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# Intense Precipitation causing Floods over Himalayan Region of Northern India – A case study on Role of Atmospheric Rivers

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**ABSTRACT**
Atmospheric rivers carry a large amount of water vapour and travel long distances in the lower levels of earth's atmosphere. They are usually found in the mid-latitude region moving up and down, drawing most of the water vapour from the tropical regions when they move up and bringing cold air from the northern regions when they move down. They play an important part in the global water cycle. Climatic changes due to manmade activities disturb the general flow and many a time they are responsible for extreme precipitation and flooding. Northern India receives isolated snow and rainfall due to western disturbances. In the absence of external forces, like atmospheric rivers this activity is rarely vigorous. In this study, an attempt has been made to identify and bring to light the role of the Atmospheric Rivers in triggering sudden extreme precipitation along the Himalayan mountainous regions of North India, under favorable synoptic conditions due to Western disturbances.

**Key words**: western disturbance, trough, atmospheric river, cloud burst, upper air circulation, precipitable water content

## INTRODUCTION

Atmospheric rivers (ARs) are narrow regions of water vapor transport in the lower atmosphere that travel long distances of the Earth carrying large concentrations of water vapor. The term atmospheric rivers was coined for the first time by researchers Zhu and Newell (1998) when they observed that most of the water vapor in the atmosphere was transported in relatively narrow regions roughly 400 km wide. Since then, a number of studies have been published (Trenberth 1999; Ralph et al., 2004; Bao et al., 2006; Ralph et al., 2006; Roberge et al., 2009; Guan et al., 2010; Dettinger et al., 2011; Lavers et al., 2011; Neiman et al., 2011; Moore et al., 2012) building on this concept and many climate researchers are applying these ideas and methods to their fields. The main characteristics or defining features of the Atmospheric Rivers are:

1) Integrated Water Vapour concentrations (IWV) such that if all the water vapor in the atmospheric column were to be condensed into liquid water the result would be 2 or more cm thick water as precipitation.

2) Wind speeds of greater than 12.5 meters per second in the lowest 2 km.

3) A shape that is long and narrow, no more than 400 to 500 Km wide and extending for thousands of Kilometers sometimes across entire ocean basins.

These narrow plumes of enhanced moisture transport occur in the lower troposphere in the low-level jet region (within the warm sector) of extra-tropical cyclones and typically form a subsection of the broader warm conveyor belt. They are usually found in the mid-latitude region swinging up and down and drawing most of the water vapour from the tropical regions when they move up towards the Arctic, and similarly bringing cold air from the northern regions when they move down. Ralph et al. (2004) have established the value of using SSM/I satellite observed IWV as a proxy for atmospheric river detection offshore. Research during the past decade has emphasized the role of Atmospheric Rivers in the global mid latitude water cycle and the sudden change in weather. Man-made climate change disturbs the pattern of atmospheric flow around the globe's northern hemisphere. The fluctuations in the course of the Atmospheric Rivers are the main causes of the most extreme precipitation and flooding in areas where these features encounter mountains. At the same time, they also make important contributions to snow and water available in these regions.

Heavy rainfall can result, especially when ARs make landfall because of the convergence and thus vertical uplift within an AR, and most significantly when the moisture-laden air is forced to rise over mountains. There are two approaches, in general, to indentify ARs. The first method evaluates the Integrated Water Vapor (IWV) in the atmosphere via satellite measurements (Ralph et al., 2004; Neiman et al., 2008; Guan et al., 2010), or to calculate the vertically integrated horizontal water vapour transport between 1000 hPa and 300 hPa, using atmospheric reanalysis data (Zhu and Newell, 1998; Roberge et al., 2009; Jiang and Deng, 2011). ARs are also detected using IWV and daily wind speeds and directions at 925 hPa as proposed by Neiman et al. (2009) and was subsequently applied to reanalysis data and climate model projections to study ARs making landfall in California (Dettinger, 2011). The second method considers the hydrologic impacts

**Table1**. List of incidences of cloudbursts and heavy rainfall causing floods under study.

| S.No. | Date | Location | Rainfall (mm) | Destruction |
|---|---|---|---|---|
| 1. | 06-08-2010 | Leh, Jammu and Kashmir | 250 | Heavy rains triggered flash floods. Loss of life and property |
| 2. | 15-09-2010 | Almora, Uttarakhand | 173.1 | Heavy rains and flood causing floods |
| 3. | 02-06-2011 | Kupwara, Jammu and Kashmir | 36 | Mud slides and flood |
| 4. | 09-06-2011 | Doda, Jammu and Kashmir | 42.7 | Heavy rains, flood and mud slides |
| 5. | 20-07-2011 | Manali, Himachal Pradesh | 3.2 | Heavy rains and flood |
| 6. | 16-06-2013 | Kedarnath, Uttarkashi, Rudra-prayag, Dunda, Uttarakhand State | 162,207,108,185 | Floods causing heavy damage to life and property. |
| 7. | 25-09-2013 | Gujarat State Rajpipla, Nandod, Vansad, Tilakwada, Waghal,Silvasa | 380,323,377,349,280,243 | Heavy continuous rains and Floods |

of these events. The extremes in hydrological variables like intense precipitation causing floods were extensively studied (Ralph et al., 2006; Lavers et al., 2011; Neiman et al., 2011). To determine if an AR was the cause of the flooding, the atmospheric state (IWV/IVT/specific humidity and wind fields) preceding the heavy precipitation and flood events was analyzed.

Our understanding of extreme weather relies on our knowledge of the behavior of the atmosphere in general and our ability to predict how the atmosphere will behave in the future. Many research studies have been carried out on Atmospheric Rivers and their implications for mid-latitude countries. However, no such study exists for Indian region, where cloud bursts, heavy precipitation and mud slides take place , almost every year, in parts of Himalayas. An attempt is made in this paper, to explain the extreme precipitation in Himalayan region based on the phenomenon of Atmospheric Rivers. Case studies of seven such events during 2010 to 2013 are discussed.

## DATA AND METHODOLOGY

Seven incidences of cloudbursts along with landslides and floods over the hilly regions of J&K and Himachal Pradesh (Table 1) have been studied. The global images of the Integrated Water Vapour (IWV) concentrations have been obtained from the Special Sensor Microwave Imager (SSM/I) of the polar orbiting satellites that provide frequent global measurements of IWV over the oceans. Measurements of IWV were previously available only from a few regions where the balloons and related instruments were deployed. This imager works very well over the oceans and due to its developed spatio-temporal coverage, the Atmospheric Rivers can be studied in ways that previous Water vapour data could not. Rainfall data in this study are obtained from National Data Center, India Meteorological Department. Analyzed synoptic weather charts and weather reports have been taken from Weather Forecasting Division, of IMD, Pune. Satellite Imageries are obtained from IMD and Dundee (http://www.sat.dundee.ac.uk/). NCEP/NCAR Reanalysis is used for describing the flow of water vapour. Reports from various other organizations like National Disaster Mitigation Agency (NDMA), National Centre for Medium Range Weather Forecasting (NCMRWF) are also consulted.

## RESULTS AND DISCUSSION

On August 6, 2010, Leh in Ladakh region of Jammu and Kashmir experienced cloud burst and the heavy rains that followed triggered flash floods and mudslides. There was heavy loss of life and property rendering thousands of people homeless. The area recorded a heavy rainfall of about 150mm/hr. This region known as cold desert, normally receives a very little rainfall at an altitude of 3500 mtrs. Similar cloud burst took place on August 7, 2010 at various areas of Kralpora about 100km from Srinagar. The Kupwara district in J &K and Ramgarh area, (15 Km from Batote village) in Doda district of J&K experienced cloud bursts on 2$^{nd}$ and 9$^{th}$ June 2011, respectively. A similar cloudburst followed by heavy rains and flood took place in upper Manali in Himachal Pradesh on July 20, 2011. Almora in Uttarakhand experienced heavy rainfall and floods on September 15, 2010.The cloudburst incident

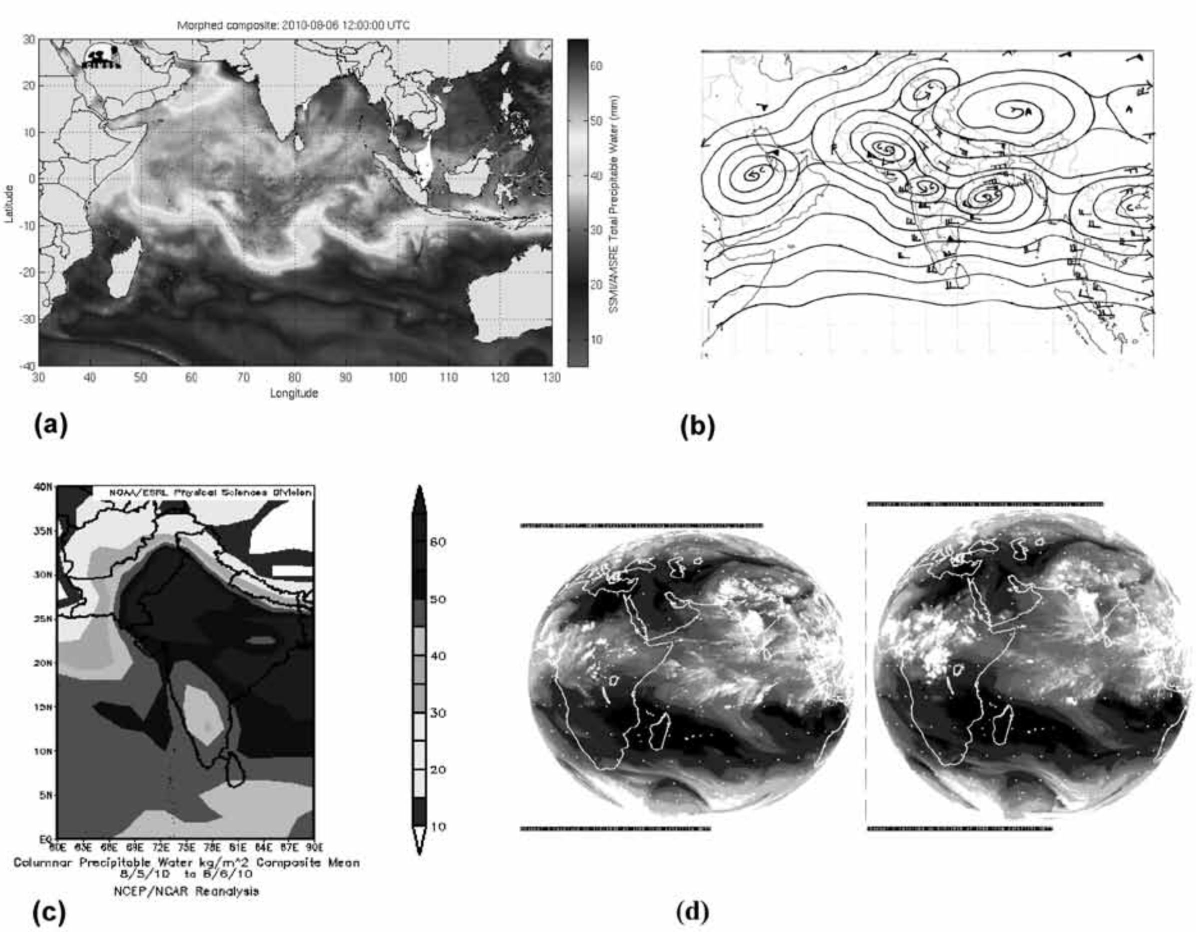


**Figure 1**. a) Special Sensor Microwave Imagery of Integrated water vapor on August 6th 2010, Leh, Jammu and Kashmir, b) Upper-air synoptic charts, c) NOAA/ESRL's composite mean analysis showing the water vapour flow over land and d) Satellite Cloud Imageries of August 6th 2010.

at Kedarnath in Uttarakhand on June 16, 2013 and the Gujarat floods of September 26th, 2013 have also been studied.

## CASE STUDIES

Incidences of cloudbursts, heavy precipitation and mudslides, as given in Table 1, have been studied taking into consideration the synoptic situation, the satellite products and the observed data to investigate the role of Atmospheric Rivers in the heavy precipitation causing floods.

### Case 1: August 6th 2010

On the 5th of August,2010 the southwest Monsoon was vigorous over some parts of Orissa and Chattisgarh and active over some parts of Punjab, Himachal Pradesh, Jammu & Kashmir, Vidarbha and Telangana. A western disturbance persisted for the last few days as an upper air cyclonic circulation extending upto 5.8 kms a.s.l. over Jammu & Kashmir and neighbourhood,and was likely to move further ENE . Jammu city reported 4.6cm rainfall on 6th and Gulmarg 4.8cm on 7th July. The Figure 1a depicts the global image of the Integrated water vapour (IWV) on the 6th of August 2010. The synoptic conditions for the day are depicted in the Figure 1b. The Upper air analysis shows a Western disturbance as an upper air cyclonic circulation extending up to 4.5km a.s.l over North Pakistan and adjoining J&K. A trough in mid and upper tropospheric westerlies with its axis at 7.6km a.s.l runs roughly along 72° E to the north of 30° N. These conditions like the WD and the trough in westerlies help to augment the water vapour and its movement forward. According to the study report on the Leh Cloudburst by Raghavendra Ashrit NCMRWF, the large scale tropospheric flow south of the western Himalayas and the cross section analysis suggests that the cloudburst evolved in a deep humid layer of flow from the northwest of Leh region. The flow from the east and southeast is relatively cold and dry. The high resolution experiments further confirm the capping of relatively warm humid flow from the northwest. This seems to inhibit the

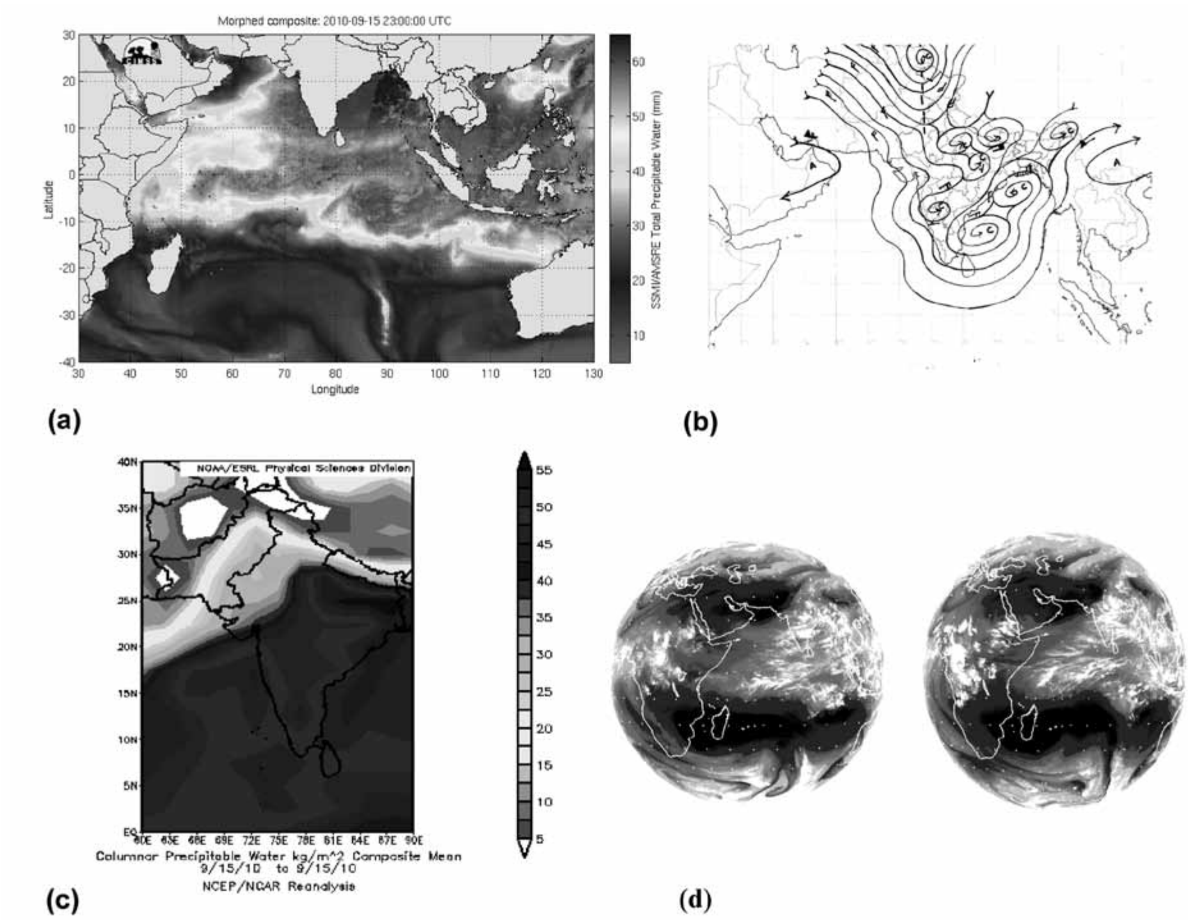

**Figure 2.** a) SSMI Imagery of Integrated water vapor on September 15th, 2010, Almora in Uttarakhand, b) Upper air analysis showing a Western disturbance as an upper air cyclonic circulation extending upto 4.5km a.s.l over North Pakistan and adjoining J&K. A trough in mid and upper tropospheric westerlies with its axis at 7.6 km a.s.l along 72°E to the north of 30°N, c) NOAA/ESRL's composite mean analysis showing the water vapour flow over land, d) Satellite images for September 15th 2010, Almora Uttarakhand.

release of instability. This feature during the Leh cloudburst partly seems to follow the processes described in Socorro et al (2010), 'A study on the deep convection close to Western Himalayas over Pakistan. Now, in Figure 1c, we see a light gray narrow region of water vapor flow coming from the Arabian Sea towards the mountains of Leh. This flow depicts a 15-20Kg/m2 of columnar precipitable water. This is the deep humid layer that is mentioned above and is also known as the Atmospheric Rivers (AR). The satellite pictures in Figure 1d clearly depicts the flow of water vapour towards Leh.

## Case 2: September 15th 2010

Almora in Uttarakhand experienced heavy outbursts of rain on 15 September,2010. During September 2010, active monsoon conditions prevailed over most parts of the country. The Figure 2a depicts the global image of the Integrated water vapour (IWV)of 15 September, 2010 over the Oceans obtained from the Special Sensor Microwave Imager (SSM/I) of the polar orbiting satellites. The synoptic situations observed are such as shown in Figure 2b. A Western disturbance as an upper air cyclonic circulation extending up to 4.5km a.s.l lay over North Pakistan and adjoining J&K. A trough in mid and upper tropospheric westerlies with its axis at 7.6km a.s.l runs roughly along 72° E to the north of latitude 30° N. The WD and the trough in westerlies help the movement of the water vapour. The satellite images for 15 Sept, 2010, Almora, Uttarakhand are seen in Figure 2c. The flow of moisture is clearly seen in the satellite images. The water vapour flow over land using NOAA/ESRL's composite mean analysis is shown in Figure 2d. Here, we see a light gray narrow region water vapour flow coming from the Arabian Sea towards the mountains of Uttarakhand. This flow depicts a 15-20Kg/m$^2$ of columnar perceptible water. This flow of water vapour also known as the AR brings sudden rains after moving up the mountains.

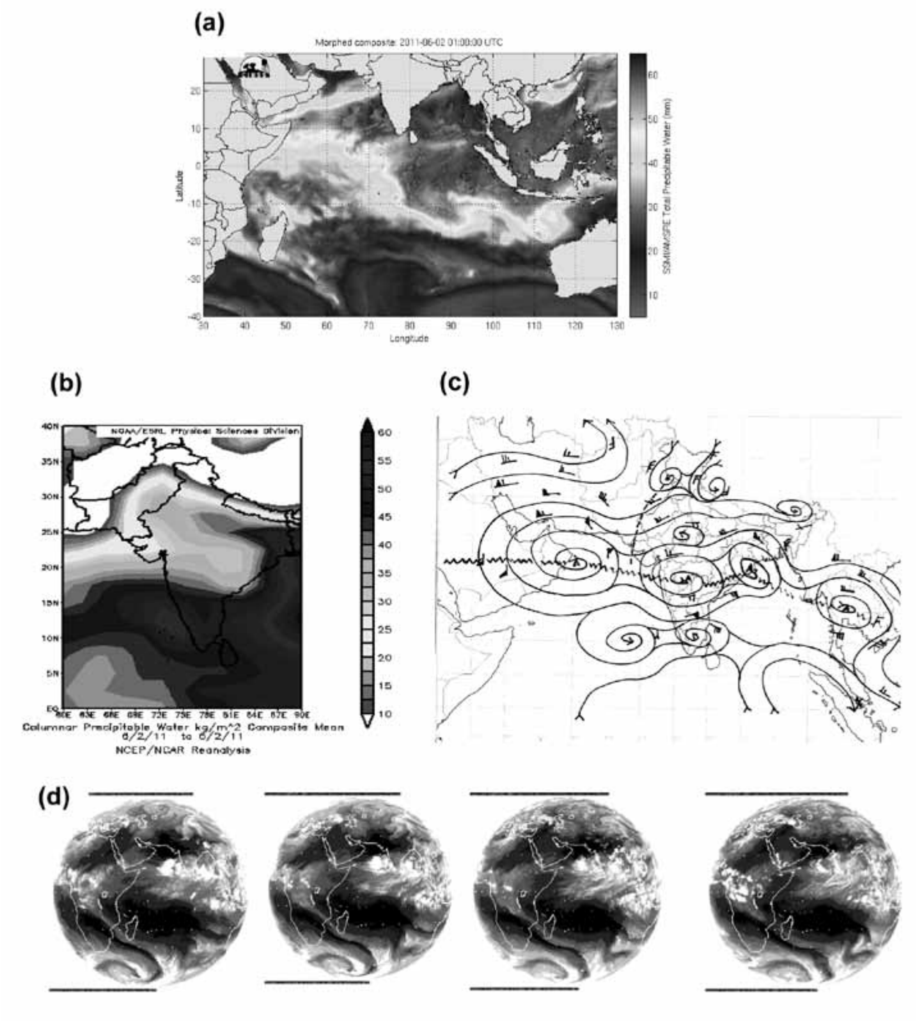


**Figure 3**. a) Special Sensor Microwave Imagery of Integrated water vapor on June 2nd, 2011, Kupwara district, J&K, b) Upper air analysis at 4.5 km a.s.l. showing a western disturbance as an upper air cyclonic circulation over north Pakistan and adjoining Jammu and Kashmir, c) Upper air analysis at 7.6km a.s.l. showing a trough in mid and upper tropospheric westerlies with its axis along 72°E to the north of Lat 30°N, d) NOAA/ESRL composite mean analysis showing the water vapour flow over land and e) satellite imageries of 2nd June 2011.

## Case 3: June 2$^{nd}$, 2011

On, June 2, 2011 Kupwara District in J&K experienced heavy rainfall. Rain or thundershowers occurred at a large number of places across the country including Jammu and Kashmir on June 1, 2011. A western disturbance as an upper air cyclonic circulation extending up to 4.5 kms a.s.l. lay over north Pakistan and adjoining Jammu & Kashmir. A trough in mid & upper tropospheric westerlies, with its axis at 7.6 kms a.s.l. ran roughly along Long. 72° E to the north of Lat. 30° N. The above two systems were expected to move ENE. Rain and thundershowers occurred at many places including J&K. The western disturbance as an upper air cyclonic circulation extending upto 4.5 kms a.s.l. lay over Jammu & Kashmir and neighbourhood. The trough in mid & upper tropospheric westerlies with its axis at 7.6 kms a.s.l. ran roughly along longitude 75° E to the north of Lat. 30° N. The WD and the trough in westerlies are illustrated in Figures 3b and 3c. The trough and the WD have contributed in accelerating the flow of water vapour northward.

The Figure 3a depicts the Integrated water vapour (IWV) for June 2$^{nd}$ 2011. The synoptic conditions for the same day have been studied. The water vapour flow over land is presented in Figure 3d. Here, we see a light gray narrow region of water vapour flow coming from the Arabian Sea towards the mountains of J&K. This flow depicts a 15-20Kg/ m$^2$ of columnar precipitable water. This heavily laden water vapour winds move up the mountains and precipitate to give heavy rains. The cloud imageries corresponding to the above mentioned situation are shown in Figure 3e.

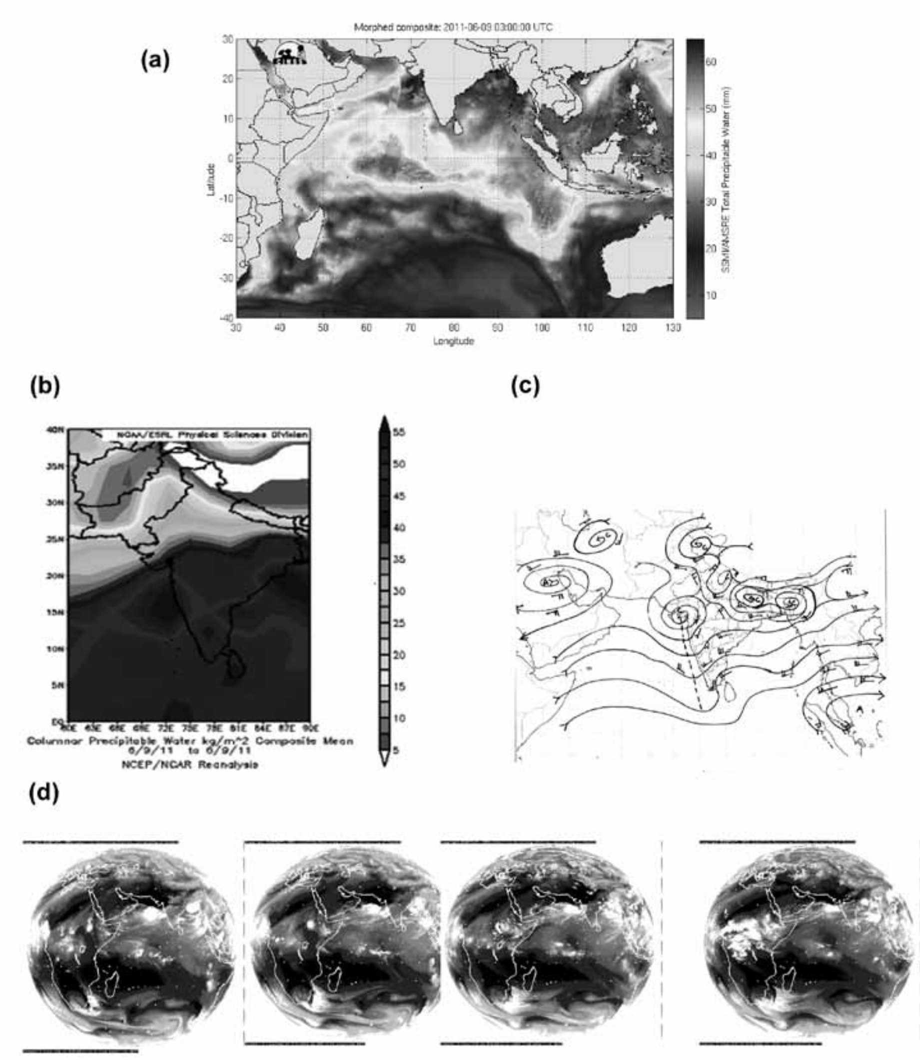


**Figure 4**. a) SSMI Integrated water vapor on June 9th 2011, Doda district, J&K, b) Upper air synoptic chart depicting a trough in mid and upper tropospheric westerlies with its axis roughly along longitude 82°E to the north of latitude 30°N, c) NOAA/ESRL composite mean analysis showing the water vapor flow in the lower levels and d) Satellite Images of June 9th 2011.

## Case 4: June 9, 2011

On June 9th 2011, Doda region in Jammu and Kashmir experienced a sudden very heavy rainfall that led to heavy loss of life and property. The synoptic situations observed during that period were as follows. On 8th June the southwest Monsoon advanced into some parts of central and north Bay of Bengal, parts of Nagaland-Manipur-Mizoram-.Heavy Rainfall was reported on 9th over Doda region causing floods. Figure 4b depicts the synoptic conditions for 9th June 2011. It is seen that a trough in mid and upper tropospheric westerlies with its axis at 7.6 km a.s.l extended roughly along Long. 82° E to the north of Lat 30° N. This trough was present on the 8th June and moved away on the 9th June 2011. This helped in the eastward flow of water vapour. The Figure 4a depicts the integrated water vapour (IWV) for 9th June 2011 over the Oceans. Global images of the Integrated Water Vapour (IWV) concentrations have been obtained from the Special Sensor Microwave Imager (SSM/I) of the polar orbiting satellites. The flow of the water vapour over the land obtained for 9th June using NOAA/ESRL, Physical Science Division's Composite Pictures is shown in Figure 4c. This figure shows a narrow light gray region of 15-20Kg/m$^2$ of columnar perceptible water, which collides with the cold mountainous air, resulting in a cloud burst. The global satellite imageries depicting the cloud patterns are shown in Figure 4d.

## Case 5: July 20,2011

Manali, Himachal Pradesh, experienced heavy rainfall on the 20th of July, 2011. During this period, the southwest monsoon had been active all over India. One more cyclonic

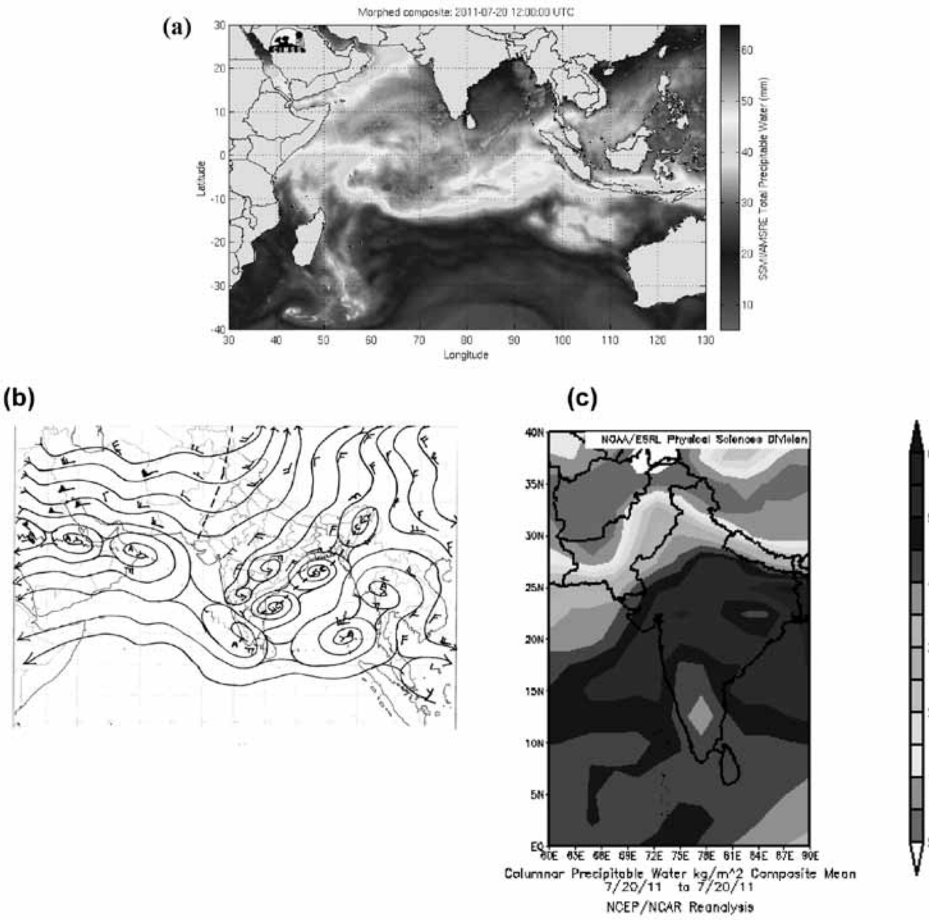


**Figure 5.** a) Special Sensor Microwave Imagery of Integrated water vapor on July 20th 2011, Manali, Himachal Pradesh, b) Upper air analysis showing Western Disturbance as an upper air cyclonic circulation extending up to 4.5 km a.s.l. over J&K and neighbourhood, c) NOAA/ESRL composite mean analysis showing the water vapor flow in the lower levels.

circulation over Bihar & neighbourhood lay over Gangetic West Bengal & neighbourhood and extended up to 3.6 kms a.s.l. The western disturbance as an upper air cyclonic circulation extended up to 4.5 kms a.s.l. over Jammu & Kashmir and neighbourhood. The WD that was present during the past few days was set to move ENE.

The Figure 5a depicts the global image of the Integrated water vapour (IWV) for 20th July 2011 over the Oceans. The upper air conditions for the same day are presented in fig 5(b). The Western Disturbance as an upper air cyclonic circulation extending upto 4.5km a.s.l. over J&K and neibhourhood was persisting. This movement helped in the eastward flow of the AR. The water vapour flow over land using NOAA/ESRL's composite mean analysis is studied in Figure 5c. Here, we see a light gray narrow region of water vapour flow coming from the Arabian sea towards the mountains of Manali, Himachal Pradesh. This flow depicts a 15-20Kg/m2 of columnar precipitable water. This heavy flow of water moved upwards above the mountains. It got capped by cold air and resulted in heavy bursts of rain.

## Case 6: June 16th 2013

In June, 2013 Uttarakhand experienced heavy downpour spanning three days from 14-16 June resulting in many landslides and flooding in this area and left thousands of pilgrims as well as the local people dead and others stranded in the area. Fairly widespread rain occurred over Uttarakhand on 13th June. On 14th June, Southwest monsoon advanced into J&K covering entire Uttarakhand. Southwest Monsoon covered the entire country on the 16th June. SWM was vigorous over Uttaranchal, HP and East Rajasthan. A trough in the mid & upper tropospheric westerlies runs with its axis at 5.8 kms a.s.l. roughly along Long. 72° E to the north of Lat. 30° N. System was likely to move ENE wards. Rainfall of 13.7 Cm was reported on 16th Dehra Dun 22.0,. On 17th June, the southwest Monsoon was vigorous over Uttarakhand, Himachal Pradesh, west Madhya Pradesh, Gujarat State and Konkan & Goa and active over Kerala. The trough in the mid & upper tropospheric westerlies now extended in the upper

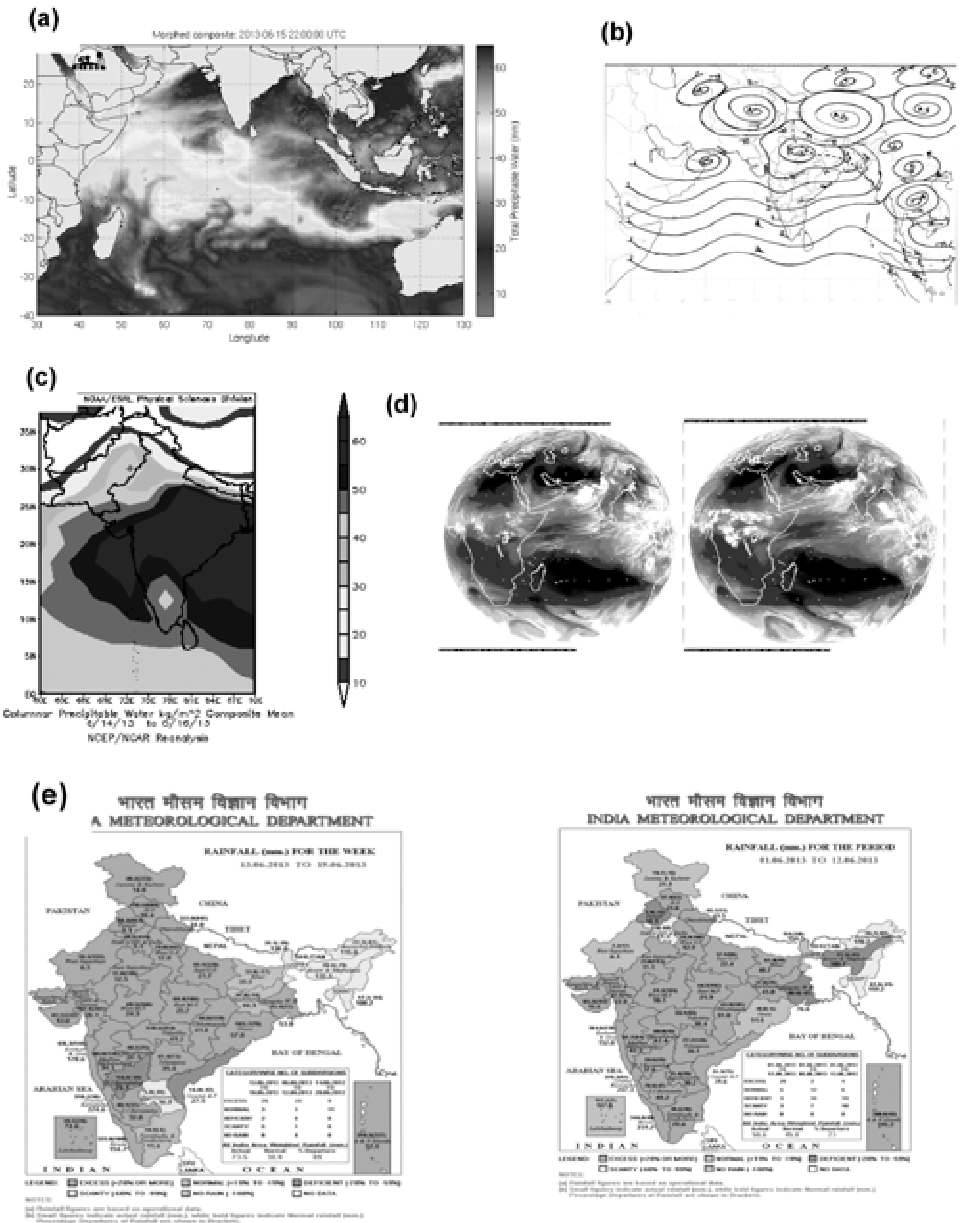


**Figure 6**. a) SSMI Integrated water vapor on June 16th, 2013, Uttarakhand, b) Analysed charts showing Upper air trough and other synoptic features, c) NOAA/ESRL's composite mean analysis showing the water vapour flow over land, d) Satellite images of June 16 Uttarakhand Floods and e) Weekly reports showing rainfall over India during the week of the floods and the rainfall in the previous week.

tropospheric westerlies with its axis at 9.2 kms a.s.l. roughly along Long. 75° E to the north of Lat. 30° N. The rainfall reported on 17th, Paonta Sahib was 40.5 Cm, Dehra Dun 37.0 Cm., and Mukteswar18.3 Cm.

The Figure 6a depicts the global image of the Integrated water vapour (IWV)of June 16th , 2013, of the Uttarakhand heavy downpour from the SSM/I of the polar orbiting satellites.

The synoptic situation of that day is shown in Figure 6b. Here, it can be noted that the trough in the westerlies is again prominent and that helps in the transport of the water vapour. The Figure 6c depicts the water vapour flow over land using NOAA/ESRL's composite mean analysis. Here, we see a yellow light gray narrow region of water vapour flow coming from the Arabian sea and flowing towards the mountains of Uttarakhand. This flow depicts a 15-20Kg/m$^2$ of columnar precipitable water. This heavily laden stream of water vapour was instrumental in the sudden downpour. The Satellite images of June 16 Uttarakhand Floods is depicted in the Figure 6d.

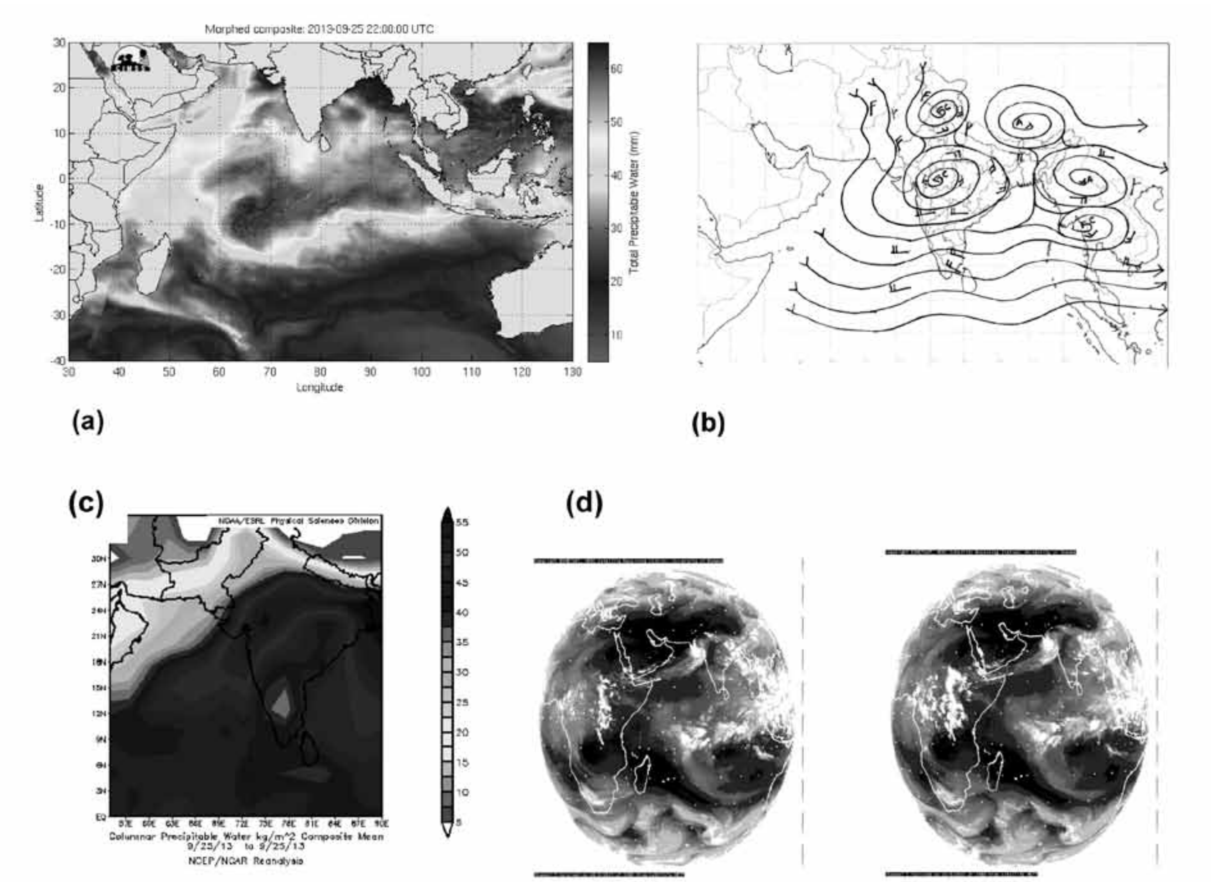


**Figure 7.** a) IWV illustration of Gujarat floods on September 25th 2013, b) Upper air analysis showing the cyclonic circulation extending up to 4.5 kms a.s.l. over southwest Madhya Pradesh and adjoining north Gujarat Region and southeast Rajasthan, c) Water vapour flow as seen in NOAA/ESRL's composite mean analysis and d) Satellite images of Gujarat Floods, 25 September 2013.

## Case 7: September 25th 2013

The Figure 7a depicts the global image of the integrated water vapour (IWV) of 25 September, 2013, over the Oceans. The observed synoptic situations are shown in Figure 7b, Upper air analysis shows cyclonic circulation extending upto 4.5 kms a.s.l. over southwest Madhya Pradesh and adjoining north Gujarat Region and southeast Rajasthan, a cyclonic circulation extending upto 1.5 kms a.s.l. over northwest Bay of Bengal and neighbourhood. The east-west trough is seen roughly along Lat. 22° N between 2.1 & 3.6 kms a.s.l. The trough in mid and upper tropospheric westerlies with its axis at 5.8 kms a.s.l. was seen roughly along Long. 70° E to the north of 30° N. The water vapour flow over land using NOAA/ESRL's composite mean analysis is seen in Figure 7c. Here, we see a thick black narrow region of water vapour flow coming from the Arabian Sea towards Gujarat. This flow depicts a 40-45 Kg/m$^2$ of columnar precipitable water. This depicts a very deep humid layer of water vapour. This narrow thick black region is the AR with heavy concentration of water vapour. This Water vapour cooled when it reached the coast and resulted in very heavy rains and sudden floods. The Satellite images of Gujarat Floods, September 25, 2013 are shown in Figure 7d.

It can be observed from the animated images that the water vapour flow is from west to east along the equator and runs around the globe. Breadth wise it extends up to 10ºN and 10ºS. But it can be observed that over some regions, it extends and branches out to over 30 degrees. The same can be observed over the Arabian sea where the Integrated Water vapour flow extends over 25ºN. This heavily concentrated integrated Water Vapour then was carried further by the eastward moving systems like the Western Disturbances and troughs in Westerlies along with high wind speeds that carry them to the upper reaches of the mountains. Here they cool and condense large part of their heavy burden of vapour (e.g. Stohl et al., 2008). This results in sudden heavy rains resulting in flash floods and landslides.

All the seven incidences under study together with the upper air flow pattern depicting the synoptic situations are illustrated and the resulting extreme rainfall events are discussed. A study on the deep convection close to

Western Himalayas reveals mainly moist Arabian Sea low level air traversing desert land, where surface flux of sensible heat enhances buoyancy. As the flow approaches the Himalayan foothills, the soil may provide an additional source of moisture if it was moistened by a previous precipitation event. Low level and elevated layers of dry, warm, continental flow apparently cap the low level moist flow, inhibiting the release of instability upstream of the foothills. The convection is released over the small foothills as the potentially unstable flow is orographically lifted to saturation as discussed by Socorro et al. (2010).

## CONCLUSIONS

It can be seen from this study that the eastward moving cyclonic circulations in the northern latitudes of India in conjunction with the atmospheric rivers drawing water vapour from the lower latitudes under the circumstances of positive interference result in extremely heavy and intense precipitation over the higher reaches of northern India. Atmospheric Rivers result in heavy precipitation when they confront mountainous terrain, such as those found on the Himalayan ranges of the North India. Thus, understanding the behavior of the Atmospheric Rivers can provide a better linkage that leads to determine how the changing climatic patterns influence extreme precipitation and floods in India.

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