GEOFIZIKA VOL. 25 No. 2 2008

Professional paper
UDC 551.577

Mesoscale objective analysis of daily rainfall with satellite and conventional data over Indian summer monsoon region

S. G. Narkhedkar[1], S. K. Sinha[1] and A. K. Mitra[2]

[1]Indian Institute of Tropical Meteorology, Pune, India.

[2]National Centre for Medium Range Weather Forecasting, Noida, India

Received 23 June 2008, in final form 20 November 2008

A mesoscale objective analysis scheme for producing daily rainfall analysis on a regular latitude/longitude grid over the Indian monsoon region is described. The Barnes scheme is applied to interpolate irregularly distributed daily rainfall data on to a regular grid. The spatial resolution of the interpolated arrays is 0.25 degrees of latitude by 0.25 degrees of longitude. Daily rainfall derived from INSAT IR radiances and raingauge observations are combined to produce this analysis. Some objectively determined constraints are employed in this study: (i) weights are determined as a function of data spacing, (ii) in order to achieve convergence of the analysed values three passes through the data are considered and there is automatic elimination of wavelengths smaller than twice the average data spacing. The case of a typical westward moving monsoon depression during the 1994 monsoon season is selected to represent the characteristics of the analysed rainfall. Objective analyses of six days (16 to 21 August 1994) have been carried out using Barnes three pass scheme. The weighting function scale length parameter (c, denominator in the exponential Gaussian weight function) is varied from over a range of values and the root mean square (rms) errors are computed to select the appropriate value of c. The value of c depends on the number of correction passes being performed and on the density of the observations. The characteristics of the output field from this analysis system have been examined by comparing the analysed rainfall with the observed values. The heavy rainfall over the Western Ghat of India has been clearly brought out in this analysis.

Keywords: Mesoscale analysis, Barnes three pass scheme, rainfall analysis

1. Introduction

Rainfall is generally regarded as the most important meteorological parameter affecting economic and social activities in India. Rainfall observations are needed to support a range of services extending from the real time monitoring and prediction of flood events to climatological studies of drought. Over the Indian summer monsoon region the large scale circulation and the monsoon flow are controlled and modulated by the latent heat released from the rain. There is a large seasonal variation of rainfall over the Indian region. One of the most important parameters to understand and describe different aspects of the Indian summer monsoon is the spatial and temporal distribution of large scale precipitation over this region.

The existing observational network and synoptic methods of forecasting cannot predict mesoscale events except in very general terms. The meteorological data available on the Global Telecommunication System (GTS) and raingauge data of the India Meteorological Department (IMD), New Delhi primarily cater to synoptic analysis and forecasting. These data do not have the required resolution in space and time to resolve and define mesoscale systems. There is an increasing demand for high resolution mesoscale weather information from different sectors like aviation, air pollution, agro-meteorology and hydrology. Mesoscale meteorology is of special importance as local severe weather events cause extensive damage to property and life. Lack of data on the mesoscale is one of the primary reasons for the poor understanding of mesoscale phenomena over the Indian region. For wide range of applications rainfall measurements over India are interpolated or extrapolated to ungauged locations where the information is desired but not measured. Numerical interpolation of irregularly distributed data to regular N-dimensional array is usually called "objective analysis". Objectively analysed data prepared by the National Centre for Medium Range Weather Forecasting (NCMRWF), Noida (Uttar Pradesh) and IMD are of 1.5° lat./long. resolution which is rather coarse for mesoscale NWP models which are generally having a resolution of 10 to 50 km (0.1. to 0.5° lat./long.).

Mesoscale analysis is an important prerequisite for mesoscale research and modelling work. It has evolved into a specialized activity involving data acquisition, quality control checks, background first guess from the model, data ingest and assimilation. As of today over the Indian region no analysed data are available on the mesoscale. Thus there is an urgent need to start work in developing a mesoscale analysis system. Our aim is to prepare a high resolution rainfall data set over data rich regions. In this context we have tried to develop an objective analysis scheme of daily rainfall on a mesoscale grid. Raddatz (1987) examined the spatial representativeness of point rainfall measurements for Winnipeg (Canada) for two accumulation periods – one day and one month. Bussieres and Hogg (1989) made objective analysis of daily rainfall on a mesoscale grid using four different types of objective analysis schemes and compared the merits and weaknesses/limitations of different analysis techniques. Using Radar patterns as a reference data they concluded that optimum interpolation technique and Shepard objective analysis were found more suitable than the other two schemes studied. Major NWP centres operational global models have studied inter-comparison of rainfall forecast (Janowiak, 1992, 1994; White, 1995). In all these studies the comparison were made with the Global Precipitation Index (GPI) (Arkin and Meisner, 1987) type of rain data using satellite information. But for studies related to mesoscale weather forecasting better daily rainfall datasets of higher density/resolution are required. As the operational NWP model resolutions have increased, mesoscale analysis of rainfall has become an important and urgent requirement. The Cressman objective analysis was judged least suitable for interpolation of daily rainfall. Mitra et al. (1997, 2003) analysed daily rainfall using the Cressman (1959) scheme over the Indian monsoon region by combining daily raingauge observations with the daily rainfall derived from INSAT IR radiances. Sinha et al. (2006) made objective analysis of daily rainfall over Maharashtra (India) on a mesoscale grid. This study presents a modification of the Barnes successive correction method to analyse daily rainfall on a mesoscale grid over the Indian summer monsoon region by combining the INSAT derived daily rainfall with the raingauge observations. Rajeevan et al. (2006) have developed a high resolution gridded daily rainfall dataset for the Indian land region using Shepard's scheme. Roy Bhowmik and Das (2007) have made daily rainfall analysis by merging raingauge observations and satellite estimates.

Barnes (1964, 1973) proposed an analysis scheme, which has largely replaced the Cressman analysis scheme (1959). The Cressman scheme corrects the background grid point values by a linear combination of residuals between predicted and observed values. These residuals are then weighted according to their distances from the grid point. The background field at each grid point is successively adjusted on the basis of nearby observations in a series of scans (usually three to four) through the data. The cutoff radius C_R (the radius of the circle containing the observations which influence the correction) is reduced on successive scans in order to build smaller scale information into the analyses where data density supports it. The objective analysis schemes of Cressman (1959) and Barnes (1973) are both weighted average techniques. One important difference is the choice of cutoff radius C_R. Cressman weights do not approach zero asymptotically with increasing distance as they do in the Barnes technique but instead abruptly become zero at distance equal to C_R. This aspect of the Cressman scheme causes a serious problem when the data distribution is not uniform. The Barnes technique is widely used in mesoscale analysis (e.g. Doswell, 1977; Maddox, 1980; Koch and McCarthy, 1982) because of its versatility, simplicity and speed. This scheme is typically univariate, employing data observed at discretely spaced points to retrieve a 2-dimensional distribution of interpolated values after only two passes. The first pass interpolates the observed data to a uniform grid using a weighted average, in effect providing its own background field. The second pass then interpolates a correction to the first pass field and adds it to those values. The second pass, which yields incremental changes to the initial field, use shorter length scales so that relatively greater weight is assigned to observations close to an analysis grid point. Achtemeier's (1987) results suggested that the desired improvements were possible if the traditional two-pass version developed by Barnes (1973) were modified to include a third pass.

2. Synoptic conditions and data

2.1. Synoptic conditions

Monsoon depressions are very important for the spatial and temporal distribution of rainfall over India. Generally, 24 hour accumulated rainfall amounts to 10–20 cm and isolated rainfalls can exceed 30 cm in 24 hours. On any particular morning heavy rainfall exceeding 7.5 cm in 24 hours extends to about 500 km ahead and 500 km to the rear of the depression centre. This area has a width of 400 km which lies entirely to south of the depression centre. The highest rainfall is in the SW sector. Contribution of total rainfall associated with the depression is 11 % to 16 % in the left sector along the track (Mooley, 1973). During the Indian summer monsoon, short duration rainfall fluctuations are mainly due to westward passage of depressions; fluctuations in the intensity, location of the monsoon trough and the low level westerly jet stream over the Arabian Sea. On average, two to three monsoon depressions are observed per month during the monsoon period with July and August having the highest frequencies. These systems have horizontal dimensions of around 500 km and their usual life span is about a week (Das, 1986). For the Indian region the standard deviation and the coefficient of variability for annual, summer monsoon (June to September total) and monthly rainfall are reported in tabular form and/or charts by Rao et al. (1971) and the India Meteorological Department (1981). A general result in these reports is that rainfall amount and its relative variability are inversely related. Further, Singh and Mulye (1991) have found that absolute measures of variability, e.g. standard deviation, absolute mean deviation and mean absolute inter-annual variability increase linearly with mean rainfall.

Daily rainfall analysis was carried out for a six day period starting from August 16, 1994. This period was a very active phase of the monsoon which caused heavy rainfall associated with the monsoon trough and also along the west coast of India. On 17 August a monsoon depression formed over the northwest of the Bay of Bengal and intensified into a deep depression on 18 August. Subsequently it moved in a northwesterly direction and lay over the northwestern part of the country on 20 August. It weakened into a low-pressure area by 21 August.

2.2. Rainfall data

The domain of our analysis extends from 69° E to 97° E and 7° N to 35° N cast on a fine mesh of 0.25° by 0.25° latitude/longitude grid. This particular domain covers the Indian region. The 24 hour accumulated (valid at 03 UTC) rainfall values from IMD raingauge observations coming through the GTS were collected. The GTS rainfall data over India were supplemented by additional rainfall data obtained from the INSAT–IR radiance data. Figure 1a shows the distribution of about 364 observations on a typical day. The differ-

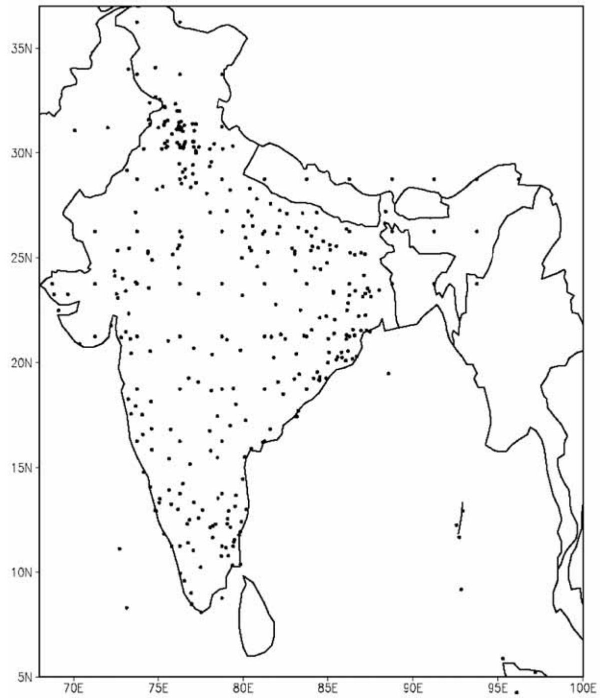

Figure 1a. Locations of the different stations over Indian region.

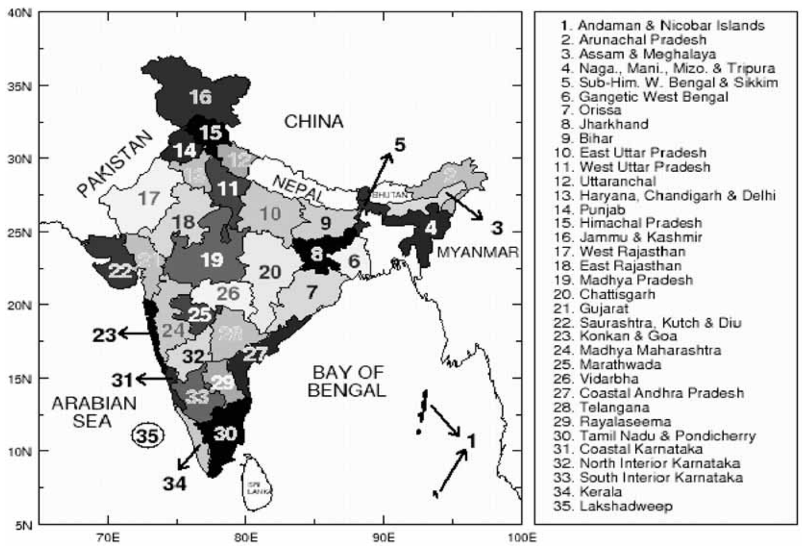

Figure 1b. Map showing different meteorological sub-divisions of India.

ent sub-divisions of India are shown in Figure 1b, (www.tropmet.res.in/Data Archival/Map of sub-division). This will help in locating the various locations over Indian region, which have appeared in the discussion part of the analysis.

2.3. Satellite data

The estimated rainfall from the INSAT IR data is based on the GOES Precipitation Index (GPI) technique, (Arkin and Mesiner, 1987; Arkin et al., 1989). Geostationary satellite INSAT–2B was located at 93.5°E longitude and was having IR channels at 8 km resolution. These rainfall estimates from INSAT were obtained from Satellite Meteorology Division of IMD (Mitra et al., 1997).

3. Methodology

The Barnes scheme stems from the classical Fourier analysis approach that treats an unknown distribution of a field variable as a composite of sinusoidal components. In the Barnes scheme, there are four selectable parameters that influence the analysis: (1) the effective band width (scale length) of the weighting function which acts as a filter, (2) the convergence parameter used to change the effective bandwidth on successive correction passes, (3) the cutoff radius beyond which the weighting function is set to zero, i.e., radius of influence of each observation and (4) the number of correction passes applied. Different authors have used different nomenclatures for the scale length which appear as a squared parameter in the denominator of the Gaussian exponential function. Barnes (1964, 1973) and Achtemeier (1989) called the squared parameter 4κ; Dosswell (1977) called it 4κ; Maddox (1980) renamed it $4c$; Koch et al. (1983) called it just κ; Smith and Leslie (1984) called it α. Caracena et al. (1984) and Pauley and Wu (1990) called it λ_0; Mills et al. (1997) called it D, Spencer et al. (2003) choose to refer to scale length itself λ and thus λ^2 as a smoothing parameter. In this study we have used c^2 as the scale length parameter.

In this section we describe the Barnes three pass successive correction scheme. Only portion of the theory developed by Barnes (1973) and Koch et al. (1983) are reproduced here to provide the reader with the necessary background to understand this study. If a variable $f(x_m, y_m)$ is observed at a location designated by m, then the first pass interpolated field at a grid point (i, j) is described by:

$$g_1(i,j) = g_0(i,j) + \frac{\sum_{m=1}^{N} w_m f(x_m, y_m)}{\sum_{m=1}^{N} w_m} \tag{1}$$

The weight W_m is assigned according to the distance r_m between the observation point (x_m, y_m) and the grid point (i, j) and is given by:

$$w_m = \exp(\frac{-r_m^2}{c^2}) \tag{2}$$

This Gaussian function is isotropic. That is the weight assigned to a given observation in two-dimensional space is independent of the direction that observation lies from a given grid point. N is the number of observations, the scale length c is the smoothing parameter that controls the response characteristics of the analysis. The weights for the observations farther than a distance $5c$ from a particular grid point are set to zero. This "cutoff radius", whose value is well within the guidelines suggested by Pauley and Wu (1990), and it allows the analysis scheme to bypass those observations whose influence upon a particular grid point is negligible. Because of the smoothing properties of the weighting function W, the first pass field $g_1(i,j)$ generally departs significantly from the observations. Hence the process is repeated to achieve the desire degree of fit to the observations. To accomplish this the first pass estimate is corrected by a weighted average of departures at observation points, where the departure is defined by $f(x_m,y_m) - g_1(x_m,y_m)$. The analysis after pass (n) is given by:

$$g_n(i,j) = g_{n-1}(i,j) + \frac{\sum_{m=1}^{N} w'_m \left[f(x_m,y_m) - g_{n-1}(x_m,y_m) \right]}{\sum_{m=1}^{N} w'_m} \tag{3}$$

where:

$$w'_m = \exp(\frac{-r_m^2}{\gamma c^2}) \tag{4}$$

Since no background field is used in this study, $g_0(i,j)$ in Eq. (1) is zero during the initial pass. For the second pass ($n = 2$) of the analysis scheme (first correction pass), the background field g_1 is non-zero and simply the first pass analysis. Similarly for the third pass of the analysis scheme (second correction pass), the background field is simply the second pass analysis. The weights produced by this function are in the range 0 to 1. γ is a numerical convergence parameter that controls the difference between the weights on the two consecutive passes, and lies between 0 and 1 ($0 < \gamma < 1$). Thus the weighting function has a steeper fall-off on the final pass in an attempt to build smaller scales into the analysis. For each of the two correction passes the convergent parameter is held constant. Barnes (1964) objective analysis scheme without γ is convergent but it requires several more passes to reach the same degree of convergence as compared to Barnes (1973) version with γ which requires only two passes through the data.

A simple bilinear interpolation between the values of $g_0(i,j)$ at four surrounding grid points can be used to obtain an estimate for $g(x_m,y_m)$ at each data location. If the average spacing of the data and the grid points is small compared to some wavelength, then the fraction (between 0 – 1) of amplitude retained at a given wavelength after the second pass is given by (Barnes, 1973):

$$R' = R_0(1 + R_0^{\gamma-1} - R_0^{\gamma}) \tag{5}$$

where $R_0 = \exp(-\pi^2 c^2 / L^2)$ is the response after the first pass in which L is the horizontal wavelength. The response function R' is the measure of the degree of convergence after the second pass through the data. The final response function for the three pass analysis scheme following Achtemeier (1989) is

$$R'' = 1 - (1 - R_0)(1 - R_0^{\gamma})^2 \tag{6}$$

The shape of the response curve is illustrated in Figure 2. An important characteristics of the Barnes scheme is its theoretical response function, by which the degree of the smoothing of the input data can be predicted as a function of wavelength. Barnes (1973) defines the response R as a fraction of amplitude of input data $f(x,y)$ retained in the smoothed and interpolated field

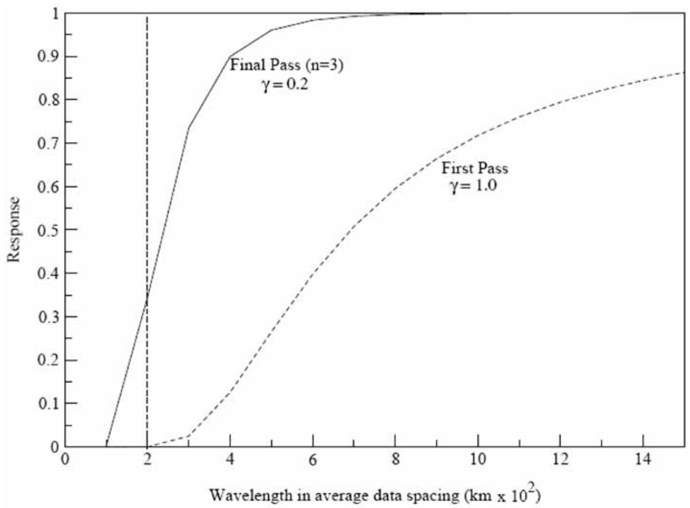

Figure 2. First pass (dashed line, γ = 1.0) and final pass (solid line, γ = 0.2) response curves as a function of wavelength in average data spacing for the three-pass objective analysis scheme corresponding to $c^2 = 4 \times 10^4$ km^2.

$g(x,y)$. At a particular wavelength $R = 1$ implies that the interpolated field captures the original field exactly at that wavelength, while $R = 0$ implies that the analysis has completely suppressed any amplitude at that wavelength.

3. Results and discussion

3.1. Scale length, average data spacing and grid resolution

The scale length c is sometimes written as a multiple of the data spacing. However, when the observations are irregularly distributed, defining the data spacing is ambiguous. When the data spacing is severely non-uniform, Koch et al. (1983) suggested the data spacing Δn, which has the following form:

$$\Delta n = \sqrt{A}\,\left\{(1+\sqrt{N})/(N-1)\right\} \tag{7}$$

Here, A is the area of the data network and N is the number of observations. This value of Δn represents what the average data spacing would be if the observations were uniformly distributed within the data network. Barnes (1964, 1973), Doswell (1979), Maddox (1980), Koch and McCarthy (1982) suggested that the ratio between grid spacing Δx and data spacing Δn should lie in the range of ~ 0.3 – 0.5. There are sound reasons for these empirical findings. Since five grid points are required to represent a wave (Peterson and Middleton, 1963) on a grid and the minimum resolvable wave is of $2\Delta n$ scale, then Δx should not be longer than $\Delta n/2$ to ensure proper representation of resolvable wavelengths. Further, unrealistic divergence and vorticity fields which are very sensitive to grid length may result when the grid is too small. Hence the grid length should not be much smaller than data spacing. For these reasons Barnes scheme imposes the constraint that $\frac{\Delta n}{3} \le \Delta x \le \frac{\Delta n}{2}$. Given this definition of the data spacing, we are prepared to define a scale length c. For the first pass analysis of a multi-pass Barnes objective analysis, selecting a proper value for c is important. Although theoretically, there are large number of combinations of c and γ that will produce a given response, some combinations are better than others. Table 1 gives some of the combinations used by different researchers. Figure 2 shows the range of responses that can be obtained for different values of Δn, under the constraint that γ should lie between 0.2 to 1.0. For the first pass value of R_0, which is a function of wavelength (L), following Achtemeier (1989) a negligible value of 2.5×10^{-4} for the initial response R_0, at $2\Delta n$ is chosen and then $R_0(L)$ is calculated using the equation

$$R_0(L) = 0.00025^{\left(\frac{2\Delta n}{L}\right)^2} \tag{8}$$

Table 1. Different combinations of c and γ (Δn: Average Data Spacing)

	Koch et al. (1983)	Mills et al. (1997)	Spencer et al. (2003)
c	$1.43 \times \Delta n$	$0.973 \times \Delta n$	$1.75 \times \Delta n$
γ	0.2	0.3	0.33

Table 2. Characteristics of different parameters used in the analysis.

Input Parameters	Weighting function	Initial Guess	Interpolation from grid to station	Number of iterations	Radius of Influence	Scale length (c)
Barnes 3-pass scheme	Exp $(-r_m^2/\gamma c^2)$	Not required	4-point average	3	$5c$	200 km

The final pass response $R''(L)$ are computed using Eq.(6). Achtemeier (1989) has chosen his scale length c so that the waves shorter than $2\Delta n$ (Nyquist wavelength) are strongly filtered. For $R_0(2\Delta n) = 0.00025$ the final response R'' at the $2\Delta n$ wavelength was 0.34465 for $\gamma = 0.2$. Thus under this constraint, high frequency noise generated by random errors will be effectively filtered from the analysis. For the current system we have chosen $\gamma = 0.2$ for the two inner passes and this corresponds to a scale length of $1.833 \times \Delta n$. This means that the scale length c is determined by the average data spacing, such that the maximum response should not exceed e^{-1} at $2\Delta n$ scale for $\gamma = 0.2$.

3.2. Analysis

As mentioned earlier the analysis domain is a 113 × 113 grid whose size is 2800 km × 2800 km (grid length $\Delta x = 25$ km). Analysis of daily rainfall (16 to 21 August 1994) have been made using the Barnes 3-pass scheme. Although analyses were made for six days, Figures 3 to 6 show the analysed rainfall from 17 to 20 August when the monsoon depression was passing in a northwesterly direction from the Bay of Bengal to North-West India. For the 2-pass scheme, Koch et al. (1983) considered γ to be in the range of 0.2 to 1.0, while Barnes (1973) suggested $0.2 < \gamma < 0.4$. In this experiment we have chosen a scale length of $1.833 \times \Delta n$ ($\approx$ 200 km) for outer pass ($\gamma = 1.0$). For the two inner passes γ was chosen to be 0.2 to add a reasonable amount of details to the analysed rainfall. On 17 August when the depression was forming over North-West Bay, the objectively analysed field (Figure 3) showed 2 to 4 cm rainfall over different parts of India. 5 cm of rainfall was also observed over the North-East and over Punjab. On 18 August when the system intensified into a deep depression, analysis (Figure 4) shows heavy rain area along the west coast of India with a maximum value of 10 cm. 8 to 16 cm of rainfall was also observed over different parts of Orissa. On 19 August the depression further moved in land and was situated over Central India. The analysed field (Figure 5) showed high spatial variability. Over Central India 6 cm and North-East 10 cm of rain were observed. Along the West-Coast at higher latitude 12 cm rainfall was seen. According to the Indian Daily Weather Report the monsoon was vigorous over coastal Karnataka and caused heavy rainfall over Agumbe (13° 30' N, 75° 02' E) and Mangalore (12° 52' N, 74° 51' E). This was also reflected in this analysis which shows maximum of 14 cm of rain over

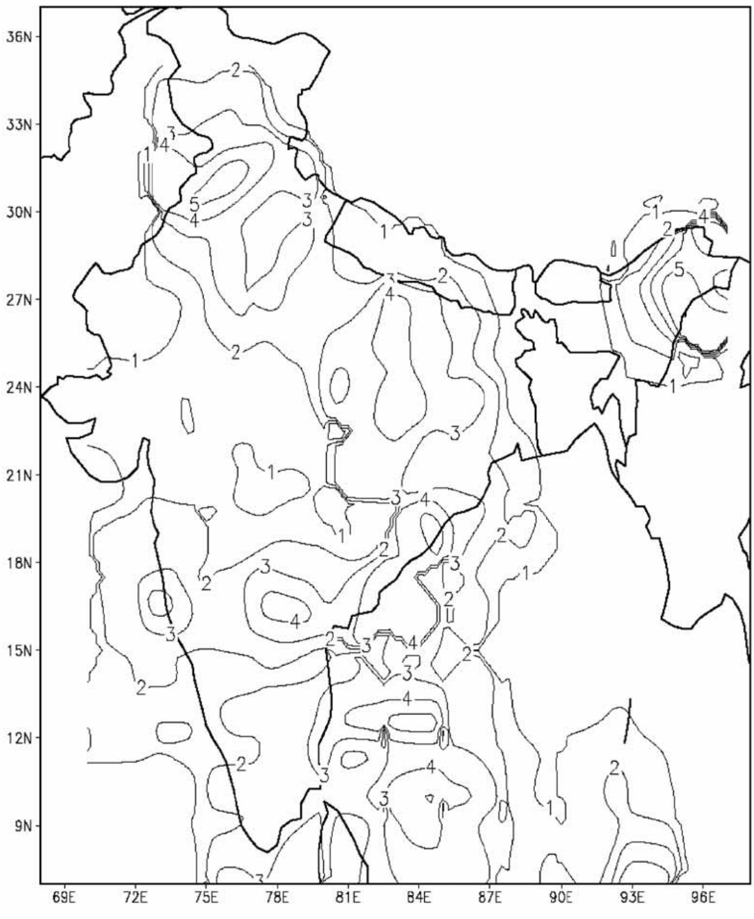

Figure 3. Objective analysis of August 17, 1994.

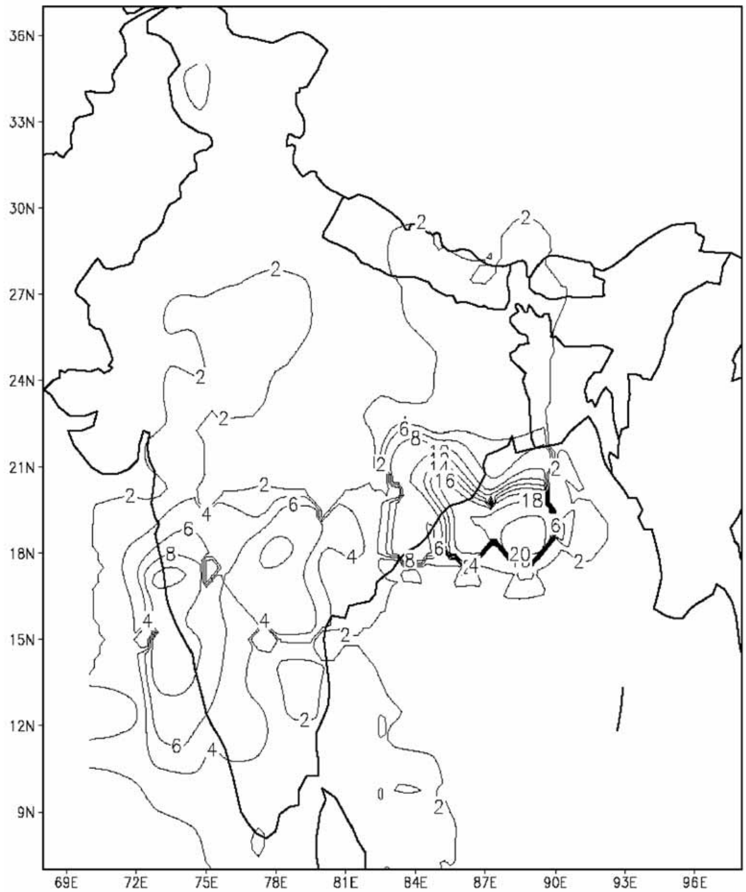

Figure 4. Objective analysis of August 18, 1994.

coastal Karnataka. On 20 August (i.e. the day before depression dissipated) the system moved in a west-north-westerly direction and was over East Rajasthan. The monsoon has been vigorous in Gujarat region and active in West Madhya Pradesh and coastal Karnataka. Our analysis of 20 August (Figure 6) indicates also heavy rain over the above regions. 12–16 cm of rainfall was observed over Gujarat and 10 cm of rainfall was seen over Karnataka. Analysis also showed heavily raining area over the region 18° N, 81.5° E and near Jammu and Kashmir in North India.

Figure 7 shows the total analysed rainfall for the six days analysis period, from 16 to 21 August. The total analysed rain showed large numbers of maximas with lot of spatial variability. The West-coast has a maxima of 40 cm

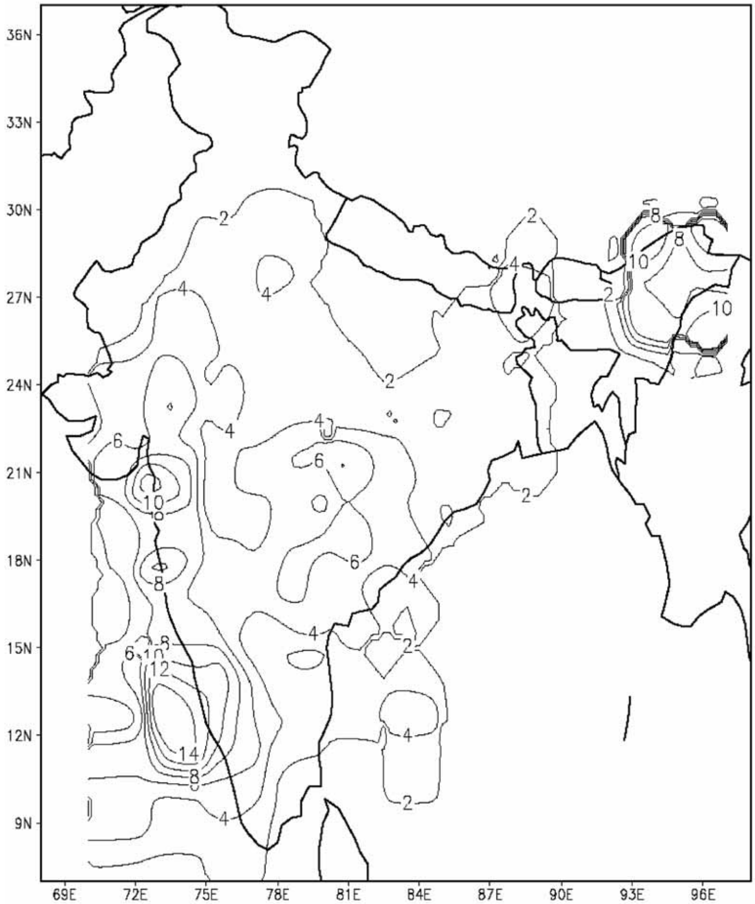

Figure 5. Objective analysis of August 19, 1994.

rain and North-India has another maxima of 45 cm. To assess the accuracy of the analysed rainfall, root mean square (rms) errors for the six days were computed by comparing the analysed rainfall against independent data not used in the analysis. This is known as the cross validation approach and has been used widely since Gandin (1963). In this case, out of total observations 95 % of the data were used in the analysis and the verification was done on the remaining 5 % data selected randomly. In the verification the analysed values were interpolated to observation locations. The rms errors were generally between 1.79 to 2.5 cm. Often a mean absolute error (mae) is a more reasonable measure of rainfall analysis accuracy than rms error. Table 3 shows the different type of errors. Further to this one may ask whether the computed small rms errors

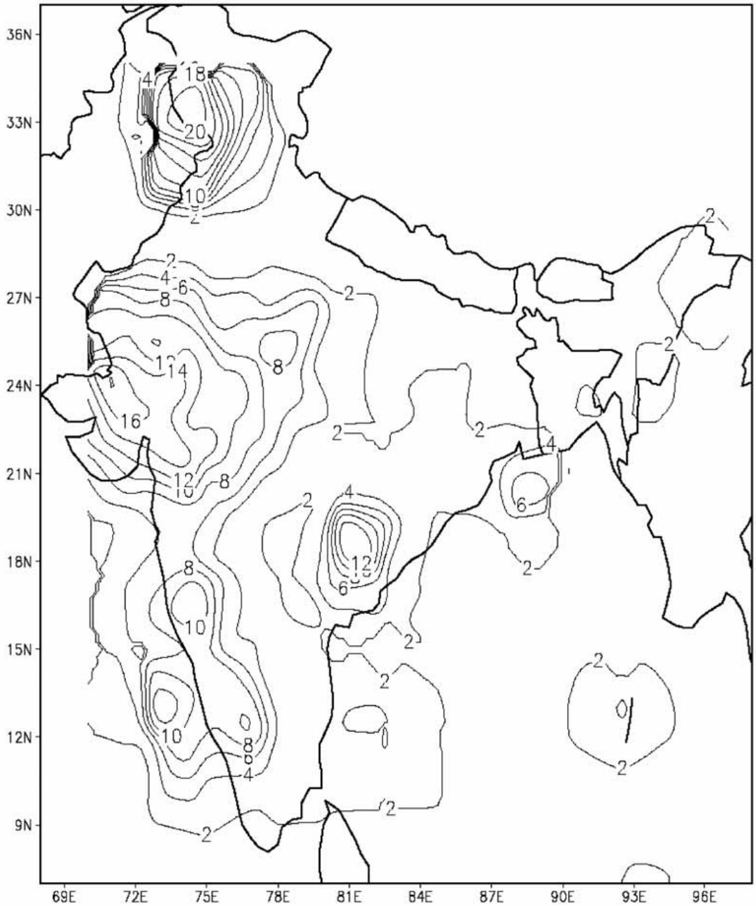

Figure 6. Objective analysis of August 20, 1994.

Table 3. Errors for different days (cm) August 1994 over Indian region.

August 1994	RMS Errors	MAE
16	2.14	1.70
17	1.96	1.59
18	1.79	1.43
19	2.50	2.08
20	2.24	1.89
21	2.24	1.82

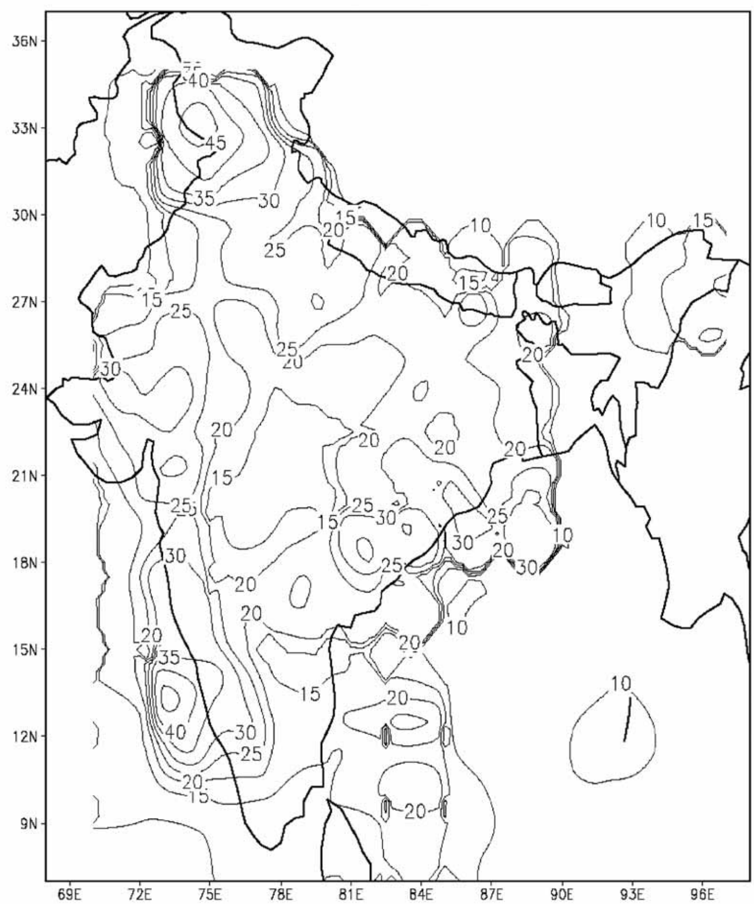

Figure 7. Objective analysis of total (16 – 21 August 1994) rainfall.

were due to truncation of C_R at $5c$. The same analyses were performed with C_R extended to include information from all stations. The mean absolute error difference in the two analyses was negligible. The reason that the difference was very small essentially due to the fact that $C_R = 5c$ captured all of the information available for the particular choice of c for this experiment. Extending C_R did not improve the analysis accuracy because the weights are very close to zero beyond this value of C_R.

If the computation time is of no concern, Barnes recommended that all observations should be used to determine the weighted sums, regardless of how distant they are. On some computers, this may produce underflow in the eval-

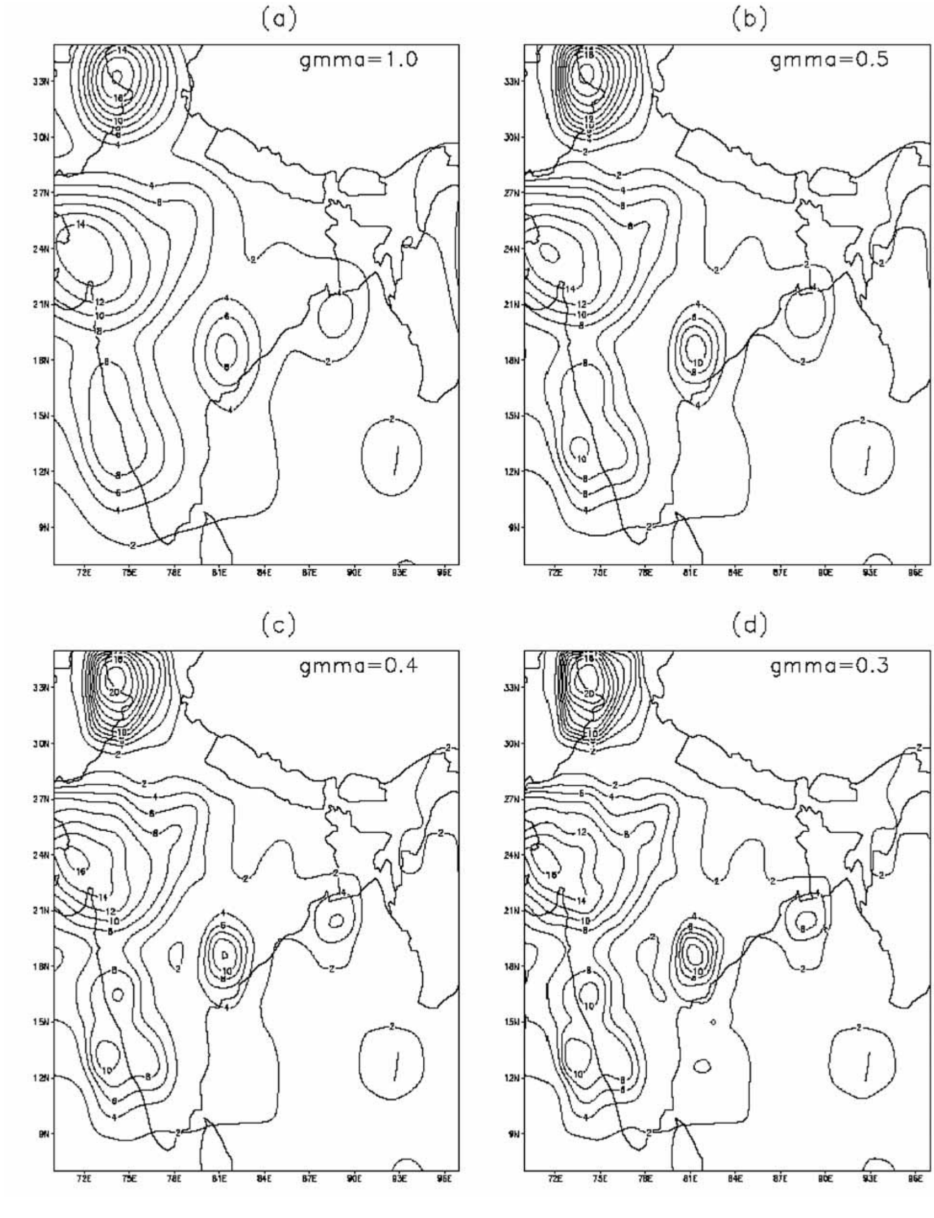

Figure 8. Objective analysis of 20 August for different values of γ.

uation of the assigned Gaussian weight value, in which case one should limit C_R to be some arbitrary large value that does not cause underflow problems.

To examine how the analysis changes with different values of γ (1.0, 0.5, 0.4 and 0.3) we displayed the analyses of 20 August (Figure 8 (a–d)). It can be seen from Figure 2 that the response is lower when the value of γ was large and accordingly dampen the analysis details. The changes in the analyses that took place with the variation of γ are shown in Figure 8 (a–d). When $\gamma = 1.0$, we found rainfall maximum of 18 cm over Jammu and Kashmir in North India, whereas over the same region $\gamma = 0.5$, 0.4 and 0.3 showed 20 cm rain. Similarly over the region 18° N, 82° E $\gamma = 0.4$ and 0.3 showed maximum rain of 12 cm, whereas $\gamma = 1.0$ and 0.5 produced 8 and 10 cm rain respectively. Over Gujarat 16 cm rain was seen in all the Figures of 8 except Figure 8 (a), whereas Figure 6 which was for $\gamma = 0.2$ showed slightly more than 16 cm rain over Gujarat. Along the West coast of India rainfall slowly increased with the reduction of γ, when maximum of 10 cm rain was observed (Figure 8(c, d)). 12 cm of rain was seen when γ is further reduced to 0.2 (Figure 6). Thus it can be concluded that the lower value of γ (higher response) produced more local maxima with enhanced rainfall and higher spatial variability.

4. Conclusions

No worthwhile mesoscale research and modeling work can be carried out without good analysis of mesoscale data for the Indian region. This study analyzing daily rainfall over Indian region is an effort in this direction. It is possible to generate and analyse data sets of large scale daily rain over the monsoon area on a regular grid by complimenting the satellite derived rain from INSAT with the daily raingauge data using the Barnes objective analysis method. The inclusion of satellite data produced the final (after three pass) analysed data set which is able to represent major rain systems associated with monsoon. For model verification this type of analysed rainfall will be very much useful. The scale length parameter was objectively determined from the average data spacing. We have chosen to perform a three-pass Barnes analysis. Two-pass Barnes analysis has been popular (e.g. Koch et al., 1983), but the limitation to two-pass was largely based on lack of computing power at that time. Three-pass Barnes objective analysis scheme with $\gamma = 1.0$ for outer pass and 0.2 for two inner passes was applied. Root mean square error comparing the analysed field with the observed data was low suggesting that the analysed fields are closer to the observations. For producing better quality of rainfall analysis we require more uniformly distributed rainfall observations. Here, it is necessary to remember that a spatial variability of seasonal scale rainfall is much lower as compared to daily rainfall. This scheme has the following advantages.

1. Two or three passes are required to reach the convergence.

2. Background field (first guess) is not required. Therefore analysis can be performed without the use of model.

3. This scheme is computationally efficient with filter response characteristics that are known functions of the average data spacing.

Mesoscale analysis involves assimilation of data from different sources and sensors. Future plans include use of RADAR data along with satellite data to complement the existing raingauge data. The scale length used in this study then can be adjusted accordingly. RADAR data has the potential to provide the rainfall at high temporal and spatial resolution not available from other sources. Our main task is to combine optimally the rainguage data with the data from other sources. It is also possible that a first guess field provided by mesoscale numerical weather prediction model could be used to replace the first pass through the data.

Acknowledgements – The authors are thankful to the Director of the Indian Institute of Tropical Meteorology, Pune for providing facilities and keen interest in this study and to Head of the Forecasting Research Division for encouragement. Thanks are due to India Meteorological Department for providing us with the data.

References

Achtemeier, G. L. (1987): On the concept of varying influence radii for a successive corrections objective analysis, *Mon. Weather Rev.*, **115**, 1760–1771.

Achtemeier, G. L. (1989): Modification of a Successive Corrections Objective Analysis for Improved Derivative Calculations, *Mon. Weather Rev.*, **117**, 78–86.

Arkin, P. A. and Meisner, B. N. (1987): The relationship between large-scale convection rainfall and cold cloud over the western hemisphere during 1982–84, *Mon. Weather Rev*., **115**, 51–74.

Arkin, P. A., Rao, A.V. R. K. and Kelkar, R. R. (1989): Large-Scale precipitation and OLR from INSAT-1B during the 1986 southwest monsoon season, *J. Climate*, **2**, 619–628.

Barnes, S. L. (1964): A technique for maximizing details in a numerical weather map analysis, *J. Appl. Meteorol*., **3**, 396–409.

Barnes, S. L. (1973): Mesoscale objective map analysis using weighted time-series observations. NOAA Tech. Memo. ERL NSSL-62, National Severe Storms Laboratory, Norman, OK 73069, 60 pp. ŠNTIS COM–73–10781Ć.

Bussieres, N. and Hogg, W. (1989): The objective analysis of daily rainfall by distance weighting schemes on a mesoscale grid, *Atmos. Ocean*, **27**, 521–541.

Caracena, F., Barnes, S. L. and Doswell III, C. A. (1984): Weighting function parameters for objective interpolation of meteorological data. Preprints, 10th Conf. on Weather Forecasting and Analysis. Clearwater Beach, FL, Amer. Meteor. Soc., 109–116.

Cressman, G. P. (1959): An operational objective analysis system, *Mon. Weather Rev*., **87**, 367–374.

Das, P. K. (1986): *Monsoons*. WMO monograph no. 613, WMO, Geneva. 155 pp.

Doswell, C.A. (1977): Obtaining meteorologically significant surface divergence fields through the filtering property of objective analysis, *Mon. Weather Rev.*, **105**, 885–892.

Gandin, L.S. (1963): *Objective analysis of meteorological fields (in Russian)*. Israel Program for Scientific Translation, 242 pp.

India Meteorological Department (1981): *Climatological atlas of India. Part I: Rainfall*, New Delhi, 69 charts.

Janowiak, J. E. (1992): Tropical rainfall: a comparison of satellite-derived rainfall estimates with model precipitation forecasts, climatologies and observations, *Mon. Weather Rev.*, **120**, 448–462.

Janowiak, J. E. (1994): An evaluation of NMC/NCAR reanalysis tropical rainfall during 1986-88. Proc. Of the 19th Annual Climate Diagnostics Workshop, College Park, MD., Nov. 14-18, 1994. US Dept. of commerce, 238–241.

Koch, S. E. and McCarthy, J. (1982): The evolution of an Oklahoma dry line. Part II Boundary-layer forcing of mesoconvective systems, *Mon. Weather Rev*., **39**, 237–257.

Koch, S. E., Desjardins, M. and Kocin, P. J. (1983): An interactive Barnes objective map analysis scheme for use with satellite and conventional data, *J. Clim. Appl. Meteorol*., **22**, 1487–1503.

Maddox, R. A. (1980): An objective technique for separating macroscale and mesoscale features in meteorological data, *Mon. Weather Rev*., **108**, 1108–1121.

Mills, G. A., Weymouth, G., Jones, D., Ebert, E. E., Manton, M., Lorkin, J. and Kelly, J. (1997): *A National objective daily rainfall analysis system*. BMRC Techniques Development Report, No.1, 30 pp.

Mitra, A. K., Bohra, A. K. and Rajan, D. (1997): Daily rainfall analysis for Indian summer monsoon region, *Int. J. Climatol*, **17**, 1083–1092.

Mitra, A. K., Das Gupta, M., Singh, S. V. and Krishnamurti, T. (2003): Daily rainfall for the Indian monsoon region from merged satellite and rain gauge values: Large-scale analysis from real-time data, *J. Hydrometeorol*., **4**, 769–781.

Mooley, D. A. (1973): Some aspects of Indian monsoon depressions and associated rainfall, *Mon. Weather Rev*., **101**, 271–280.

Pauley, P. M. and Wu, X. (1990): The theoretical, discrete and actual response of the Barnes objective analysis scheme for one and two-dimensional fields, *Mon. Weather Rev*., **118**, 1145–1163.

Peterson, D. P. and Middleton, D. (1963): On representative observations, *Tellus*, **5**, 387–405.

Raddatz, R. L. (1987): Mesoscale representativeness of rainfall measurements for Winnipeg, *Atmos. Ocean*, **25**, 267–278.

Rajeevan, M., Bhate, J., Kale, J. D. and Lal, B. (2006): High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells, *Curr. Sci. India*, **91**, 296–306.

Rao, K. N., George, C. J. and Abhyankar, V. P. (1971): *Nature of the frequency distribution of Indian rainfall (monsoon and annual). Report No. 168*, India Meteorological Department, Pune (India).

Roy Bhowmik, S. K. and Das, A. K. (2007): Rainfall analysis for Indian monsoon region using the merged raingauge observations and satellite estimates: Evaluation of monsoon rainfall features, *J. Earth Syst. Sci.*, **116**, 187–198.

Singh, N. and Mulye, S. S. (1991): On the relations of the rainfall variability and distribution with the mean rainfall over India, *Theor. Appl. Climatol*., **44**, 209–221.

Sinha, S. K., Narkhedkar, S. G. and Mitra, A. K. (2006): Barnes objective analysis scheme of daily rainfall over Maharashtra (India) on a mesoscale grid, *Atmosfera*, **19**, 59–76.

Smith, D. R., Leslie, F. W. (1984): Error determination of a successive correction type objective analysis scheme, *J. Atmos. Ocean. Tech.*, **1**, 120–130.

Spencer, P. L., Stensrud, D. J. and Fritsch, J. M. (2003): A method for improved analyses of scalars and their derivatives, *Mon. Weather Rev.*, **131**, 2555–2576.

White, G. H. (1995): An intercomparison of precipitation and surface fluxes from operational NWP analysis/forecast system. CAS/JSC WGNE Report No. 22, WMO/TD–No. 723.

SAŽETAK

Mezoskalna objektivna analiza dnevne oborine pomoću satelitskih i konvencionalnih mjerenja nad područjem indijskog ljetnog monsuna

S. G. Narkhedkar, S. K. Sinha i A. K. Mitra

Ovdje je opisana shema mezoskalne objektivne analize za dobivanje dnevne oborine u pravilnoj geografskoj mreži nad područjem monsuna u Indiji. Za nejednako raspoređene podatke o dnevnoj oborini primijenjena je Barnes-ova shema za interpolaciju u pravilnoj mreži. Prostorna rezolucija interpoliranih podataka vrši se svakih 0.25° geografske širine i 0.25° geografske dužine. Analiza je omogućila kombinirani uvid u dnevnu oborinu izvedenu na temelju satelitskih slika i mjerenja kišomjernih postaja. Ovdje se koriste neka objektivna ograničenja: (i) težine su određene kao funkcije udaljenosti podataka, (ii) radi postizanja konvergencije analiziranih vrijednosti koriste se tri filtra kroz podatke čime se postigla automatska eliminacija valnih duljina manjih od dvostruke srednje udaljenosti među podacima. Za predstavljanje karakteristika analizirane oborine, odabran je slučaj tipične monsunske depresije koja se kreće prema zapadu tijekom monsunske sezone godine 1994. Napravljene su objektivne analize od 6 dana (od 16. do 21. kolovoza 1994.) korištenjem Barnes-ove sheme. Pritom je mijenjana težinska funkcija parametra skale duljine (c, nazivnik u eksponencijalnoj Gauss-ovoj težinskoj funkciji) za čitav niz vrijednosti, te je računan korijen srednje kvadratne pogreške za određivanje odgovarajuće vrijednosti c-a. Vrijednost c ovisi o gustoći mjerenja te o broju korištenih korektivnih filtra. Ispitivale su se karakteristike analiziranog izlaznog polja pomoću usporedbe s analiziranom mjerenom oborinom. U ovoj su analizi jasno izvedene obilne oborine nad zapadnim Ghat-om u Indiji.

Ključne riječi: Mezoskalna analiza, Barnes-ova troslojna shema, analiza oborine

Corresponding author's address: Dr. S. G. Narkhedkar, Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune – 411 008, India, e-mail: narkhed@tropmet.res.in