Applications of satellite based rainfall measurements

Satellite based rainfall measurements have a wide range of applications in the fields of hydrology, weather forecast, monsoon studies, climate studies etc. From the plethora of applications, certain selected applications of satellite based rainfall measurements are addressed in this chapter.

At larger scales statements of rainfall based on conventional sources of data are fragmentary and incomplete in their coverage over vast areas. This is mainly because precipitation reports based on ground measurements over larger areas are sparse and nearly absent over oceanic regions. The first attempt using satellites to explicate climatological rainfall patterns was reported by Barrett [1971]. They carried out their analysis over oceanic regions bounded by $30^\circ N$ and $30^\circ S$, and $90^\circ E$ and $180^\circ E$. Rainfall maps generated for weekly, monthly, seasonal and annual scales gives the opportunities to study the short term and long term fluctuations of rainfall intensity and distributions. Satellite evaluation of rainfall distributions over oceanic regions helps to understand long-term anomalies in the rainfall patterns. Indian summer monsoon is a large ocean-land phenomenon where the rainfall signatures have to be observed in larger scales. IMD has a large network of ground measurements through which seasonal rainfall is monitored at broader scales. The Indian land region is divided into
meteorological sub-divisions based on the meteorologically homogeneous areas of the Indian subcontinent. In this chapter, rainfall monitoring of Indian summer monsoon, using INSAT Multi Spectral Rainfall Estimation algorithm (IMSRA) for the year 2009 using Kalpana-1 measurements are explained. Many recent studies have suggested the variations in the summer monsoon rainfall. The changes in rainfall over the equatorial trough (ET) region play a significant role in the overall variations of rainfall over India. In this chapter, a study regarding the long-term changes in the summer monsoon rainfall over the ET is also discussed.

6.1 Indian Summer monsoon monitoring using Kalpana-1 based rainfall measurements

IMSRA technique has been developed based on multi-spectral signatures of clouds from WV and TIR bands from Kalpana-1 and microwave signatures from TRMM satellite. This method is presently operational at IMD. From the 3-hourly rainfall derived from Kalpana-1 measurements accumulated daily, weekly and monthly rain is computed. The onset phase and further progress of the monsoon 2009 is monitored using these rainfall maps. The onset of monsoon over Kerala took place on 23 May 2009. Subsequent to the onset, a severe cyclonic storm “Aila” formed over the Bay of Bengal. This retarded the further advancement of the monsoon [IMD 2009].

The weekly rainfall map for 21-27 May using the IMSRA algorithm is shown in Figure 6.1a. From this figure, it is also clear that the IMSRA algorithm is capable to capture the cyclonic rain features. The increase in rain associated with the cyclonic activity over the region can be observed clearly from this figure. The lull in rainfall activity that happened due to the cyclone can be inferred from the deficit rain shown by present algorithm over the land during 28 May - 3 June (Figure 6.1b). After the hiatus, the monsoon further advanced along the west coast of India. Again, the prolonged pause of the monsoon activities continued till 8 - 20 June.

The weekly rainfall map covering the period 11 - 17 June is shown in Figure 6.1c. In
Figure 6.1: Weekly rainfall (mm) map covering the period (a) 21 to 27 May, (b) 28 May to 3 June, (c) 11 to 17 June and (d) 2 to 8 July, 2009 using Kalpana-1 measurements
June, deficit in rainfall is observed due to the unfavorable phase of the El Nio and Southern Oscillation (ENSO) and the equatorial Indian Ocean Oscillation (EQUINOO) and also the eastern equatorial Indian Ocean was warmer than the other years and much warmer than the Bay [Francis and Gadgil, 2010]. Associated with the formation of a depression over the Arabian Sea during 23 - 24 June south-west monsoon showed some revival and a weak progress over some more parts of the peninsular and Central India during 21 to 27 June. By 30 of June, most parts of the country got covered by the monsoon and during July the monsoon activity was nearly normal. Two low pressure systems and a deep depression were observed over this period. The weekly rainfall map of 2 - 8 July (Figure 6.1d) shows that the central India and parts of eastern and western India got satisfactory rainfall.

The sub-divisional scale rainfall was computed according to the procedure given in chapter 3 [Prakash et al., 2009, 2010, Mahesh et al., 2014a]. The accumulated rain of the active phase of monsoon is compared with the rain estimated by the India Meteorological
Department (IMD). The results of the comparison of the rain estimated by IMSRA technique and IMD for the month July is given in Figure 6.2a and Figure 6.2b respectively. The departure of rainfall is computed according to the IMD climatological data and the classification of rain excess, normal, deficient and scanty rainfall is made according to the IMD scheme. The results show that the rain estimated using the IMSRA technique is in good compliance with the IMD rain over most of the parts of India. However, the performance of the algorithm over western coastal region and north-eastern regions is relatively poor. The two sub-divisions namely, Coastal Andhra Pradesh, Tamilnadu and Pondicherry show excess rainfall from satellite-based data, whereas IMD data show deficient and normal rainfall over these sub-divisions, respectively. The underestimation of rainfall over the west coast of India from satellite-based rainfall data can clearly be seen. It might be due to the heterogeneous terrain of those regions with orographic presence and the coastal effects. Other than orographic areas, the island regions (Andaman and Nicobar, and Lakshadweep) also show significant deviation from the IMD estimated rain. It might be due to the error introduced in the Tbs by the contrasting features of land and ocean. The monthly accumulated rainfall for the month
Table 6.1: Statistical comparison of algorithm over all land and non orographic region

<table>
<thead>
<tr>
<th>Parameters</th>
<th>All Land</th>
<th>Non Orographic Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Matches</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.60</td>
<td>0.77</td>
</tr>
<tr>
<td>RMSE (mm)</td>
<td>117.16</td>
<td>71.42</td>
</tr>
</tbody>
</table>

of August using Kalpana-1 GPI [Prakash et al., 2011a] and IMSRA techniques is shown in Figure 6.3. The rainfall estimation method of GPI algorithm is given in chapter 3. Both the techniques show similar patterns of rainfall qualitatively, however, the spatial variation of rainfall is better captured by the IMSRA technique.

The seasonal rainfall map for the south-west monsoon (June to September) using the IMSRA algorithm and IMD is given in Figure 6.4a and Figure 6.4b respectively. Both of the rainfall maps show that most of the sub-divisions got deficient rainfall. IMSRA derived rainfall map shows that 14 meteorological sub-divisions received normal rainfall, 21 sub-divisions received deficient rainfall and 1 sub-division namely, Himachal Pradesh received scanty rainfall during this season. The IMD-based rainfall map shows that 3 sub-divisions received excess rainfall, 11 sub-divisions received normal rainfall and 22 sub-divisions received deficient rainfall. However, the accumulated rainfall over the orographic regions like sub-divisions situated windward side of the west coast is underestimated by the satellite-based estimates. The underestimation of rainfall by Kalpana-1 over these regions due to complexity in precipitation processes is also discussed by Prakash et al. [2010]. They validated Kalpana-1 derived IMSRA estimates using rain gauge data over the Indian region at 3-hourly, daily and monthly scales and reported that this algorithm performs reasonably well over the non-orographic regions. The sub-divisional scale rainfall maps generated using Kalpana-1 data was used as a space input for the drought monitoring during the monsoon season of 2009. The progress of monsoon and total rainfall over the meteorological sub-divisions were monitored by the IMSRA technique.

For the quantitative inter-comparison, scatter plot has been drawn between the Kalpana-1 and IMD accumulated sub-divisional monthly rainfall (Figure 6.5a).
Figure 6.4: Seasonal rainfall map using (a) Kalpana-1 and (b) IMD for June to September, 2009

Figure 6.5: Scatter plot between sub-divisional monthly accumulated rainfall (a) over land and (b) over non-orographic regions derived by Kalpana-1 and IMD measurements
The result (Table 6.1) gives a correlation of 0.60 (CI range 0.48 - 0.70 at 95% confidence level) with an error for estimated rainfall of 117.16 mm. Figure 6.5b shows the comparison of rainfall omitting the orographic regions. The correlation is improved to 0.77 (CI range 0.69 - 0.83 at 95% confidence level) with an error for estimated rainfall of 71.42 mm. The underestimation of rainfall by Kalpana-1 is noticeably reduced after excluding the orographic regions. The results depicts that the IMSRA algorithm is able to capture rainfall in most parts of India except for orographic regions that has been addressed by Mahesh et al. [2014b]. This analysis clearly indicates the potential of the satellite-based rainfall estimates for the monsoon monitoring at meteorological sub-divisional scale.

6.2 Long-term changes in the summer monsoon rainfall over the equatorial trough region

The variations in the summer monsoon rainfall over the equatorial trough (ET) play an important role in the variations of rainfall over India at intra-seasonal timescale. Long-term changes in the summer monsoon rainfall over the ET has been investigated for a 34 year (1979-2012) period using gauge adjusted multi-satellite Global Precipitation Climatology Project (GPCP) rainfall data. Figure 6.6 illustrates the 34-year (1979-2012) climatology of the GPCP rainfall rate over the north Indian Ocean and adjoining continental landmass during the summer monsoon season (June-September). The large-scale features of monsoon rainfall such as two peak rainfall belts, one situated over the west coast of India and another located over the windward side off the Arakan Yoma mountain chain of Bangladesh/Myanmar, and higher monsoon rainfall over the eastern Indian Ocean are well captured by this merged rainfall analysis. The equatorial trough (ET) bounded by 0° – 10°S and 60° – 100°E receives rainfall ranging from 3 mm day\(^{-1}\) to 9 mm day\(^{-1}\) with large spatial variability during this season. The eastern equatorial trough (EET) (0° – 10°S and 80° – 100°E) receives higher monsoon rainfall of about 7-9 mm day\(^{-1}\) associated with higher sea surface temperature,
leading to intense convection, as compared to the western equatorial trough (WET) 
($0^\circ - 10^\circ S$ and $60^\circ - 80^\circ E$).

![Figure 6.6: Climatology of the seasonal summer monsoon rainfall (mm day$^{-1}$) over the Indian monsoon region computed from the GPCP data for the period 1979-2012. The rectangular boxes show the locations of the western ($0^\circ - 10^\circ S$ and $60^\circ - 80^\circ E$) and eastern ($0^\circ - 10^\circ S$ and $80^\circ - 100^\circ E$) equatorial trough regions.](image)

Moreover, the monsoon rainfall over the ET exhibit large intraseasonal oscillations [Sikka and Gadgil, 1980], [Ramesh Kumar et al., 2005] and influences the ISMR at intraseasonal timescale. But, the role of seasonal monsoon rainfall over the ET on the ISMR is not investigated so far. Since the WET and EET behaves differently to the monsoon rainfall over the middle India (MI) at intra-seasonal scale [Ramesh Kumar et al., 2005], the relationship between area averaged seasonal rainfall over the WET and EET with MI ($20^\circ - 24^\circ N$ and $72^\circ - 88^\circ E$) are investigated separately (Figure 6.7).

The scatter plot of seasonal rainfall over the WET and MI shows a positive linear relationship, whereas the scatter plot of seasonal rainfall over the EET and MI shows a
Figure 6.7: Scatter plots of seasonal monsoon rainfall (mm day$^{-1}$) averaged over the (a) WET and MI, (b) EET and MI. Number of points (N), correlation coefficient ($r$), and p-value are also given in each plot.
negative linear relationship. But, the correlation coefficient is poor in both the cases [Prakash et al., 2014]. However, this analysis strengthens the fact that the monsoon rainfall over the WET and EET behaves differently to the rainfall over the MI at intra-seasonal and seasonal timescales. Now, it becomes important to investigate whether the monsoon rainfall over the WET and EET are correlated. Figure 6.8 shows the scatter plot between area averaged seasonal rainfall over the WET and EET for the 34-year period. Interestingly, the result shows that the monsoon rainfall over these two regions is negatively correlated (correlation coefficient = -0.32). These results clearly suggest that the analysis of long-term changes in the monsoon rainfall over these two regions of ET should be done separately.

The time-series of the seasonal monsoon rainfall averaged over the WET and EET for the period 1979 to 2012 is presented in Figure 6.9 which shows significant interannual variations in the monsoon rainfall over these two regions. The WET shows an increase of 0.04 mm day\(^{-1}\) year\(^{-1}\) and the EET shows a decrease of 0.02 mm day\(^{-1}\) year\(^{-1}\) in the monsoon rainfall during the study period [Prakash et al., 2014]. However, the p-value clearly shows that the increase in the monsoon rainfall over the WET is statistically significant (p-value = 0.01) whereas the decrease in the monsoon rainfall over the EET is not statistically significant (p-value = 0.50). Hence, these results suggest that the summer monsoon rainfall over the WET is consistently increasing, but the EET does not show significant long-term changes in the monsoon rainfall during the last 34 years.

Furthermore, we have also investigated the changes in the frequency of daily monsoon rain events over these two regions using the daily GPCP rainfall data. As the GPCP rainfall data at daily scale is available since 1997, this analysis is done for last 16-years (1997-2012). The area averaged daily rainfall is classified into four categories such as very light or negligible rain (less than 2.5 mm day\(^{-1}\)), light rain (2.5-7.5 mm day\(^{-1}\)), moderate rain (7.6-35.5 mm day\(^{-1}\)), and heavy rain (greater than 35.6 mm day\(^{-1}\)) as per criteria declared by the India Meteorological Department. The percentage contributions of the each type of daily rain events to the total rainfall during the summer monsoon season over both the regions are shown in Figure 6.10. The WET receives about 86% of
Figure 6.8: Scatter plot of seasonal monsoon rainfall (mm day\(^{-1}\)) averaged over the WET and EET. Number of points (N), correlation coefficient (r), and p-value are also shown in the plot.
Figure 6.9: Time-series of the seasonal summer monsoon rainfall over the (top) WET and (bottom) EET regions. The number of points (N), equation of best fit line, and p-value are also shown.
monsoon rainfall from very light or negligible rain events and the heavy rain events are very rare (0.17%). In contrast, the frequency of moderate and heavy rain events during the monsoon season over the EET is notably higher than the WET. This difference in the frequency of daily rain events over these regions lead to higher seasonal rainfall over the EET than WET (Figure 6.6).

The time-series of the frequency of very light, light, moderate, and heavy daily rain events are shown in Figure 6.11 and the corresponding percentage changes in the frequency of daily monsoon rain events over these two regions are given in Table 6.2.

The results show that the frequency of very light and heavy rain events over the WET
Figure 6.11: Temporal variations (1997 to 2012) in the frequency of (a-b) very light or negligible (less than 2.5 mm day$^{-1}$), (c-d) light (2.5-7.5 mm day$^{-1}$), (e-f) moderate (7.6-35.5 mm day$^{-1}$), and (g-h) heavy (>35.6 mm day$^{-1}$) daily rain events during the summer monsoon season over the WET (blue) and EET (red) regions. The linear fit lines are represented by dashed lines.
Table 6.2: Percentage annual changes in the frequency of daily monsoon rain events over the WET and EET between 1997 and 2012

<table>
<thead>
<tr>
<th>Daily rainfall (mm day$^{-1}$)</th>
<th>WET</th>
<th>EET</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2.5</td>
<td>−0.05</td>
<td>0.41</td>
</tr>
<tr>
<td>2.5 – 7.5</td>
<td>0.60</td>
<td>−0.40</td>
</tr>
<tr>
<td>7.6 – 35.5</td>
<td>0.08</td>
<td>−0.82</td>
</tr>
<tr>
<td>&gt;35.6</td>
<td>−3.71</td>
<td>1.76</td>
</tr>
</tbody>
</table>

is decreasing by -0.05% and 3.71% per year respectively whereas the frequency of light and moderate rain events are increasing by 0.60% and 0.08% per year respectively. This convincingly suggests that the increase in the monsoon rainfall over the WET is primarily associated with the increase in the frequency of light rain events.

Although the frequency of heavy rain events is decreasing over this region but its contribution is very less to the total rainfall (Figure 6.10). Conversely, the frequency of very light and heavy rain events is increasing at a rate of 0.41% and 1.76% per year respectively over the EET whereas the frequency of light and moderate rain events is decreasing by 0.40% and 0.82% per year, respectively. These results show that the frequency of daily rain events is consistently changing over the EET even though the seasonal monsoon rainfall over the EET does not show significant long-term change. But, such analysis with only 16-years of data is not adequate to arrive at a firm conclusion regarding the long-term changes in the frequency of daily monsoon rain events. Hence, it is suggested to wait for a couple of decades to reanalyze the long-term changes in the frequency of daily monsoon rain events over the oceanic region in order to get an explicit conclusion.