Mausam, (1979), 30, 1, 113-118

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Quantitative precipitation forecasting for hydrological prediction over catchment areas with inadequate aerological data by the method of atmospheric water balance

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(*Received 3 July 1973*)

ABSTRACT. In this paper attempt has been made to estimate rate of precipitation per unit area in and around northeast India containing the catchment of river *Bhagirathi* by the method of atmospheric water balance as developed by Palmen.

In order to overcome the inadequacy of upper air temperature, wind and humidity data, due to the absence of a radiosonde/rawin station in the catchment and the paucity of a close network of such stations in the neighbourhood, radiosonde/rawin data of remote stations like Allahabad, Calcutta, Gauhati, Delhi, Nagpur, Visakhapatnam and Port Blair have been made use of for working out the specific humidities at isobaric levels by drawing isopleths of specific humidities and interpolating the values at intermediate points. The isopleths themselves have been drawn with due regard to the airmass prevailing over the area during the rainstorm period. Similarly, isopleths of U and V components of the observed upper winds prevailing over the region have been drawn with reference to the synoptic situation. Upper wind data of pilot balloon stations have also been utilised in addition to those of the radiosonde/rawin stations for the drawing of isopleths of wind.

The divergence of wind has then been calculated by using finite difference method.

The rates of precipitation at different stations and consequently the isohyets of total amounts of precipitation for 9 hours have been compared with those of the observed rainfall at 0830 and 1730 hours of the same day, for individual days of the rainstorm period. The estimated precipitation for 9-hour has also been compared with the observed precipitation at 0830 IST of the next day as the calculated isohyetal pattern for 24 hours was identical with that of the 9 hours except in the magnitudes of the station precipitation.

The mean observed storm precipitation has also been compared with the mean calculated amounts of precipitation for the same period as also the precipitation for the period of the storm and 1-day prior to the storm.

Storm efficiencies have been calculated between the observed rainfall and the estimated amounts of rainfall.

Daily and the mean vertical distribution of the horizontal transport of moisture has been plotted for the storm period.

1. Introduction

The expression known as the atmospheric water balance equation as developed by Palmen (1967) can be written as :

$$E - P = \frac{1}{g}\int_{p_0}^{p} \frac{\partial q}{\partial t}\, dp + \frac{1}{g}\int_{p_0}^{p} (\nabla .\, q\,\mathbf{V})\, dp$$

where E is the evapotranspiration, P is the total rate of precipitation per unit area of the ground, q is the specific humidity, p_0 is the pressure at the ground and p is the pressure at the top and $\mathbf{V}$ the horizontal wind vector.

The term $\frac{1}{g}\int_{p_0}^{p} \frac{\partial q}{\partial t}\, dp$ gives the change, of water vapour content per unit area and time whereas the term $\frac{1}{g}\int_{p_0}^{p} (\nabla .\; q\;\mathbf{V})\, dp$ represents the divergence of the horizontal vapour flux.

During an intense and prolonged rainstorm situation F can be neglected. The term $\frac{1}{g}\int_{p_0}^{p} \frac{\partial q}{\partial t}\, dp$ can be neglected under the

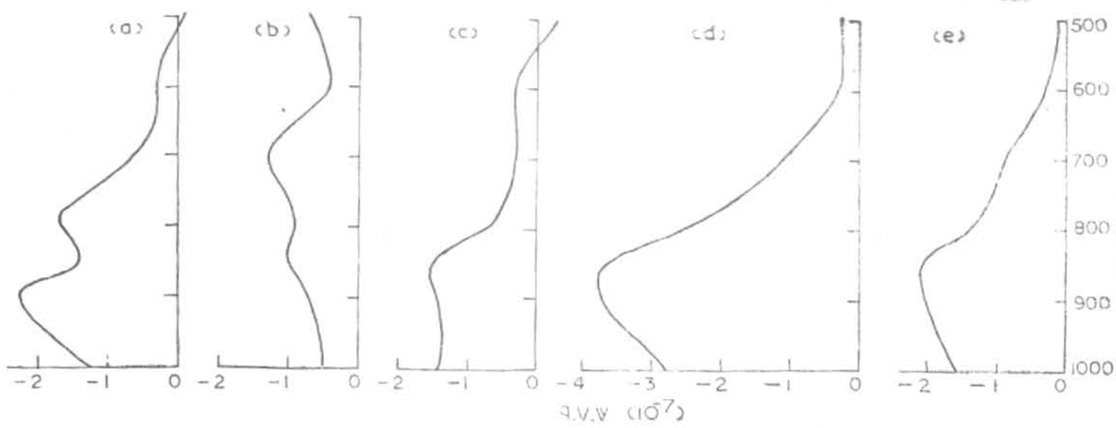


Fig. 1. Mean moisture convergence ($q \cdot \nabla . \mathbf{V}$)

(a) 29 Jun 1965, (b) 30 Jun 1965, (c) 1 Jul 1965 (d) 2 Jul 1965, (e) 30 Jun-2 Jul 1965 at 0530 I.S.T.

assumption that in course of time there is no drastic change in the precipitable water content of the atmosphere over a place and due to its being of lesser magnitude in comparison to the divergence term. The formula in its simplified form can be written as :

$$P = - \frac{1}{g} \int_{p_0}^{p} (\nabla . \, q\mathbf{V}) \, dp$$

$$\approx - \frac{1}{g} \int_{p_0}^{p} (q \, \nabla . \, \mathbf{V}) \, dp$$

2. Rainstorm and associated synoptic situation

The area chosen for the present study is from 20°N to 26°N and 84°E to 92°E comprising of the Bhagirathi catchment and the adjoining areas of Bihar, Orissa, Assam and Meghalaya, Nagaland, Manipur, Mizoram and Tripura and Bangla Desh. The catchment itself lies in the border areas of Bihar plateau and Gangetic West Bengal with a total area of about 25,000 sq. km. One intense rainstorm of 3-day duration, *viz.*, rainstorm of 30 June to 2 July 1965, over Bhagirathi catchment was chosen for this study. The successive rainfall depths yielded by this rainstorm were 4.16, 5.76 and 4.27 cm respectively. The rainstorm was due to the formation of a low pressure area over West Bengal and the adjoining parts of Bangla Desh with upper air cyclonic circulation extending upto 4·0 km above mean sea level on 29 June. The low gradually shifted to the east and lay over Bangla Desh on 1 July though weakened. On the 2nd, however, only the monsoon axis was manifested and was running from Ferozepore to Balasore through Banda.

3. Method adopted

T e upper air data of all the radiosonde/rawin and pilot balloon observatories in the area under study for 0530 hours of 29 June to 2 July were taken for analysis. Isopleths of the U and V components of the surface and upper winds prevailing over the area have been drawn for the surface and the isobaric levels of 900, 850, 800, 700, 600 and 500 mb with reference to the synoptic situation. The divergence of wind has then been calculated at various stations by using finite differences. We realise that this method is not very satisfactory especially when we consider the noise in measurements of upper winds. But considering that the flux of moisture is important for precipitation forecasts we have adopted the method, despite its obvious limitations. We propose to examine more refined techniques later. Isopleths of specific humidities were also drawn at the surface and the upper levels, with the help of dew point temperature data from the radiosonde stations over the region. The values of the specific humidities at intermediate places have then been interpolated.

Based on 0530 hours upper wind and specific humidity data divergence of the moisture flux at various isobaric levels have been calculated by the formula $-q \nabla . \mathbf{V} \, dp$ for individual days of the storm as well as for 1-day prior to the rainstorm. Average vertical distribution of the moisture flux for the duration of the storm has also been plotted. These are shown in Figs. 1(a-e).

The rates of precipitation at different stations and consequently the total precipitation for 9 and 24 hours period for individual days of the storm as well as for a day prior to the storm have been estimated by the Palmen formula as given above. Isohyetal patterns for 9 hours estimated rainfall have been compared with the isohyets of observed rainfall at 0830 hours and 1730 hours of the same day and 0830 hours of the next day.

The isohyetal pattern of the average rainfall as estimated by the formula for the storm period as well as for 29 June to 1 July, one day prior to successive storm days, have been compared with that of the mean observed rainfall for the storm period.

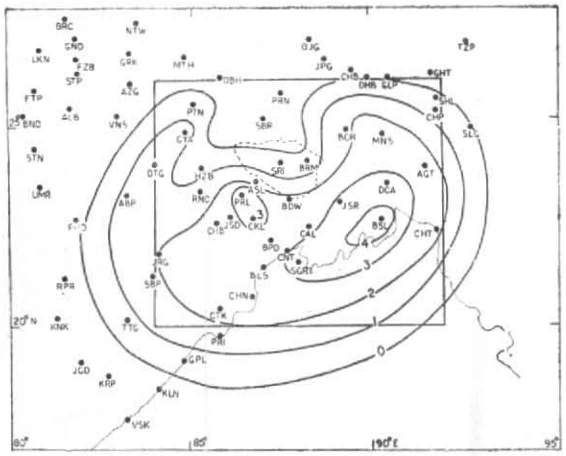


Fig. 2(a). Estimated (9-hr) isohyetal map (29 June 1965)

4. Discussion of results

4.1. *Vertical distribution of moisture flux*

(*i*) A plot of the computed moisture convergence from the values of the surface and isobaric levels of 900, 850, 800, 700, 600 and 500 mb for 1-day prior to the rainstorm for individual days of the rainstorm, and for the average values of the storm period is shown in Figs. 1(a-e) respectively. It is noticed from these graphs that on the day prior to the rainstorm, *i.e.*, on 29 June 1965, maximum convergence of the moisture flux was occurring at 900 mb level with a secondary maxima at 800 mb level. There was, however, a marked decrease in convergence at 850 mb level. The first maxima on the next day lifted to 850 mb level, the moisture flux decreasing at 800 mb and then gradually increasing to maximum at 700 mb and then decreasing and reaching a minimum at 600 mb level. Above the 600 mb the convergence of moisture flux increased again at 500 mb level but since value at further higher levels were not available, it could not be categorically concluded that a third maxima existed.

On 1 July, maximum moisture flux was attained at 850 mb. The convergence rapidly decreased aloft with slight divergence at 500 mb level. On the 2 July the maximum convergence of moisture flux was taking place at about 880 mb level. The magnitude of the convergence was also highest on this day. The moisture transport decreased rapidly above this level with a minimum at 600 mb beyond this level it slowly increased upto 500 mb level.

(*ii*) *Average vertical distribution of moisture flux for the duration of the rainstorm*

From the graph of the average vertical distribution of the moisture flux for the duration of the storm (Fig. 1e), it is noticed that the convergence of the moisture flux gradually increased from the surface and attained a maximum at 850 mb level. The influx of moisture gradually decreased and attained a minimum at 500 mb level. In the average vertical distribution of the moisture flux no secondary maxima is noticed, the moisture flux itself attaining the maximum at about 1.5 km above mean sea level slightly above the level of non-friction which is generally 900 metre above mean sea level.

It appears that the frictional motion of the air in the lower layers of the atmosphere is one of the important carriers of the moisture in the vertical.

4.2. *Estimated and observed rainfall*

Based on 0530 hr upper wind and specific humidity data as obtained by drawing isopleths of U and V fields and of specific humidities, divergence of the moisture flux at various isobaric levels and the rate of precipitation have been calculated by the formula :

$$P = -\frac{1}{g}\int_{p_0}^{p} (q\,\nabla.\,\mathbf{V})\,dp$$

The rates of precipitation and consequently the total precipitation for 9 hours and 24 hours period have been calculated by integrating the convergence from the surface upto 500 mb level. These have been compared with the actual amounts of rainfall at 0830 hr, 1730 hr of the same day and those of the 0830 hr of the next day.

(*i*) The estimated rainfall pattern for 9 hours period for 29 June (Fig. 2a), one day prior to the actual rainstorm, shows two centres of high rain one over Chakulia and Purulia and the other over Saugar Islands, eastern parts of Gangetic West Bengal and adjoining parts of Bangla Desh. The general area of precipitation covers parts of Orissa, south Bihar, Gangetic West Bengal, Nagaland, Manipur, Mizoram and Tripura and Bangla Desh.

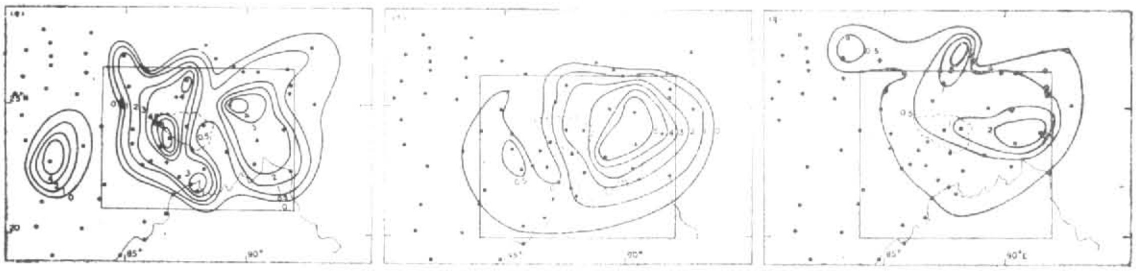
The pattern of actual rainfall at 0830 hr of the next day (Fig. 2b) shows that the centre of high rain near Chakulia in the estimated hours moved by about 2° to the east and merged into the other centre of high rain over Bangla Desh and appeared as one extended area of high rain over Gangetic West Bengal, Bangla Desh and adjoining areas in the observed pattern.

(*ii*) The precipitation pattern obtained by the divergence of moisture flux for 9 hours period for 30 June (Fig. 2c) shows that there are two centres of high rainfall, one over Bihar plateau and adjoining parts of Orissa and the other over eastern parts of Gangetic West Bengal, Bangla Desh, Nagaland, Manipur, Mizoram and Tripura.

On comparing the isohyetal pattern of the estimated amounts of rainfall for 9 hours with the

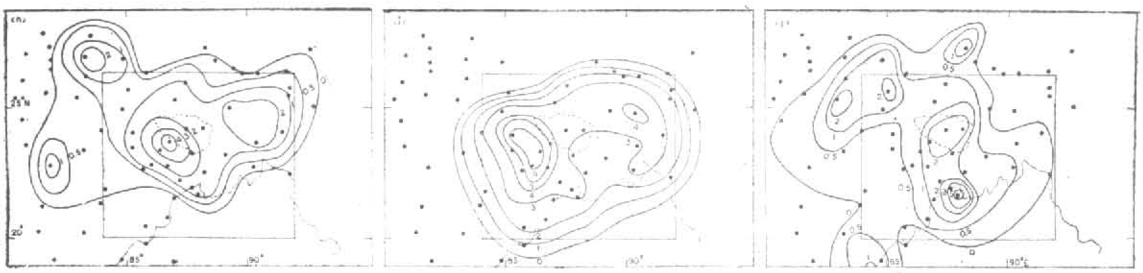
(b) Observed rainfall (0830 IST) (c) Estimated (9 hrs) (d) Observed rainfall (1730 IST)

Figs. 2(b-d). Isohyetal map of 30 June 1965



(e) Observed rainfall (0830 IST) (f) Estimated (9 hrs) (g) Observed rainfall (1730 IST)

Figs. 2 (e-g). Isohyetal map of 1 July 1965



(h) Observed rainfall (0830 IST) (i) Estimated (9 hrs) (j) Observed rainfall (1730 IST)

Figs. 2(h-j). Isohyetal map of 2 July 1965

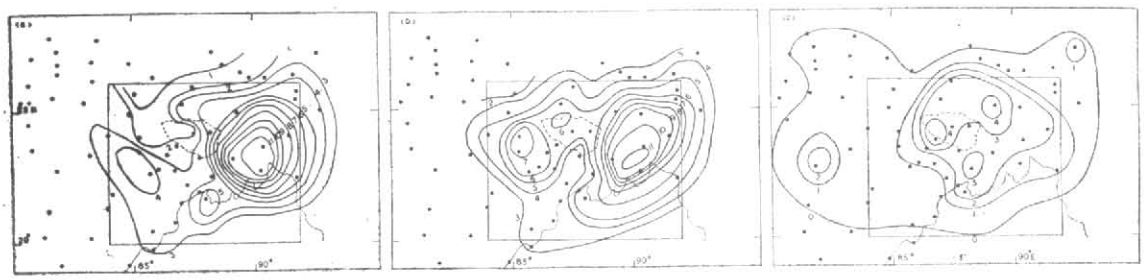


Fig. 3(a). 29 June-1 July 1965 Fig. 3(b). 30 June-2 July 1965 Fig. 3(c). 30 June-2 July 1965

Estimated mean 24-hr isohyetal maps Observed mean 24-hr isohyetal map

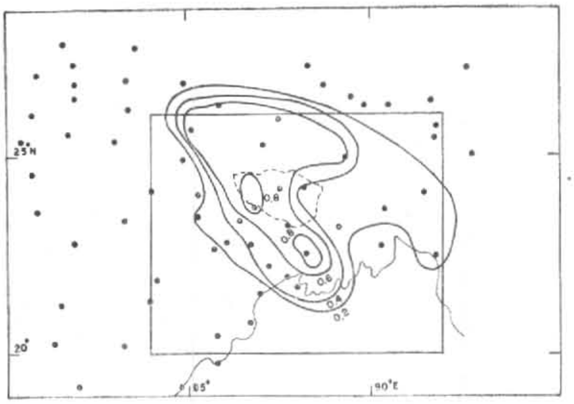


Fig. 4. Precipitation efficiency ratio

isohyetal pattern of the osberved amounts of rainfall at 0830 hr of the same day, it is seen that the two centres of high rain in the calculated appear to have merged into one extended area of high rain in the observed over Gangetic West Bengal, Bangla Desh and neighbouring areas. On comparison with the 1730 hr of observed rainfall of the same day Fig. 2(d), it is seen that a single centre of high rain exists slightly displaced northwards.

On comparison with the observed rainfall at 0830 hr of the next day Fig. 2(e) it is seen that there are two areas of high rain in the isohyetal pattern of the observed rainfall, one over Bihar and the adjoining areas of Gangetic West Bengal and the other over Bangla Desh and adjoining areas of Nagaland, Manipur, Mizoram and Tripura. The centre over Bihar appears to have shifted by about 2° E of the estimated centre based on horizontal transport of moisture the previous morning while for the other areas the shift is towards the north.

(*iii*) The isohyetal pattern of the estimated amounts of rainfall for 9 hours on the 1 July (Fig. 2f) shows an area of precipitation comprising of north Orissa, Bihar, Gangetic West Bengal, Bangla Desh and adjoining areas of Nagaland, Manipur, Mizoram and Tripura. There is a belt of high rain from Suri in Bihar to Agartala. On comparison with the isohyetal pattern of the observed rainfall at 0830 hr of the same day, it is noticed that a distinct area of high rain exists over Bihar, Gangetic West Bengal and north Orissa in the observed pattern which is reflected as bulges in the estimated isohyetal pattern.

On comparing the isohyetal pattern of the estimated amounts of rainfall for 9 hours with the isohyetal pattern of 1730 hr of observed rainfall for the same day (Fig. 2g) it is noticed that there is similarity in the general area of precipitation between the two patterns. The centre of high rain near Mymensingh in Bangla Desh in the estimated has shifted slightly to the south in the observed rainfall pattern.

On comparing the isohyetal pattern of the estimated amounts of rainfall with that of the observed rainfall at 0830 hr of 2 July (Fig. 2h) it is noticed that there are two areas of high rain in the observed isohyetal pattern instead of one in the estimated. The area of high rain estimated near Mymensingh in Bangla Desh is similar to one observed in the recorded rainfall pattern of 0830 hr of 2 July. The enlongated bulge through Asansol in the peripheral isohyets of the estimated rainfall pattern of 1 July has appeared as area of high rain near Asansol while the other two bulges near Calcutta and Purnea exist in the isohyetal pattern of observed rainfall also. The general area of precipitation, however, in the observed rainfall pattern resembles with that of the estimated.

(*iv*) The isohyetal patterns of the estimated amounts of rainfall for 9 hours for 2 July (Fig. 2i) shows an area of high rain over Bihar plateau and the other over Bangla Desh, the general area of precipitation, however, covers north Orissa, Bihar, Gangetic West Bengal, Bangla Desh, Nagaland, Manipur, Mizoram and Tripura. On comparing this 9 hours estimated pattern with the isohyetal pattern of the observed rainfall recorded at 0830 hr of the same day (Fig. 2h) it is noticed that there is a resemblance to a marked degree between the two patterns as regards the general area of precipitation. The area of high rain over Bihar plateau in the estimated rainfall pattern shows a shift of about $1\frac{1}{2}$° towards the east in the rainfall pattern of the observed amounts of rainfall at 0830 hr. The area of high rain over Bangla Desh and adjoining areas in the estimated almost coincides with that of the observed rainfall pattern.

On comparison with the recorded rainfall pattern for 1730 hr of the same day (Fig. 2j) it is noticed that the centre of high rain over Bihar plateau in the estimated pattern has shifted to the east by about 2° in the observed. The centre of rain over a southern portion of Gangetic West Bengal in the observed rainfall pattern can, however, be compared with bulge in the estimated pattern towards Saugar Islands. There is no area of high rain in the observed rainfall pattern over Bangla Desh as compared with the estimated.

4.3. *Average estimated rainfall*

(*i*) *Estimated mean (24 hours) rainfall for 3 days, i.e., 29 June-1 July and its comparison with the observed mean rainfall (24 hours) for the storm period (30 June-2 July)* — On comparison it is noticed that high rainfall areas near Ranchi and Saugar islands in the estimated pattern of the rainfall (Fig. 3 a) have shifted in the northeasterly direction by about 2° during successive 24 hours in the observed pattern of mean rainfall of 30 June to 2 July (Fig. 3c). The high rainfall area over Bangla Desh in the computed was not comparable with the realised rainfall. The area of precipitation as estimated, however, coincides with the area of precipitation as observed by the mean rainfall recorded during the storm period.

(*ii*) *Estimated mean rainfall for the duration of the storm versus mean observed rainfall for the same period* — The isohyetal pattern of the estimated rainfall (Fig. 3b) shows two areas of high rain one over Bihar plateau and the other over Bangla Desh and the adjoining areas of Nagaland, Manipur, Mizoram and Tripura embedded in the general area of precipitation comprising of north Orissa, Bihar, Gangetic West Bengal, Bangla Desh, Nagaland, Manipur, Mizoram and Tripura.

On comparison with the mean observed rainfall recorded at 0830 hr of the same period (Fig. 3c) it is seen that the high rainfall one over Bihar plateau and another near Sabour in the estimated have shifted eastwards by about 2°. The area of high rain over Bangla Desh in the estimated has no counterpart in the observed rainfall pattern. The precipitation areas in both the patterns almost coincide with each other.

5. Precipitation efficiency

Efficiency ratio between the observed mean rainfall and the estimated mean rainfall for the duration of the rainstorm is as follows :

(i) *Station precipitation efficiency*

Station efficiency ratios have been calculated between the observed mean rainfall for 24 hours for the storm period, *viz.*, 30 June to 2 July and the estimated mean rainfall for 24 hours from the divergence of moisture flux. A plot of these ratios is shown in Fig. 4.

It is seen that there are well defined areas of high rain one near Asansol and the other near Calcutta where the ratios almost approximate to unity thereby indicating that the estimated amounts of rainfall have almost equalled to the realised rainfall during the period of the rainstorm. These two areas are almost at the same places where areas of high rain are located both in the estimated as well as in the observed pattern of rainfall, but for the little shifted towards the northeast in the isohyetal pattern of the observed mean rainfall. The peripheral station efficiency isopleth of 0.2 indicates the general area of precipitation that was realisable from the amounts of precipitation as estimated from divergence of moisture flux. This area of precipitation almost coincides with the general area of precipitation as revealed by the isohyetal pattern of the observed mean rainfall during the storm period.

There is, however, no uniformity of the station efficiency ratios for the entire precipitation belt due presumably to different amounts of convergence available due to peculiar features of the orography and the synoptic situation. It is also seen that the greater agreement with the estimated values is achieved in the regions of observed heavy rainfall.

(ii) *Storm efficiency*

Storm efficiency ratio for the area bounded by the latitudinal belt 20°N-26° N and longitudinal belt 84°E-92°E between the average isohyetal depth of the observed mean rainfall and the average depth of estimated mean rainfall for the storm period was found to be 0·3 which may be used as a multiplying factor for the computed average depth of precipitation over the area to get the average depth of precipitation over the area under study during an expected storm based on synoptic situation.

6. Conclusion

(*i*) Vertical distribution of moisture flux reveals that the day-to-day the maximum transport of moisture may be confined to the lower layer of the atmosphere due to gradual incursion of moisture near 900 mb and 800 mb, but, the life history of a storm lasting for a few days, the mean maximum moisture flux is established at 850 mb, which is above the friction layer.

(*ii*) Atmospheric water balance does indicate the broad area of precipitation which is comparable to that observed. But, quantitative measurements of precipitation did not show good agreement. We attribute this to the inaccuracies in divergence computation.

(*iii*) For a rainstorm lasting a few days, and under the influence of a well marked synoptic situation, there is close correspondence between the areas of precipitation as estimated by the divergence of moisture flux and the areal extent of observed rainfall.

(*iv*) There appears to be a constant factor, known as the storm efficiency ratio which, when applied to the average precipitation depth estimated by the water balance equation, gives the average expected depth of precipitation over a fairly large area. This factor need to be obtained for a large number of storms over a particular area under different synoptic types.

(*v*) The actual spells of high and low rain may be forecast on the basis of synoptic situation and orographic features and these factors may be applied to the estimated amount of rainfall to give a better judgement of the overall precipitation belt.

Acknowledgements

The authors are grateful to Dr. P. Koteswaram, Director General of Observatories for his keen interest in Hydrometeorological studies and to Shri P.S. Harihara Ayyar, Director (Hydrometeorology) for going through the manuscript and offering his valuable suggestions. Thanks are also due to S/Shri S.D. Gaur and S.C.Verma for their assistance in the preparation of this manuscript.

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