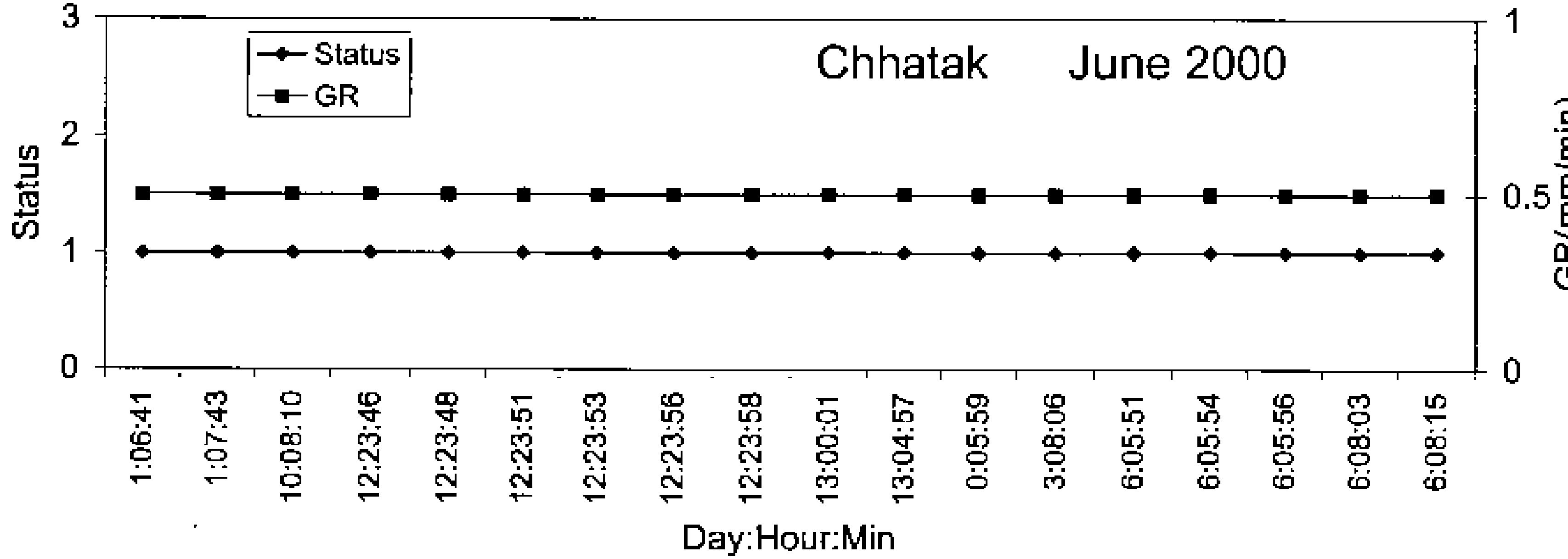

Fig. 9. Radar Status and rain gauge rain rate (GR) for June 2000 at Chhatak.

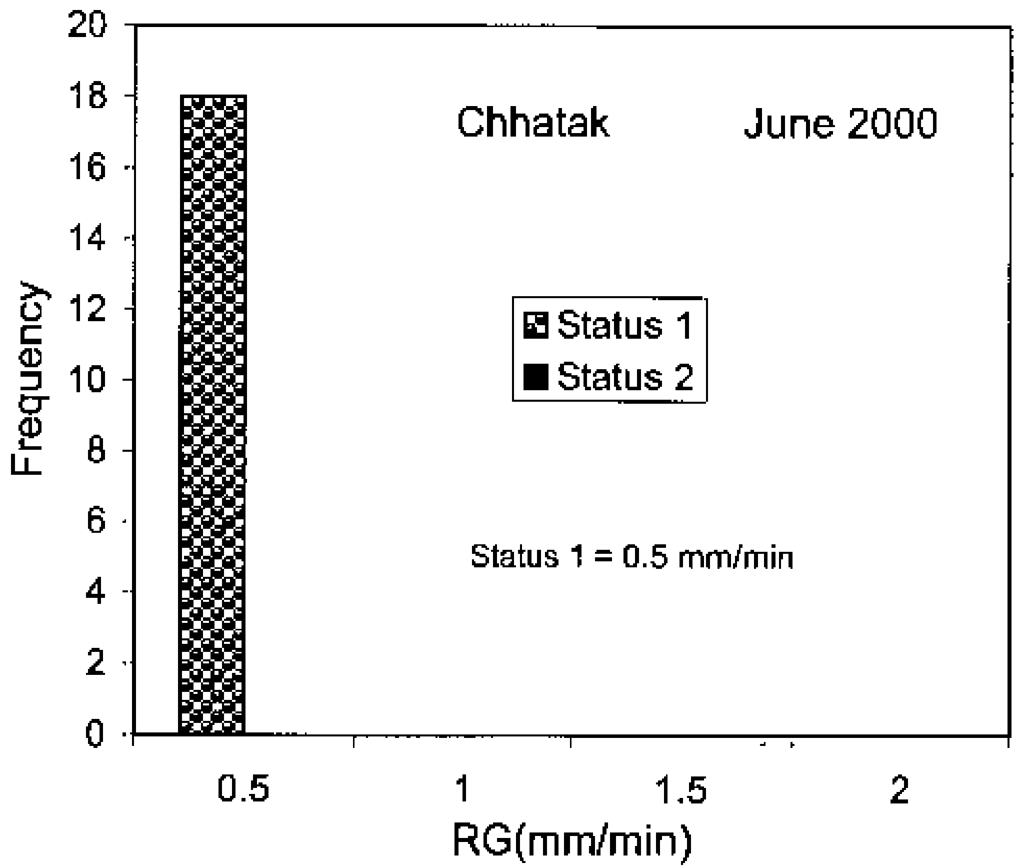

Fig. 10. Radar frequency and rain gauge rain rate (RG) for June 2000 at Chhatak.

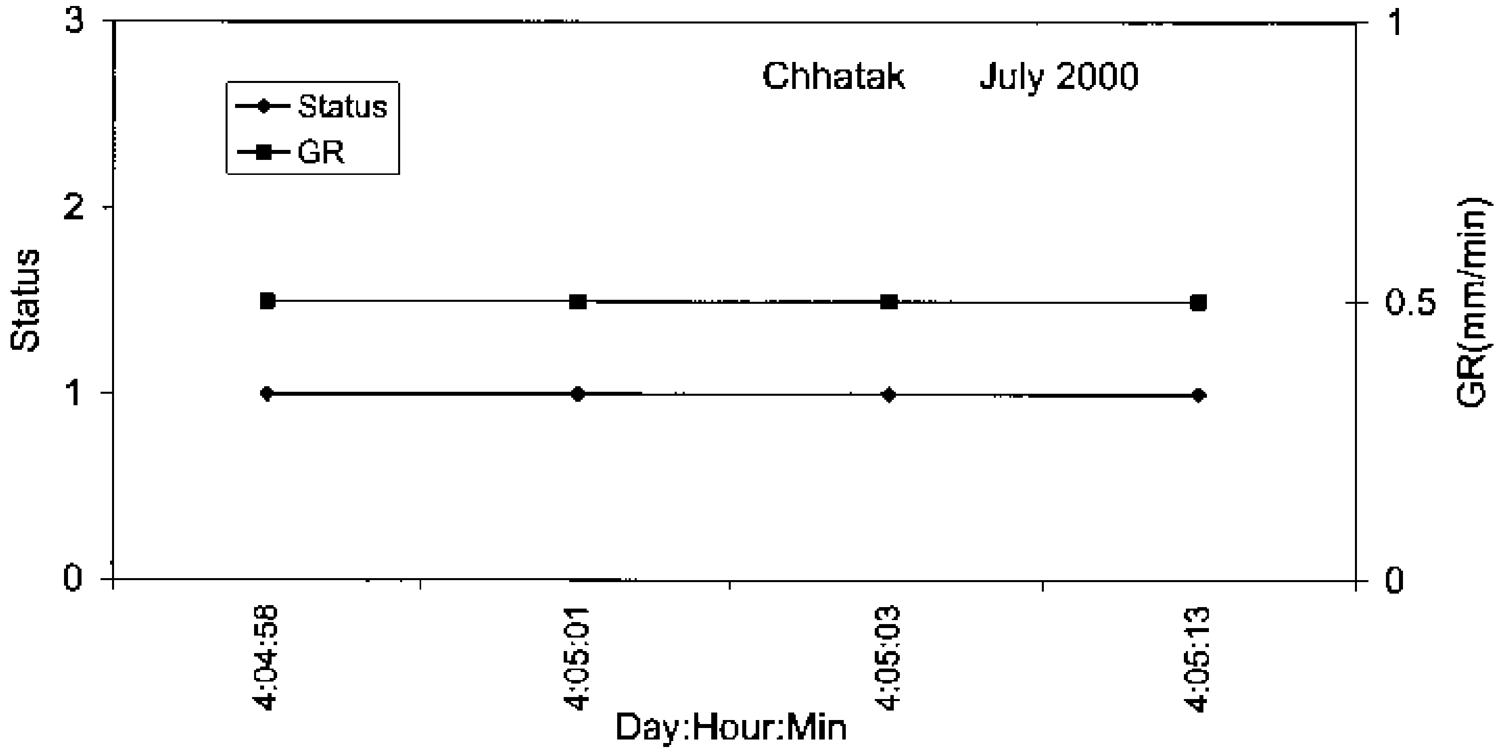

Fig. 11. Radar Status and rain gauge rain rate (GR) for July 2000 at Chhatak.

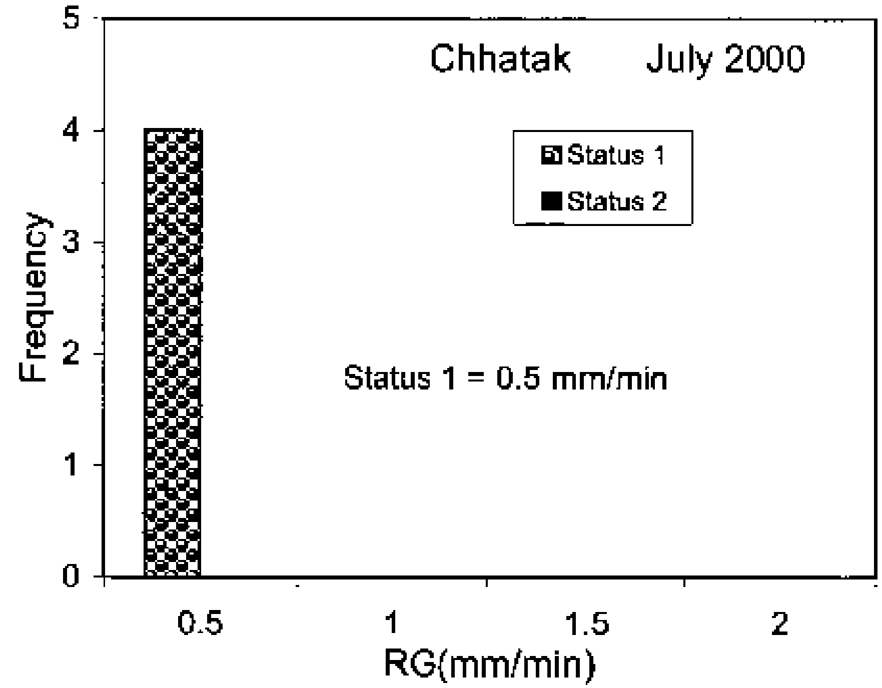

Fig. 12. Radar frequency and rain gauge rain rate (RG) for July 2000 at Chhatak.

5.4 Rain Rate-Netro Haor

At station Netro Haor the analysis is performed on the radar data for the months May, June and July 2000. The results for station Netro Haor are discussed here.

5.4.1 ***May 2000:*** In May 2000 we have to analyze 253 radar images at station Netro Haor. In this month there are 1283 rain gauge indications of rain gauge (GR) at this station. Among 253 radar images and 1283 GR indications, we found 95 matched events between radar and GR data as shown in Fig. 13. Out of 95 data matching there are 72 matched for Status 1, 21 matched for Status 2 and 2 matched for Status 3 (Fig. 14). Among 72 matched in Status 1 radar indicates 62 matched corresponding to GR=0.5 mm/min, 7 matched corresponding to GR=1 mm/min, 1 matched corresponding to GR=1.5 mm/min, 1 matched corresponding to GR=2 mm/min and 1 matched corresponding to GR=3 mm/min (Fig. 14). Among 21 matched in Status 2 radar indicates 14 matched corresponding to GR=0.5 mm/min, 4 matched corresponding to GR=1 mm/min, 1 matched corresponding to GR=1.5 mm/min and 2 matched corresponding to GR=2 mm/min (Fig. 14). In Status 3 all 2 matched corresponding to GR=3 mm/min (Fig. 14). It is found that at Netro Haor for the month of May 2000, GR is 0.619 mm/min corresponds to Status 1, 0.788 mm/min corresponds to Status 2 and 3 mm/min corresponds to Status 3 i.e., Status 1 ≅ 0.619 mm/min, Status 2 ≅ 0.788 mm/min and Status 3 ≅ 3 mm/min.

5.4.2 ***June 2000:*** In June 2000 we have to analyze 192 radar images at station Netro Haor. In this month there are 1344 rain gauge indications of rain gauge (GR) at this station. Among 192 radar images and 1344 GR indications, we found 89 matched events between radar and GR data as shown in Fig. 15. Out of 89 data matching there are 79 matched for Status 1 and 10 matched for Status 2 (Fig. 16). Among 79 matched in Status 1 radar indicates 66 matched corresponding to GR=0.5 mm/min, 9 matched corresponding to GR=1 mm/min, 3 matched corresponding to GR=1.5 mm/min and 1 matched corresponding to GR=2 mm/min (Fig. 16). In Status 2 radar indicates 6 matched corresponding to GR=0.5 mm/min and 4 matched corresponding to GR=1 mm/min (Fig. 16). It is found that at Netro Haor for the month of June 2000, GR is 0.62 mm/min corresponds to Status 1 and 0.78 mm/min corresponds to status 2 i.e., Status $1 \cong 0.62$ mm/min and Status $2 \cong 0.78$ mm/min.

5.4.3 ***July 2000:*** In July 2000 we have to analyze 79 radar images at station Netro Haor. In this month there are 715 rain gauge indications of rain gauge (GR) at this station. Among 79 radar images and 715 GR indications, we found 28 matched events between radar and GR data as shown in Fig. 17. Out of 28 data matching there are 28 matched for Status 1. (Fig.18). Among 28 in Status 1 radar indicates 28 corresponding to GR=0.5 mm/min, (Fig.18). It is found that at Netro Haor for the month of July 2000, GR is 0.5 mm/min corresponds to Status 1 i.e., Status $1 \cong 0.5$ mm/min.

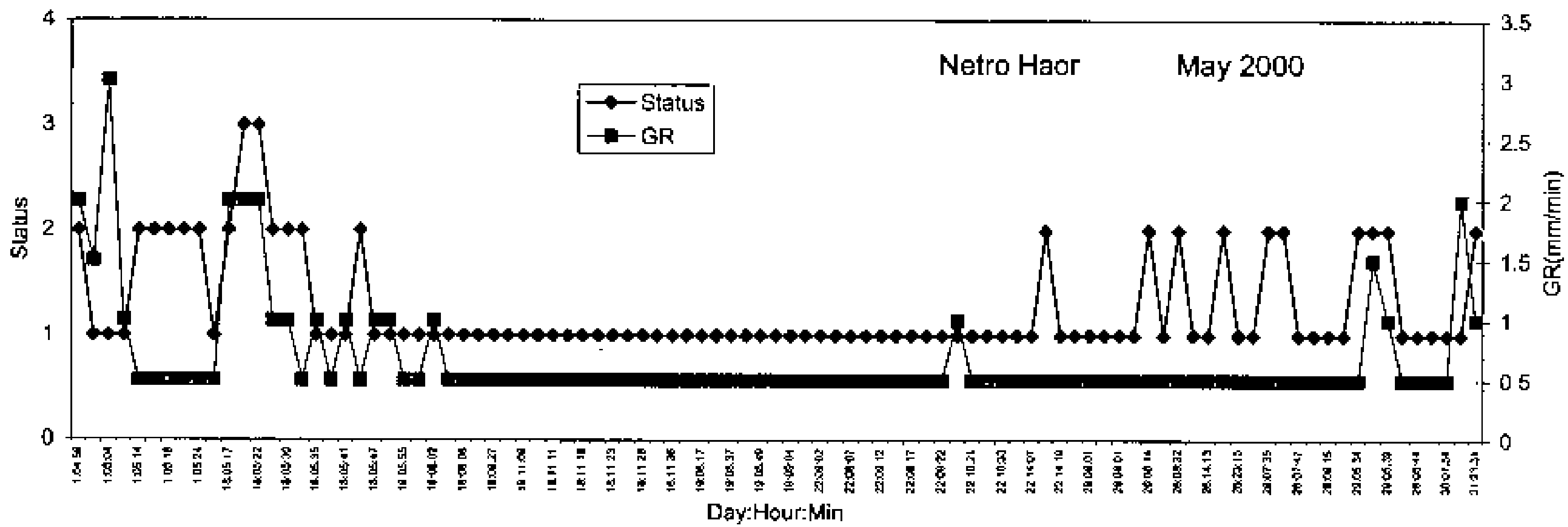

Fig. 13. Radar Status and rain gauge rain rate (GR) for May 2000 at Netro Haor.

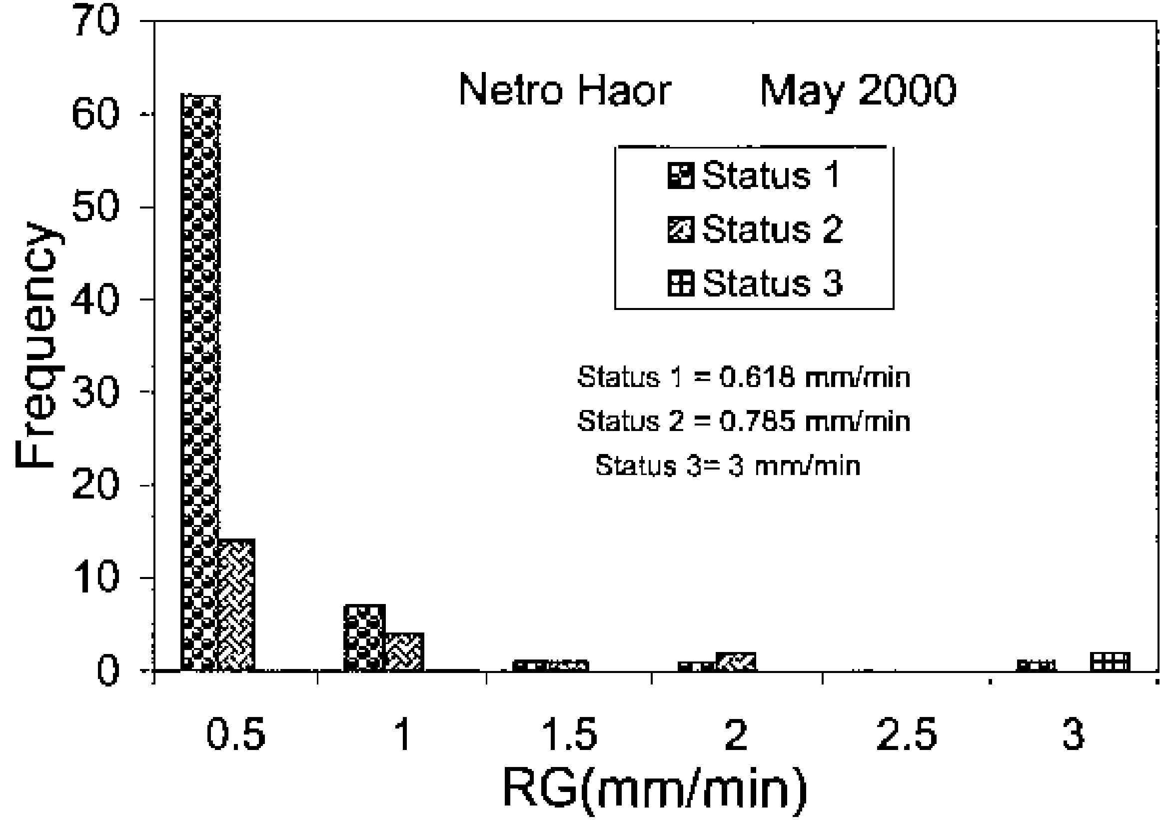

Fig. 14. Radar frequency and rain gauge rain rate (RG) for May 2000 at Netro Haor.

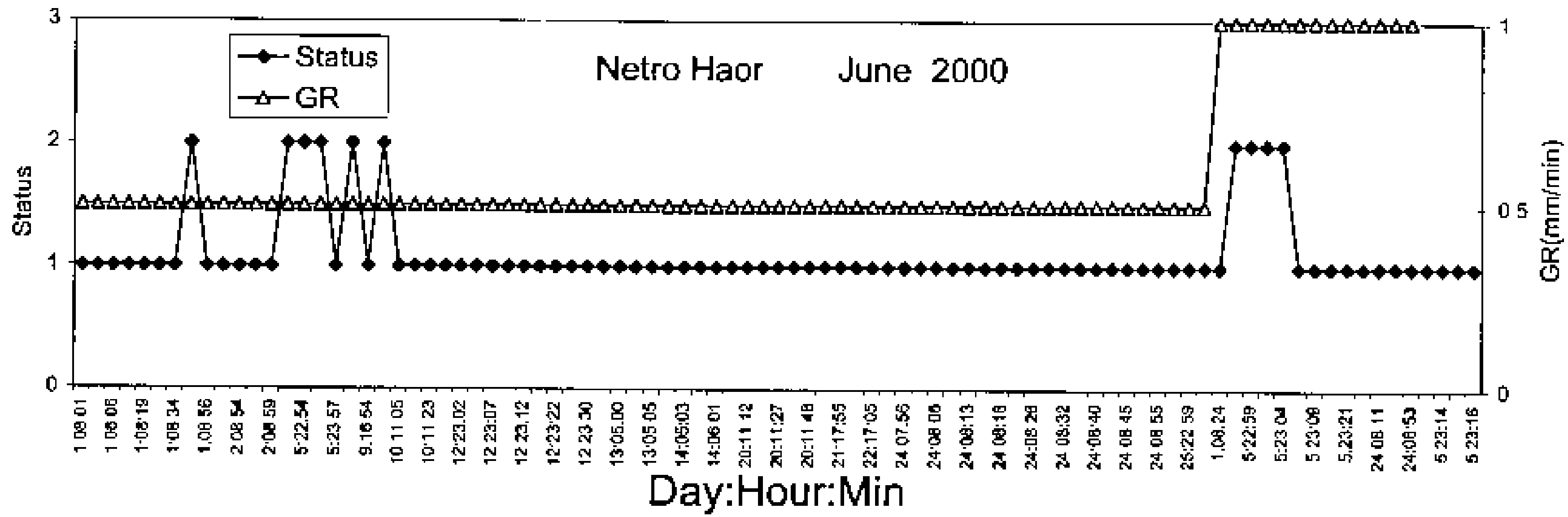

Fig. 15. Radar Status and rain gauge rain rate (GR) for June 2000 at Netro Haor.

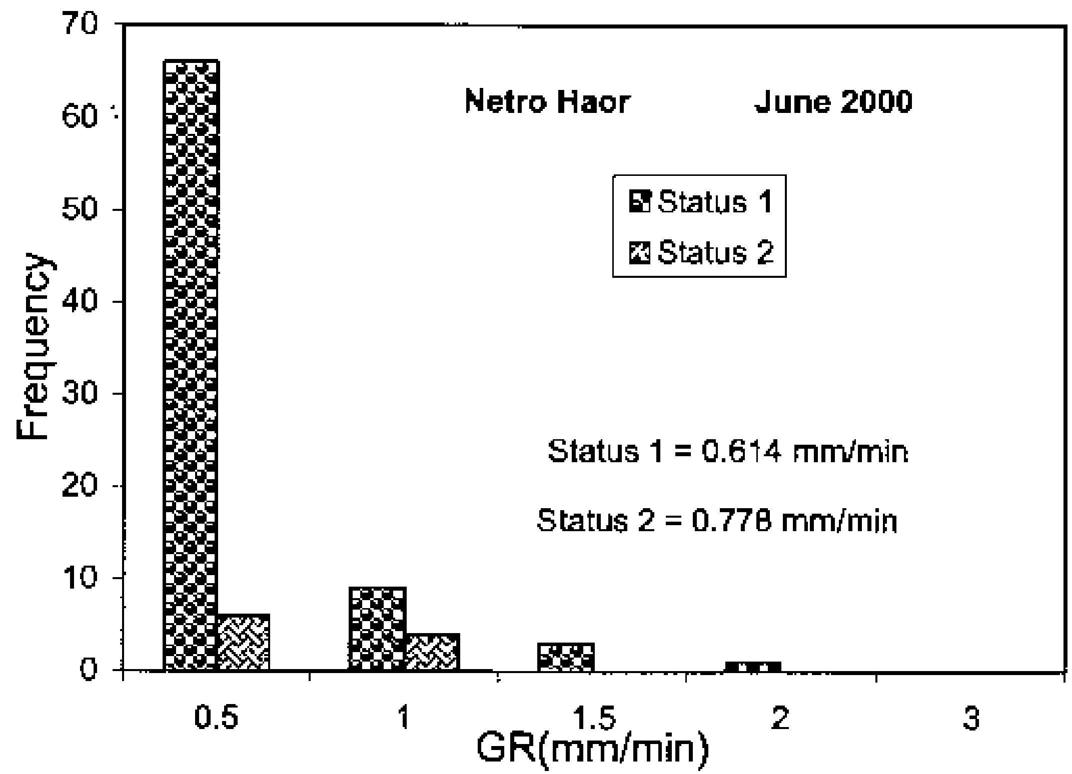

Fig. 16. Radar frequency and rain gauge rain rate (RG) for June2000 at Netro Haor.

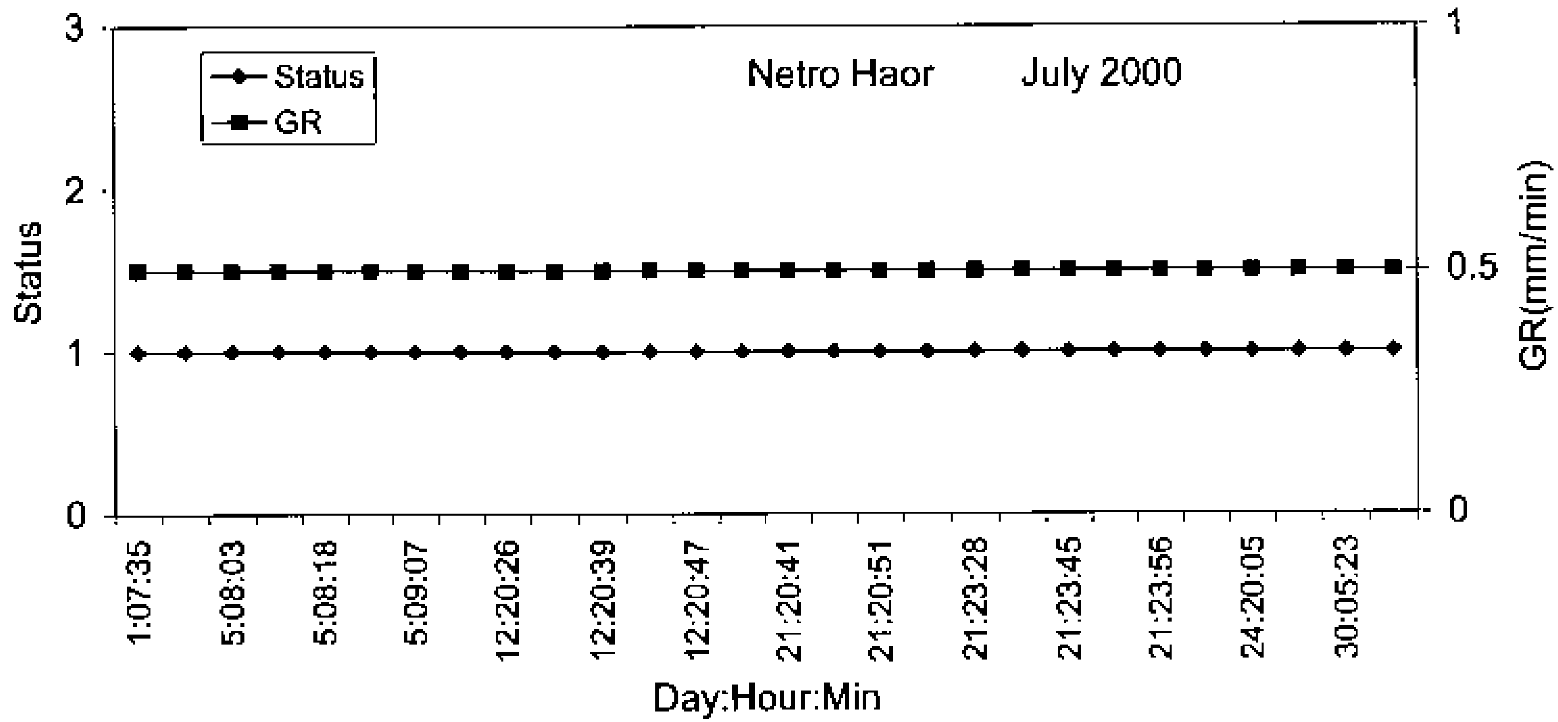

Fig. 17. Radar Status and rain gauge rain rate (GR) for July2000 at Netro Haor.

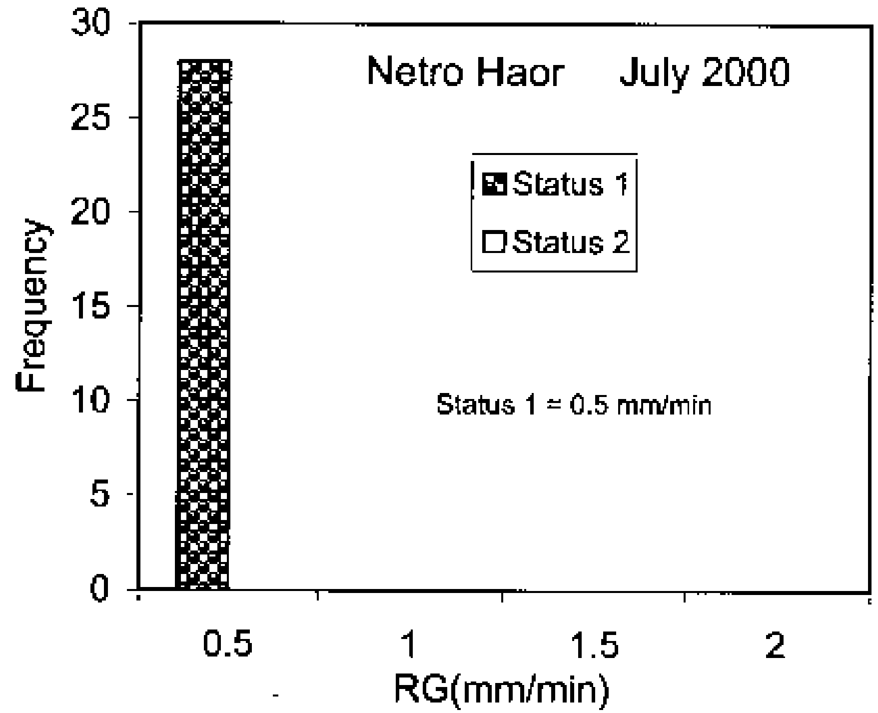

Fig. 18. Radar frequency and rain gauge rain rate (RG) for July2000 at Netro Haor.

5.5 Monthly Rain Rate

5.5.1 Monthly Rain Rate - Amalshid

May-June-July: Fig. 19 shows the monthly averaged rainfall for different Status at Amalshid. It is seen that rain rate is GR=0.5 mm/min for Status 1 for the months May, June and July. The rain rate is also same for Status 2.

5.5.2 Monthly Rain Rate – Chhatak

May-June-July: Fig. 20 shows the monthly averaged rainfall for different Status at Chhatak. It is seen that rain rate is GR=0.5 mm/min for Status 1 for the months May, June and July and for Status 2 GR=0.531 mm/min.

5.5.3 Monthly Rain Rate – Netro Haor

May-June-July: Fig. 21 shows the monthly averaged rainfall for different Status at Netro Haor. It is seen that rain rate is GR=0.597 mm/min for Status 1 for the months May, June and July. The rain rate is GR=0.758 mm/min for Status 2 and GR=3 mm/min for Status 3 for the months May, June and July.

5.6 Frequency

5.6.1 Frequency – Amalshid

May-June-July: Fig. 22 shows that frequency is existed for GR=0.5 for both Status 1 and Status 2.

5.6.2 Frequency – Chhatak

May-June-July: Fig. 23 shows that frequency is high for GR=0.5 mm/min for both Status 1 and Status 2. Very low frequency is existed for GR=1 mm/min for Status 2.

5.6.3 Frequency – Netro Haor

May-June-July: Fig. 24 indicates the frequency for different Status for corresponding to different GR values. It is seen that frequency is higher at GR=0.5 mm/min. Frequency existed upto GR=2 mm/min.At Netro Haor for the months May, June, July GR is 0.598 mm/min corresponds to status 1, 0.758 mm/min corresponds to status 2 and 3 mm/min corresponds to status 3. i.e., status 1 $\cong$ 0.598 mm/min, status 2 $\cong$ 0.758 mm/min and status 3 $\cong$ 3 mm/min (Fig. 24).

5.7 Average Rain Rate:

Fig. 25 shows that the average rain rate for different Status for different stations. In average we can see that for Amalshid, Chhatak and Netro Haor during May, June and July Status 1 corresponds to GR=0.5 mm/min, status 2 corresponds to GR=0.531 mm/min and Status 3 corresponds to GR=3 mm/min (Fig 25).

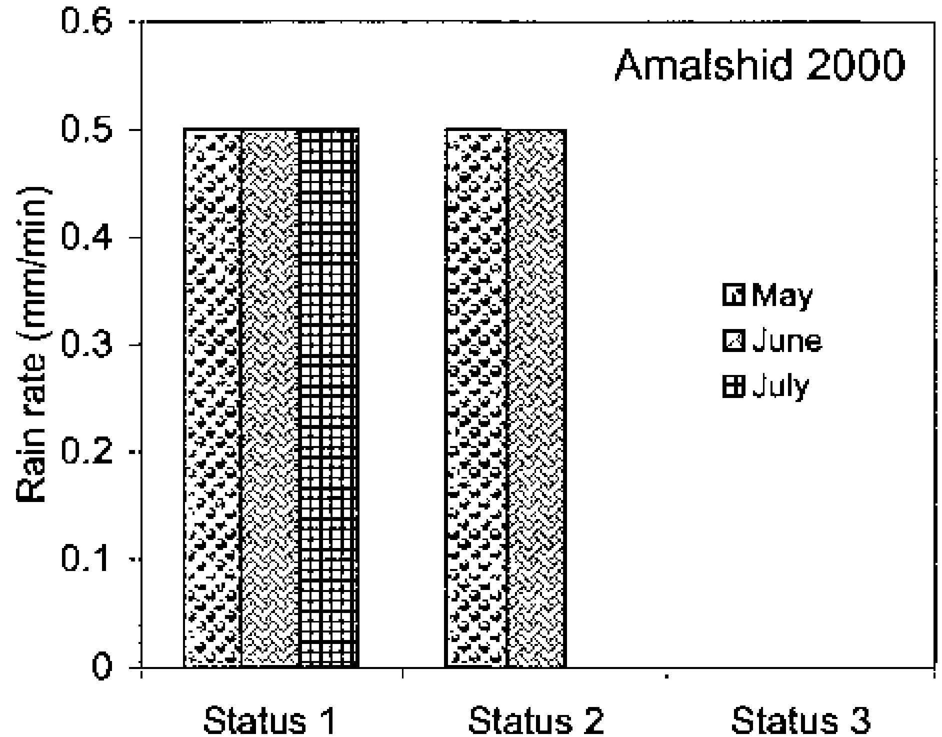

Fig. 19. Rain rate at different Status for different months at Amalshid.

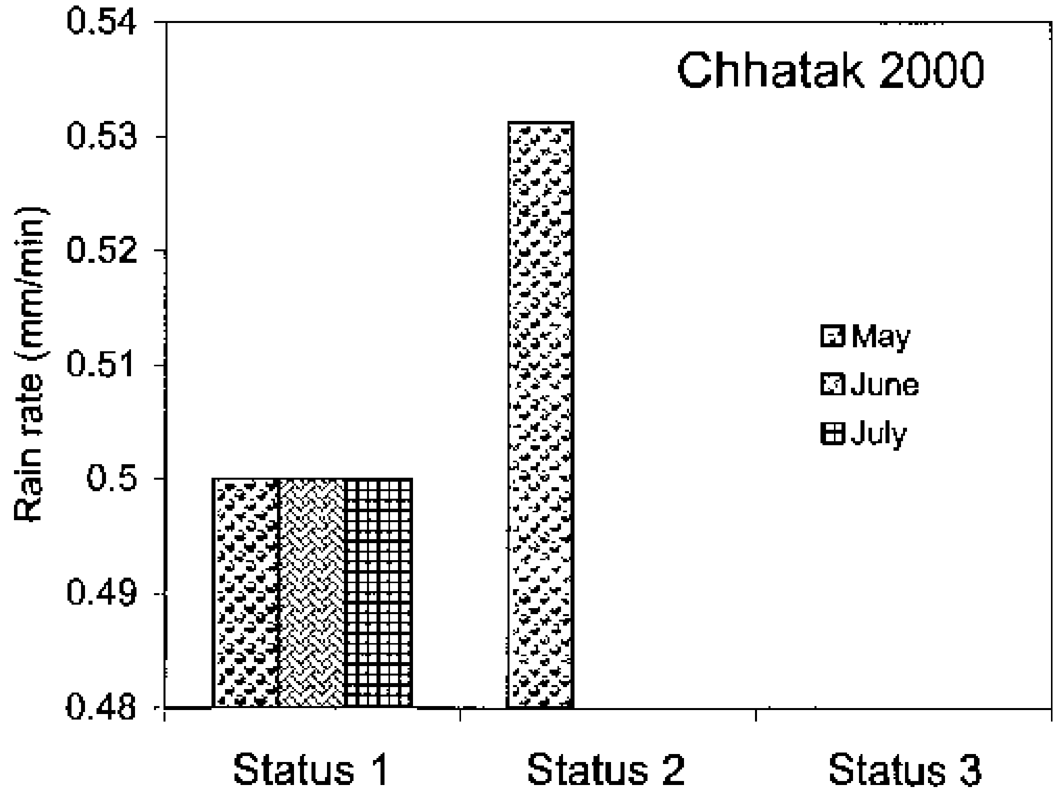

Fig. 20. Rain rate at different Status for different months at Chhatak.

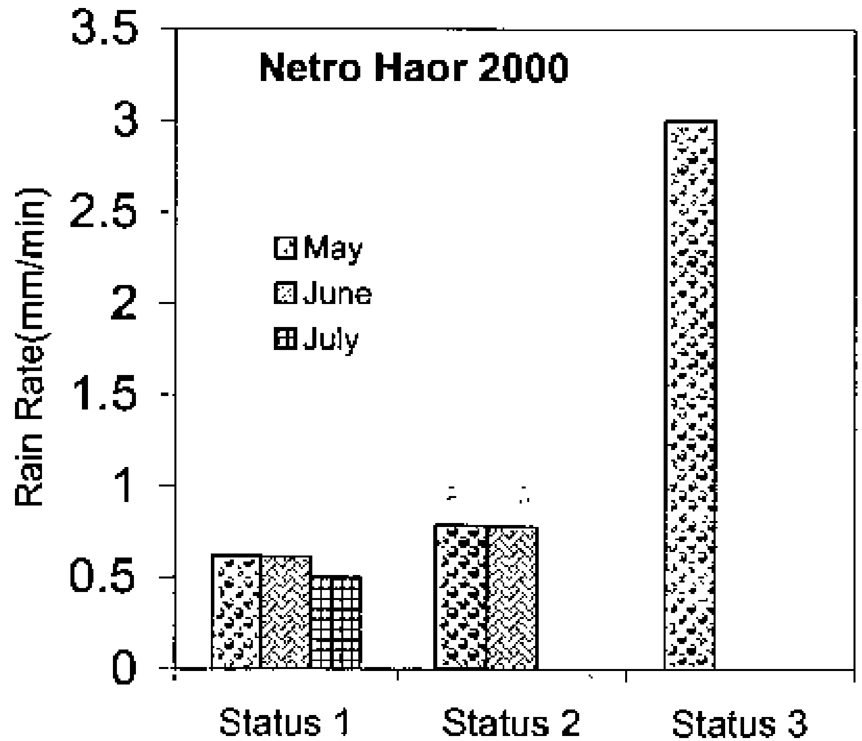

Fig. 21. Rain rate at different Status for different months at Netro Haor.

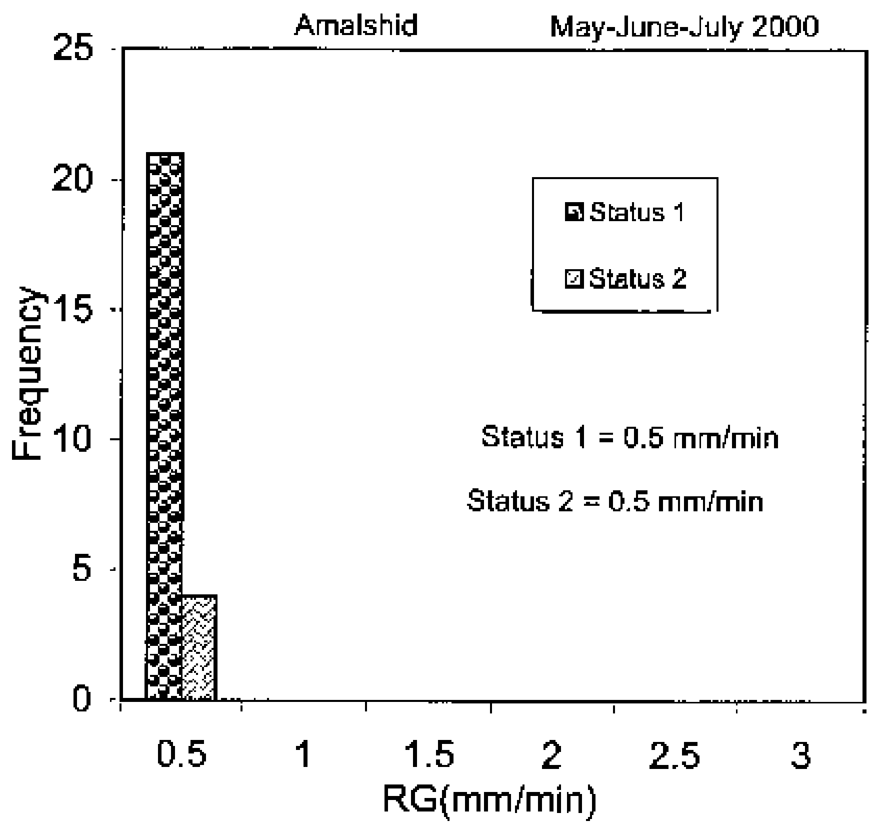

Fig. 22. Radar frequency and rain gauge rain rate (RG) for different months at Amalshid.

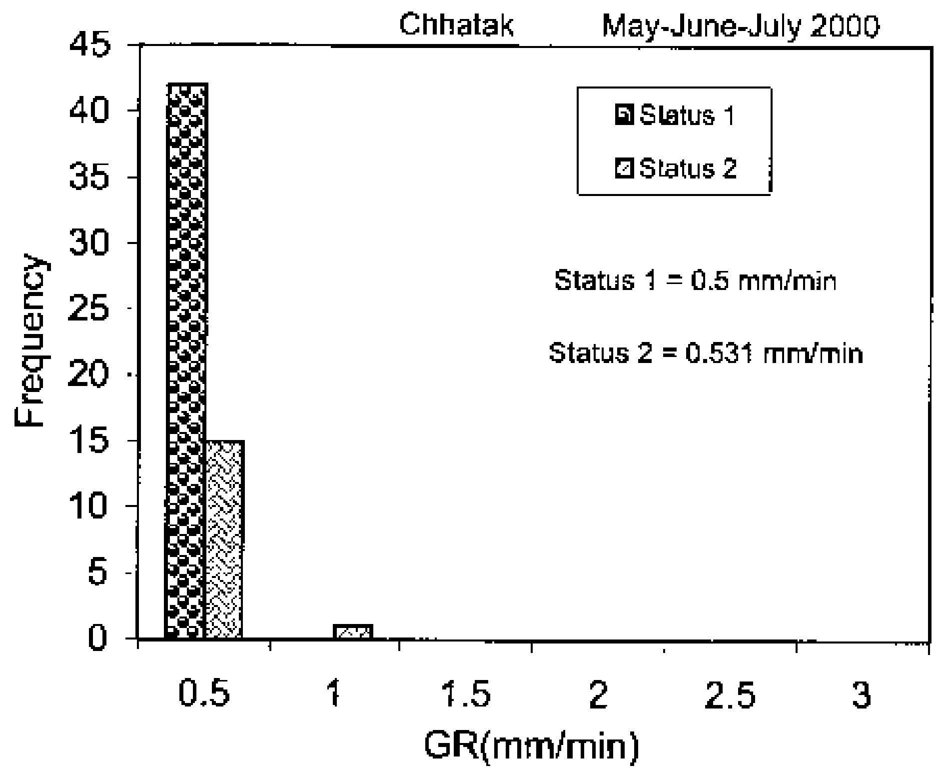

Fig. 23. Radar frequency and rain gauge rain rate (RG) for different months at Chhatak.

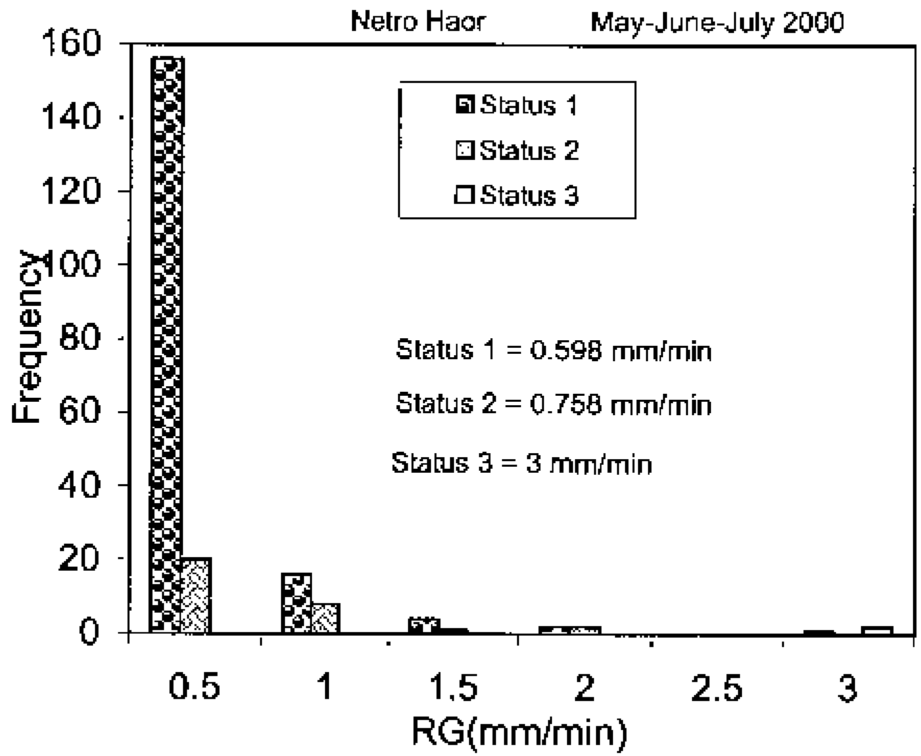

Fig. 24. Radar frequency and rain gauge rain rate (RG) for different months at Netro Haor.

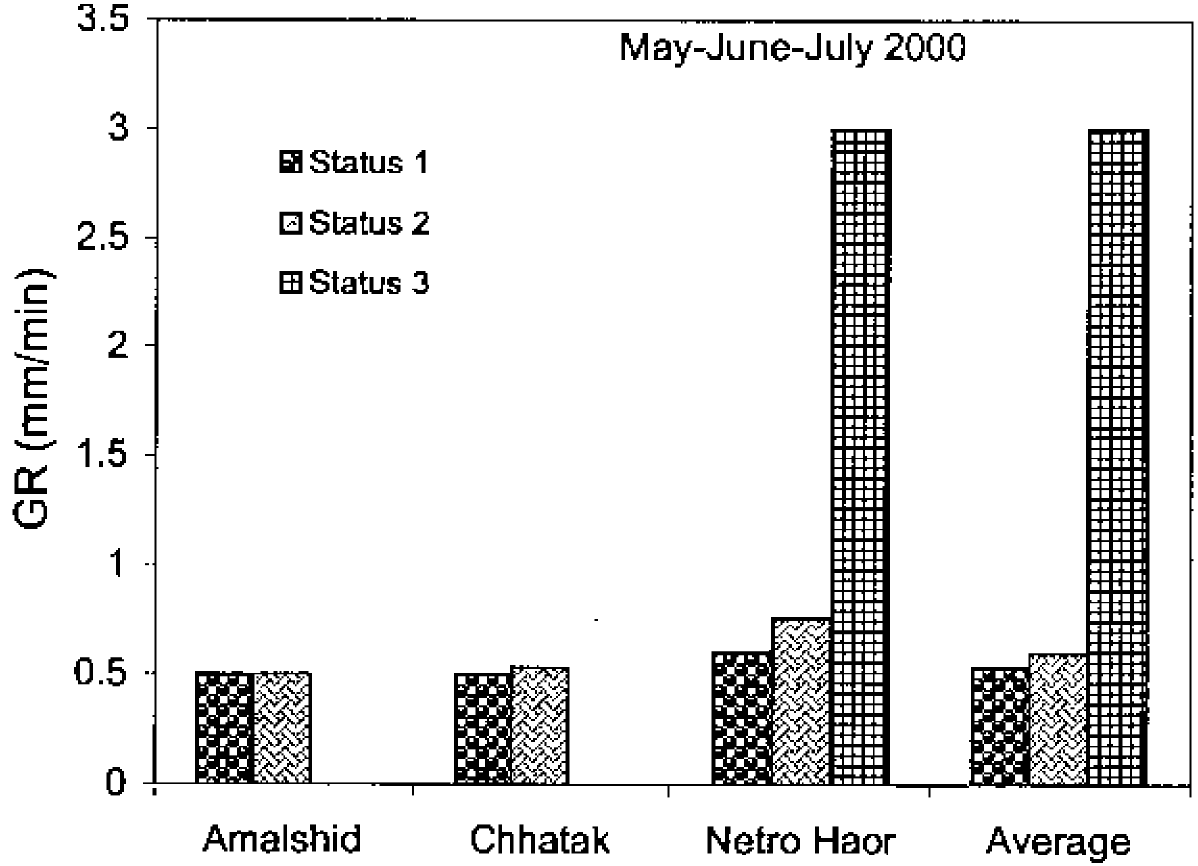

Fig. 25. Average rain rate at different Stations.

5.8 Assignment of rain rate:

In this section assignment of rain rate from radar data is discussed for the station Netro Haor for the months of May, June and July 2000.

5.8.1 Netro Haor-*May 2000*:

In Fig. 26 horizontal axis shows case number represented by minute and vertical axis shows rain rate of rain gauge in mm/hr at Netro Haor in the month May 2000. The case number indicated by minute means the event with its duration. There are 14 cases with different durations. The rain gauge indication is different for different cases, i.e., rain rate for individual case is different and lies from 3 mm/h to 90 mm/h. On an average the rain rate is 17.02 mm/h. The frequency in different status is also represented in Fig. 26.

5.8.2 Netro Haor-*June 2000*:

In Fig. 27 horizontal axis shows case number represented by minute and vertical axis shows rain rate of rain gauge in mm/hr at Netro Haor in the month June 2000. The case number indicated by minnte means the event with its duration. There are 9 cases with different durations. The rain gauge indication is different for different cases. i.e., rain rate for individual case is different and lies from 3.36 mm/h to 39.84 mm/h. On an average the rain rate is 16.06 mm/h. The frequency in different status is also represented in Fig. 27.

5.8.3 Netro Haor-*July 2000*:

In Fig. 28 horizontal axis shows case number represented by minute and vertical axis shows rain rate of rain gauge in mm/h at Netro Haor in the month July 2000. The case number indicated by minute means the event with its duration. There are 5 cases with different durations. The rain gauge indication is different for different cases. i.e., rain rate for individual case is different and lies from 5.64 mm/h to 30 mm/h. On an average the rain rate is 10.47 mm/h. The frequency in different status is also represented in Fig. 28.

5.8.4 Netro Haor-*May-June-July 2000*:

In Fig. 29 horizontal axis shows case number represented by minute and vertical axis shows rain rate of rain gauge in mm/hr at Netro Haor for the month May, June and July 2000 The case number indicated by minute means the event with its duration. There are 28 cases with different durations. The rain gauge indication is different for different cases. i.e. rain rate for individual case is different and lies from 10.47 mm/h to 17.02 mm/h. On an average the rain rate is 15.84 mm/h. The frequency in different status is also represented in Fig. 29.

In this way we can assign GR value corresponding to each Status of radar data. We need to verify this result for other months and other stations. Then we may finally clarify the rain rate for BMD radar data in their corresponding status. After that counting the total pixel (resolution: 2.5 x 2.5 km^2) in a PPI scan we can easily estimate rainfall.

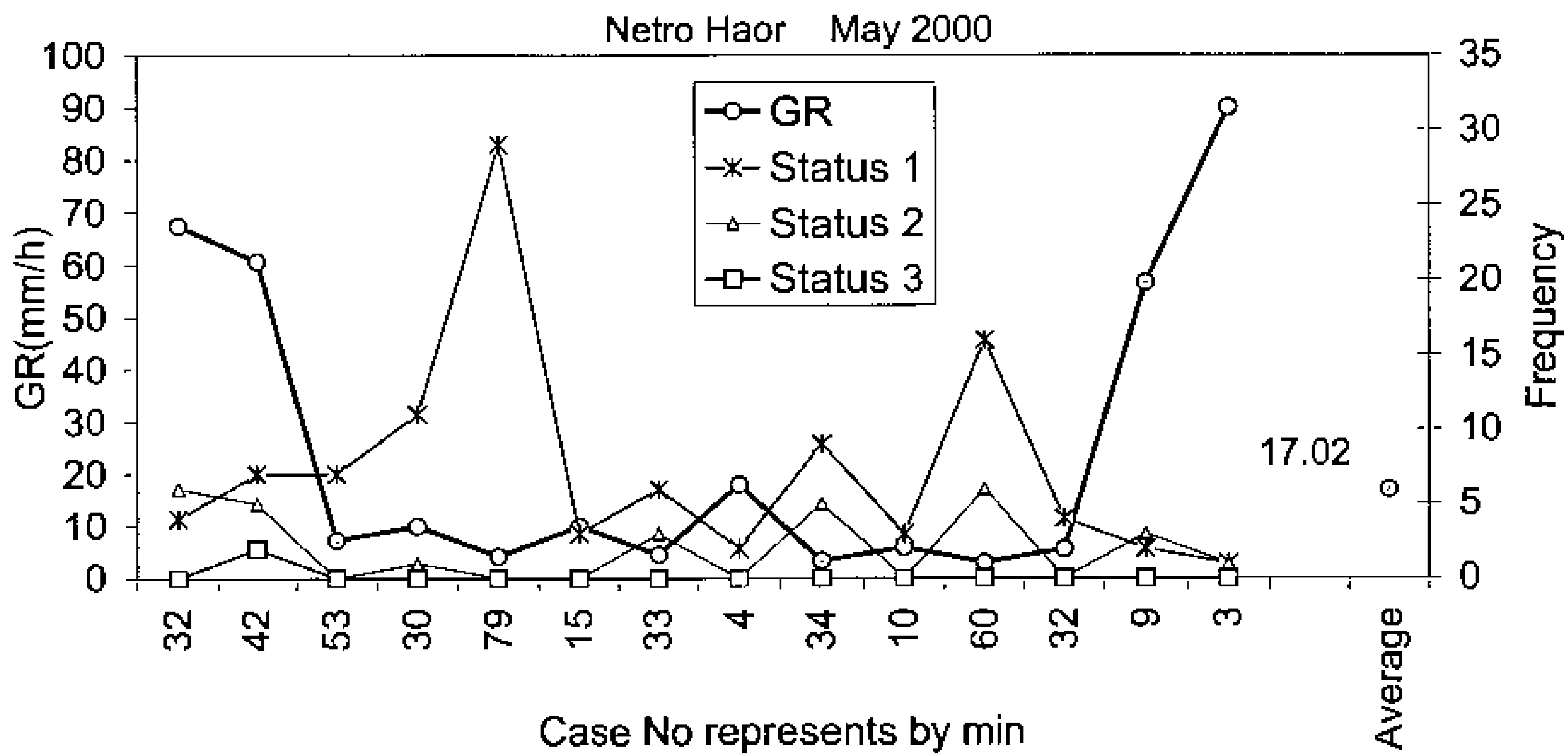

Fig. 26. Assignment of rain rate for May 2000 at Netro Haor.

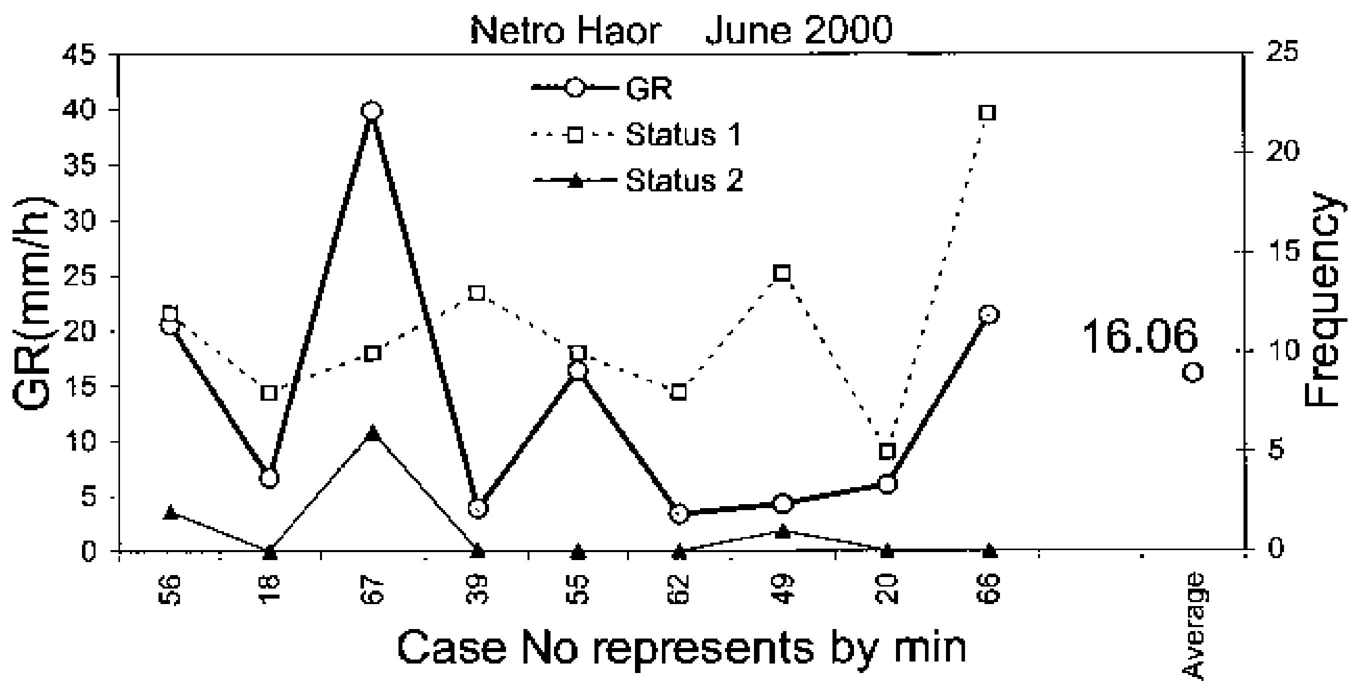

Fig. 27. Assignment of rain rate for June 2000 at Netro Haor.

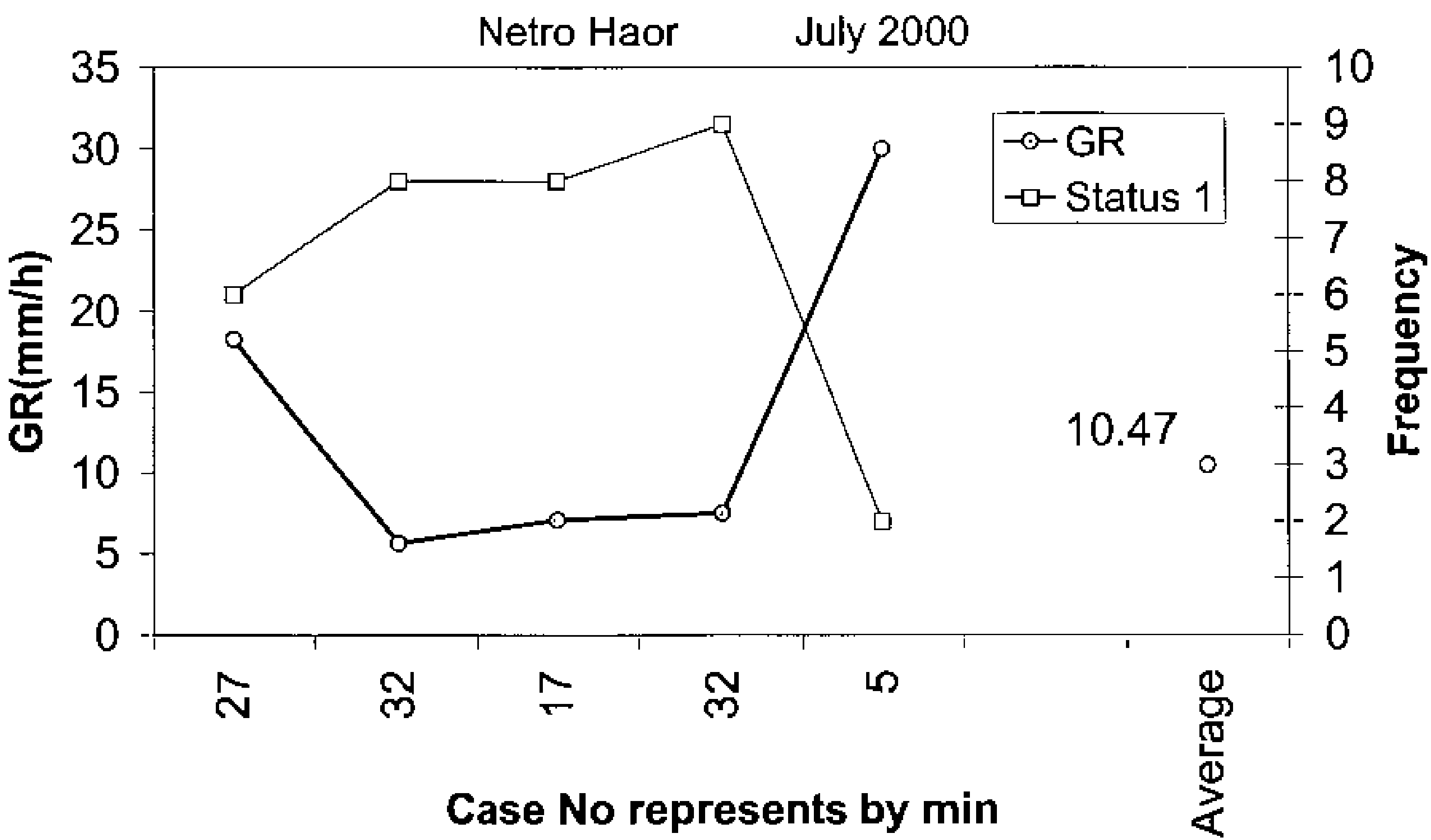

Fig. 28. Assignment of rain rate for July 2000 at Netro Haor.

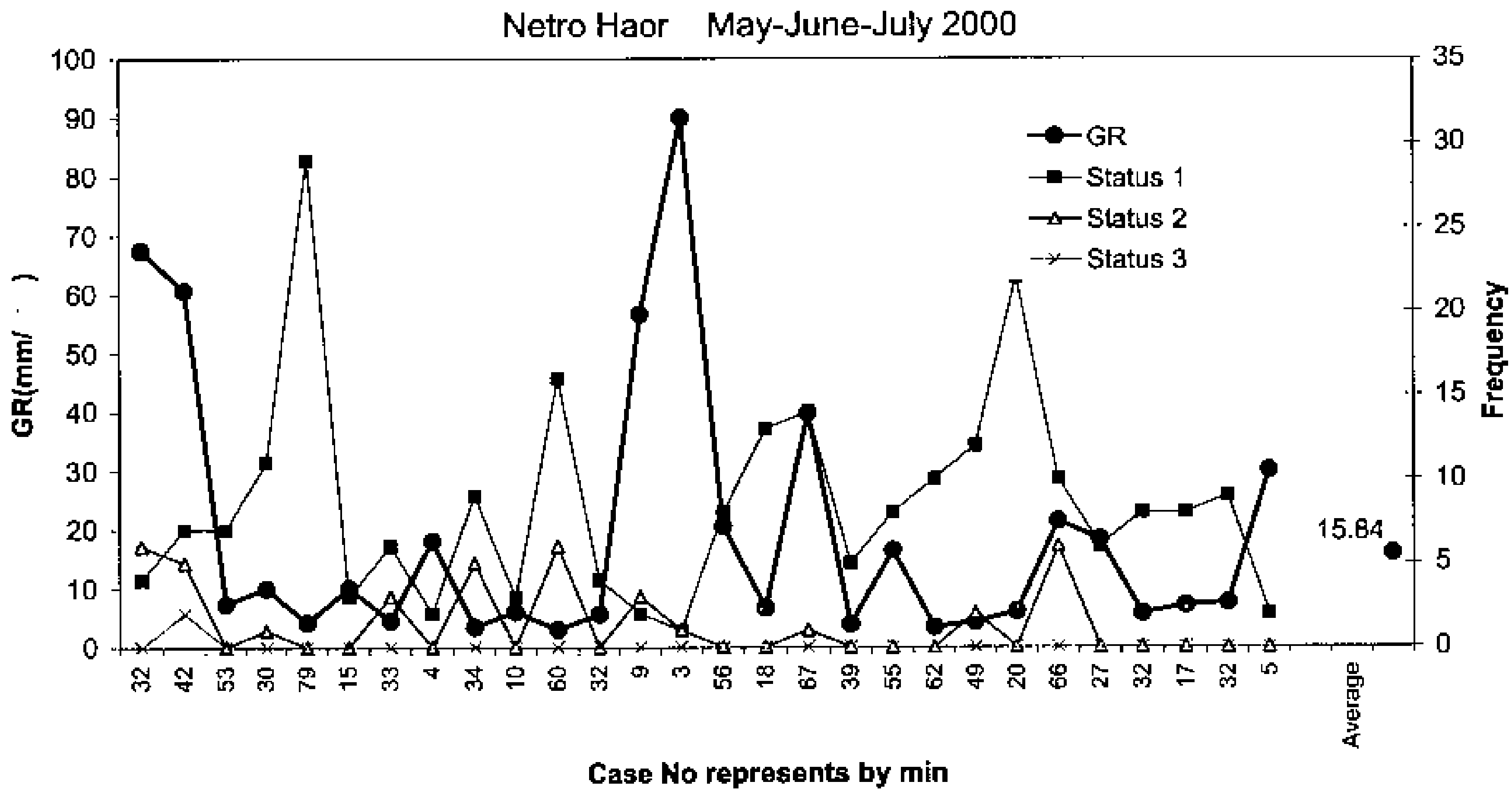

Fig. 29. Assignment of rain rate for different months at Netro Haor.

CHAPTER 6

CONCLUSIONS

Chapter 6 CONCLUSIONS

Analyzing radar data from May to July 2000 and calibrating with raingauge rainfall in Sylhet region we found that Status 1 (1~4 mm/h) and Status 2 (4~16 mm/h) is dominant. It is also found that at Amalshid the rain rate is 0.5 mm/min for both Status 1 and Status 2 in May 2000. The rain rate is 0.5 mm/min for both Status 1 and Status 2 in June 2000 and 0.5 mm/min for Status 1 in July 2000.

At Chhatak the rain rate is 0.5 mm/min for Status 1 and 0.53 mm/min for Status 2 in May 2000. The rain rate is 0.5 mm/min for Status 1 in June 2000 and 0.5 mm/min for Status 1 in July 2000.

At Netro Haor the rain rate is 0.619 mm/min for Status 1, 0.788 mm/min for Status 2 and 3 mm/min for status 3 in May 2000. The rain rate is 0.62 mm/min for Status 1 and 0.78 mm/min for Status 2 in June 2000 and the rain rate is 0.5 mm/min for Status 1 in Jnly 2000.

In average the rain rate is 0.5 mm/min for Status 1, 0.531 mm/min for Status 2 and 3 mm/min for Status 3.

These above rain rates are over estimated because all of them are equal to or more than 30 mm/h. This overestimation comes because we used only matched events and raingauge indication is not less than 0.5 mm/min(=30 mm/h).

Calibrating radar data with raingauge rainfall for some events it is found that rain rate lies between 10.47 mm/h to 17.02 mm/h and in average it is 15.84 mm/h for May-June-July

This rain rate is closer to rain rate over Bangladesh reported in other literatures [Khandaker Papiya Sultana, 2001]. This assigned rain rate 15.84 mm/h is reasonable for Sylhet region. We need more data for other years and also for other parts of Bangladesh for final assignment.

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Appendix-A Data Summary for three months at three stations.

Amalshid May 2000

Summary	Radar image	161	
	GR indication	882	
	Matched	15	
	Status 1	13	Average rain rate 0.5 mm/min
	Status 2	2	Average rain rate 0.5 mm/min
	Rain Rate (mm/min)	Count	Count
		Status1	Status2
	0.5	13	2
	1	0	0
	1.5	0	0

Chhatak May 2000

Summary	Radar image	288	
	GR indication	1055	
	Matched	36	
	Status 1	20	Average rain rate 0.5 mm/min
	Status 2	16	Average rain rate 0.53 mm/min
	Rain Rate (mm/min)	Count	Count
		Status 1	Status 2
	0.5	20	15
	1	0	1
	1.5	0	0
	2	0	0
	2.5	0	0
	3	0	0
	SUM	20	16

Netro Haor May 2000

Summary	Radar image	253		
	GR indication	1283		
	Matched	95		
	Status 1	72	Average rain rate 0.619 mm/min	
	Status 2	21	Average rain rate 0.788 mm/min	
	Status 3	2	Average rain rate 3 mm/min	
	Rain Rate (mm/min)	Count	Count	Count
		Status 1	Status 2	Status 3
	0.5	62	14	0
	1	7	4	0
	1.5	1	1	0
	2	1	2	0
	2.5	0	0	0
	3	1	0	2
	SUM	72	21	2

Amalshid June 2000

Sumamry	Radar	124		
	GR	1180		
	Matched	8		
	Status 1	6	Average rain rate 0.5 mm/min	
	Status 2	2	Average rain rate 0.5 mm/min	
	Rain Rate (mm/min)	Count	Count	
		Status 1	Status 2	
	0.5	6	2	
	1	0	0	
	1.5	0	0	
	2	0	0	
	SUM	5	2	

Chhatak June 2000

Summary	Radar image	249	
	GR indication	1826	
	Matched	18	
	Status 1	18	Average rain rate 0.5 mm/min
	Status 2	0	

	Rain Rate (mm/min)	Count	Count	
		Status 1	Status 2	
	0.5	18	0	
	1	0	0	
	1.5	0	0	
	2	0	0	
	2.5	0	0	
	3	0	0	
	SUM	18	0	

Netro Haor June 2000

Summary	Radar image	192	
	GR indication	1344	
	Matched	89	
	Status 1	79	Average rain rate 0.62 mm/min
	Status 2	10	Average rain rate 0.78 mm/min

	Rain Rate (mm/min)	Count	Count	
		Status 1	Status 2	
	0.5	66	6	
	1	9	4	
	1.5	3	0	
	2	1	0	
	2 5	0	0	
	3	0	0	
	SUM	79	10	

Amalshid July 2000

Summary	Radar image	63		
	GR indication	489		
	Matched	2		
	Status 1	2	Average rain rate 0.5 mm/min	
	Status 2	0		
	Rain Rate (mm/min)	Count	Count	
		Status 1	Status 2	
	0.5	2	0	
	1	0	0	
	1.5	0	0	
	2	0	0	
	2.5	0	0	
	3	0	0	
	SUM	2	0	

Chhatak July 2000

Summary	Radar image	107		
	GR indication	976		
	Matched	4		
	Status 1	4	Average rain rate 0.5 mm/min	
	Status 2	0		
	Rain Rate (mm/min)	Count	Count	
		Status 1	Status 2	
	0.5	4	0	
	1	0	0	
	1.5	0	0	
	2	0	0	
	2.5	0	0	
	3	0	0	
	SUM	4	0	

Netro Haor July 2000

Summary	Radar image	79		
	GR indication	715		
	Matched	28		
	Status 1	28	Average rain rate 0.5 mm/min	
	Status 2	0		
	Rain Rate (mm/min)	Count	Count	
		Status 1	Status 2	
	0.5	28	0	
	1	0	0	
	1.5	0	0	
	2	0	0	
	2.5	0	0	
	3	0	0	
	SUM	28	0	

Appendix-B Matched Data for three months at three stations.

Matched events for May 2000 at Amalshid

year	month	day	hr	min	Status	RG (mm/min)
2000	5	1	5	1	1	0.5
2000	5	1	5	17	1	0.5
2000	5	1	5	34	1	0.5
2000	5	1	5	50	1	0.5
2000	5	18	8	12	1	0.5
2000	5	18	8	18	1	0.5
2000	5	18	8	40	2	0.5
2000	5	18	8	45	2	0.5
2000	5	18	8	55	1	0.5
2000	5	18	9	3	1	0.5
2000	5	26	8	21	1	0.5
2000	5	26	8	29	1	0.5
2000	5	26	8	34	1	0.5
2000	5	26	8	45	1	0.5
2000	5	26	8	50	1	0.5

Matched events for May 2000 at Chhatak

year	month	day	hr	min	Status	RG (mm/min)
2000	5	18	8	7	1	0.5
2000	5	18	8	15	1	0.5
2000	5	18	8	22	2	0.5
2000	5	18	8	28	1	0.5
2000	5	18	8	35	1	0.5
2000	5	18	8	58	2	0.5
2000	5	26	5	1	2	0.5
2000	5	26	5	27	2	0.5
2000	5	26	5	30	2	0.5
2000	5	26	5	53	2	0.5
2000	5	26	11	14	2	0.5
2000	5	26	23	47	1	0.5
2000	5	27	10	7	3	0.5
2000	5	27	10	12	2	0.5
2000	5	27	10	18	2	0.5
2000	5	27	10	22	1	0.5
2000	5	27	10	25	1	0.5

2000	5	27	10	27	1	0.5
2000	5	27	10	28	1	0.5
2000	5	27	10	32	1	0.5
2000	5	27	10	35	1	0.5
2000	5	27	10	37	1	0.5
2000	5	27	10	47	1	0.5
2000	5	28	6	0	1	0.5
2000	5	29	4	55	2	0.5
2000	5	29	4	58	2	0.5
2000	5	29	5	1	2	0.5
2000	5	29	5	3	1	0.5
2000	5	29	5	8	1	0.5
2000	5	29	5	42	1	0.5
2000	5	30	5	48	2	0.5
2000	5	30	5	53	2	0.5
2000	5	30	5	56	1	0.5
2000	5	31	5	42	1	0.5
2000	5	31	5	44	2	0.5
2000	5	31	5	47	1	0.5

Matched events for May 2000 at Netro Haor

year	month	day	hr	min	Status	RG (mm/min)
2000	5	1	5	14	2	0.5
2000	5	1	5	17	2	0.5
2000	5	1	5	19	2	0.5
2000	5	1	5	22	2	0.5
2000	5	1	5	24	2	0.5
2000	5	1	5	27	1	0.5
2000	5	18	5	33	2	0.5
2000	5	18	5	40	1	0.5
2000	5	18	5	44	2	0.5
2000	5	18	5	55	1	0.5
2000	5	18	5	58	1	0.5
2000	5	18	8	5	1	0.5
2000	5	18	8	7	1	0.5
2000	5	18	8	12	1	0.5
2000	5	18	8	27	1	0.5
2000	5	18	8	55	1	0.5
2000	5	18	11	6	1	0.5
2000	5	18	11	8	1	0.5
2000	5	18	11	11	1	0.5
2000	5	18	11	16	1	0.5

2000	5	18	11	18	1	0.5
2000	5	18	11	21	1	0.5
2000	5	18	11	23	1	0.5
2000	5	18	11	26	1	0.5
2000	5	18	11	28	1	0.5
2000	5	18	11	31	1	0.5
2000	5	18	11	36	1	0.5
2000	5	19	8	4	1	0.5
2000	5	19	8	17	1	0.5
2000	5	19	8	32	1	0.5
2000	5	19	8	37	1	0.5
2000	5	19	8	42	1	0.5
2000	5	19	8	49	1	0.5
2000	5	19	8	54	1	0.5
2000	5	19	9	4	1	0.5
2000	5	22	8	59	1	0.5
2000	5	22	9	2	1	0.5
2000	5	22	9	4	1	0.5
2000	5	22	9	7	1	0.5
2000	5	22	9	9	1	0.5
2000	5	22	9	12	1	0.5
2000	5	22	9	14	1	0.5
2000	5	22	9	17	1	0.5
2000	5	22	9	19	1	0.5
2000	5	22	9	22	1	0.5
2000	5	22	10	21	1	0.5
2000	5	22	10	24	1	0.5
2000	5	22	10	33	1	0.5
2000	5	22	11	55	1	0.5
2000	5	22	14	7	1	0.5
2000	5	22	14	14	2	0.5
2000	5	22	14	19	1	0.5
2000	5	22	14	37	1	0.5
2000	5	26	6	1	1	0.5
2000	5	26	6	4	1	0.5
2000	5	26	8	1	1	0.5
2000	5	26	8	6	1	0.5
2000	5	26	8	14	2	0.5
2000	5	26	8	34	1	0.5
2000	5	26	12	32	2	0.5
2000	5	26	14	5	1	0.5
2000	5	26	14	13	1	0.5
2000	5	26	23	10	2	0.5
2000	5	26	23	15	1	0.5
2000	5	27	10	52	1	0.5
2000	5	28	7	35	2	0.5

2000	5	28	7	42	2	0.5
2000	5	28	7	47	1	0.5
2000	5	28	8	3	1	0 5
2000	5	28	8	15	1	0.5
2000	5	28	11	35	1	0.5
2000	5	29	5	34	2	0.5
2000	5	29	5	42	1	0.5
2000	5	29	5	44	1	0.5
2000	5	29	6	52	1	0.5
2000	5	30	7	54	1	0.5

year	month	day	hr	min	Status	RG (mm/min)
2000	5	1	5	7	1	1
2000	5	18	5	27	2	1
2000	5	18	5	30	2	1
2000	5	18	5	35	1	1
2000	5	18	5	41	1	1
2000	5	18	5	47	1	1
2000	5	18	5	52	1	1
2000	5	18	8	2	1	1
2000	5	22	9	24	1	1
2000	5	29	5	39	2	1
2000	5	31	23	31	2	1

year	month	day	hr	min	Status	RG (mm/min)
2000	5	1	4	59	1	1.5
2000	5	29	5	37	2	1.5

year	month	day	hr	min	Status	RG (mm/min)
2000	5	1	4	56	2	2
2000	5	18	5	17	2	2
2000	5	18	5	19	3	2
2000	5	18	5	22	3	2
2000	5	31	23	29	1	2

year	month	day	hr	min	Status	RG (mm/min)
2000	5	1	5	4	1	3

Matched events for June 2000 at Amalshid

year	month	day	hr	min	Status	RG (mm/min)
2000	6	1	8	31	1	0.5
2000	6	13	11	1	1	0.5
2000	6	21	17	6	1	0.5
2000	6	24	20	59	2	0.5
2000	6	24	21	1	2	0.5
2000	6	28	5	17	1	0.5
2000	6	28	5	27	1	0.5
2000	6	28	5	57	1	0.5

Matched events for June 2000 at Chhatak

year	month	day	hr	min	Status	RG (mm/min)
2000	6	1	6	41	1	0.5
2000	6	1	7	43	1	0.5
2000	6	10	8	10	1	0.5
2000	6	12	23	46	1	0.5
2000	6	12	23	48	1	0.5
2000	6	12	23	51	1	0.5
2000	6	12	23	53	1	0.5
2000	6	12	23	56	1	0.5
2000	6	12	23	58	1	0.5
2000	6	13	0	1	1	0.5
2000	6	13	4	57	1	0.5
2000	6	24	5	59	1	0.5
2000	6	27	8	6	1	0.5
2000	6	30	5	51	1	0.5
2000	6	30	5	54	1	0.5
2000	6	30	5	56	1	0.5
2000	6	30	8	3	1	0.5
2000	6	30	8	15	1	0.5

Matched events for June 2000 at Netro Haor

year	month	day	hr	min	Status	RG (mm/min)
2000	6	1	8	1	1	0.5
2000	6	1	8	4	1	0.5
2000	6	1	8	6	1	0.5
2000	6	1	8	16	1	0.5
2000	6	1	8	19	1	0.5

2000	6	1	8	21	1	0.5
2000	6	1	8	34	1	0.5
2000	6	1	8	39	2	0.5
2000	6	1	8	56	1	0.5
2000	6	2	8	41	1	0.5
2000	6	2	8	54	1	0.5
2000	6	2	8	57	1	0.5
2000	6	2	8	59	1	0.5
2000	6	5	22	51	2	0.5
2000	6	5	22	54	2	0.5
2000	6	5	22	56	2	0.5
2000	6	5	23	57	1	0.5
2000	6	6	0	0	2	0.5
2000	6	9	16	54	1	0.5
2000	6	9	16	56	2	0.5
2000	6	10	11	5	1	0.5
2000	6	10	11	13	1	0.5
2000	6	10	11	23	1	0.5
2000	6	10	11	30	1	0.5
2000	6	12	23	2	1	0.5
2000	6	12	23	4	1	0.5
2000	6	12	23	7	1	0.5
2000	6	12	23	9	1	0.5
2000	6	12	23	12	1	0.5
2000	6	12	23	14	1	0.5
2000	6	12	23	22	1	0.5
2000	6	12	23	25	1	0.5
2000	6	12	23	30	1	0.5
2000	6	12	23	56	1	0.5
2000	6	13	5	0	1	0.5
2000	6	13	5	3	1	0.5
2000	6	13	5	5	1	0.5
2000	6	14	5	0	1	0.5
2000	6	14	5	3	1	0.5
2000	6	14	5	53	1	0.5
2000	6	14	6	1	1	0.5
2000	6	20	10	59	1	0.5
2000	6	20	11	12	1	0.5
2000	6	20	11	22	1	0.5
2000	6	20	11	27	1	0.5
2000	6	20	11	34	1	0.5
2000	6	20	11	48	1	0.5
2000	6	21	14	27	1	0.5
2000	6	21	17	55	1	0.5
2000	6	22	17	0	1	0.5
2000	6	22	17	5	1	0.5

2000	6	22	17	42	1	0.5
2000	6	24	7	56	1	0.5
2000	6	24	8	1	1	0.5
2000	6	24	8	6	1	0.5
2000	6	24	8	8	1	0.5
2000	6	24	8	13	1	0.5
2000	6	24	8	16	1	0.5
2000	6	24	8	18	1	0.5
2000	6	24	8	21	1	0.5
2000	6	24	8	26	1	0.5
2000	6	24	8	29	1	0.5
2000	6	24	8	32	1	0.5
2000	6	24	8	35	1	0.5
2000	6	24	8	40	1	0.5
2000	6	24	8	43	1	0.5
2000	6	24	8	45	1	0.5
2000	6	24	8	50	1	0.5
2000	6	24	8	55	1	0.5
2000	6	24	9	0	1	0.5
2000	6	25	22	59	1	0.5
2000	6	25	23	2	1	0.5
year	month	day	hr	min	Status	RG (mm/min)
2000	6	1	8	24	1	1
2000	6	1	8	26	2	1
2000	6	5	22	59	2	1
2000	6	5	23	1	2	1
2000	6	5	23	4	2	1
2000	6	5	23	6	1	1
2000	6	5	23	9	1	1
2000	6	5	23	19	1	1
2000	6	5	23	21	1	1
2000	6	5	23	26	1	1
2000	6	24	8	11	1	1
2000	6	24	8	23	1	1
2000	6	24	8	53	1	1
year	month	day	hr	min	Status	RG (mm/min)
2000	6	5	23	11	1	1.5
2000	6	5	23	14	1	1.5
2000	6	5	23	24	1	1.5
year	month	day	hr	min	Status	RG (mm/min)
2000	6	5	23	16	1	2

Matched events for July 2000 at Amalshid

year	month	day	hr	min	Status	RG (mm/min)
2000	7	21	23	11	1	0.5
2000	7	21	23	13	1	0.5

Matched events for July 2000 at Chhatak

year	month	day	hr	min	Status	RG (mm/min)
2000	7	4	4	58	1	0.5
2000	7	4	5	1	1	0.5
2000	7	4	5	3	1	0.5
2000	7	4	5	13	1	0.5

Matched events for July 2000 at Netro Haor

year	month	day	hr	min	Status	RG (mm/min)
2000	7	1	7	35	1	0.5
2000	7	5	8	1	1	0.5
2000	7	5	8	3	1	0.5
2000	7	5	8	16	1	0.5
2000	7	5	8	18	1	0.5
2000	7	5	9	1	1	0.5
2000	7	5	9	7	1	0.5
2000	7	5	9	21	1	0.5
2000	7	12	20	26	1	0.5
2000	7	12	20	36	1	0.5
2000	7	12	20	39	1	0.5
2000	7	12	20	42	1	0.5
2000	7	12	20	47	1	0.5
2000	7	16	23	39	1	0.5
2000	7	21	20	41	1	0.5
2000	7	21	20	44	1	0.5
2000	7	21	20	51	1	0.5
2000	7	21	20	56	1	0.5
2000	7	21	23	28	1	0.5
2000	7	21	23	36	1	0.5
2000	7	21	23	45	1	0.5
2000	7	21	23	48	1	0.5
2000	7	21	23	56	1	0.5
2000	7	22	0	1	1	0.5
2000	7	24	20	5	1	0.5

2000	7	29	5	7	1	0.5
2000	7	30	5	23	1	0.5
2000	7	30	5	26	1	0.5