The catastrophe over Jammu and Kashmir in September 2014: a meteorological observational analysis

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An observational analysis of the catastrophic rainstorm during 4–6 September 2014 over Jammu and Kashmir (J&K) presented in this study shows that the event was unprecedented in terms of the 24, 48 and 72 h accumulated rainfall. The 24 h accumulated rainfall exceeded the previously determined one-day severe rainstorm limits of 20 cm for a number of stations on 5 and 6 September 2014. Weekly cumulative rainfall (4–10 September 2014) exceeded the average rainfall of the entire monsoon season (June–September) in 6 out 18 districts of the state. A number of stations recorded all-time highest 24, 48 and 72 h accumulated rainfall during the week. Analysis of short-duration intensity of rainfall shows that the heaviest rain-rate (35 mm/h) was recorded over Kawa (Üdhampur district). The rain-rate remained less than 20 mm/h at other stations. As Kawa is on the windward side of the Pir Panjal Range, orography seems to have played a significant role. The analysis of synoptic conditions leading to unprecedented rainfall shows that the rains were caused by the interaction of the westward-moving monsoon low pressure area across central and northwest India and a eastward-moving deep trough in the mid-tropospheric westerlies. The additional low pressure areas that formed over Saurashtra and Kutch on 3 September 2014 and over head Bay of Bengal on 5 September 2014, ensured the vigour of the event was maintained through strong wind and moisture flux in J&K. NWP models could capture heavy rains over J&K only in day 1 forecast.

Keywords: Accumulated rainfall, low pressure area, observational analysis, rainstorm.

HEAVY rainfall and associated flash floods cause tremendous damage to life and property across most of the mountainous regions of the world, including the Himalaya. The Himalayan ranges are prone to heavy and prolonged rainfall events and associated flooding, particularly during the summer rainy months of June to September (monsoon season). Variability in precipitation over the Himalaya during monsoon season is controlled by the atmospheric systems (lows or depressions) that draw moisture from the Bay of Bengal[1]. The frequency of monsoon depressions formed in the Bay of Bengal is about 80% of the total number of depressions formed in the South Asia monsoon region[2]. One-third of the monsoon lows fills up on crossing 85°E and nearly half on crossing 80°E. On some occasions a westerly wave passing over North Pakistan may take the monsoon system under its grip and make it re-curve initially in a northerly direction and then northeastwards, causing heavy rains in the upper areas of Punjab and adjoining areas of Jammu and Kashmir (J&K), India[3]. The structure, track and movement of monsoon depressions and associated rainfall patterns have been studied and reviewed in detail[4,5]. The synchronization of movement of westerly waves in the extreme north with the passage of monsoon disturbances in the lower latitudes causes heavy to very heavy rainfall along the foothills of the Himalaya, in the upper areas of Punjab and adjoining areas of J&K. Heavy rainfall events in the Western Himalaya often produce landslides across the hilly terrain[6,7]. Houze *et al.*[8] and Medina *et al.*[9] have examined the TRMM rainfall over Western Himalaya; the region is prone to deep convection during monsoon. Recently, Houze *et al.*[10] have studied the heavy rainfall over Pakistan, which caused floods during July and August 2010. Similar situation occurred in July 2005 when floods were reported in River Jhelum[11]. In the mountainous region, run-off from snowmelt and glacier-melt provides the dominant contribution to river flows during the spring and summer seasons, although monsoon rainfall may also influence peak flow[12].

A continuous spell of five days of very heavy rainfall in first week of September 2014, caused disastrous floods in many parts of the northwestern state of J&K. According to media reports, the state government claimed that ‘the calamity, worst in the century, caused colossal losses to life and massive damage to housing and business sectors, public institutions particularly hospitals, road infrastructure, agriculture and transport sectors. Over 300 people lost their lives across J&K, including 85 persons from Kashmir. A preliminary survey by the government revealed that the flood damaged over 3.50 lakh structures, including 2.50 lakh residential houses and affected 12 lakh families in 5500 flood-hit villages across the state.

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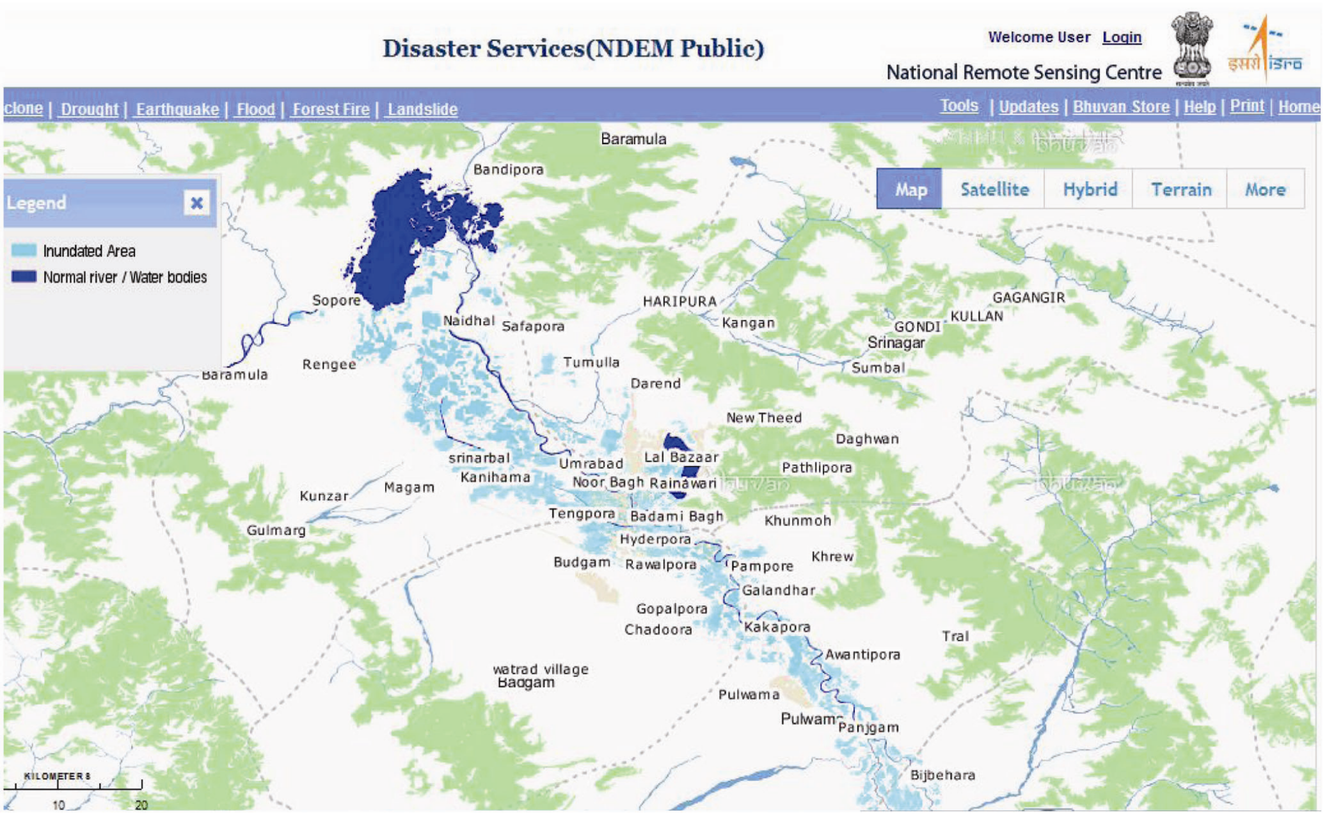

Figure 1. Inundated area in Srinagar as on 10 September 2014. (Source: NRSC, Bhuvan, website: http://bhuvan-noeda.nrsc.gov.in/disaster/disaster/disaster.php#.)

In worst-hit Kashmir, 2.60 lakh structures got damaged with 95,000 houses in Srinagar alone. It was a "disaster of international magnitude" and the losses to properties and business were in excess of rupees one trillion.' (http://www.greaterkashmir.com/news/2014/Sep/30/kashmir-flood-a-disaster-of-international-magnitude-govt-34.asp)

Heavy rainfall led to landslides and widespread flooding in the Kashmir valley. Flood waters breached embankments in many low-lying areas in Kashmir, including the capital Srinagar. Jhelum, Chenab and many other streams were flowing above danger mark. The worst affected districts were Srinagar, Anantnag, Baramulla, Pulwama, Ganderbal, Kulgam, Budgam, Rajouri, Poonch and Reasi. Figure 1 shows the flood estimated by NRSC, Bhuvan on 10 September 2014 in Srinagar and surrounding areas. Bhuvan (http://bhuvan.nrsc.gov.in*)* was launched by Indian Space Research Organisation (ISRO) in 2009. It is a software application which allows users to explore a 2D/3D representation of the surface of the Earth. The browser is specifically tailored to view India, offering the highest resolution in this region. Apart from visualization, Bhuvan provides timely disaster support services (domestic and international) free satellite data and products download facility, and rich thematic datasets. Bhuvan uses a crowd sourcing approach to enrich its maps and collect point of interest data. It also acts as a platform for hosting Government data (for example, Karnataka Forest Department datasets). It offers detailed imagery of Indian locations with spatial resolutions ranging up to 1 m. ISRO has used data provided by satellites, including Resourcesat-1, Cartosat-1 and Cartosat-2 to get the best possible imagery of India.

We analysed the event with regard to heavy rainfall and found that the severe rainstorm lasted for three days (4–6 September 2014). According to our analysis, the rainstorm was caused by large scale disturbed atmospheric conditions as a consequence of the interaction between the westward-moving monsoon low and the eastward-moving deep trough in the mid-latitude westerlies, causing extremely heavy rainfall over districts in the south-western region of J&K and adjoining Pakistan. In Uttarakhand during 16–17 June 2013, a two-day rainstorm was also caused by similar conditions as a consequence of the interaction between the westward-moving monsoon low and the eastward-moving deep trough in the mid-latitude westerlies, causing extremely heavy rainfall. Historical rainfall data of the J&K have also been analysed to show that the event was unprecedented. Meteorological features associated with this catastrophic event are studied in this article using various observations (both *in situ* and satellite). Performances of operational numerical weather prediction (NWP) models have also been evaluated.

Study region

J&K is located in the northern part of the Indian subcontinent in the vicinity of the Karakoram and Western Himalayan mountain ranges. The state is bounded by Pakistan, Afghanistan and China from west to east. There is a sharp rise in altitude from 1000 to 28,250 ft amsl within the state's four degree of latitude. The foothills of the Himalaya, rising from about 2000–7000 ft (600–2100 m), form the outer and inner zones. The Pir Panjal Range constitutes the first (southernmost) mountain rampart associated with the Himalaya in the state and is the westernmost of the Lesser Himalayas. The Vale of Kashmir is a deep, asymmetric basin lying between the Pir Panjal Range and the western end of the Great Himalaya at an average elevation of 5300 ft (1620 m). The climate is characterized by annual precipitation of about 30 inches (750 mm), derived partially from the summer monsoon and partially from western disturbances during winter. The monsoonal rainfall varies from 39.6 mm in Ladakh to 184.3 mm in Srinagar and 860.5 mm in Jammu.

Data used and methodology

For the monsoon season, Indian Meteorological Department (IMD), New Delhi publishes, in its weekly weather reports, daily rainfall for each day of the season as recorded at about 2600 rain-gauge stations comprising IMD's own network, automatic weather stations (AWS) network of IMD, state rain-gauge networks, etc. The normal daily and monthly rainfall over various stations/districts has been calculated using average data for the period 1970–2000 for which long-term records are available. Daily Indian precipitation analysis from a merges of rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates[13] during 3–7 September 2014 have been used to show rainfall over the J&K region. The rainfall rates have been calculated for some of the stations using hourly rainfall recorded in AWS installed in J&K. These data are subjected to quality control at the IMD earth station in Pune before dissemination to users.

Results

Analysis of heavy to very heavy rainfall during 3–6 September 2014

The event covering 3–6 September 2014 was perhaps unique and unprecedented, when very heavy rainfall occurred over almost the entire state. Table 1 shows station-wise, 24 h accumulated rainfall in the state (recorded from 0830 h IST of the previous date till 0830 h IST of that date). Data for some of the stations were not available, as either the rain gauges were submerged or were not approachable due to flooding. Widespread rainfall with isolated heavy rainfall was recorded on 3 September 2014, with rainfall average in the state being 31.3 mm. Heavy rainfall was recorded at three stations on 3 September 2014. On 4 September 2014, the rainfall activity increased considerably with 13 out of 30 stations reporting heavy to very heavy rainfall. The average rainfall recorded over the state was 66.9 mm. The activity increased further on 5 September 2014, with most of the stations reporting heavy to extremely heavy rainfall (16 out of 22 reporting stations). Katra (Reasi district) received 279 mm of rainfall, Batote (Ramban) 207.8 mm and many other stations received more than 125 mm of rainfall. Average rainfall for the state was 114.3 mm. Widespread heavy rainfall activity continued for another 24 h (6 September 2014) with 16 out of 23 stations reporting heavy to extremely heavy rainfall. Average rainfall for the state was 97.8 mm, with Kawa station (Udampur district) recording the highest rainfall of 260 mm. Analysis of merged gauge–satellite precipitation[9] given in Figure 2 shows that precipitation in excess of 100 mm was realized in many parts of the state during 4–6 September 2014, the area under heaviest rainfall being maximum on 5 September 2014. Some pockets in the southwestern parts of the state also received rainfall in excess of 200 mm on 5 and 6 September 2014.

Comparison with historical records

The rains over J&K were unprecedented as revealed in the 24, 48 and 72 h accumulated rainfall analysis of some IMD stations whose long-term records are available (Tables 2–4 respectively). The rainfall recorded at Anantnag, Kukernag and Quazigand surpassed the 24, 48 and 72 h records for accumulated rainfall, whereas the 48 and 72 h records were exceeded in Katra. The tables also reveal that near record rainfall was experienced at some other stations as well. The spatial distribution of the heavy rainfall days (one or more number of stations over the state recording >65 mm of rainfall) during the monsoon season for last 15 years (2000–14) over J&K was also analysed. The distribution of heavy rains was isolated (one or two stations) in September for all the years, except in 2014 when it was fairly widespread to wide spread (≥ 50% stations recorded heavy rainfall) on 4 and 5 September 2014 over the state. Besides, during the period of study, rainfall exceeded 20 cm/day (exceeding the limit of 1 day severe storm set by Dhar and Nandargi[3]) at several stations, which was not the case in similar events in the past decade. A comparison of average rainfall over the state during 3–6 September 2014 and the normal average rainfall for these dates shows that the total accumulated rainfall on these dates was 900% to more than 11,000% above their normal values (Table 1).

Table 1. Rainfall reported (mm) over stations located in various districts of Jammu & Kashmir (J&K) during 3–6 September 2014

District	Station	Rainfall reported (mm)				Actual rainfall during 3–6 September 2014	Normal rainfall during 3–6 September 2014	Deviation from normal (%)
		3 September	4 September	5 September	6 September			
Anantnag	Anantnag	58.4	180	–	–			
	Kukernag	57.7	119.4	149.5	88.6	415.2	5.5	7449
	Pahalgam	40.2	58.6	–	–			
	Pahalgam (AWS)	47	68	52	50	217	6.9	3045
Baramulla	Baramulla (AWS)	8	65	84	28	185	1.9	9637
	Gulmarg	34	106.6	128	98.2	366.8	6.5	5543
Doda	Badarwah	29.2	81.4	138.8	100.6	350	21.8	1506
Jammu	Jammu	9	39.3	101.4	218.3	368	24.1	1427
	Jammu (AERO)	7.2	44.4	–	203.6		–	–
Kathua	Katuwa	1.4	33.8	65.6	93.8	194.6	21.1	822
Kulgam	Kulgam (AWS)	49	82	138	77	346	9.8	3431
	Qazi Gund	80.4	156.7	156.7	206	599.8	5.4	11007
Pulwama	Awantipur (IAF)	39.1	51	51	67	208.1	–	–
	Malangpura (AWS)	37	61	102	66	266	–	–
Ramban	Banihal	93.7	106.8	188.8	86.1	475.4	5.4	8704
	Batote	67.8	102.4	207.8	123	501	18.2	2653
	Govindpura (AWS)	52	71	202	102	427	–	–
Reasi	Katra	21.8	67.4	279.2	209.4	577.8	41	1309
Shopian	Shopian (AWS)	42	68	140	85	335	5	6600
Srinagar	Rambagh (AWS)	18	51	52	19	140	2.6	5285
	Srinagar	20	51.8	–	–		–	–
	Srinagar (AWS)	26	54	49	23	152	–	–
Udampur	Kawa (AWS)	14	64	152	260	490	–	–
Samba	Samba	6.0	47.4	–	–	–	–	–
Badgam	Srinagar (Aero)	22.4	53.9	–		–	–	–
Ganderbal	Gund	22.6	32.6	–	–	–	–	–
Kupwara	Kupwara	2.6	45.6	68.2	15.4	131.8	3.1	4152
Leh	Leh (AWS)	11.0	0	0	6.0	–	–	–
Poonch	Poonch	0.3	1.3	9.5	–	–	–	–
Rajauri	Rajauri	20.2	43.2	–	–	–	–	–

Analysis of meteorological synoptic conditions

Monsoon was in a weak phase over northwest India during the second fortnight of August. The daily actual and normal rainfall of northwest India showed that the region experienced an explosive increase in rainfall in the first week of September 2014, more than five times the normal value during 4–6 September 2014. This revival was in association with the formation of two low pressure areas (LOWs) that lay over central India and Gujarat and later merged and moved over to northwest India, and a trough in the mid and upper troposphere that moved across extreme northwestern parts of the country. Day-to-day position of these systems is given in Figures 3–5. The first LOW had formed over west–central and adjoining northwest Bay of Bengal, off north Andhra Pradesh–South Odisha coasts on 27 August 2014. It moved across south Chhattisgarh, Vidarbha and lay over northwest Madhya Pradesh on 2 September 2014, with the associated upper air cyclonic circulation up to 500 hPa level.

On 3 September 2014, the first LOW moved to south-east Rajasthan and its neighbourhood, and the associated upper air cyclonic circulation extended up to mid-tropospheric level tilting southwards with height (Figure 3 *a–c*). Another LOW lay over Saurashtra and Kutch with the associated upper air cyclonic circulation extending up to mid-tropospheric level. At 500 hPa, a cyclonic circulation lay over North Pakistan and its neighbourhood embedded in the mid-latitude westerly trough. At 200 hPa, anticyclonic circulation lying to the south over west Uttar Pradesh provided divergence over the region (Figure 3 *d*).

On 4 September 2014, the LOW moved over to central Rajasthan and the associated upper air cyclonic circulation was seen at 850 hPa (Figure 4 *a* and *b*). The LOW over Saurashtra and Kutch moved slightly north and lay over Kutch. A north–south trough extended from Gujarat to Punjab across these two LOWs at 850 hPa and provided moisture influx from the Arabian Sea to NW India, particularly Rajasthan, Punjab and J&K. Jet maxima of 60–80 knots over J&K and adjoining regions continued to provide strong divergence at higher levels over the region (Figure 4 *c*).

On 5 September 2014, the LOW over Kutch became less marked leading to increase in wind flow from the Arabian Sea towards the LOW over Rajasthan, which moved further north and intensified into a well-marked low pressure (WML) area (Figure 5 *a*). The previous day north–south trough at 850 hPa now extended from WML

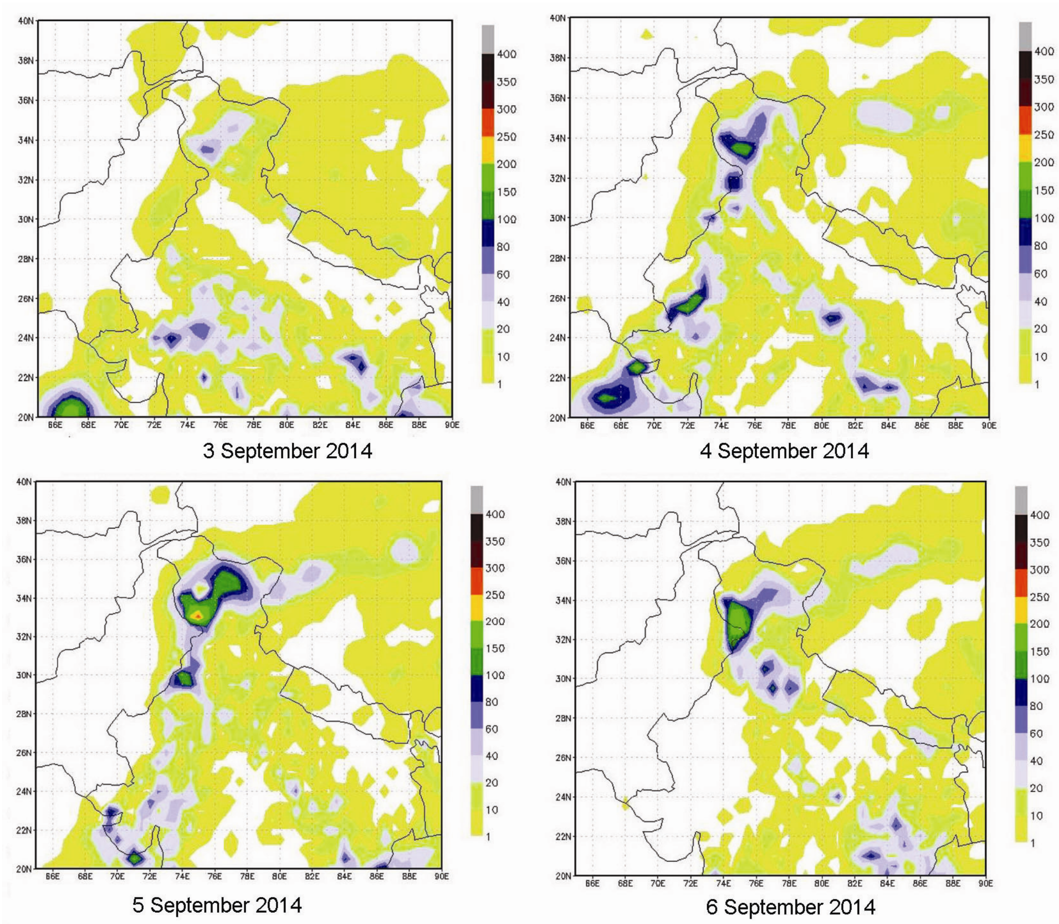

Figure 2. Daily Indian precipitation analysis (mm) formed from the merger of IMD rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates from 3 to 6 September 2014 (source: IMD and NCMRWF).

Table 2. All-time record of 24 h rainfall (mm) over J&K

	Previous record			2014	
Station	Period	24 h (mm)	Date	24 h (mm)	Date
Anantnag	1901–1982	149.4	01.09.1928	180	04.09.2014
Kukernagh	1979–2011	135.8	25.02.1987	149.5	05.09.2014
Qazi gund	1962–2013	160.9	09.09.1966	206	06.09.2014
Banihal	1962–2013	205.6	28.08.1997	188.8	05.09.2014
Batote	1979–2011	255.4	23.08.1996	208	05.09.2014
Katra	1980–2011	292.4	25.09.1988	279.2	04.09.2014

Table 3. All-time record of 48 h cumulative rainfall (mm) over J&K

	Previous record			2014	
Station	Period	48 h (mm)	Date	48 h (mm)	Date
Anantnag	1901–1982	186.7	13.01.1903	238.4	03.09.2014
Kukernagh	1979–2011	176.1	27.08.1997	268.9	04.09.2014
Qazi gund	1962–2013	282.3	27.08.1997	362.7	05.09.2014
Banihal	1962–2013	310.4	18.02.2003	300.3	04.09.2014
Batote	1979–2011	363.6	23.08.1996	331	05.09.2014
Katra	1980–2011	418.4	22.08.1996	488.6	04.09.2014

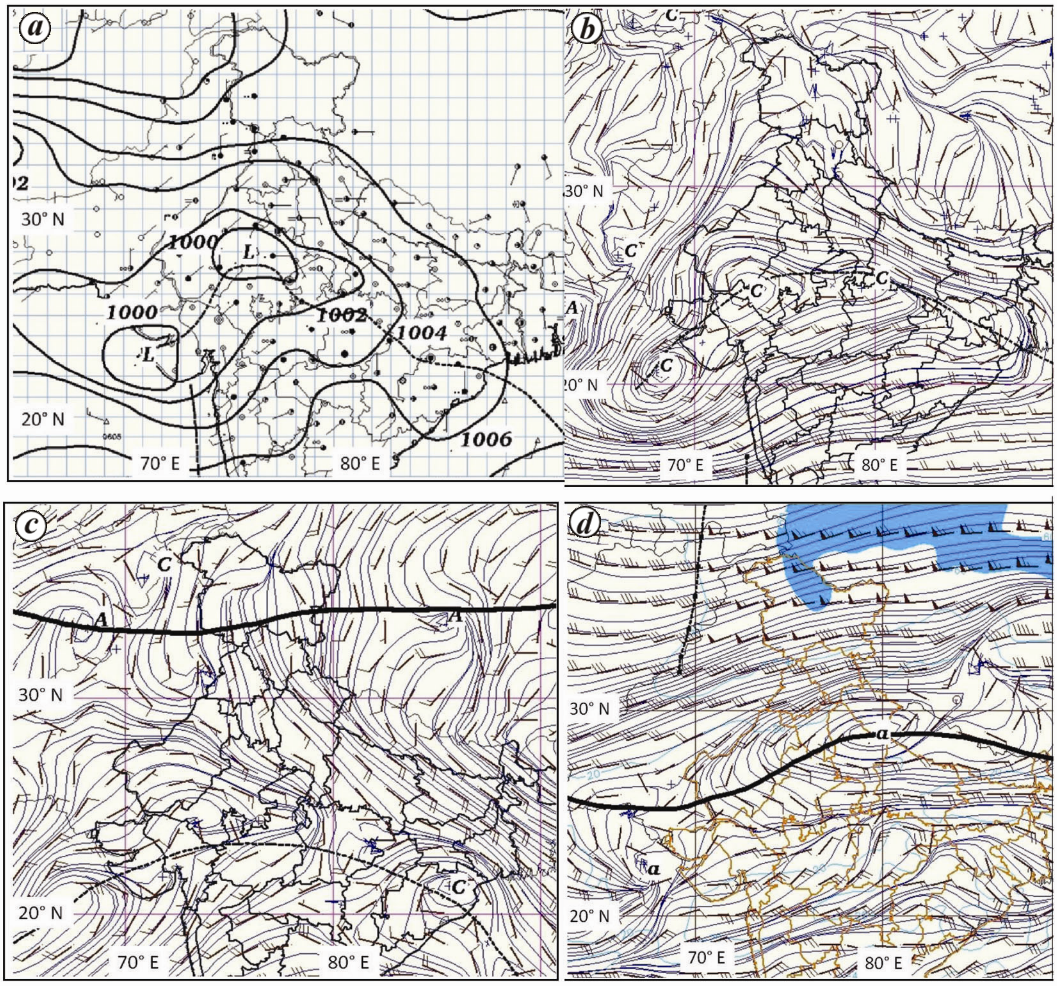

Figure 3. ***a***, Mean sea-level isobaric chart (hPa) of 0300 UTC of 3 September 2014. ***b–d***, Wind analysis: (***b***) 850 hPa; (***c***) 500 hPa and (***d***) 200 hPa based on 0000 UTC of 3 September 2014.

Table 4. All-time record of 72 h cumulative rainfall (mm) over J&K

		Previous record		2014	
Station	Period	72 h (mm)	Date	72 h (mm)	Date
Anantnag	1901–1982	210.8	16.09.1950	244.8	02.09.2014
Kukernagh	1979–2011	194.5	26.071995	357.5	04.09.2014
Qazi gund	1962–2013	300.7	17.02.2003	519.4	04.09.2014
Banihal	1962–2013	392.5	17.02.2003	389.3	03.09.2014
Batote	1979–2011	434	22.08.1996	433	04.09.2014
Katra	1980–2011	544.2	22.08.1996	698.6	04.09.2014

to the new LOW that developed over the head Bay of Bengal. It provided moisture feed from the Bay of Bengal as well. The jet maxima at 200 hPa intensified further with winds of the order of 70–90 knots (Figure 5 *d*).

Figure 6 *a* shows the longitude time-section at 500 hPa of meridional wind anomaly along 30–35°N from 1 to 7 September 2014. A thin line of strong southerly component of winds prevailed along 75°long from 1 September 2014 onwards, with strengthening of anomalous winds to more than 8 m/s from 2 to 6 September 2014. Figure 6 *b* shows the longitudinal time section of 850 hPa geopotential height anomaly averaged over 25–30°N, showing the westward movement of the low pressure area from northwest Madhya Pradesh to west Rajasthan from 1 September to 5 September 2014, and intensifying into a well-marked low pressure area over west Rajasthan on 5 September 2014. The track of the two low pressure areas as discussed above is shown in Figure 6 *c*. There was

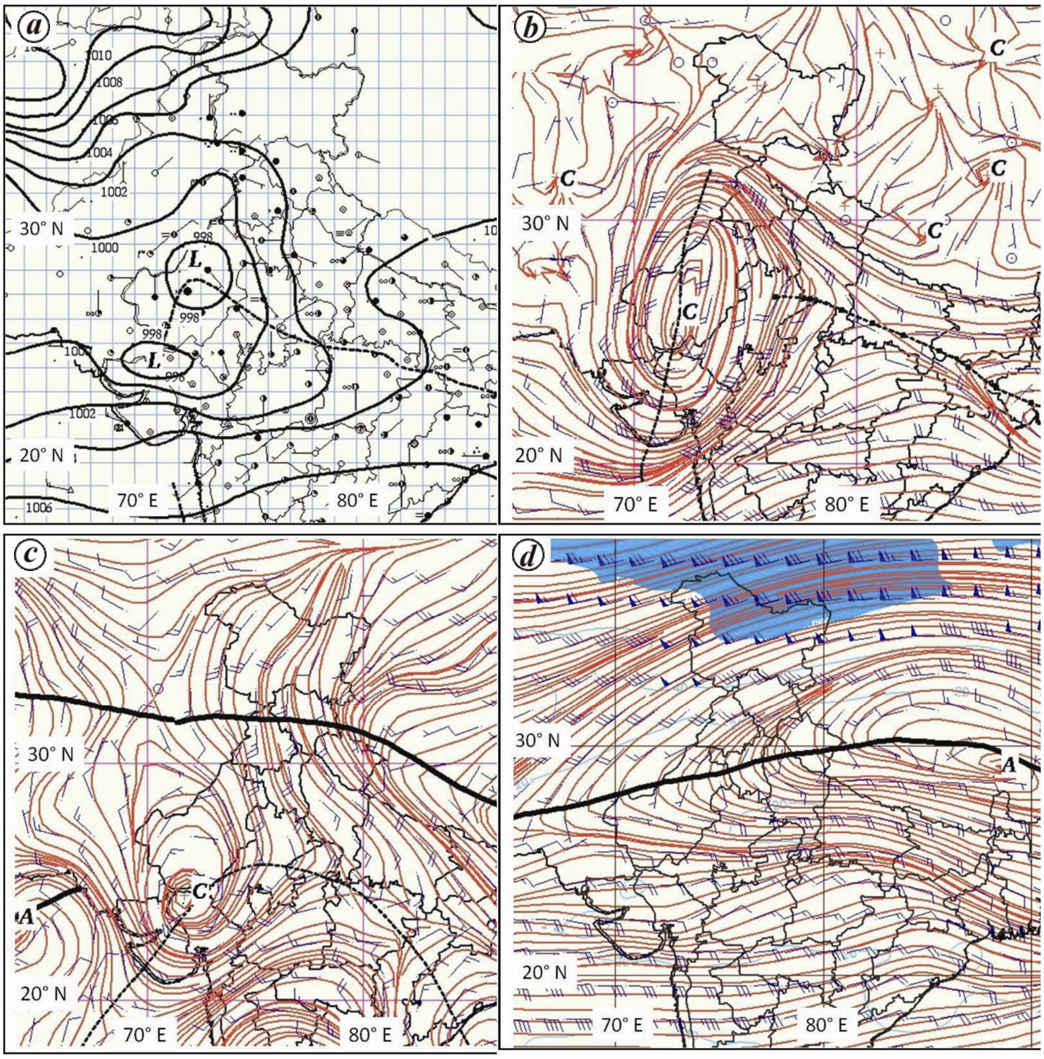

Figure 4. ***a***, Mean sea-level isobaric chart (hPa) of 0300 UTC of 4 September 2014. ***b–d***, Wind analysis: (***b***) 850 hPa, (***c***) 500 hPa and (***d***) 200 hPa based on 0000 UTC of 4 September 2014.

good amount of moisture feeding from the Arabian Sea till 4 September 2014. Thereafter, due to the formation of another LOW in the head Bay of Bengal on 5 September 2014, further moisture feed continued through southeasterly flow over J&K leading to extremely heavy rainfall during 4–6 September 2014.

Analysis of short-duration intensity of daily rainfall (3–6 September 2014)

To study the rainfall intensity, the hourly rainfall data recorded at nine automatic rain gauges of IMD are shown in Figure 7, for the period 3–6 September 2014. The AWS data from all the IMD stations are received at the Earth Station in Pune and subjected to gross error check/range check before dissemination. This check ensures that the values of all meteorological parameters are within the sensor range. The software also has a provision to check the current value of parameter for climatological consistency. The values are also subjected to time consistency check to ensure that temporal variation is within acceptable limit. The software has a provision to set maximum and minimum allowable change in the value of parameters in an hour and decide appropriate flag depending upon the result of quality check (QC) procedures. After passing the data through QC checks, they are disseminated to end-users in WMO code format[14].

The highest hourly rainfall of 35 mm was recorded in AWS Kawa (Udhampur) on 6 September 2014 between 2 and 3 h IST, followed by 17 mm in Anantnag on 6 September 2014 between 1–2 h IST and at Kulgam on 3 September 2014 between 16–17 h IST. The maximum three hourly rain-rates occurred in different three hourly intervals for 5 and 6 September 2014. For example, the three heaviest rain-rates were recorded between 0 and 3 h IST (101 mm) on 6 September 2014 in Kawa

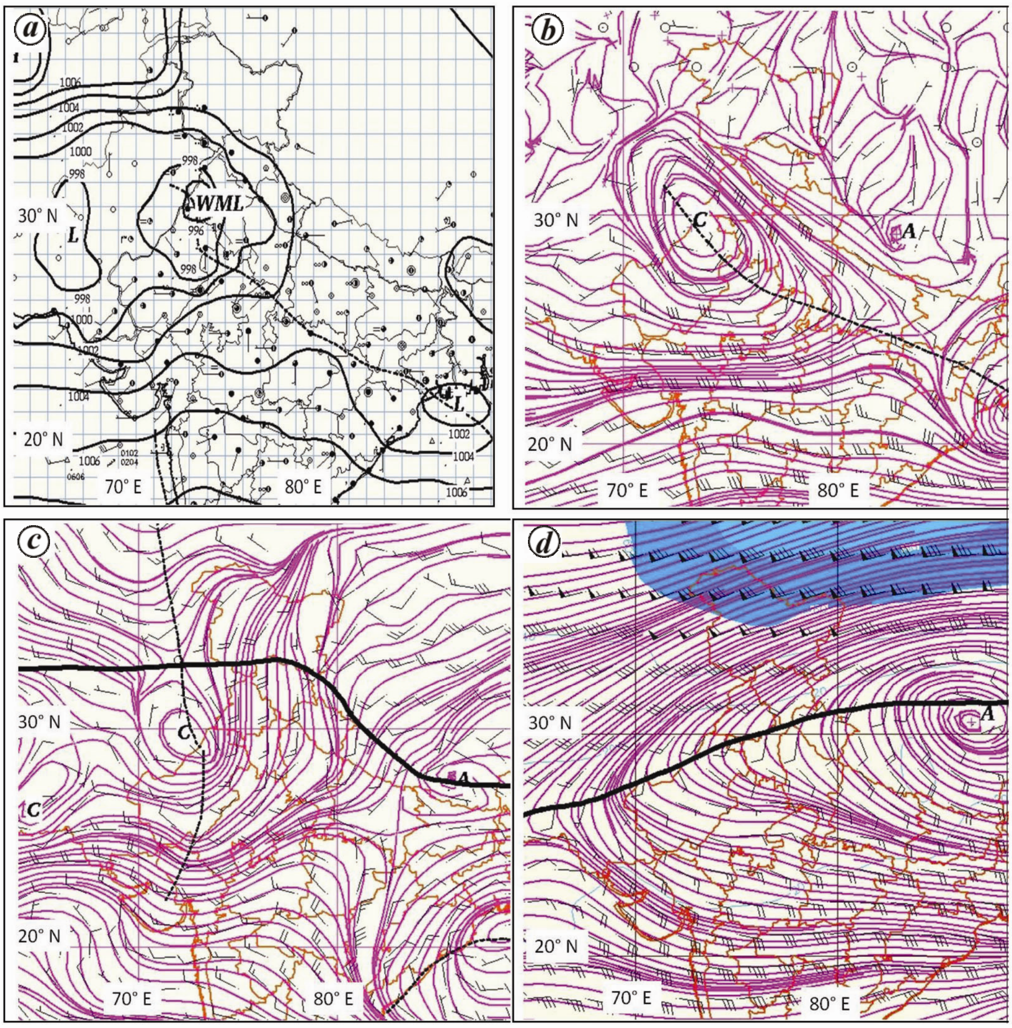

Figure 5. ***a***, Mean sea-level isobaric chart (hPa) of 0300 UTC of 5 September 2014. ***b–d***, Wind analysis: (***b***) 850 hPa, (***c***) 500 hPa and (***d***) 200 hPa based on 0000 UTC of 5 September 2014.

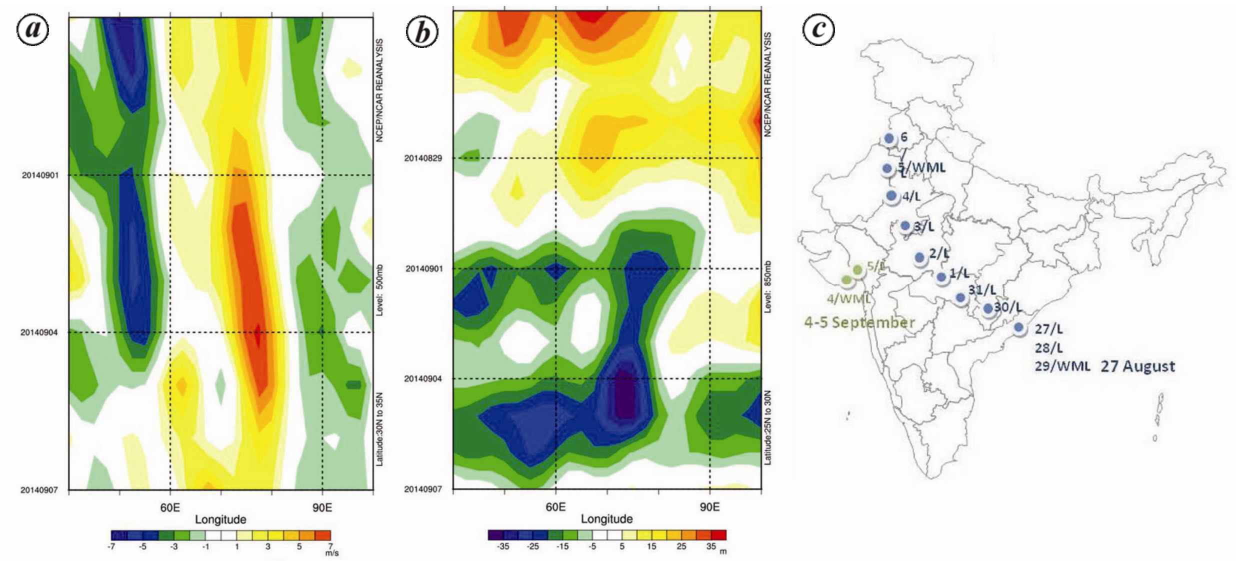

Figure 6. ***a***, Longitudinal time-section of meridional wind anomaly (m/s) along 30–35°N at 500 hPa pressure level. ***b***, Longitudinal time-section of 850 hPa geopotential height anomaly (m) averaged over 25–30°N. ***c***, Track of the low pressure systems that formed during the study period. WML, Well-marked low pressure area; L, Low pressure area.

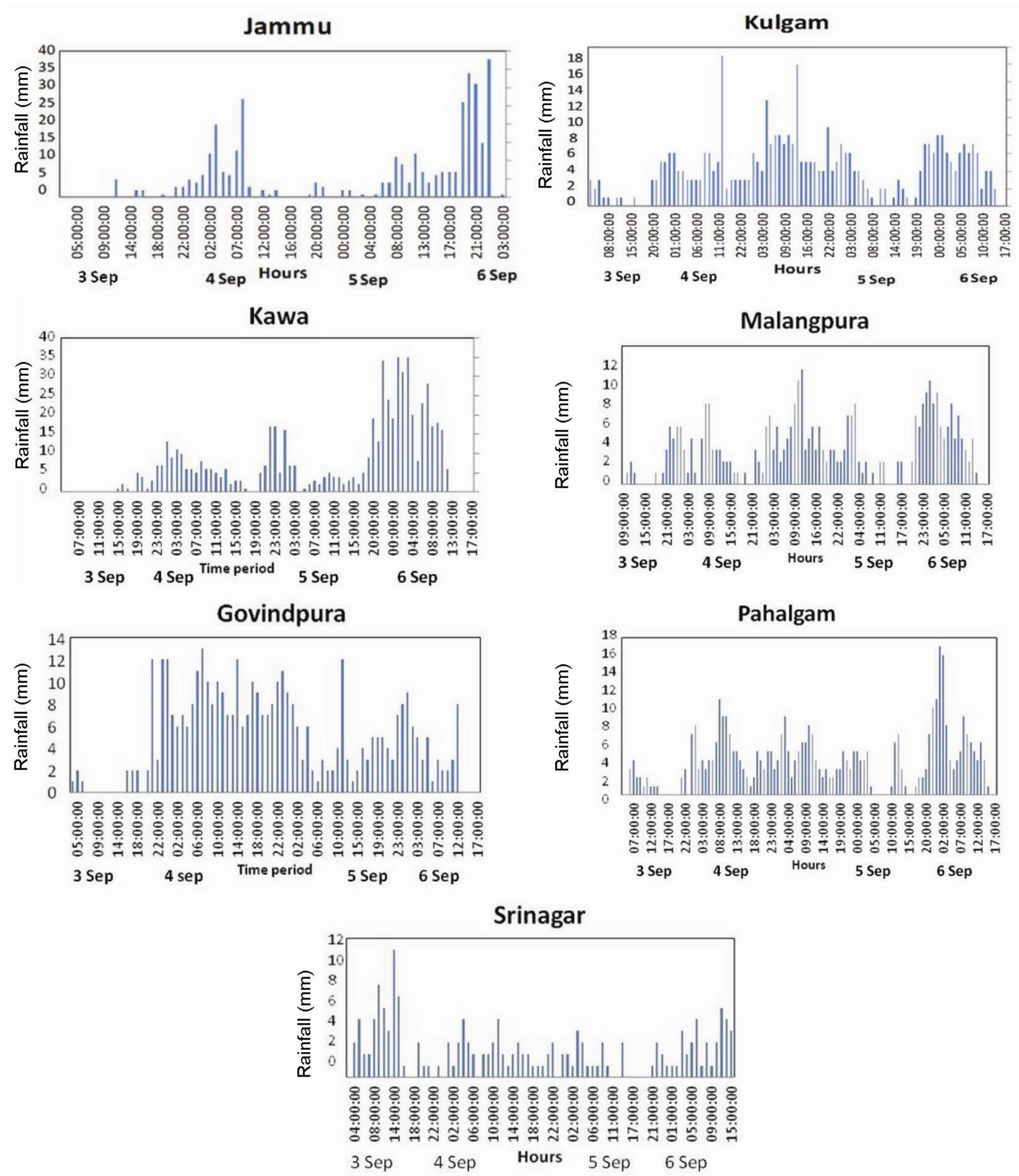

Figure 7. Hourly rainfall recorded (mm) in a few automatic weather stations of IMD in Jammu and Kashmir.

(Udhampur), 6–8 h IST (35 mm) on 4 September 2014 in Govindpur (Ramban) and between 23 h of 5 September 2014 and 2 h IST of 6 September 2014 (44 mm) at Pahalgam (Anantnag). The rains were continuous and consistent from 4 to 6 September 2014, with an average rain-rate of 10–12 mm in Kawa (Udhampur), 6–8 mm in Govindpur (Ramban), 5–7 mm in Pahalgam (Anantnag), 5–6 mm in Shopian and lesser for other AWS stations. In Srinagar rain-rate was highest on 3 September 2014 (7–8 mm) and thereafter consistent 3–4 mm rain-rate was maintained till 6 September 2014 evening. The station at Kawa (Udhampur) was worst affected, receiving nearly 340 mm of rainfall in 14 h between 20 h IST of 5 September and 10 h IST of 6 September 2014. Thus, the average maximum intensity for Kawa was about 23 mm/h. Deshpande *et al.*[15] have reported extreme rainfall for Srinagar as 40, 65, 91 and 111 mm for 1, 3, 6 and 12 h duration respectively, based on 1970–2005 records. The

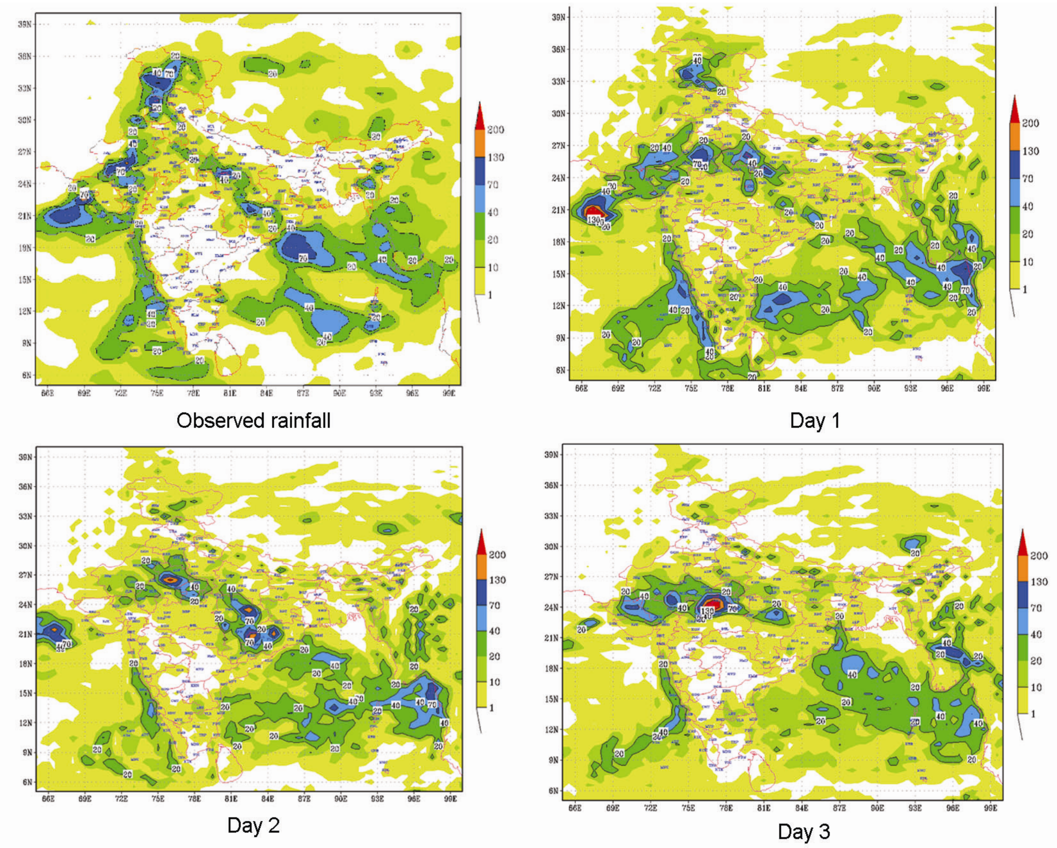

Figure 8. Observed rainfall and GFS model days 1–3 rainfall forecast (mm) for 4 September 2014.

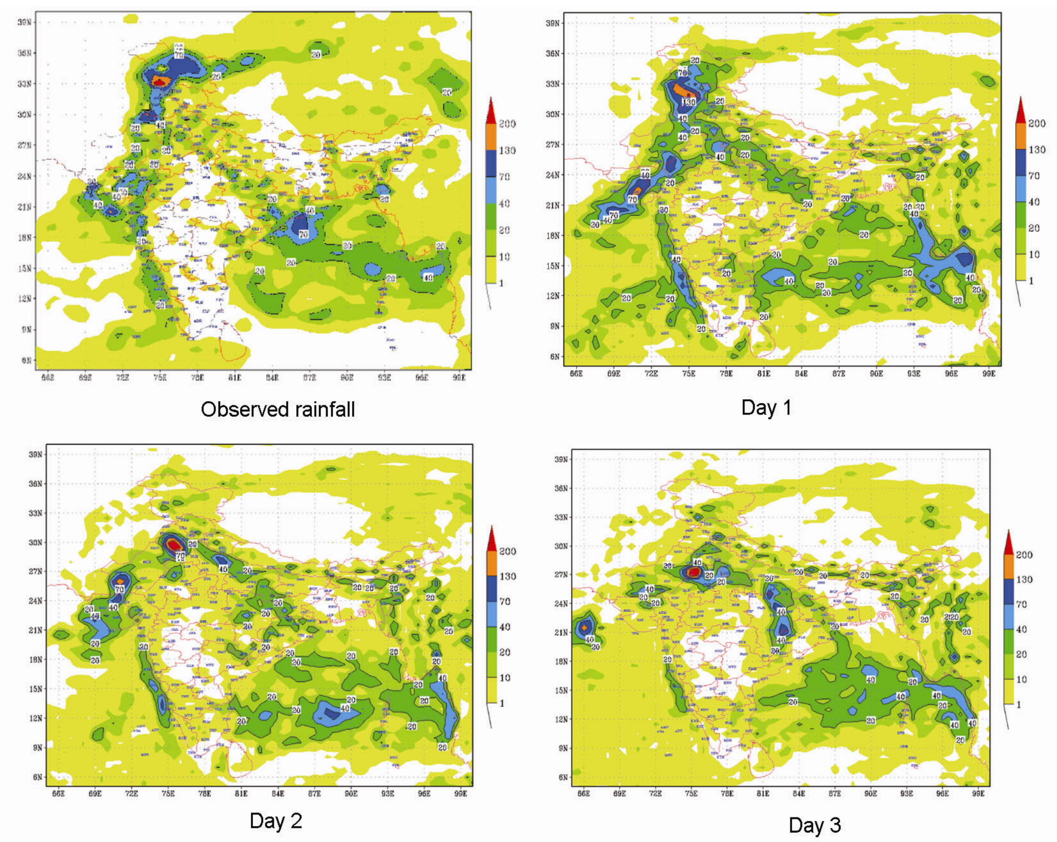

Figure 9. Observed rainfall and GFS model days 1–3 rainfall forecast (mm) for 5 September 2014.

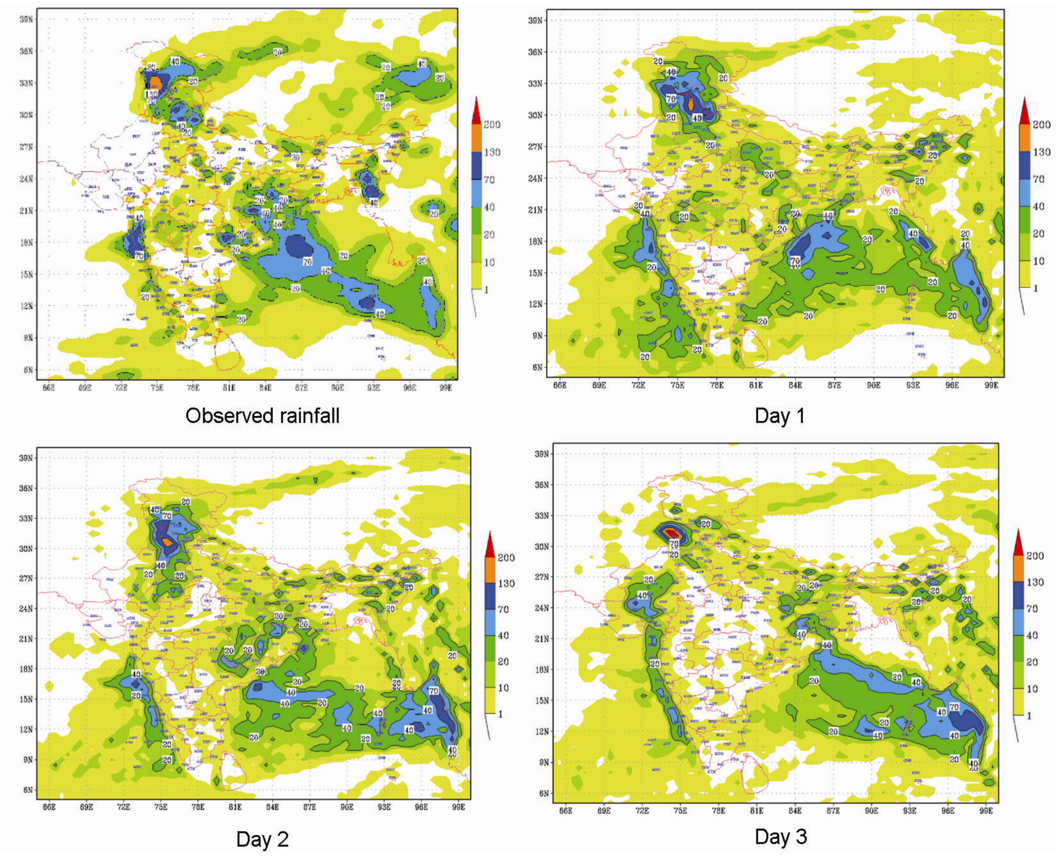

Figure 10. Observed rainfall and GFS model days 1–3 rainfall forecast (mm) for 6 September 2014.

Table 5. District-wise distribution of cumulative rainfall during 4–10 September 2014 and normal seasonal rainfall during monsoon season in J&K

District	Cumulative rainfall from 4–10 September (mm)	Normal seasonal rainfall (June–September) (mm)
Anantnag	309.1	285
Badgam	76.7	186
Baramulla	255.9	248
Doda	320.8	441
Ganderwal	32.6	184
Jammu	354.2	861
Kathua	193.2	982
Kulgam	460.2	269
Kupwara	129.2	253
Poonch	10.8	761
Pulwama	242.7	151
Rajouri	43.2	649
Ramban	425.6	401
Reasi	556	1323
Samba	47.4	861
Shopian	348.0	266
Srinagar	148.0	184
Udhampur	605.5	1377

rainfall recorded during 4–6 September 2014 for Srinagar has been much less than the maximum reported in the study.

Performance of operational NWP models

Global forecast system: The National Centre for Environmental Prediction (NCEP), USA-based global forecast system (GFS T574/L64) operational at IMD, New Delhi incorporates Global Statistical Interpolation (GSI) scheme as the global data assimilation for the forecast up to 7 days. The IMD GFS forecast rainfall (24, 48 and 72 h) valid for 4–6 September 2014 along with the corresponding observed rainfall is given in Figures 8–10 respectively. Rainfall over J&K on 4 September 2014 was reasonably captured during the day-1 forecast, although with lesser magnitude (Figure 8). Similarly, on 5 September 2014, the magnitude and location were well captured on day 1 but on days 2 and 3 the location was shifted southwards (Figure 9). On 6 September 2014, both the location and magnitude had shifted southwards on days 1–3 (Figure 10). Thus, the heavy rainfall event of J&K during 4–6 September 2014 was well captured only in the day-1 forecast.

Conclusions

The areas affected by floods were mostly districts in south Kashmir, including Anantnag, Pulwama, Baramulla and Srinagar. These are in rain-shadow region of the Pir Panjal Range of the lesser Himalaya and receive less than 300 mm rainfall during the monsoon season. The total cumulative rainfall during the week from 4–10 September 2014 over these districts was 309 (Anantnag), 256 (Baramulla), 243 (Pulwama) and 148 mm (Srinagar), which is higher than the average rainfall for the entire monsoon season in these districts (Table 5). The continuous heavy rains were due to interaction between the westward-moving monsoon low and the eastward-moving deep trough in the mid-latitude westerlies. The additional low pressure areas that formed over Saurashtra and Kutch on 3 September 2014 and over the head Bay of Bengal on 5 September 2014 ensured that the vigour of the event was maintained through strong wind and moisture flux in J&K. In this article only meteorological observational analysis using large datasets has been made. More in-depth studies are needed to analyse the dynamical factors responsible for models not performing well beyond 24 h.

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