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REMOTE SENSING OF CLOUD PRECIPITABLE WATER CONTENT USING INSAT-1D DATA

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Remote sensing of a cloudy atmosphere for the estimation of cloud precipitable water content (PWC) has been undertaken using INSAT-1D data during the monsoon month of July, 1991. The clouds have been classified using an unsupervised clustering technique based on the infrared ($11 \times 11 km^2$ resolution) and visible brightness ($2.75 \times 2.75 km^2$ resolution) characteristics. Satellite inferred cloud top temperatures have helped in estimating the top pressure and the geopotential height using the mean profiles for aerological parameters derived during the Monsoon Experiment (MONEX-79). The scheme estimates the cloud optical thickness, the liquid water path(LWP), the cloud base height and the PWC between the cloud levels. Satisfactory results for qualitative validation of base height estimation have been achieved. for quantitative validation, the estimated PWC has been correlated with the actual rainfall over numerous stations and a strong positive correlation (co-efficient of correlation equal to 0.8) has been found out. Two threshold limits viz., $PWC > 1.2 gm/cm^2$ for necessarily precipitating and $PWC < 0.35 gm/cm^2$ for never precipitating clouds, have been found out. The scheme gives accurate results for clouds which are large and really contiguous and can therefore be used efficiently for rainfall distribution analysis. Improvements are possible using data with better spatial and temporal resolutions and by modifying the scheme for night-time analysis as well.

Key Words: Cloud Classification; Cloud Base Height; Precipitable Water Content

Introduction

Conventionally, rainfall is estimated by analyzing the rainfall data collected using a dense network of rain-gauge stations. Daily rainfall is recorded and a central co-ordinating station is provided the data from all other stations. Isohyets are drawn and this information is used for hydrological studies. Lately, the meteorological satellites are being progressively used for both the estimation as well as the forecasting of rainfall. Remotely sensed imagery and digital data from the satellites offers an alternative method for this purpose. With the improvement in technology (in the spatial resolution of the radiometers), satellite data analysis has become quite a reliable, efficient and cost effective method.

Basically, there are two types of satellite observations which are used to estimate the precipitation (Arkin and Janowiak, 1991). These are: *i*) cloud top observations using infrared (IR) or visible brightness (VIS) or both (VIS/IR);

and *ii*) microwave observations of liquid and solid hydrometeors. These techniques have been labelled as indirect and direct respectively by Arkin and Meisner[2].

The indirect method utilizes VIS/IR data and aims to establish the correlation between VIS/IR characteristics and the actual rainfall. The cloud top temperature is usually determined using the infrared channel data. The associated cloud top pressure and the geopotential height can be determined using this top temperature. Cloud type identification still rests as a subjective procedure and no single classification is presently available. However, this cloud type information is useful in the initialization of the cloud water content for the estimation of cloud optical properties. The estimation of the base height using satellite data is of considerable importance. The ambiguities in the determination of cloud base height and the complications arising from the presence of precipitable water droplets are well known. This is because the ground observations usually provide reliable information for low clouds and for other clouds only in the absence of lower clouds. The high clouds, on the other hand, are easily sensed by the satellites. The middle clouds, therefore, have great uncertainties associated with them, especially when multilayered situations are present.

Several approaches relating the cloud optical properties with the satellite measured radiances[3-5] have been suggested. The liquid water path (LWP) is dependent upon the cloud top and base levels and the assumed liquid water concentration profile between these two levels. The optical thickness can be related to the LWP as given by the Stephens[3] parametrization scheme. The precipitable water content (PWC) can be estimated by integrating the mixing ratio profile between the cloud top and bottom pressure levels[6]. The correlation between the PWC and the actual rainfall can thereafter be established.

In this study, INSAT-1D (Indian Satellite) data from both the Infrared (IR) and visible (VIS) channels for 3 consecutive days in the monsoon month of July 1991 (23-25th), have been utilized. The suggested scheme identifies the cloud type, estimates the cloud top and base levels, the optical thickness, the LWP and finally the PWC between the cloud levels. Lastly, the correlation between this estimated PWC (over a scan spot/station) and the actual observed rainfall has been worked out.

Methodology

The cloud type classification is the first step if such a scheme is to be designed. Earth Resources Data Analysis (ERDAS) based image processing system has been used for this purpose. Infrared and visible data for all the three days have been classified using an unsupervised clustering technique. Next, using the scheme given by Lee and Taggart for visual cloud identification, numerous clusters have been combined into seven cloud types. The classification is based on the top temperature characteristics of each cloud. The spectral properties (infra-red and visible brightness) identified for each cloud type in this study is shown by a 2-dimensional diagram (Fig. 1).

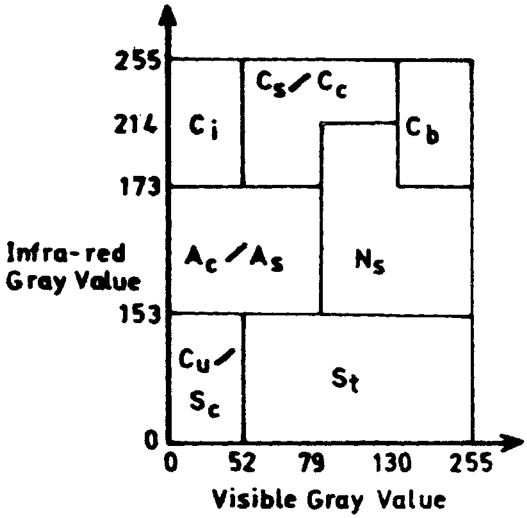


Fig 1 Cloud classification (using infrared and visible data) used in this study

Satellite infrared data are used for inferring the cloud top temperature by using a look-up table. This parameter is then used to estimate the top pressure and the geopotential height of each cloud. In our scheme, we assume that the cloud behaves like an air parcel which is in stable equilibrium with the surrounding atmosphere. This enables us to estimate the top pressure and the geopotential height using the mean profiles for aerological parameters in free atmosphere obtained during Monsoon Experiment (MONEX-79) as reported by Zaitseva[8].

Our next aim is to estimate the base height of the cloud. It may be pointed out here that till now we have fixed only the top height and have identified the cloud type for each scan spot. For the estimation of the base height we basically utilize the visible channel data for the optical thickness estimation which is then used to fix the base level of the cloud. The stepwise scheme is as follows:

Step 1: Estimate the optical thickness (τ) using the regression relation established between the visible data (VIS) and the optical thickness (explained later) given as:

$$\tau = 8.0625\left[\exp\left(\frac{0.0101 \times VIS}{\cos\mu}\right) - 1\right] \qquad \ldots (1)$$

Step 2: Estimate the LWP using the optical thickness (τ) using the relation given by Stephens[3]:

$$\log_{10}(LWP) = (0.5454 \times \tau)^{0.254} \qquad \ldots (2)$$

Step 3: Estimate the base height (z_b) by solving analytically the relations employed in the National Center for Atmospheric Research (NCAR) model (Kiehl, 1990)[9]:

$$LWP = \int_{z_b}^{z_t} w \, dz \quad \ldots (3)$$

$$w = w_0 \exp\left(-\frac{z}{h}\right) \quad \ldots (4)$$

$$h = 300 + 2900 \cos \phi \quad \ldots (5)$$

It may be observed that an exponentially decaying profile (expression (3) for the liquid water concentration has been assumed in the NCAR model. The liquid water concentration (LWC) at a height z is given as w; z_t and z_b refer to the cloud top and bottom levels respectively. The maximum LWC is therefore at the base level and is given as w_0. The liquid water scale height (h), is a latitude (ϕ) dependent quantity. It is also pertinent to point out here that the cumulonimbus (*Cb*) clouds, which are more common during the monsoon period, usually have much higher LWC values (around 2.5×10^{-3}kg m^{-3} However, since the spatial resolution (11×11km^2) of INSAT-1D for the IR channel is quite large, the choice of such high LWC value could cause significant overestimation due to pixel averaging for the *Cb* clouds. To overcome this problem, the value of w_0 has been judiciously fixed at 0.2×10^{-3} kg m^{-3} for all the clouds in this study.

The regression relationship between the optical thickness and the visible reflectance, mentioned in Step 1 needs elaboration: the authors have derived the relationship between these two parameters by regressing the optical thickness limits of each cloud type (International Satellite Cloud Climatology Project (ISCCP)) radiometric definition of cloud type (Rossow, 1990)[10] with the visible gray level limits of the corresponding cloud type (classified by the image processing (IP) technique). We form pairs of points consisting of the optical thickness limits (ISCCP) and the corresponding VIS limits for each cloud type. For example, the optical thickness limits for *Cb* clouds are 23 (minimum) and 125 (maximum) and the corresponding visible gray level limits are 130 (minimum) and 253 (maximum). So, the pairs are (23, 130) and (125; 253). Similar pairs for the other cloud types are also formed. Next, all these pairs are used for obtaining an expression between the optical thickness and the visible gray level value by regression. The final relation (expression (1)) is given as:

$$\tau = 8.0625 \left[\exp\left(\frac{0.0101 \times \mathrm{VIS}}{\cos \mu}\right) - 1 \right],$$

where μ is the solar zenith angle; VIS is the visible gray level value. The root mean square error (RMSE) for this expression is found out to be 1.02, which is very satisfactory for our purpose. However, note that the number of data pairs are rather small and therefore the RMSE expected is also small.

This stepwise procedure provides the likely base height which can be further used for PWC estimation. These base height are then validated with ground observations taken at the time coinciding with the satellite data (0600

UTC) However, there are possibilities of geometric errors in coordinate fixing and pixel averaging.

Next, the precipitable water content (PWC) is estimated. For this purpose we proceed as follows:-

The fractional precipitable water Δw contained between any two levels of the atmosphere, separated by a pressure interval of Δp, is given by:

$$\Delta w = \frac{r \times \Delta p \times 1000}{g} \quad \ldots (6)$$

where r is the humidity mixing ratio in gm/gm of air and g is the acceleration due to gravity. We estimate this fractional precipitable water contained between the cloud top and bottom levels (which have been previously estimated) and refer to this quantity as PWC in the entire paper. The humidity mixing ratio is derived using the tephigram for near saturated condition. The PWC is therefore given as:

$$PWC = \sum_{\text{Cloud Base } Pr}^{\text{Cloud Top } Pr} r \times \Delta p \times \frac{1000}{g} \quad \ldots (7)$$

In order to establish the correlation between this estimated PWC and the actual observed rainfall, we compare these two (PWC and rainfall) for 18 rain-gauge stations which are uniformly spread all over India. The 24-hour rainfall (observed) at 8:30 A.M. (0300 UTC) at each rain-gauge station is matched with the average PWC value (average of the estimated PWC over the station at 0600 UTC for the same day and the preceding day at 0600 UTC). Therefore, it has been assumed that the average PWC is representative for the entire period starting at the preceding morning till the next day morning (day on which 24-hour rainfall has been observed). The coefficient of correlation between these two has also been found out. The regions with fairly equal PWC distribution have been demarcated and these have been compared with the actual rainfall distribution.

Results and Discussion

The cloud type classification results derived using the present scheme have been validated with the ground observations. For this purpose the cloud types identified over a number of stations (15) using the VIS/IR classification (Fig. 1) have been compared with actual cloud type data (provided by Northern Hemispheric Analysis Center (NHAC), New Delhi) taken at the time coinciding with the satellite data. This comparison is shown in Table 1. It may be observed that: *i*) in general the qualitative validation is reliable; *ii*) there is over-estimation of cloud top temperature (coldness) over atleast two stations., viz. Bombay and Bhopal; and *iii*) the usual problem of under-estimation of cirrus top temperature is observed over Madras station, as a result of which the clouds over Madras have been identified as middle level clouds (altocumulus) rather than high level cirrus clouds.

The estimated base height has been validated both qualitatively as well as quantitatively. Qualitatively, the base heights estimated using the scheme have been found to be in good agreement (Table I) with the usual classification of low, middle and high clouds (based on the base levels) viz. Low: 0-2km; Middle: 2-6km; High: >6km. However, the base height of Stratus (St) clouds have been observed to be significantly higher than 2 km, thereby, requiring further investigations. The overall accuracy of the entire scheme i.e. a positive correlation of the PWC with the actual rainfall, indicates the suitability of the scheme for the estimation of base height itself and therefore, validates quantitatively.

The average PWC estimated over each scan spot (entire Indian region) for all the three days has been plotted. A comparison of the distribution of the estimated PWC and the observed rainfall distribution for all the days have been shown in Figs 2 (*a*) & (*b*), 3 (*a*) & (*b*) and 4 (*a*) & (*b*). It may be observed that the two corresponding figures are highly comparable.

In order to quantify these results, 18 stations (numbered in Figs 2, 3, 4) have been selected. Table II shows the comparison of the estimated PWC and the actual rainfall observed at these stations. The coefficient of correlation is found out to be +0.79, which is quite significant. Threshold limits for precipitating and non-precipitating clouds have been identified and are as follows:-

PWC > 1.2 ------ always precipitating

PWC < 0.35 ------ never precipitating

where all PWC values are in gm/cm^2.

Table I

Cloud type classification and cloud base height validations with ground observations

Station	Cloud Type (scheme derived)	Base Character (scheme derived)		Cloud Type (ground observation)
		Height (km)	Type	
Amritsar	C_S/C_U	7-08	High	A_C/C_I (High)
Delhi	A_C/A_S	4.98	Middle	A_C (Middle)
Jaipur	A_U/A_S	4.62	Middle	N_S/A_C (Middle)
Lucknow	C_U/S_C	1.71	Low	S_C (Low)
Allahabad	C_U/S_C	1.77	Low	S_C (Low)
Calcutta	C_S/C_U	8.08	High	$S_C/N_S/C_C$ (Mixed)
Bhubaneshwar	N_S	7.31	High	A_C/N_S (Middle)
Bhopal	C_B	3.62	Middle	S_T (Low)
Ahmedabad	C_B	4.13	Middle	C_B (Low)
Udaipur	C_B	4.02	Middle	C_B (Low)
Nagpur	A_C/A_S	4.11	Middle	S_T/N_S (Middle)
Bombay	N_S	4.8	Middle	S_T/C_S (Low + High)
Hyderabad	S_T	2.48	(Mid-low)	S_T/A_C (Mid-low)
Bangalore	S_T	2.56	(Mid-low)	S_T/A_C (Mid-low)
Madras	A_C	3.69	(Middle)	C_I (High)

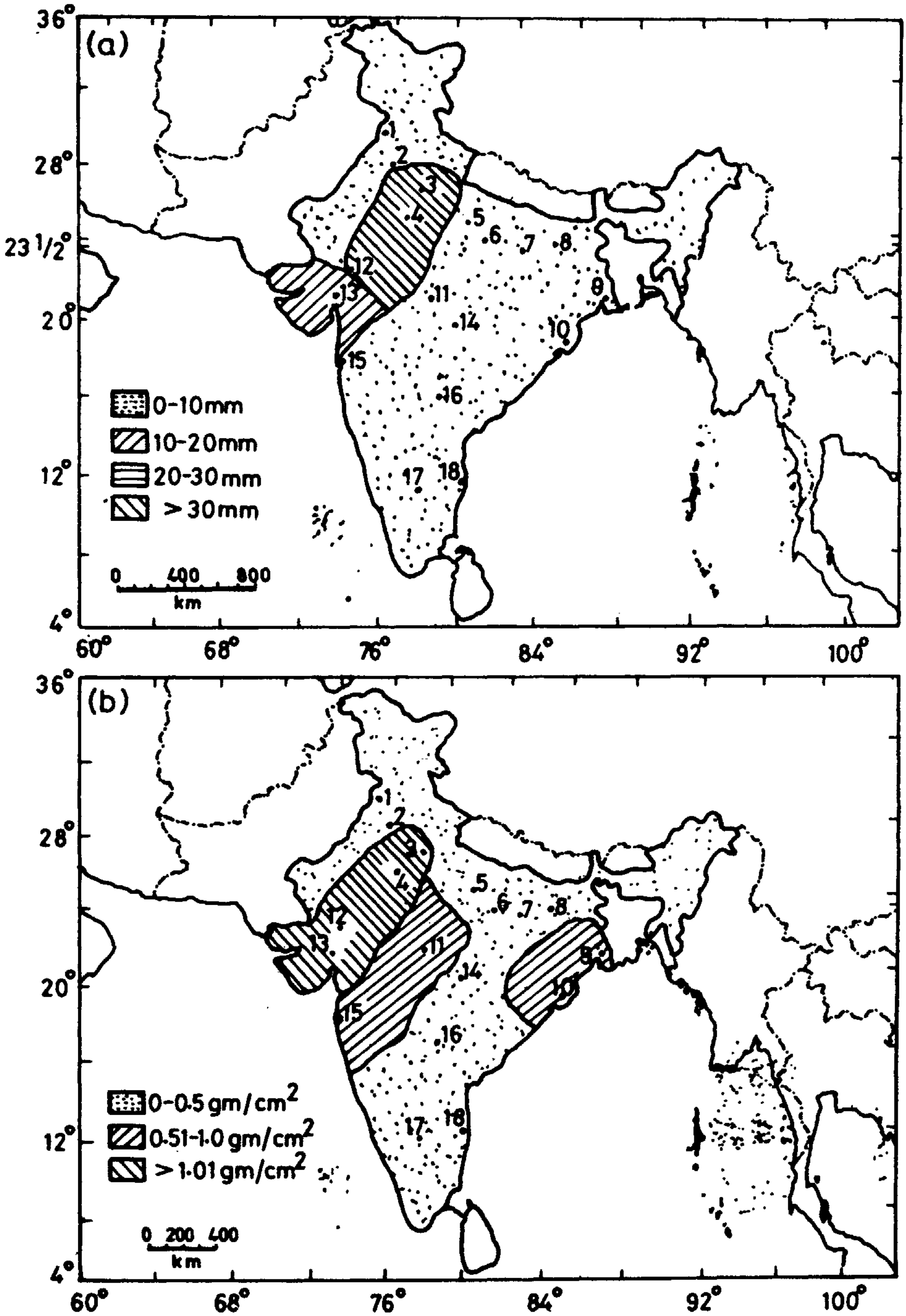
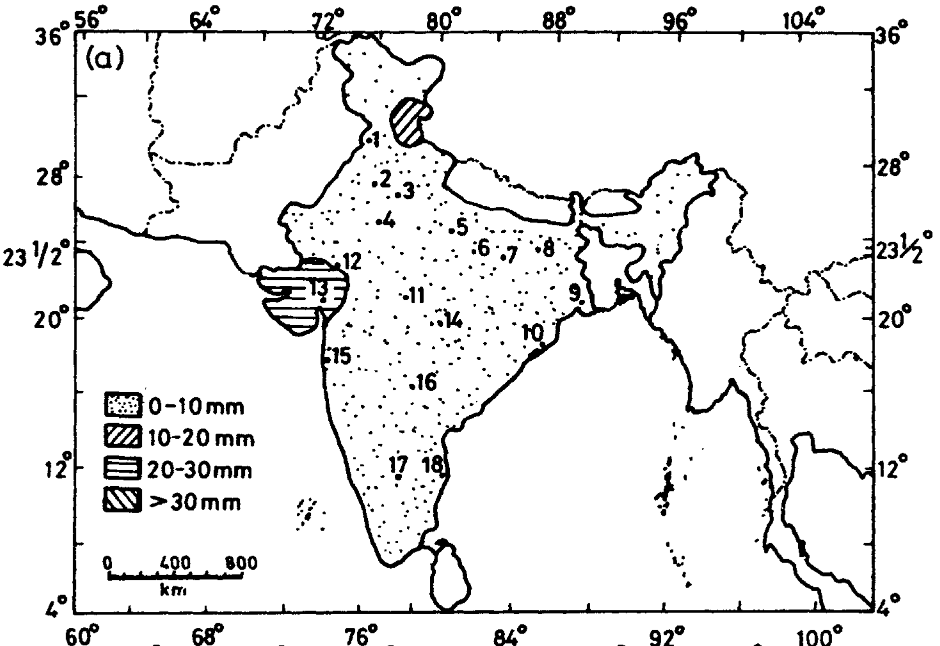


Fig 2(*a*) Rainfall distribution (actual) over India on 23-7-91

Fig 2(*b*) Precipitable water content (estimated) over India on 23-7-91



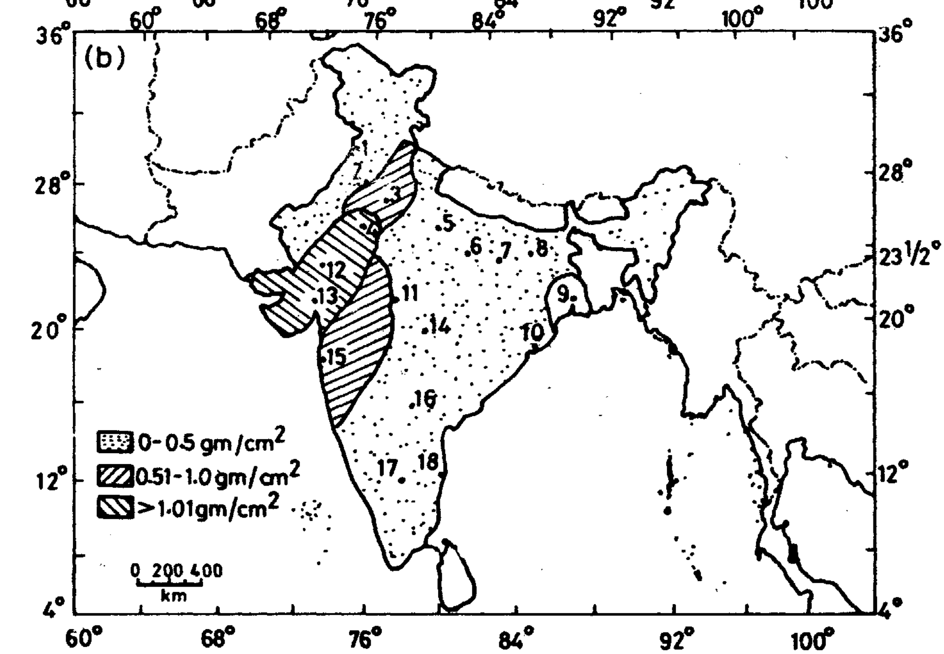


Fig 3(*a*) Rainfall distribution (actual) over India on 24-7-91

Fig 3(*b*) Precipitable water content (estimated) over India on 24-7-91

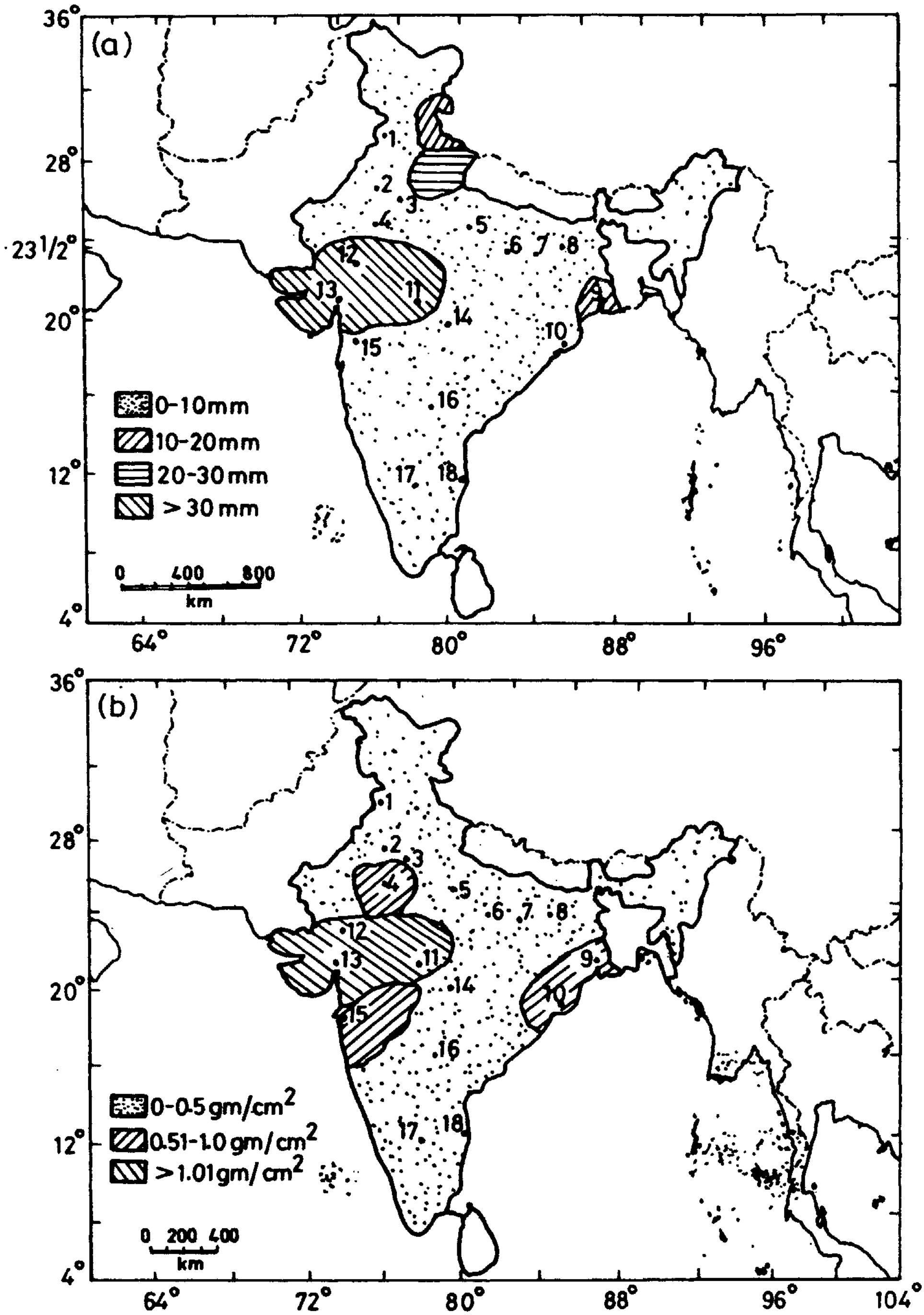


Fig 4(*a*) Rainfall distribution (actual) over India on 25-7-91

Fig 4(*b*) Precipitable water content (estimated) over India on 25-7-91

Table II

Comparison of estimated PWC and actual rainfall for all three days over the 18 stations

Station	23-7-91		24-7-91		25-7-91	
Name	PWC gm/cm²	Rainfall mm	PWC gm/cm²	Rainfall mm	PWC gm/cm²	Rainfall mm
Amritsar	0.22	0	0.16	0	0.37	4
Hissar	0.30	0	0.23	0	0.54	0
Delhi	1.30	43	0.86	0	0.45	17
Jaipur	1.55	46	1.13	0	0.55	7
Lucknow	0.34	0	0.36	2	0.33	0
Allahabad	0.37	1	0.37	1	0.35	trace
Varanasi	0.30	trace	0.38	6	0.26	0
Patna	0.50	0	0.41	2	0.41	0
Calcutta	0.85	3	0.88	0	0.68	10
Bhubaneshwar	0.51	1	0.34	0	0.50	0
Bhopal	0.63	3	0.45	5	1.30	56
Udaipur	1.52	34	1.03	2	1.25	43
Ahmedabad	1.03	11	1.06	22	1.36	59
Nagpur	0.44	0	0.40	4	0.36	trace
Bombay	0.72	5	0.70	1	0.59	3
Hyderabad	0.37	0	0.37	0	0.33	trace
Bangalore	0.35	trace	0.35	trace	0.35	—
Madras	0.27	0	0.31	0	0.31	0

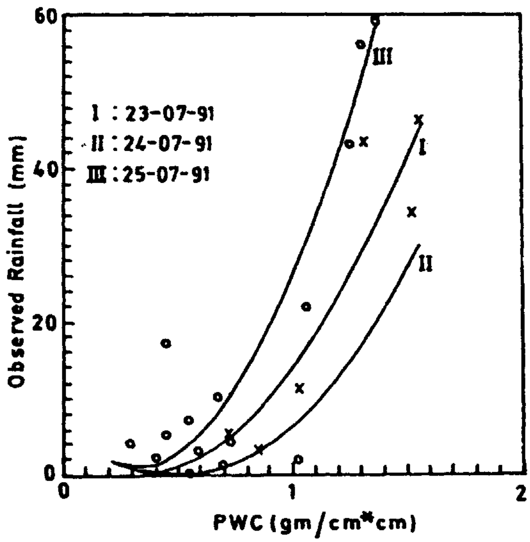


Fig 5 Actual rainfall versus precipitable water content estimated over 18 stations

This implies that whenever the PWC for any type of cloud exceeds 1.2 gm/cm^2 value it necessarily precipitates since it cannot hold any excess water. Also, the PWC has to attain a limit of at least 0.35 gm/cm^2, for any cloud type, so as to start precipitating.

Fig. 5 shows the curves for rainfall versus the estimated PWC for all the days. It can be observed that a curvilinear relationship (best fit curve is a polynomial of degree 2 exists between the two. It is also noteworthy that in the initial portion of the curves (till PWC < 0.5), there is little change in the rainfall. As an improvement to this analysis, we plot the curves for rainfall versus that value of PWC which is in excess of 0.5 gm/cm^2 (i.e., PWC-0.5) for only those values of PWC which are greater than 0.5 gm/cm^2. The corresponding curves are shown in Fig. 6. These curves show a better linear profile than the initial curves (Fig. 5). Fig. 7 shows the ellipse which is formed by enclosing all the plotted points of Fig. 6. The coefficient of correlation for this set is found to be 0.8, which is slightly better than the previous one (coefficient of correlation equal to 0.79).

Since the PWC has been found to be a good indicator of the actual rainfall, it can be used for actually estimating the rainfall. In that case, reliable and quick estimates of the rainfall distribution can be obtained in a cost effective manner. This scheme, using satellite data can therefore be conveniently used for this purpose.

In the scheme, errors are possible on a number of accounts: *i*) when clouds are smaller than the instrument's field-of-view (FOV); *ii*) geometric errors aris-

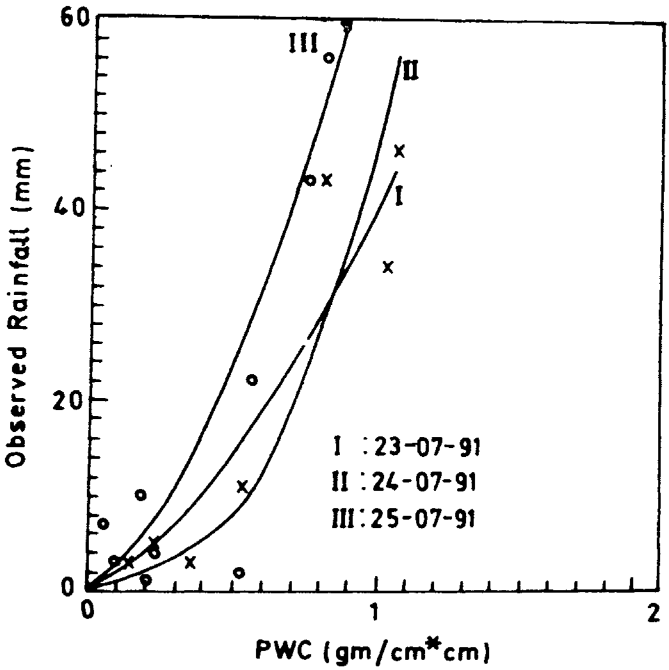


Fig 6 Actual rainfall versus (PWC-0.5) values for PWC values greater than 0.5gm/cm^2 only

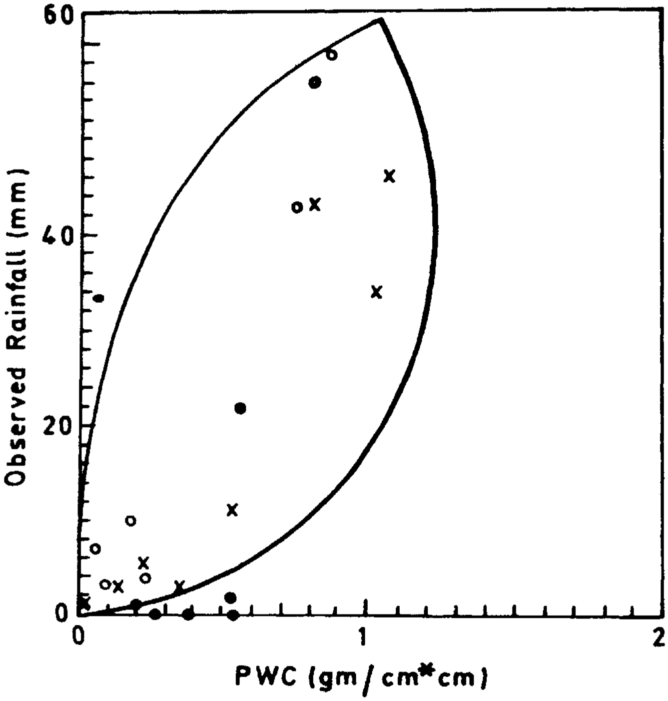


Fig 7 Ellipse formed by enclosing all plotted points of figure 6

ing due to exact co-ordinate fixing of the stations; and *iii*) errors in assuming the averaged PWC to be representative of 24-hour duration. The scheme can therefore be improved by utilizing 4-hour data for PWC estimation. Also; since VIS data is used for cloud type identification, this scheme needs to be modified for night-time analysis.

Conclusions

The cloud type classification scheme using unsupervised clustering technique yields fairly reliable results, especially when clouds are areally large and contiguous (as during the monsoon period). Errors in identification are observed when clouds smaller than instruments FOV are present. The under-estimation of cirrus top temperature is also observed. The base height estimation has been validated both qualitatively and quantitatively. The estimated PWC has been found to be strongly correlated (coefficient of correlation of 0.8) with the actual rainfall observed over 18 stations. There is a good resemblance between the PWC and rainfall distribution for entire India during the study period. Two threshold limits viz., PWC > $1.2 gm/cm^2$ for necessarily precipitating clouds and PWC < $0.35 gm/cm^2$ for non-precipitating clouds, have been found out. The overall accuracy of the scheme is satisfactory. It can, therefore, be used for reliable and quick estimates of the actual rainfall distribution. Further improvements are possible with finer spatial resolutions ($1 \times 1 km^2$) and temporal resolutions (4-hourly satellite data) and suitably modifying the scheme for night-time analysis.

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