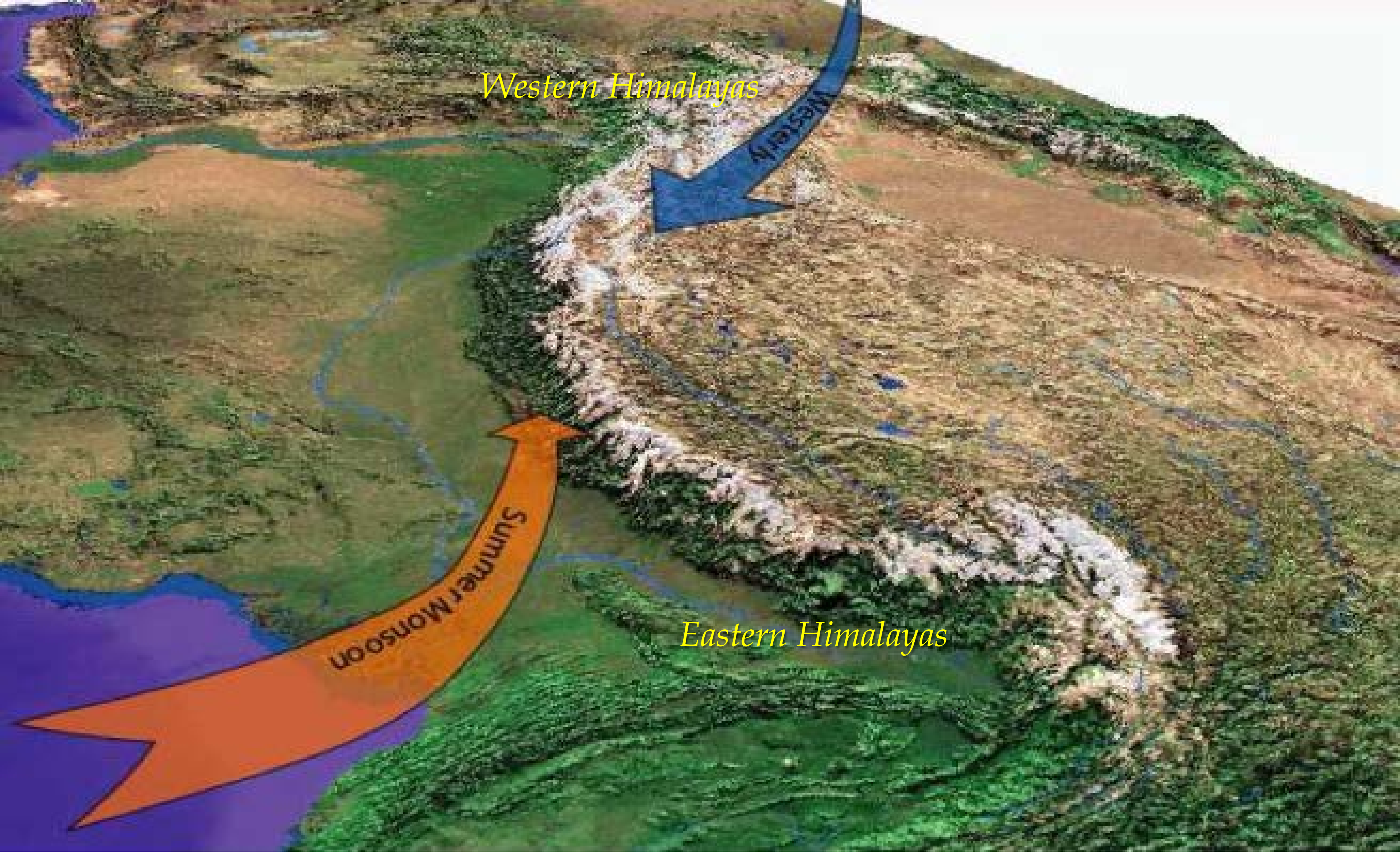


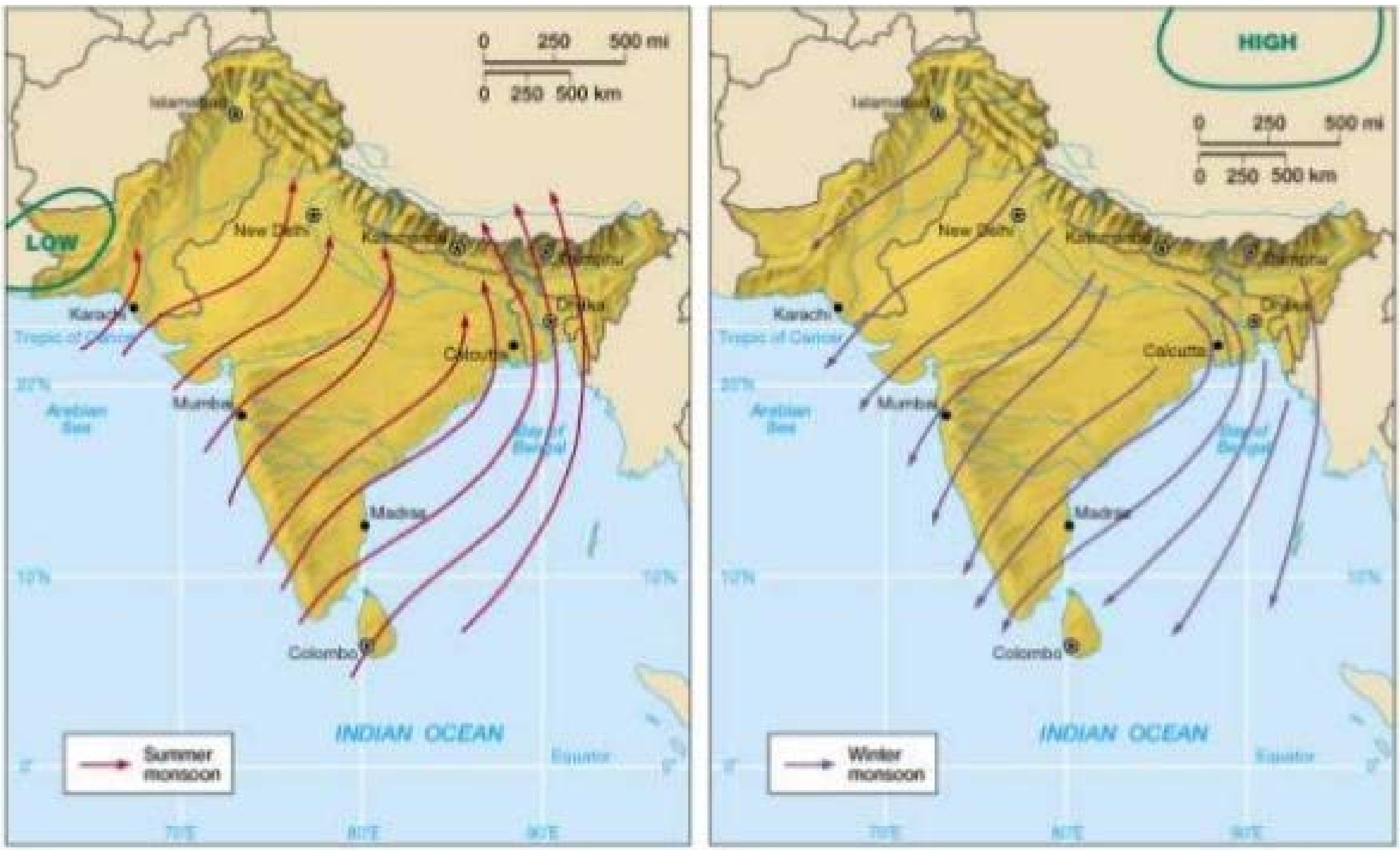
Indian monsoon, associations with mid-latitude circulation and extreme precipitation

Ramesh Vellore, Centre for Climate Change Research,
Indian Institute of Tropical Meteorology, Pune, India.

GOTHAM International Summer School
Potsdam, Germany
September 18-22, 2017

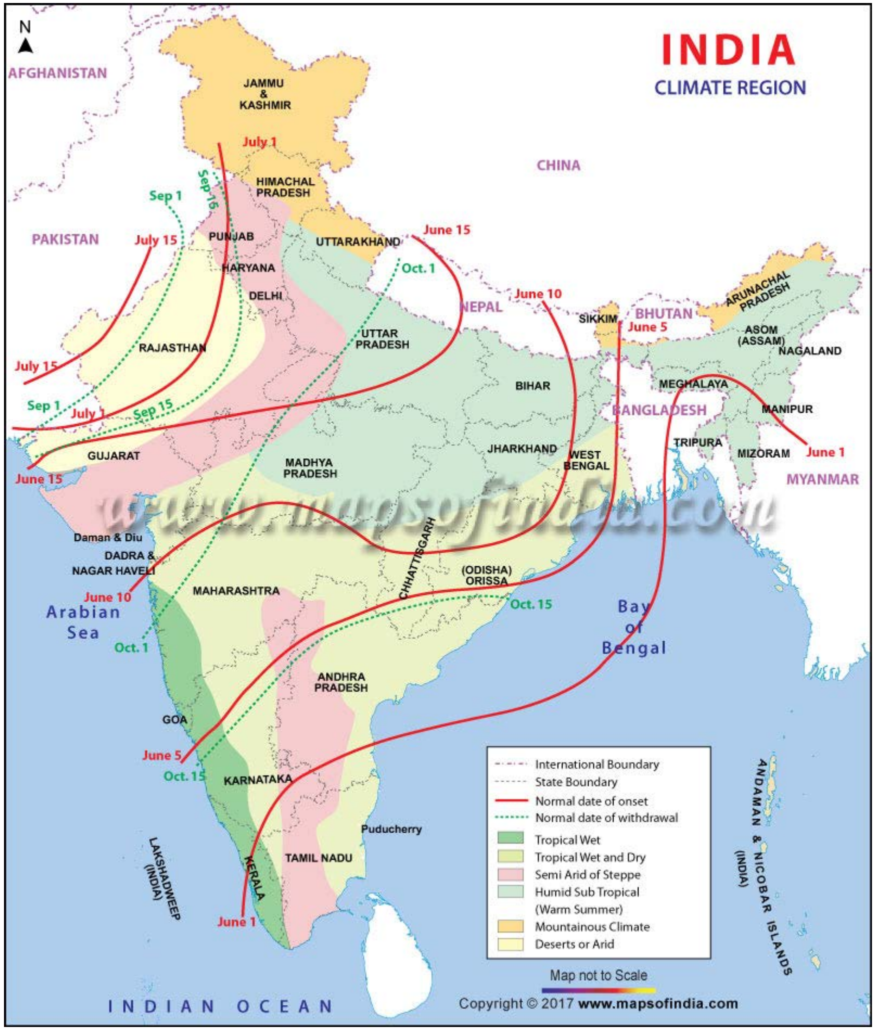
Indian Monsoons

Summer monsoons bring in moisture from the Indian Ocean and produce large amount of rain



***Monsoon** is traditionally defined as a seasonal reversing wind accompanied by seasonal changes in precipitation, but is now used to describe seasonal changes in atmospheric circulation and precipitation associated with the asymmetric heating of land and sea.*

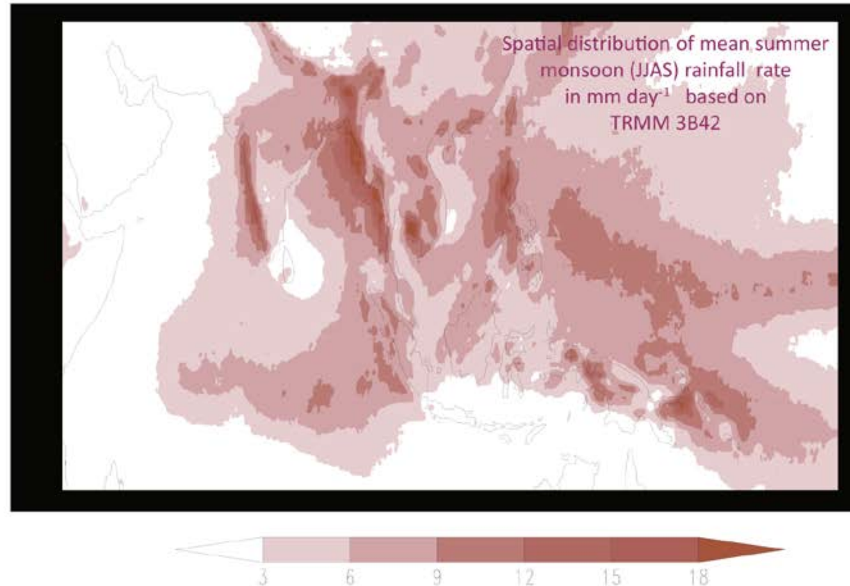
Indian Monsoons

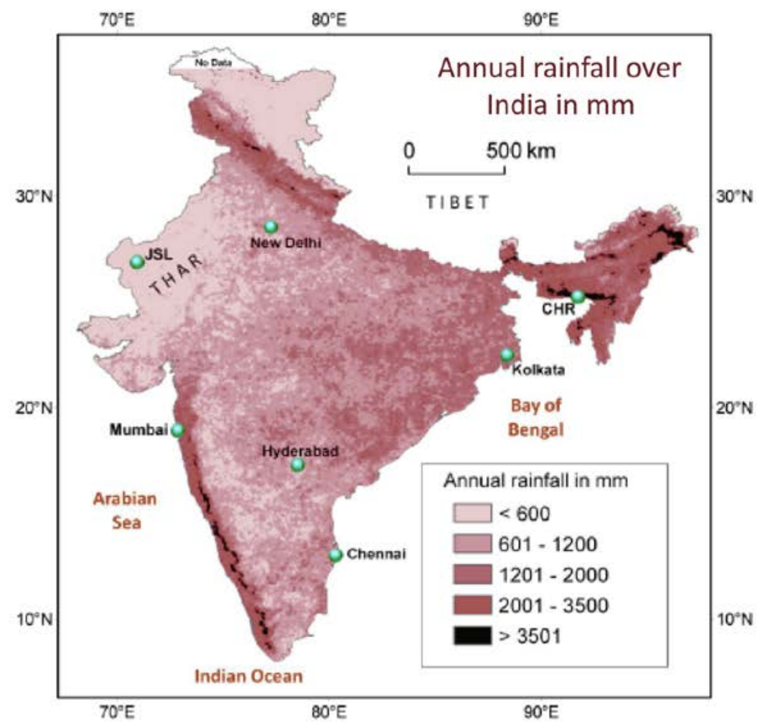


Onset and Withdrawal of Summer monsoon

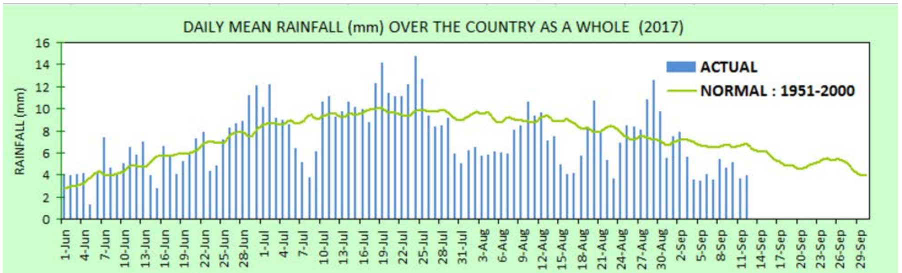
Rainfall from TRMM satellite. Data source: http://www.geog.ucsb.edu/~bodo/TRMM/

A.K. Singhvi and R. Krishnan (2014): Chapter in book 'Landscapes and Landforms of India'



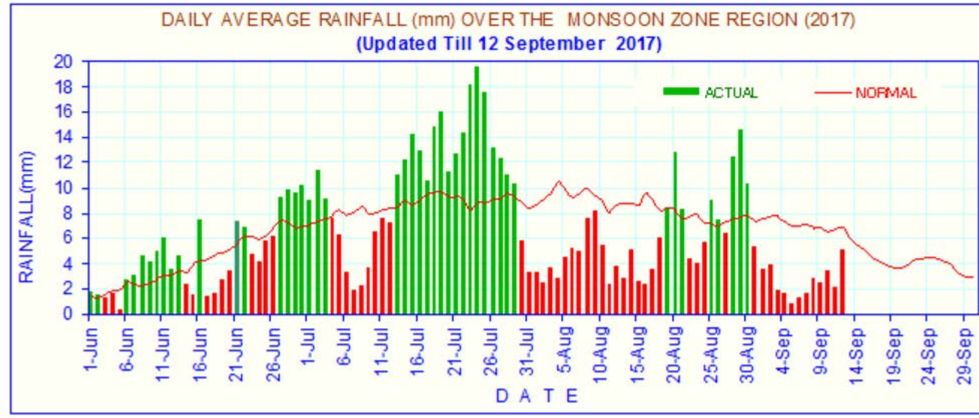


Source: http://www.imd.gov.in/

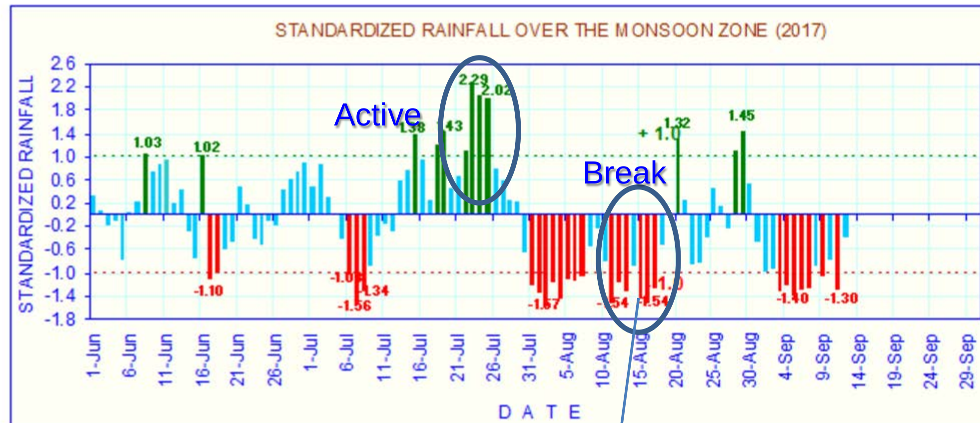


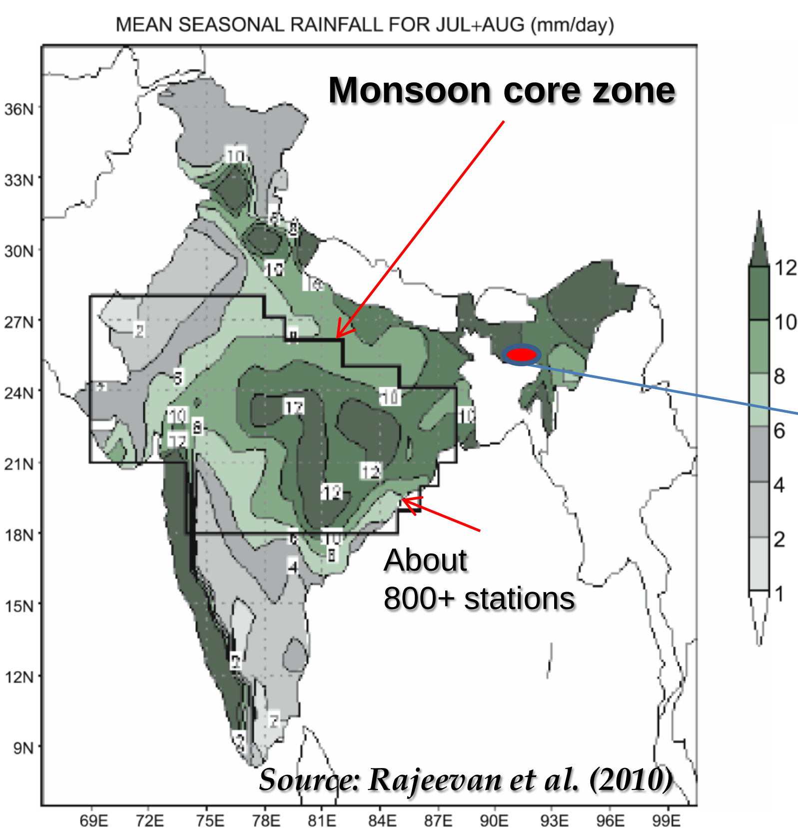
Daily evolution of 2017 All-India India summer monsoon (AISMR) rainfall

Active (wet) and Break (dry) spells during summer monsoon

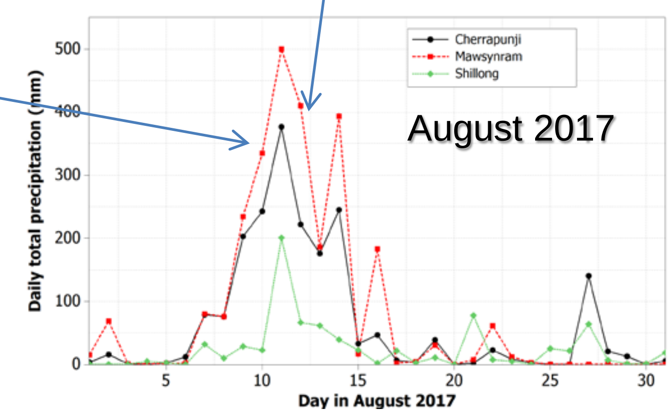


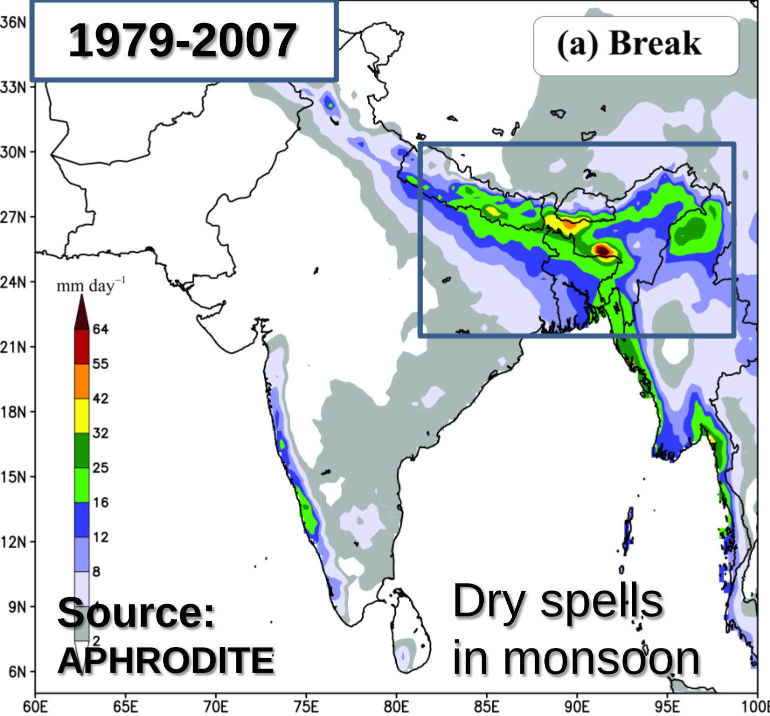
Heavy rain = 6 to 12 cm
Very heavy rain = 12 to 24 cm
Extremely heavy rain > 24 cm

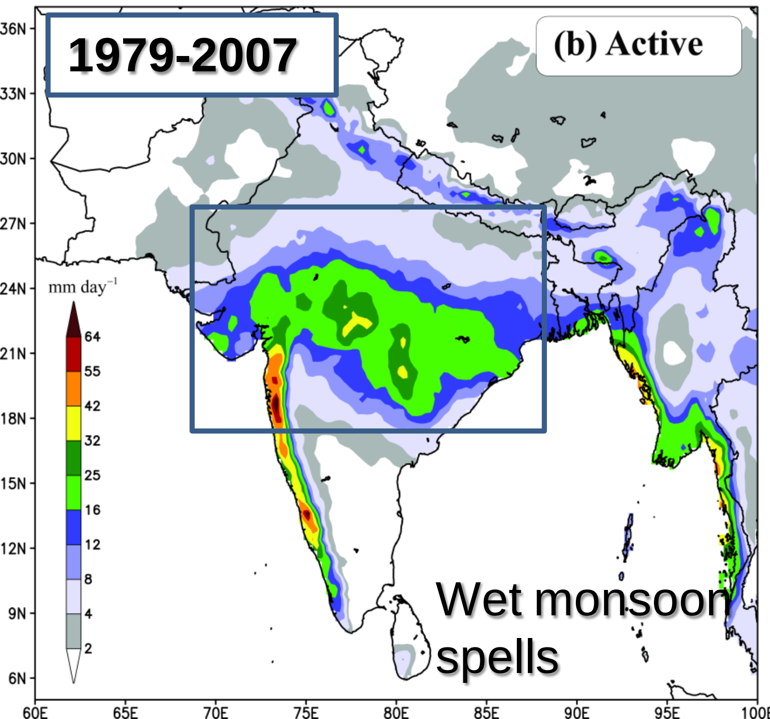




The (active) break spell has been identified as the period during which the standardized rainfall anomaly is less (more) than −1.0 (+1.0), consecutively for three days or more.







Weak/subdued/Break Monsoon

Rainfall is less than half the normal

Rainfall activity is confined to northeastern parts of India

Weaker wind speeds: Wind speed is up to 12 knots (over the Sea)

Active/vigorous Monsoon

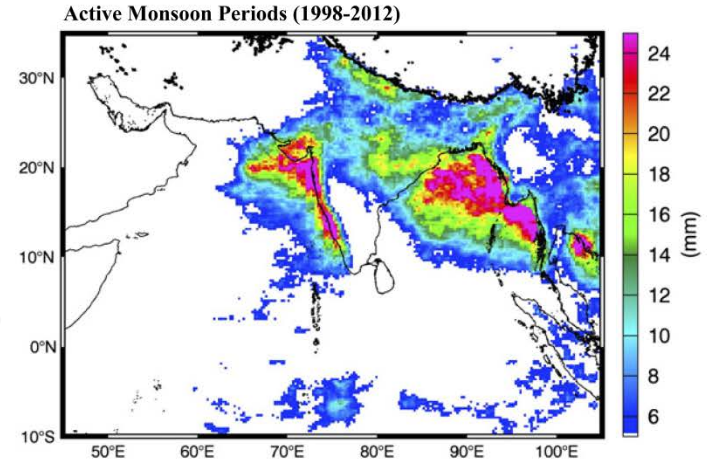
Rainfall is fairly widespread over the land area

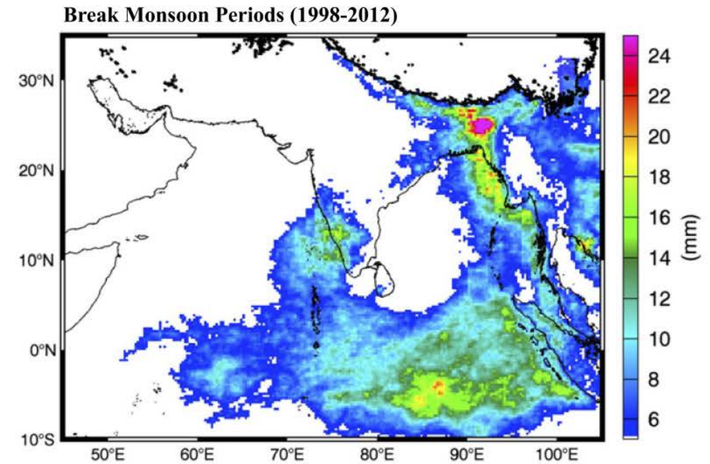
Rainfall 1½ to 4 times the normal

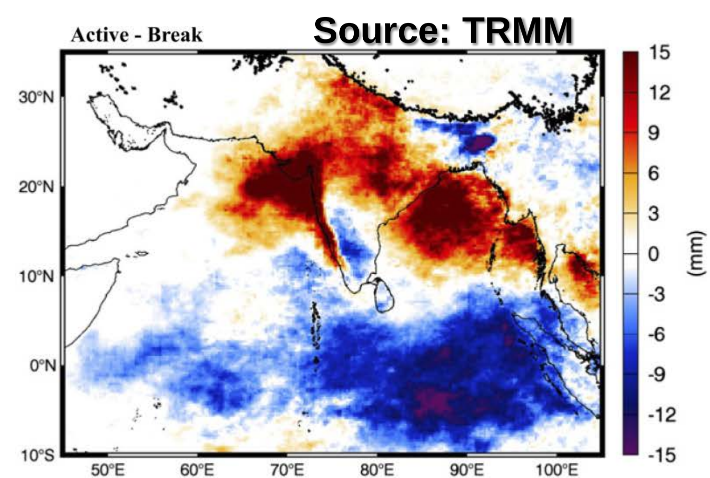
The rainfall in at least two stations should be 5 cm

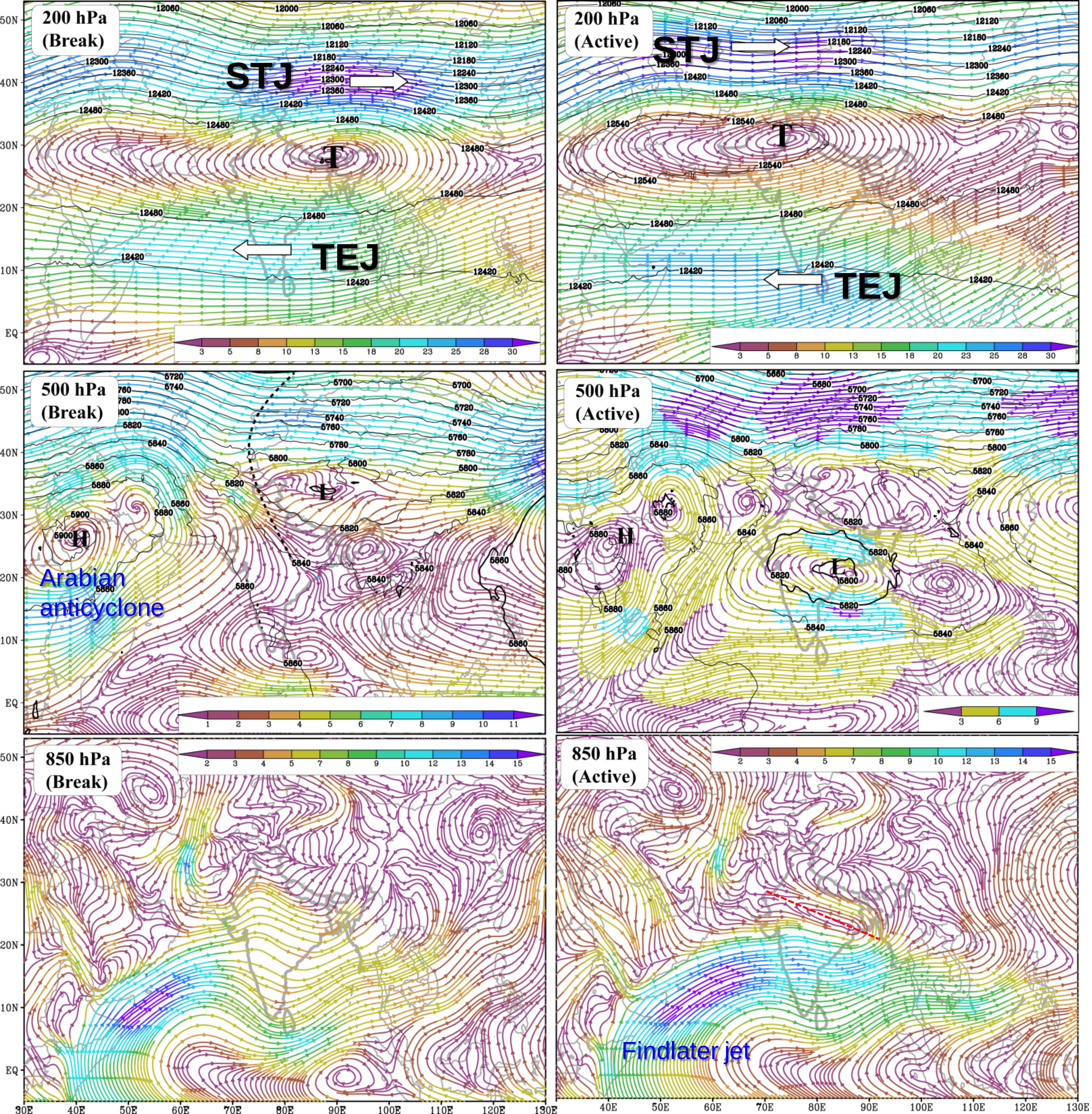
Stronger wind speeds: Wind speed is between 23 to 32 knots (over the Sea)

Vigorous monsoon:
Rainfall > 4 times normal
Wind speeds > 32 knots









Summer monsoon archetypal circulation patterns

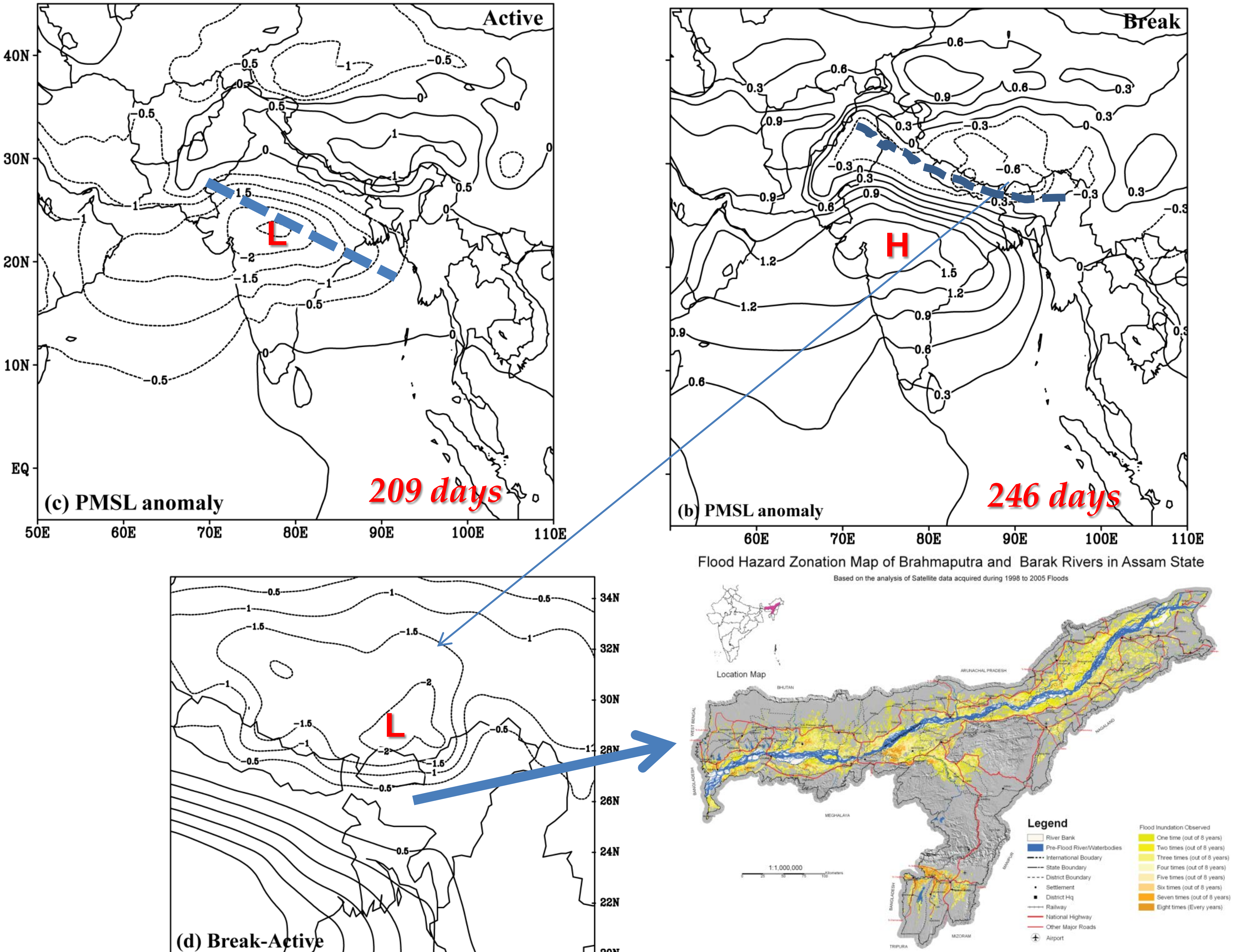
200 hPa
T: Tibetan anticyclone
STJ: Subtropical jet stream
TEJ: Tropical easterly jet

The Himalayas act as a barrier between STJ and TEJ – therefore the positioning of these jets is critical for the Himalayan rainfall.

500 hPa

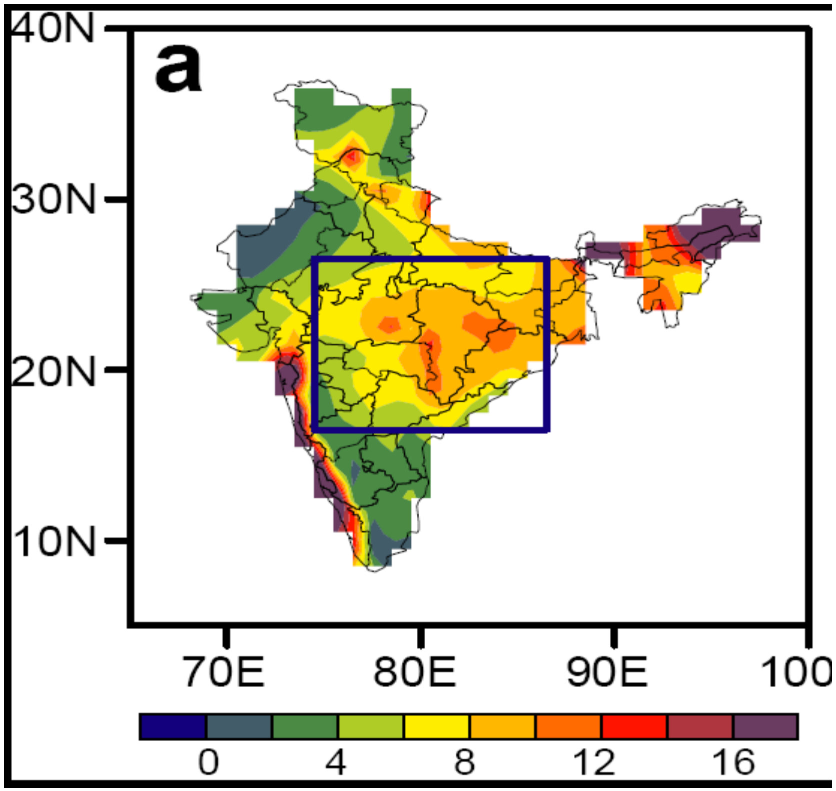
850 hPa

Source: ERA-Interim



http://dsc.nrsc.gov.in/DSC/Flood/HistoricFloods.jsp

Increasing Trend of extreme rain events over the monsoon core region

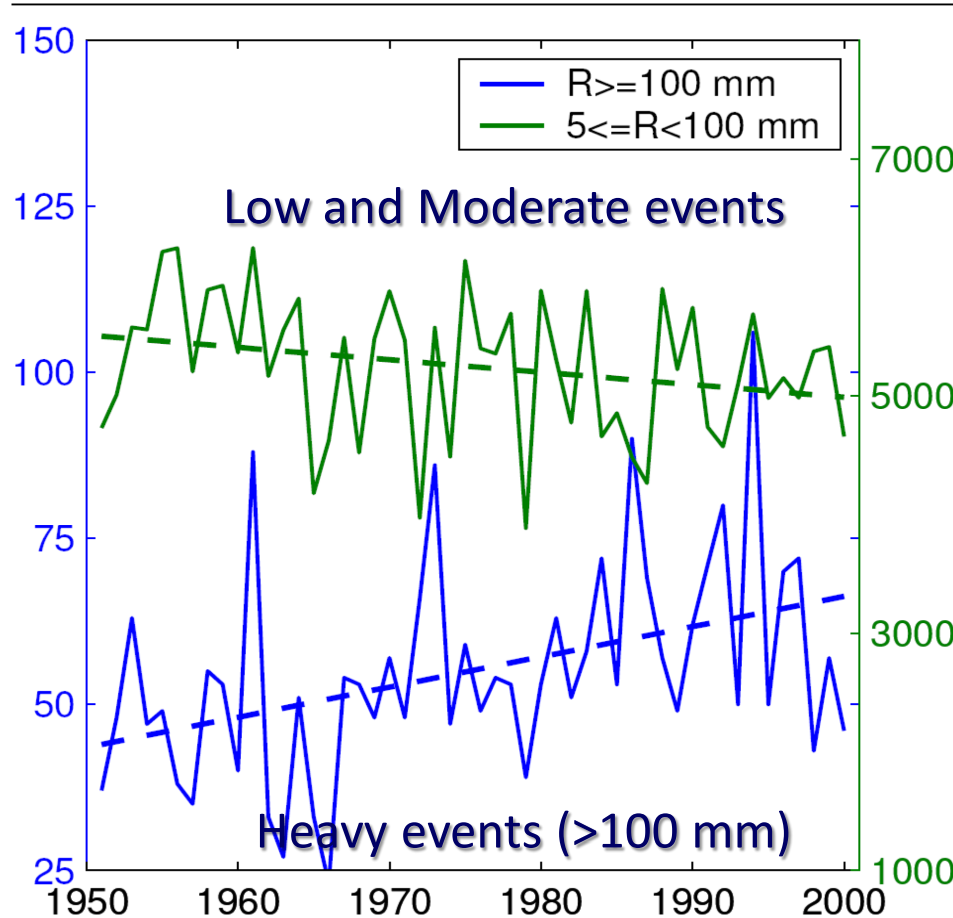


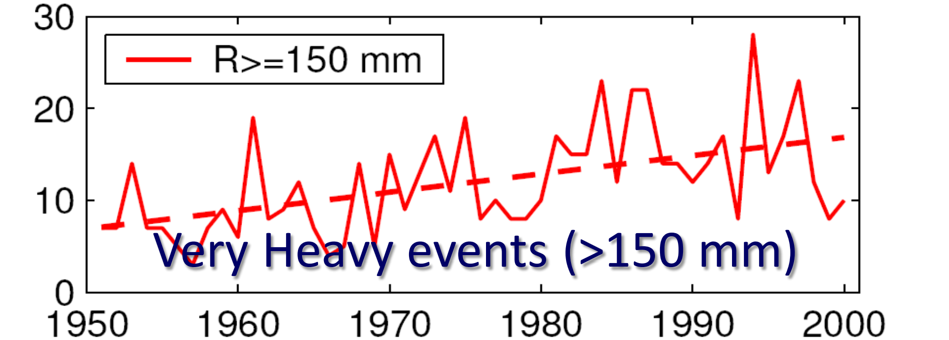
Increasing Trend of Extreme Rain Events Over India in a Warming Environment

B. N. Goswami,[1]* V. Venugopal,[2] D. Sengupta,[2] M. S. Madhusoodanan,[2] Prince K. Xavier[2]

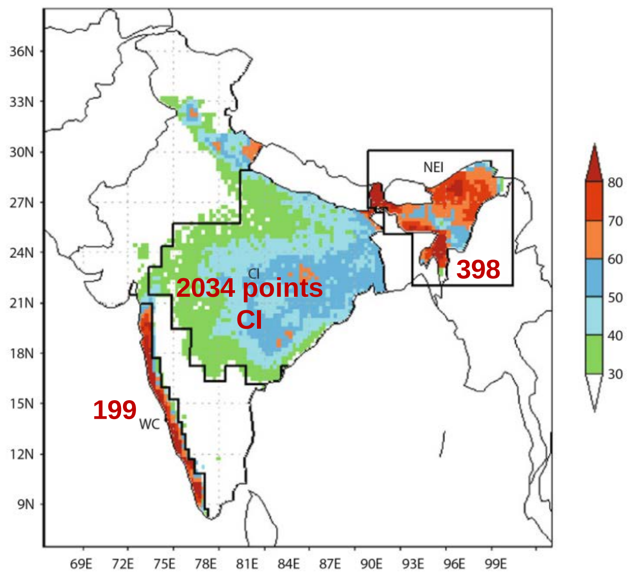
1 DECEMBER 2006 VOL 314 SCIENCE

Time series of count over Central India





Trends in the Frequency of the Extreme Rainfall

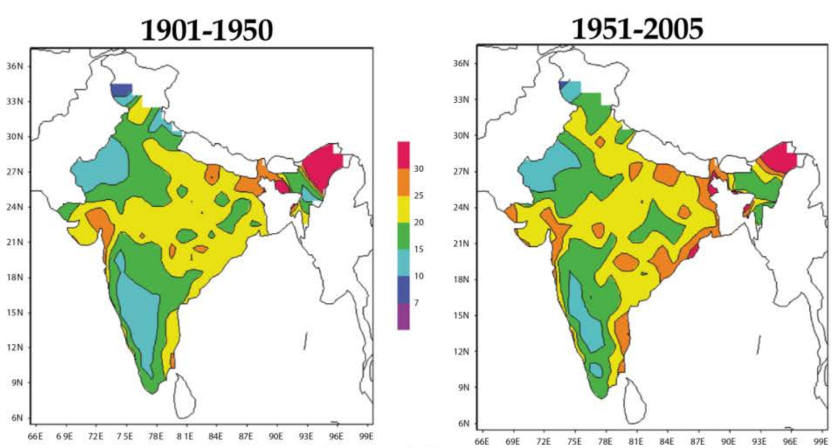


Mean of the grid point frequency of extreme rain events

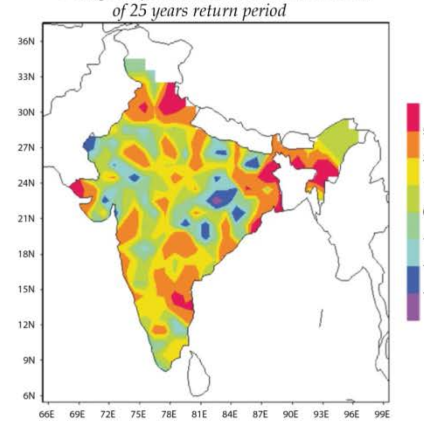
Grid points within CI = 30-60 days/season
Grid points within WC and NEI = greater than 60 days/season of extreme precipitation events

Highest grid point rainfall recorded over CI, NEI and WC during the period 1901-2010 are 763 mm, 940 mm, and 821 mm, respectively.

Pai and Sridhar (2015): Long term trends in the extreme rainfall events over India.
"High-Impact Weather Events over the SAARC Region" , DOI 10.1007/978-3-319-10217-7_15



Extreme values (in cm) for 25 years return period

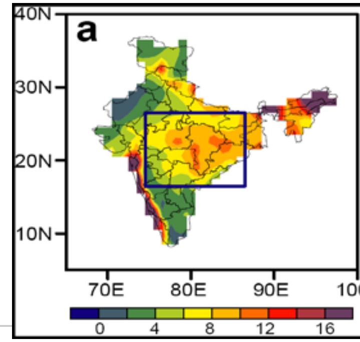


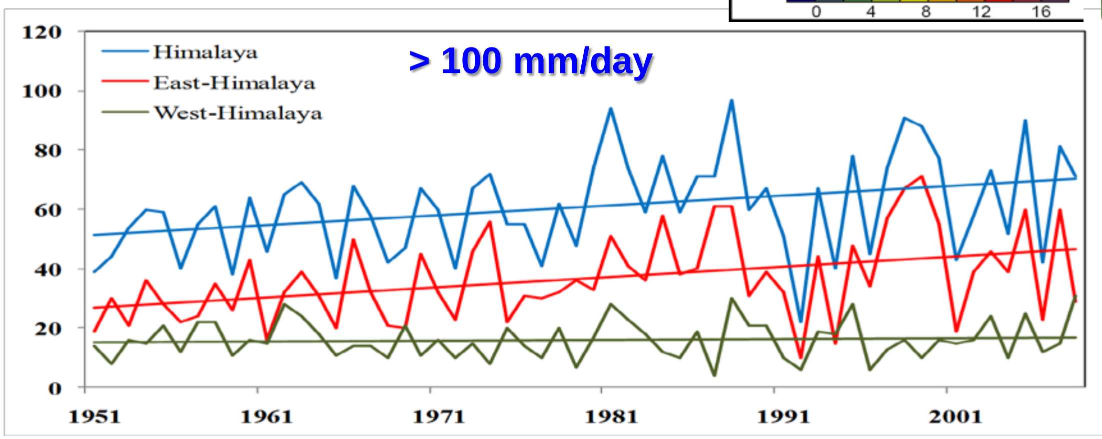
Source: Guhathakartha, 2015

- ***The flood risk has increased in recent period (1951–2005) in most parts of the country except Chhattisgarh, parts of Odisha, Bihar, extreme west Rajasthan and west Madhya Pradesh.***
- ***The increase is more in West Bengal, Assam & Meghalaya, Jharkhand, coastal Odisha, coastal Andhra Pradesh, Uttarakhand and adjoining areas and Kutch.***

Extreme precipitation events over the Himalayas

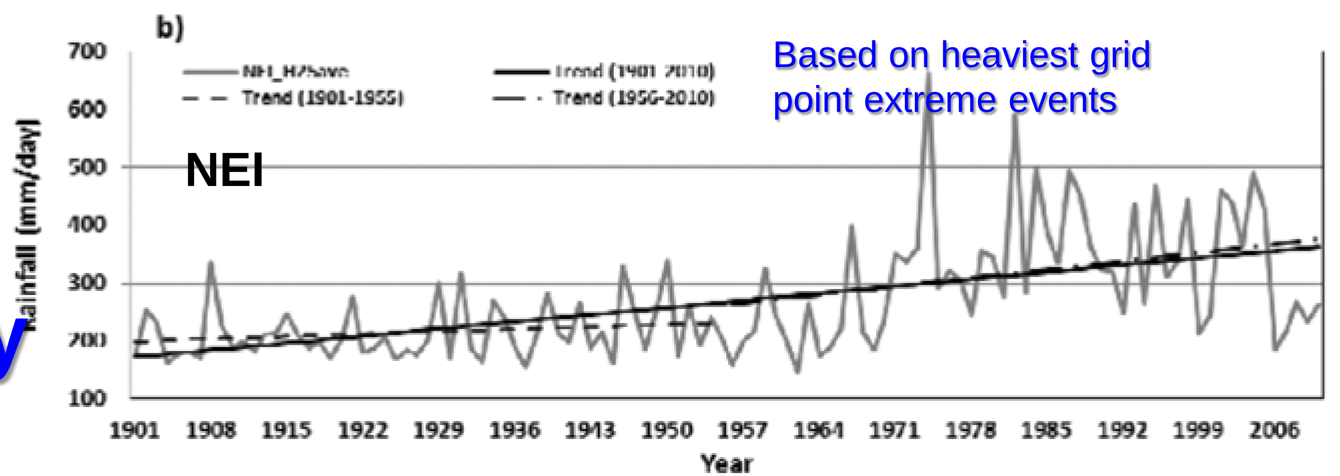
Observations (Source: India Meteorological Department)



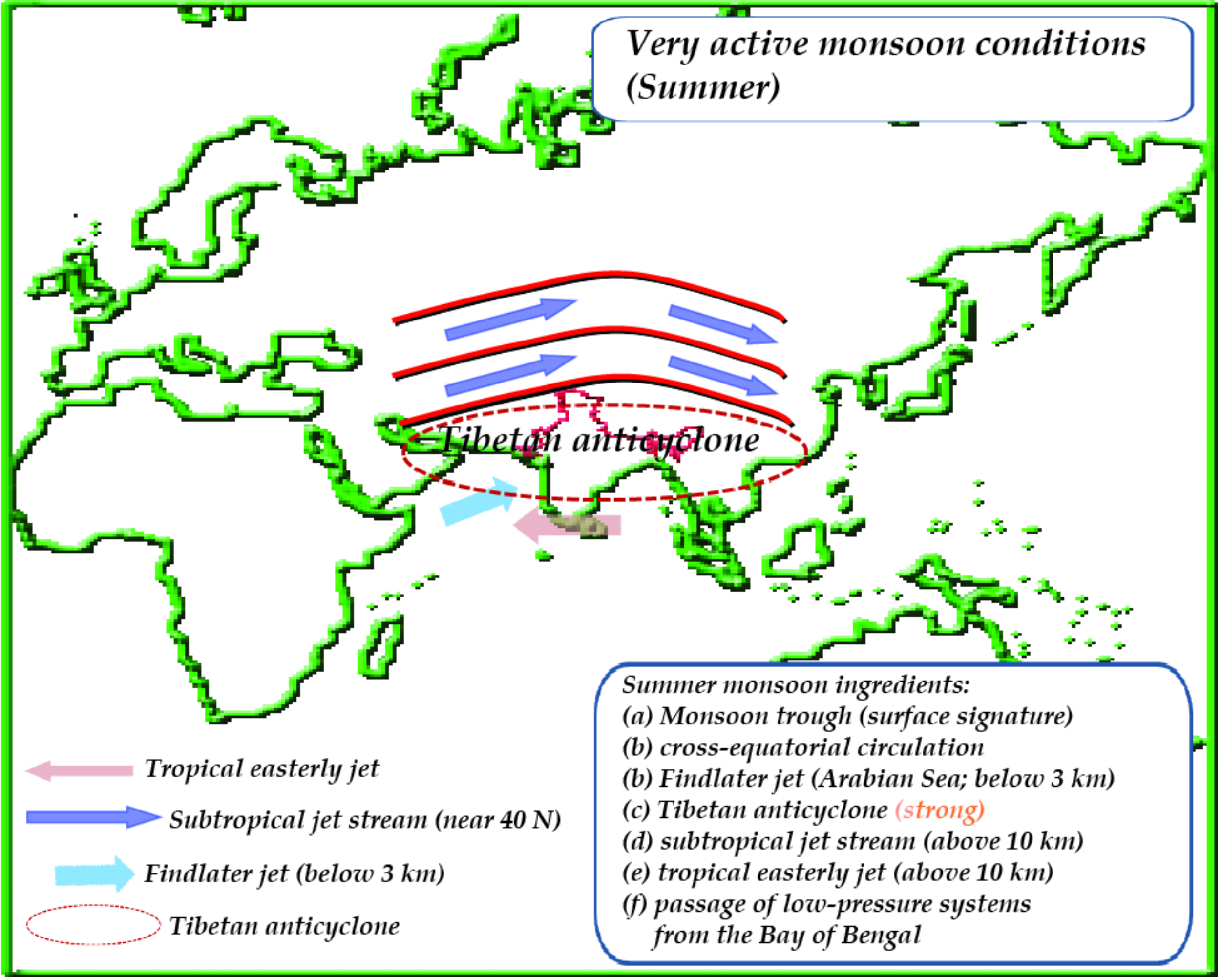


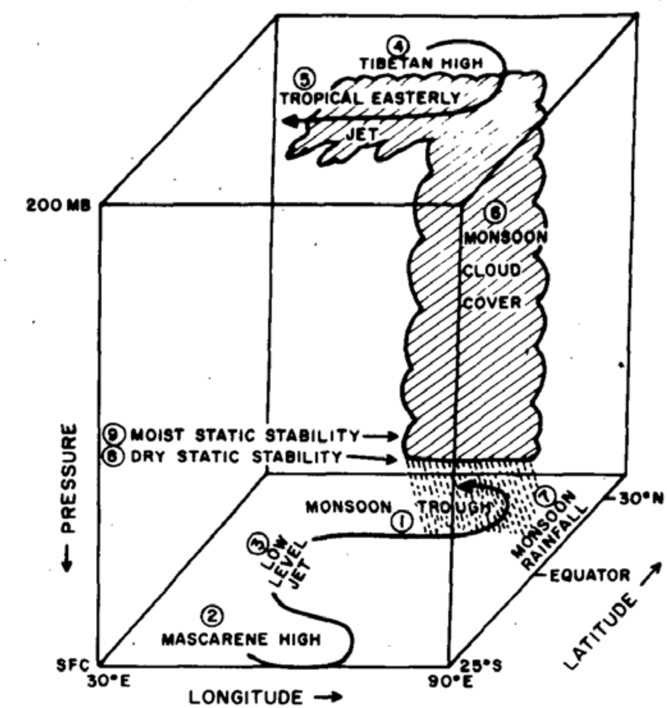
Pai and Sridhar (2015): the intensity of the extreme events show increasing trends

Limitation: Data paucity

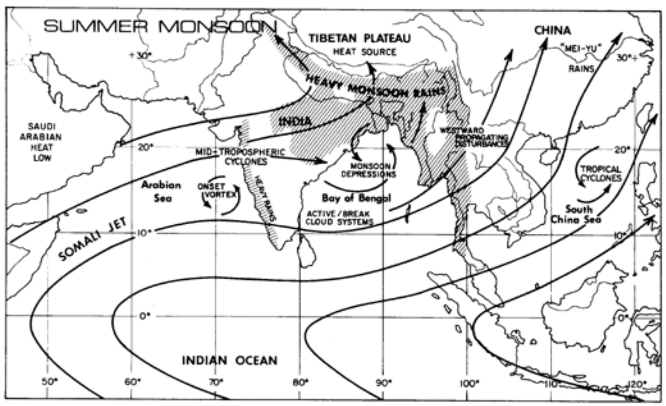


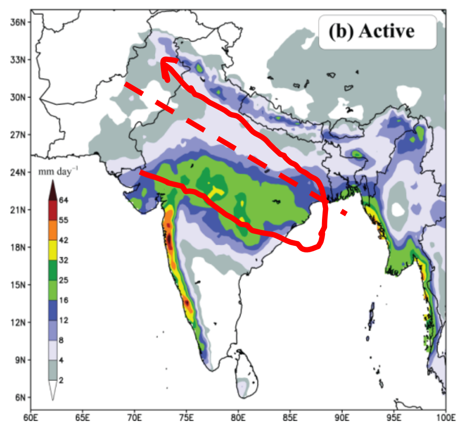
Based on heaviest grid point extreme events





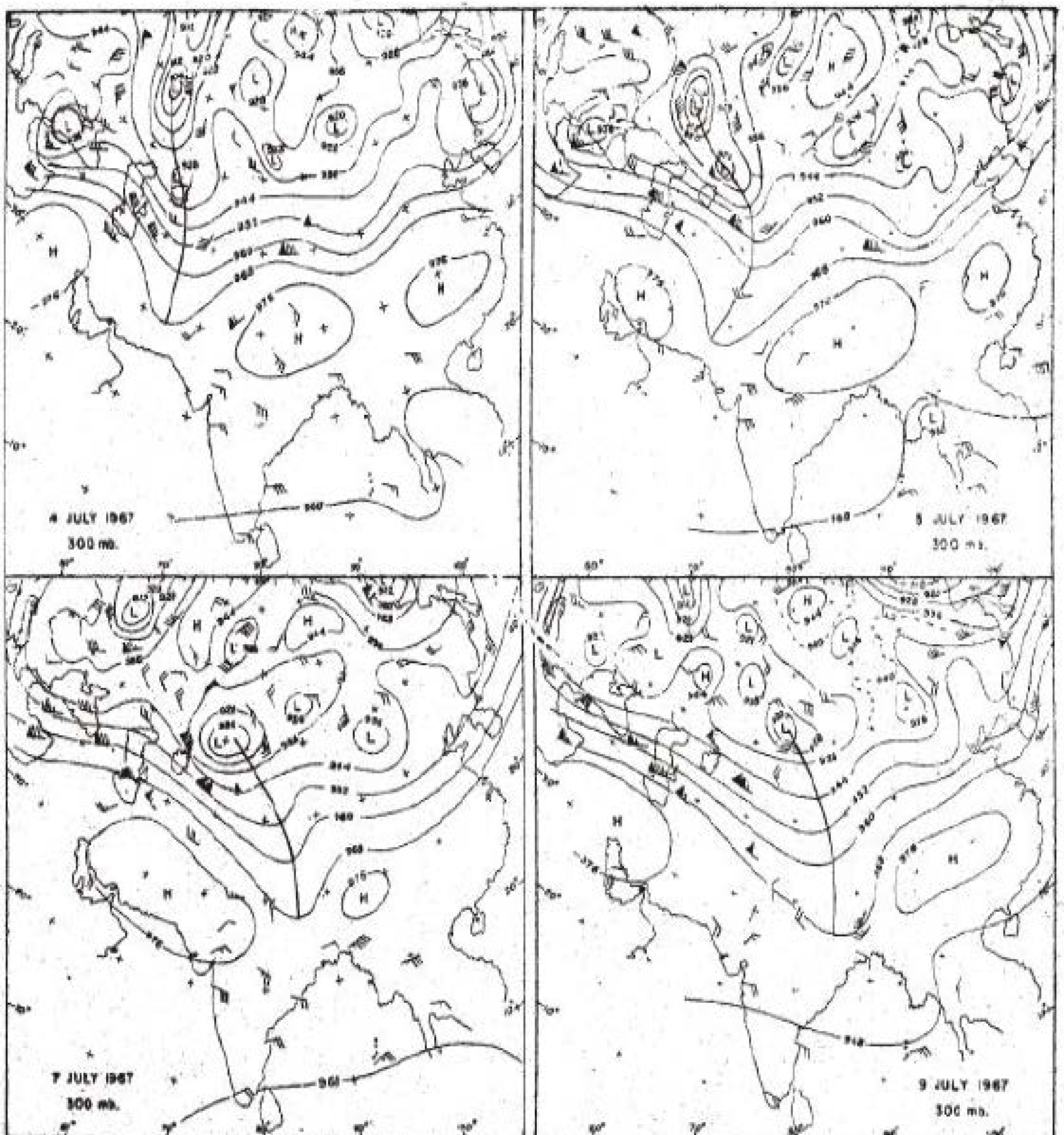
One can refer the condition as vigorous or very active when strong or robust signatures of (a)-(f) are seen





Occurrence of extreme precipitation events in the Himalayas are mostly from the penetrating monsoon circulation from east to west

Monsoon Breaks: Monsoon-extratropical interactions



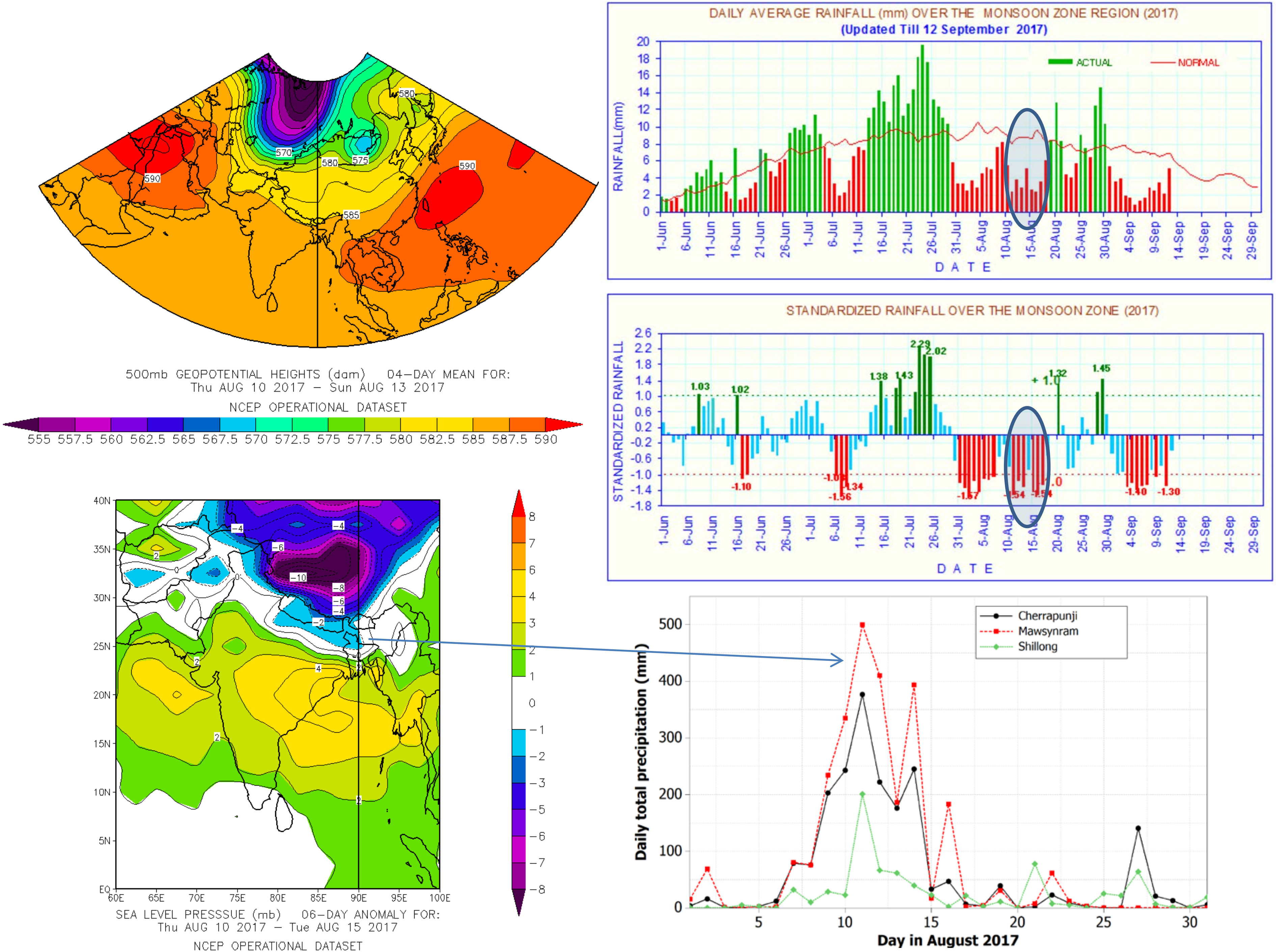
Note :- Analysis mainly based on published Russian daily weather charts

Extratropical interactions with monsoon circulation are envisioned with the passage of trough in westerlies during 'break'

Large amplitude troughs protrude into Indo–Pakistan area at 500 mb and aloft.

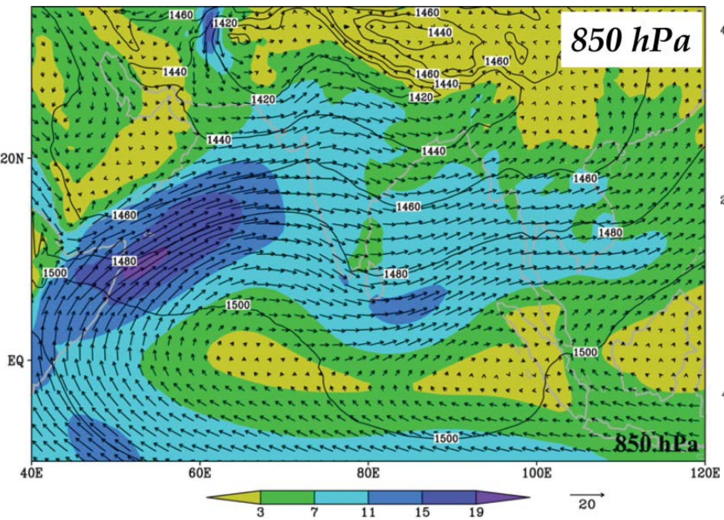
The associated upper level divergence causes heavy rainfall over and near the Himalayas.

Influence of central-eastern Himalayan orography



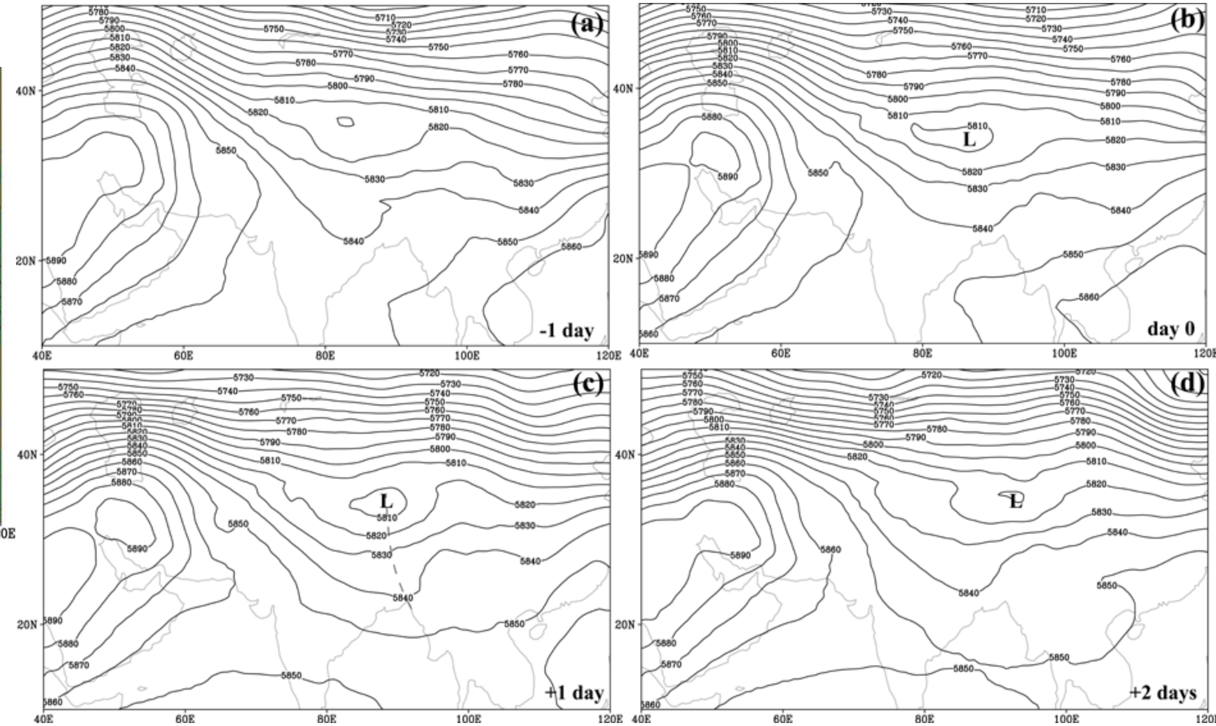
500mb GEOPOTENTIAL HEIGHTS (dam) 04–DAY MEAN FOR:
Thu AUG 10 2017 – Sun AUG 13 2017
NCEP OPERATIONAL DATASET
555 557.5 560 562.5 565 567.5 570 572.5 575 577.5 580 582.5 585 587.5 590
DAILY AVERAGE RAINFALL (mm) OVER THE MONSOON ZONE REGION (2017)
(Updated Till 12 September 2017)
RAINFALL(mm)
ACTUAL
NORMAL
DATE
STANDARDIZED RAINFALL OVER THE MONSOON ZONE (2017)
STANDARDIZED RAINFALL
DATE
SEA LEVEL PRESSSUE (mb) 06–DAY ANOMALY FOR:
Thu AUG 10 2017 – Tue AUG 15 2017
NCEP OPERATIONAL DATASET
Cherrapunji
Mawsynram
Shillong
Daily total precipitation (mm)
Day in August 2017

Monsoon southwesterlies bypassing Peninsular India

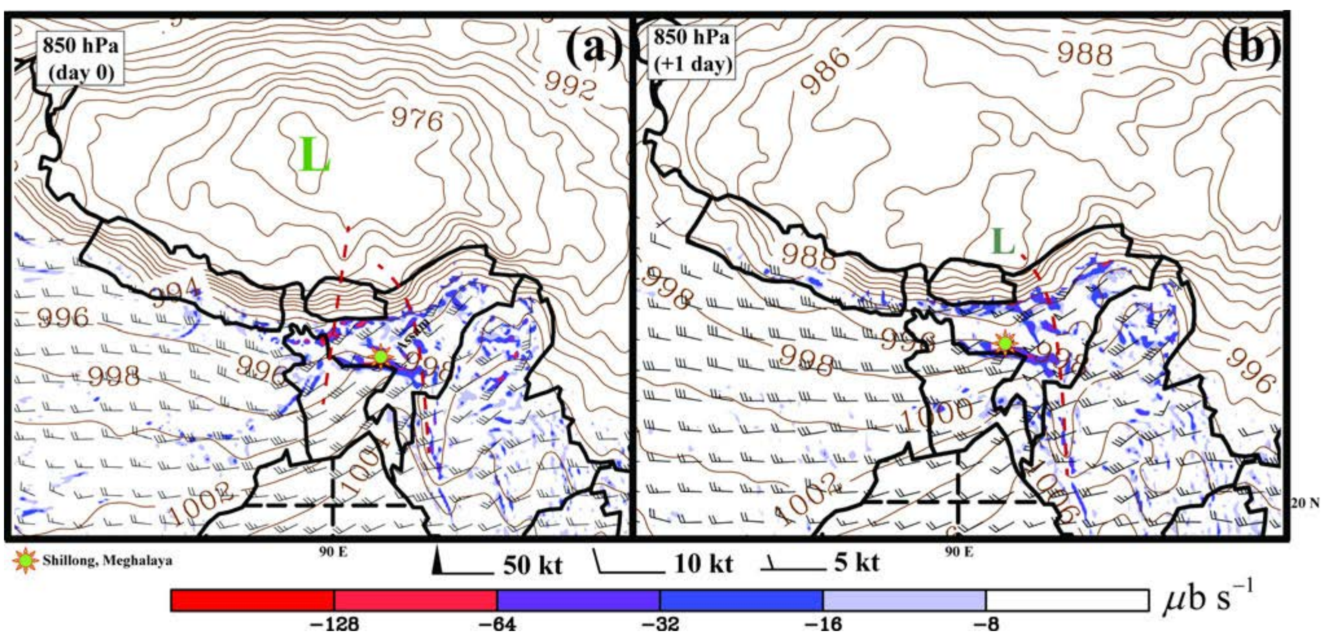


850 hPa wind composite

(Vellore et al. 2014)

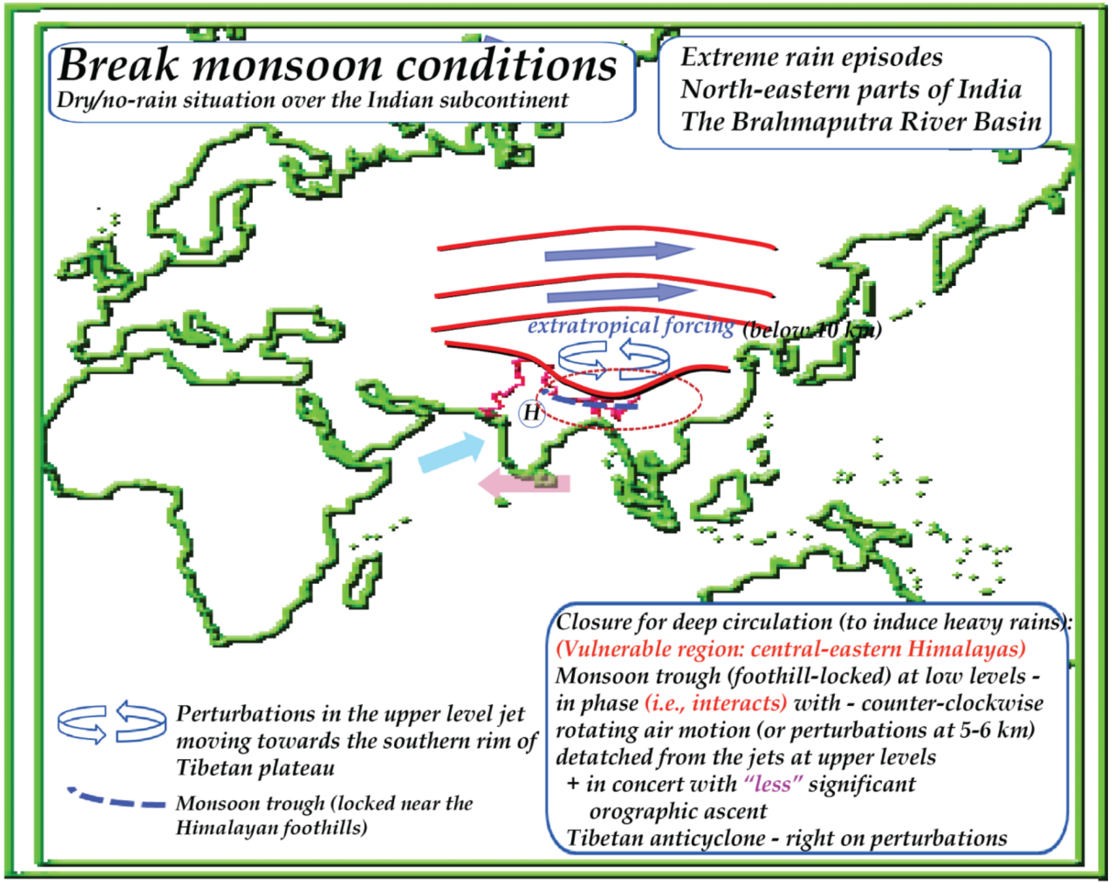


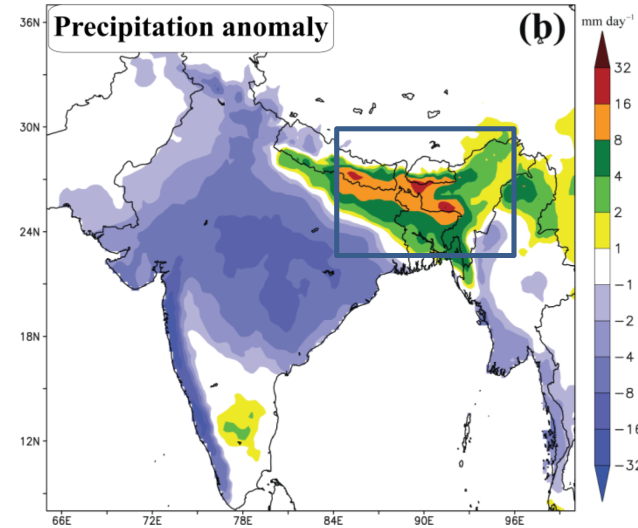
Time evolution of geopotential height fields (contour interval = 10 m) at 500 hPa valid for (1) -1 day, (b) day 0, (c) 1 day and (d) 2 days from ERA. Day 0 refers to the day of initiation of the break cycle

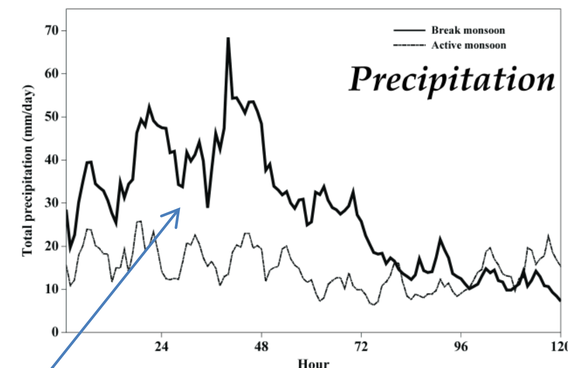


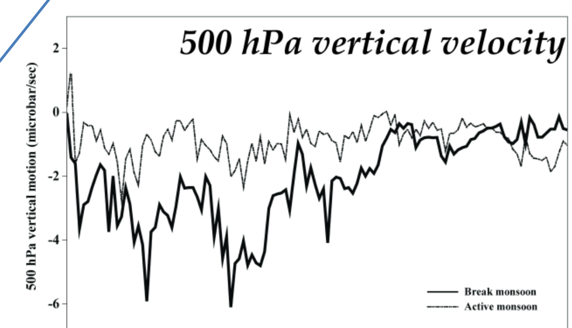
Himalayan orography does not favor mechanical uplift of air – as the monsoon flow is generally along the foothill barrier during monsoon-break situations.

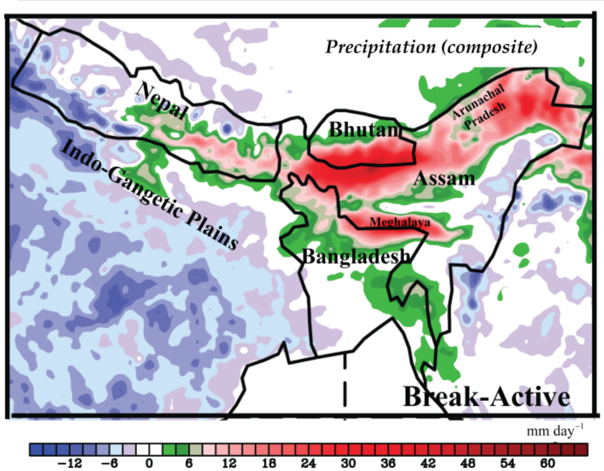
Breaks: Monsoon-extratropical interactions











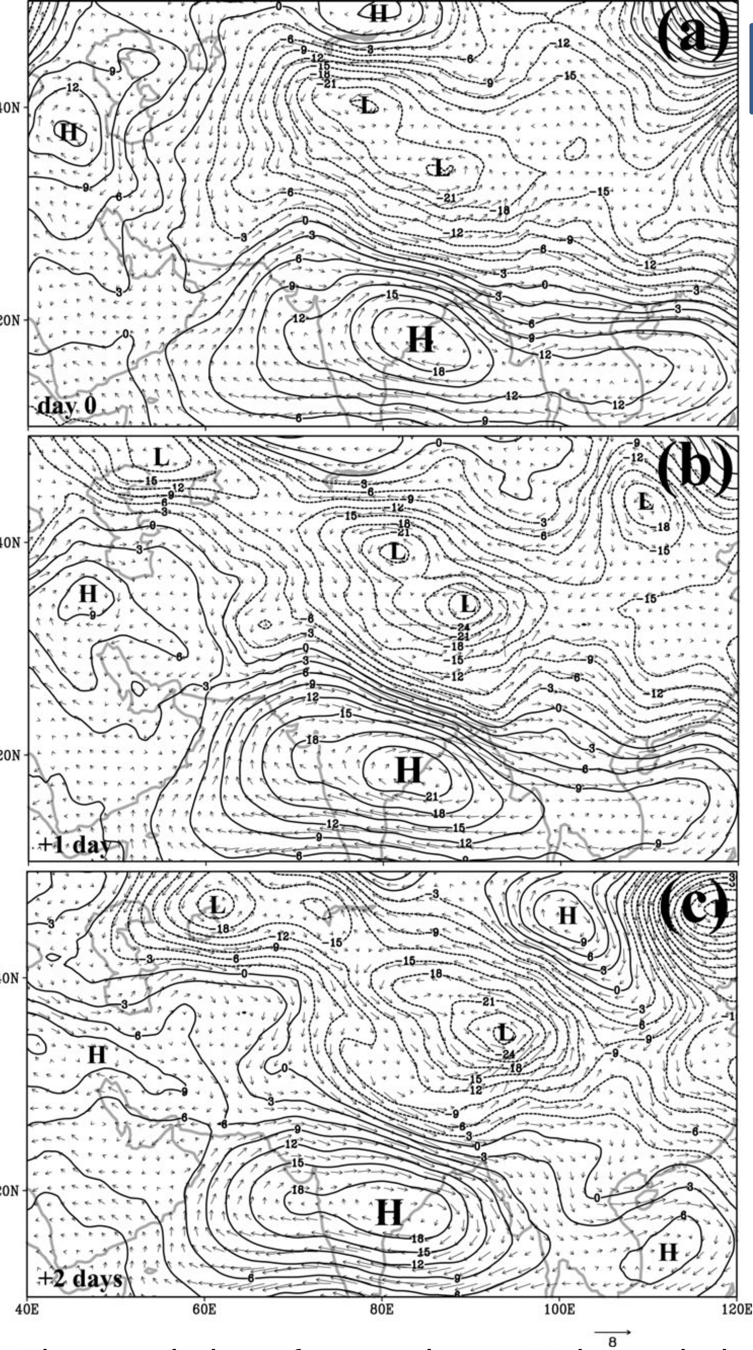
Coupling between precipitation and circulation can produce nearly a threefold increase of total precipitation over the central-Eastern Himalayan foothills during breaks as compared to active-monsoon conditions.

What is the closure?

Clim Dyn
DOI 10.1007/s00382-013-2024-1

On the anomalous precipitation enhancement over the Himalayan foothills during monsoon breaks

Ramesh K. Vellore · R. Krishnan · Jayant Pendharkar · Ayantika Dey Choudhury · T. P. Sabin



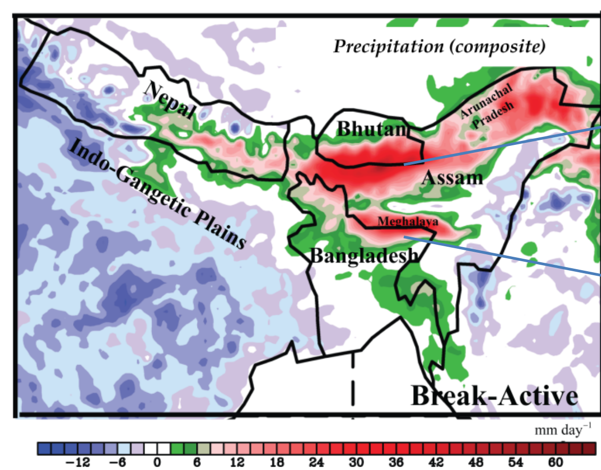
Time evolution of anomalous 500 hPa wind and geopotential height during break cycle

Monsoon-mid-latitude interactions – break cycle

During monsoon-break periods, the closure connects the foothill-locked monsoon trough (surface), extratropical forcing from the perturbations associated with the mid-tropospheric circulation, and the eastward moved Tibetan anticyclone (200 hPa) – these 3 elements stacked in vertical provide the three-dimensional closure for deep vertical circulation near the central-eastern Himalayan foothills.

- *Mid-tropospheric vorticity over the central-eastern Himalayan foothills is supported by the extratropical interaction coupled to trough signature at the surface and divergent circulation at 200 hPa*

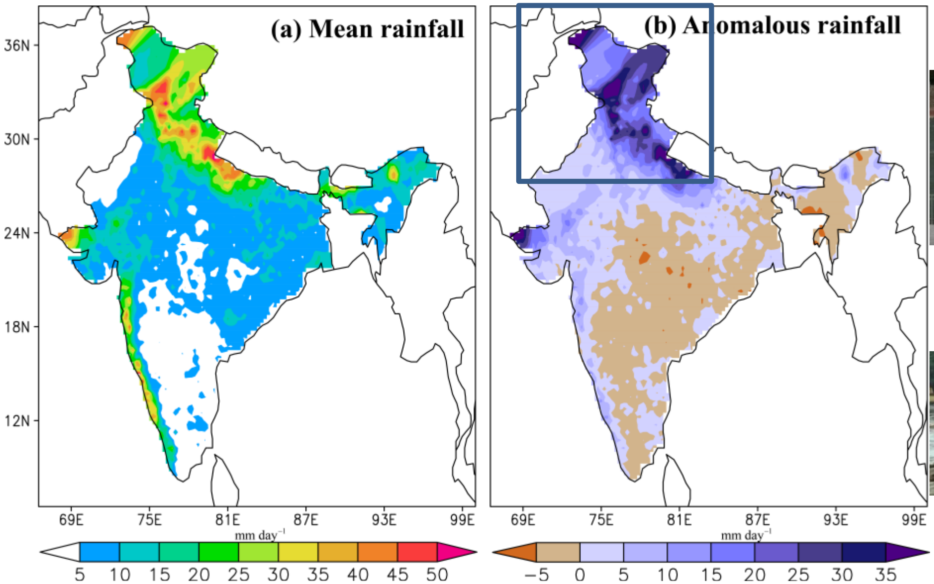
Flood vulnerablity : central-eastern Himalayas (Brahmaputra River basin)



Conceptualized as Monsoon-extratropical interaction

orographic precipitation enhancements

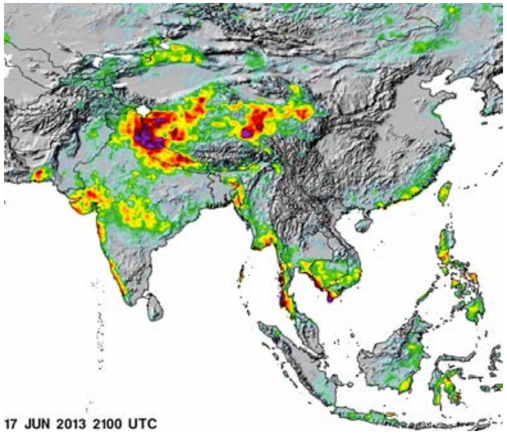
Extreme rain events in the Western Himalayas

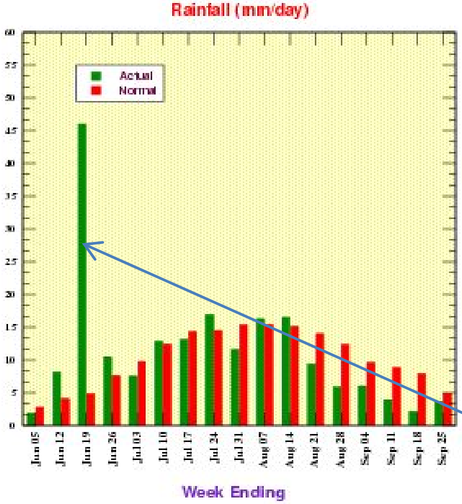


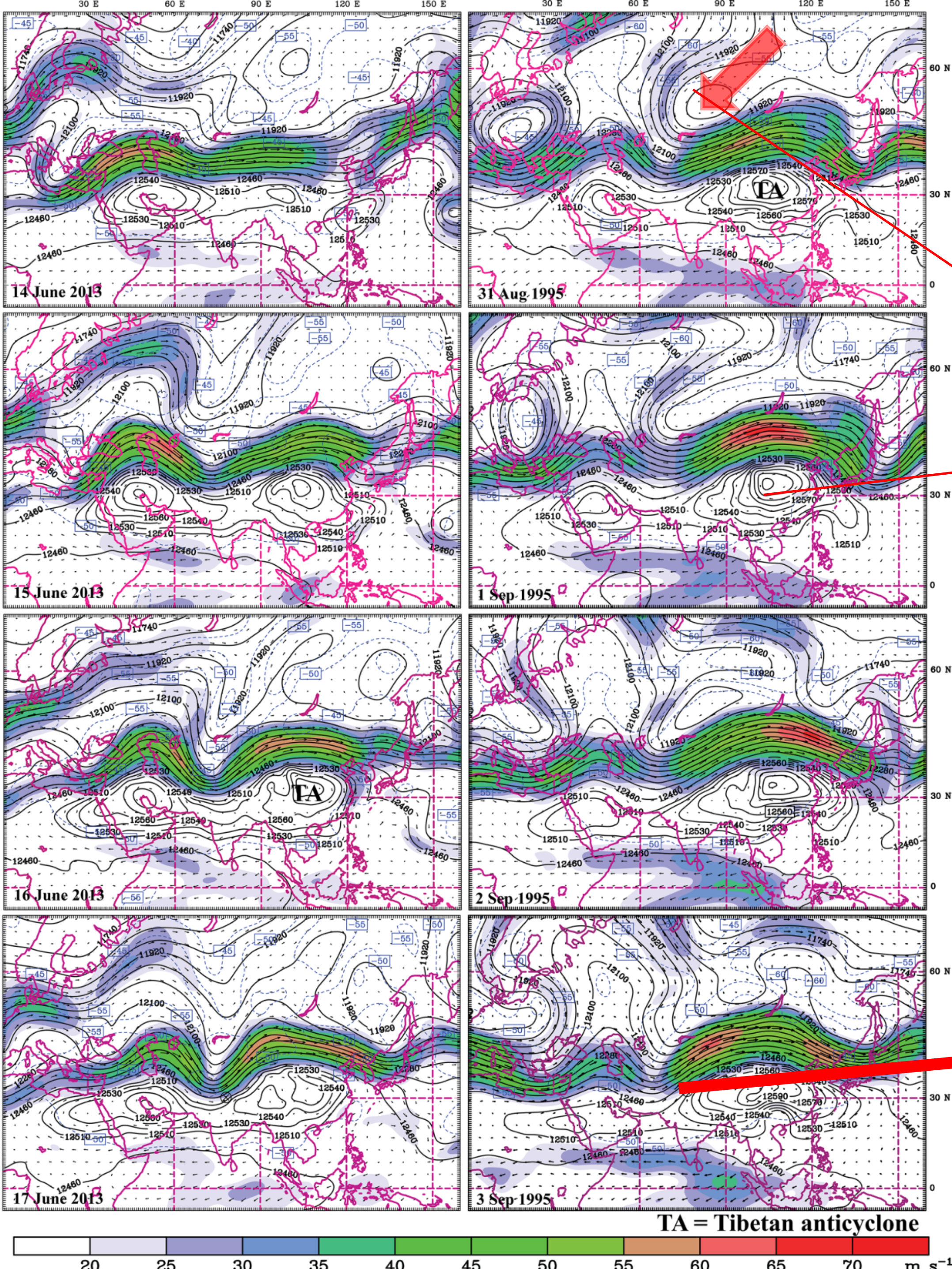
Maximum rainfall amount (mm) occurred within the box region encompassing 28°N–35°N and 75°–85°E and the day of the occurrence of the extreme event

No.	Day of the extreme event	Maximum rainfall (mm)
1	12 Aug 1979	344
2	8 Jul 1980	332
3	17 Jul 1980	217
4	29 Sep 1981	334
5	6 Jun 1982	415
6	13 Sep 1982	364
7	20 Sep 1983	357
8	11 Jul 1986	267
9	22 Jul 1988	264
10	9 Aug 1988	283
11	24 Sep 1988	408
12	25 Sep 1988	269
13	26 Sep 1988	285
14	27 Sep 1988	220
15	28 Aug 1989	252
16	10 Jul 1990	305
17	21 Jul 1992	272
18	11 Jul 1993	415
19	12 Sep 1993	277
20	16 Aug 1994	321
21	9 Sep 1994	241
22	10 Sep 1994	347
23	4 Sep 1995	360
24	5 Sep 1995	424
25	23 Aug 1996	231
26	2 Aug 1997	235
27	17 Sep 2005	207
28	16 Sep 2006	214
29	31 Jul 2008	460
30	20 Sep 2008	351
31	25 Jul 2009	301
32	16 Aug 2011	234
33	**17 Jun 2013**	**367**
34	**18 Jun 2013**	**229**

A classic example- Uttarakand rain episode (17-18 June 2013)

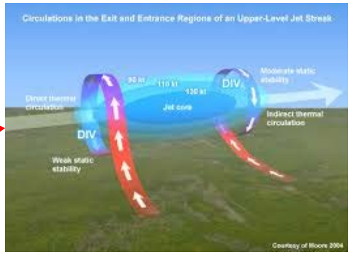




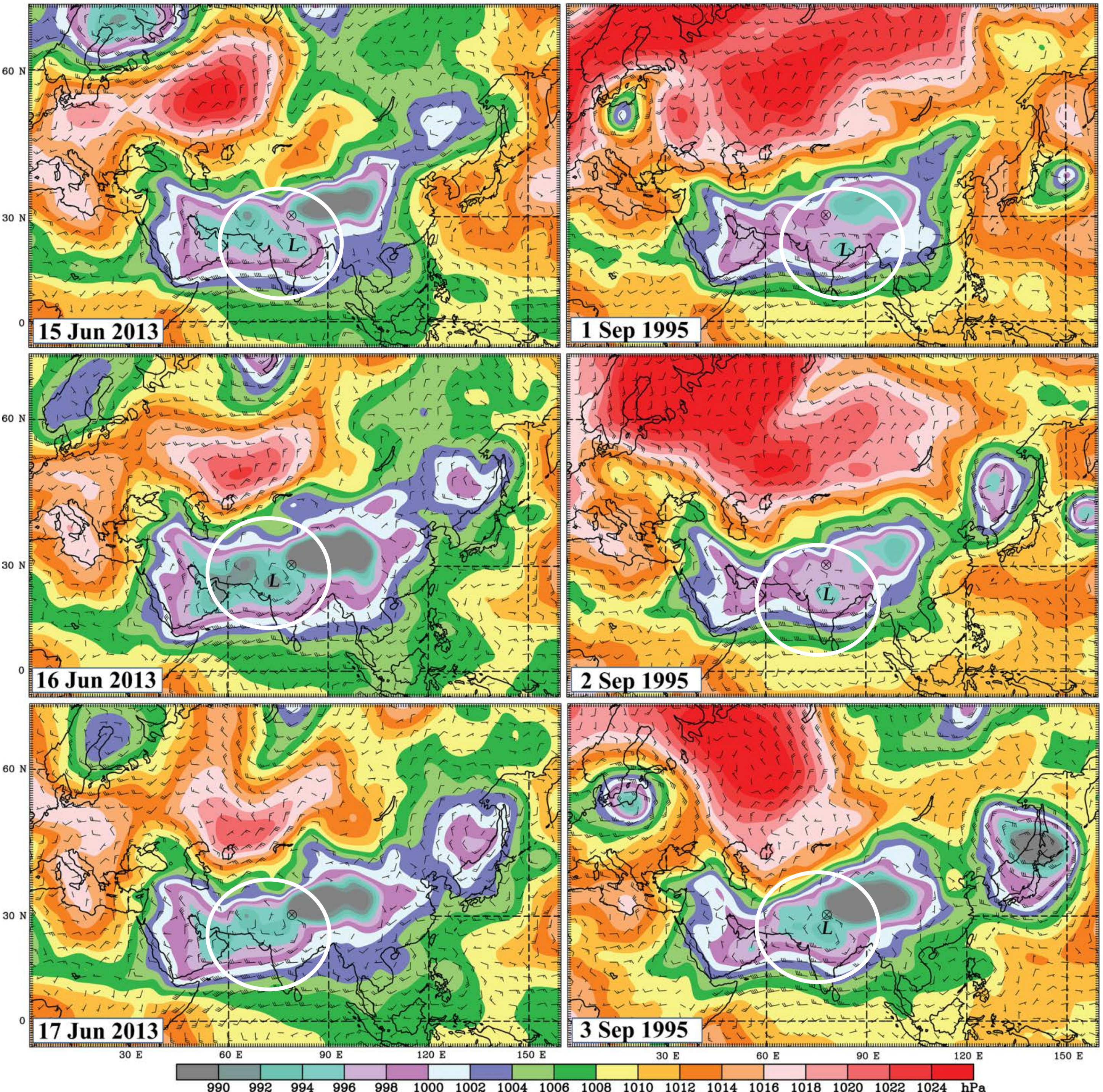


Sequence of dynamical processes Vellore et al. (2016)

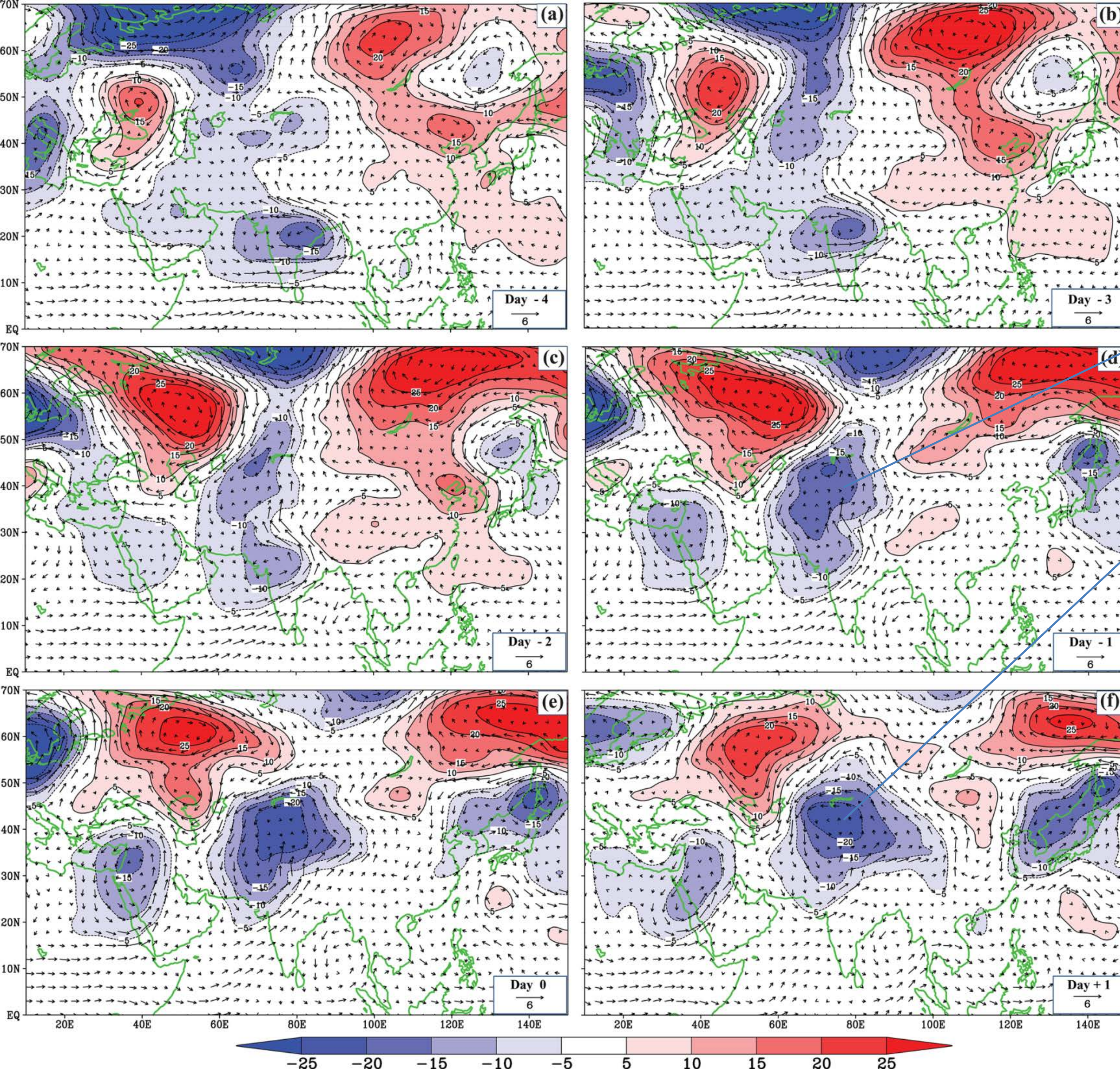
- Monsoon conditions are relatively not stronger as seen during active-monsoon periods.
- Upper level circulation commence with extratropical Rossby wave breaking signatures
- Splitting of Tibetan anticyclone (TA)
- Deeper equatorward penetrating large-amplitude troughs
- Interactions with monsoon circulation in phase with passage of low pressure systems from Bay of Bengal
- Jet acceleration & secondary circulation dynamics in concert with orographic ascent of air along the foothill region



- Extreme rainfall over the western Himalayan foothills


15 Jun 2013
1 Sep 1995
16 Jun 2013
2 Sep 1995
17 Jun 2013
3 Sep 1995
60 N
30 N
0
30 E
60 E
90 E
120 E
150 E
L
990 992 994 996 998 1000 1002 1004 1006 1008 1010 1012 1014 1016 1018 1020 1022 1024 hPa

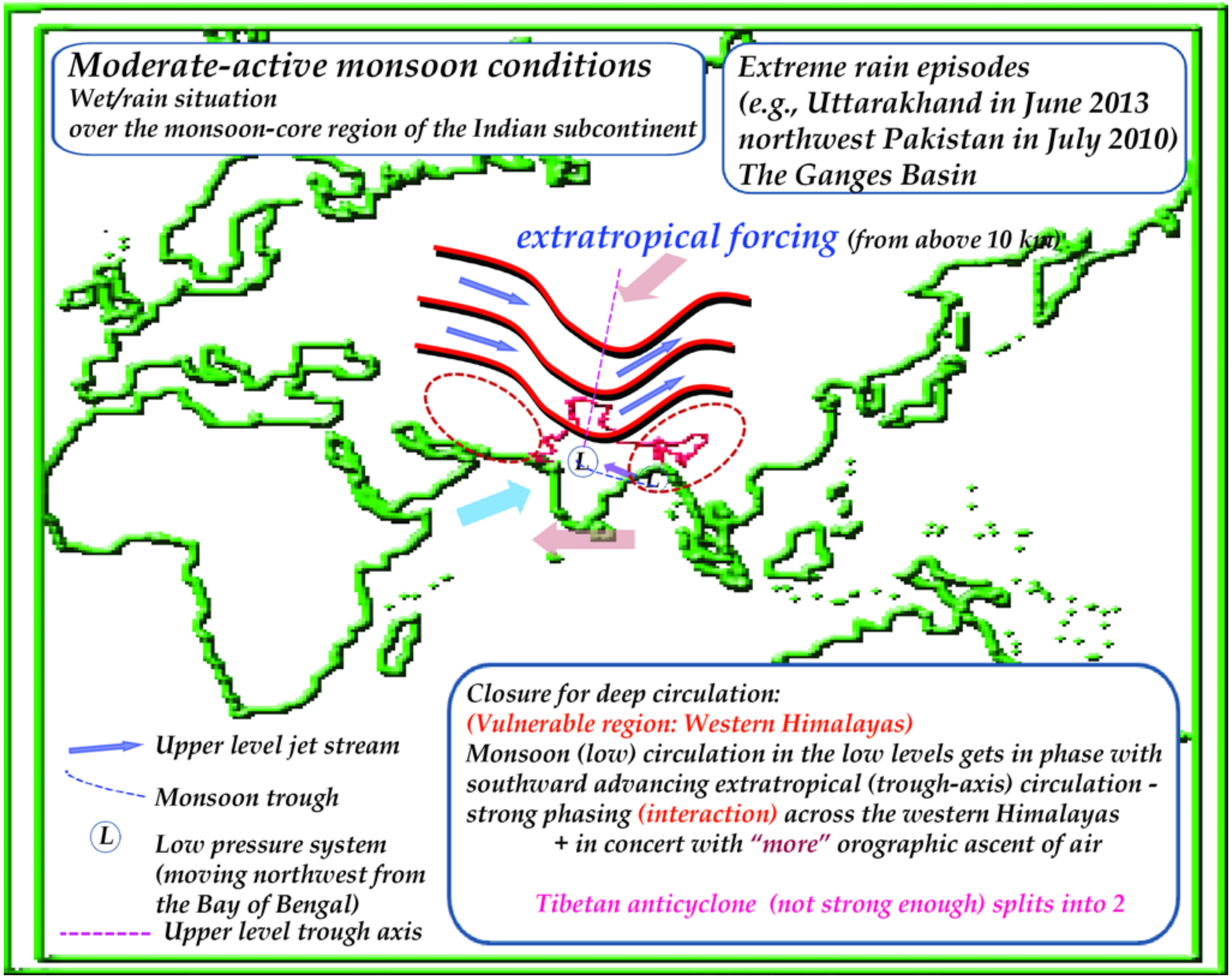
A composite map of daily anomalous circulation fields (horizontal winds–vectors; and geopotential height–*shaded*; units in meters) at 500 hPa



Source of Mid-level Vorticity

Isentropic PV

Anticyclonic Wave breaking



Moderate active monsoon conditions

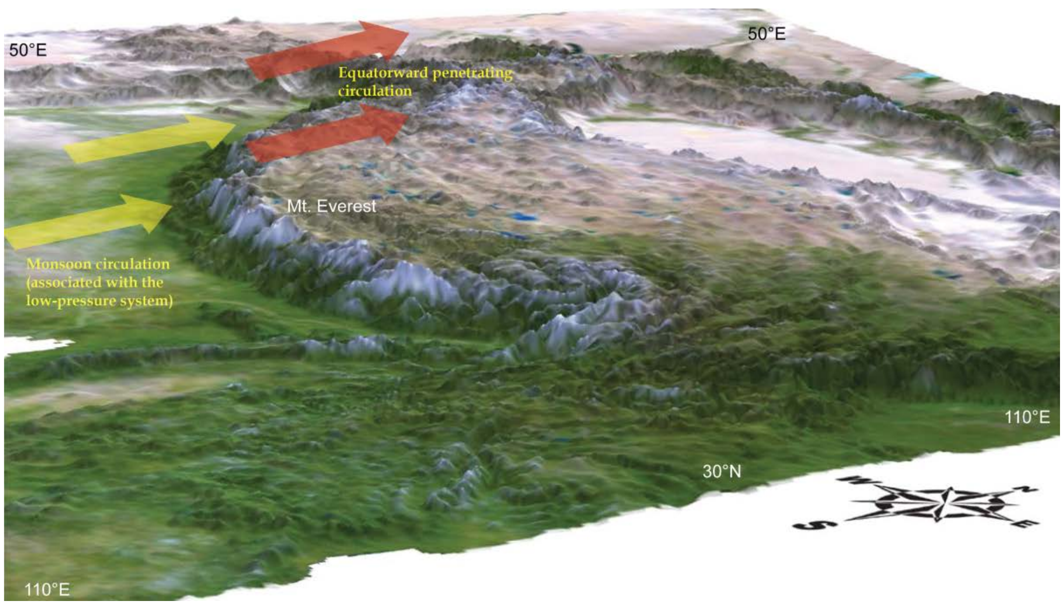
- *A moderate strength of monsoon circulation (winds slightly weaker than "very active" mentioned before)*
- *An initially weakening Tibetan anticyclone*
- *A weak and rapidly moving low-pressure system from the Bay of Bengal towards the northwestern part of India*
- *Monsoon trough signatures can either be present or absent.*
- *Tropical easterly jet can either be present or absent*
- *Monsoon rainfall amounts over the monsoon-core central India is nearly half as opposed to "very active" conditions*

Due to weakening of the Tibetan anticyclone at the upper levels, any upper level forcing triggered at extratropical latitudes will penetrate equatorward, the penetration is further amplified by the splitting of the Tibetan anticyclone into two. When the flow from the northwestward passing low-pressure system comes in phase with this penetrating flow, the flow is directed towards the western Himalayan foothill region. This is when the severity of the weather commences.

Monsoon-extratropical circulation interactions

Vellore et al. (2015). Monsoon-extratropical circulation interactions in Himalayan extreme rainfall. Clim. Dyn.

- ***Interactions are viewed as follows:***
  - ***Low-level** tropical monsoon circulation interacts with **upper level** circulation from the extratropics, and the zone of interaction is the southern slopes of the Himalayas.*



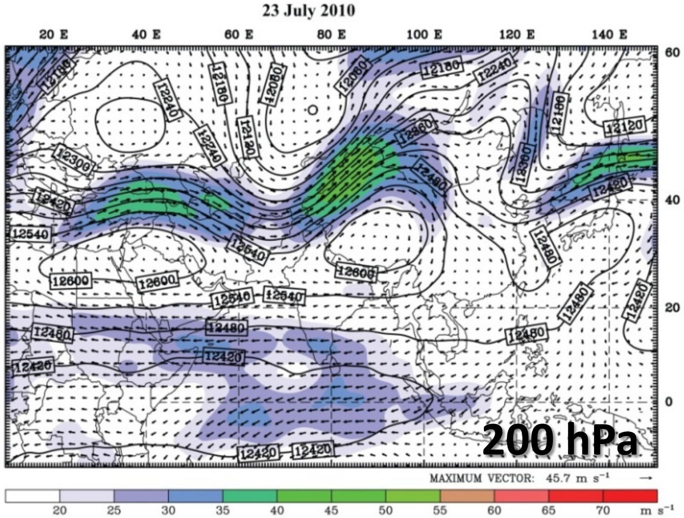
What the interactions provide:

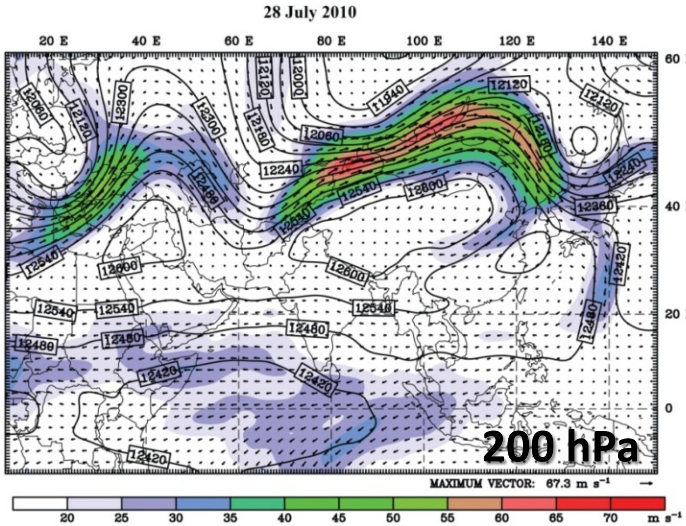
A closure for deep circulation (upward; connecting low-level monsoon circulation and southward penetrating extratropical circulation) in the vertical near the foothills.

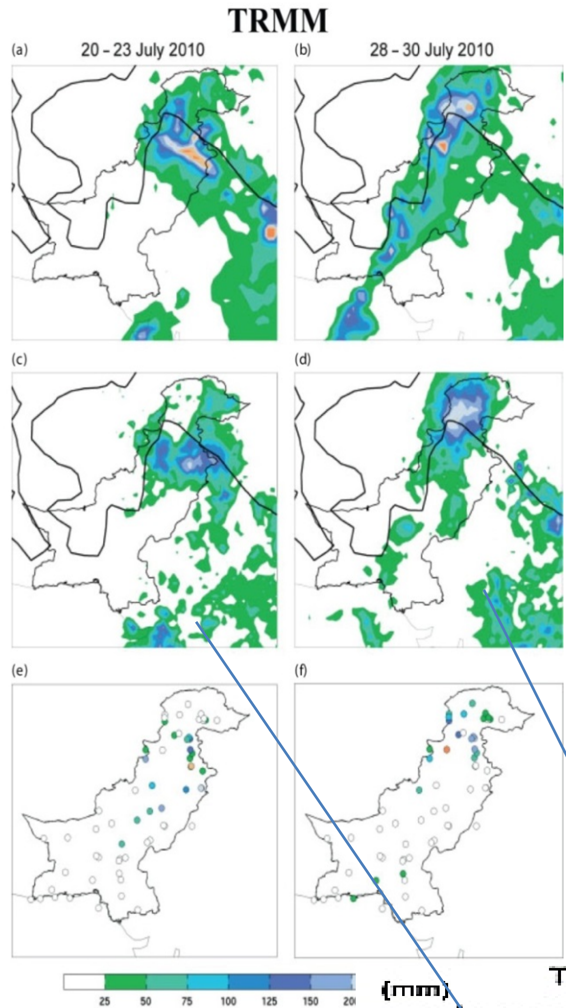
Since the monsoon flow is normal to the Himalayan barrier, further mechanical uplift of air by the Himalayan orography intensifies this closure.

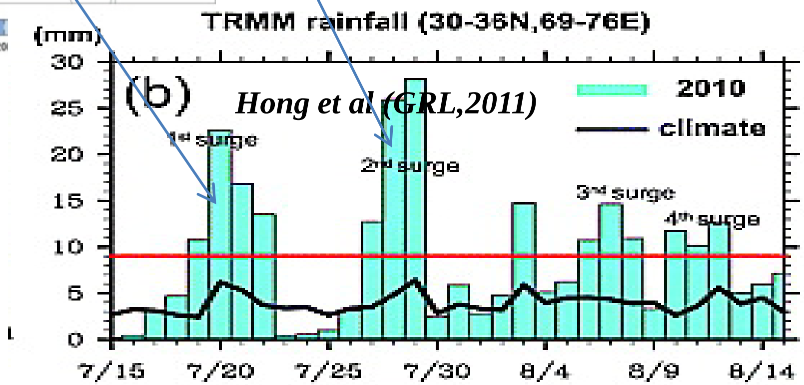
Highlight of this study: Moderate-active monsoon conditions juxtaposed with equatorward penetrating extratropical circulation favors intense flood-producing rainfall over the western part of the Himalayas.
(e.g., classic example includes the Uttarakhand episode during June 2013)

Another classic example : Pakistan floods in July 2010

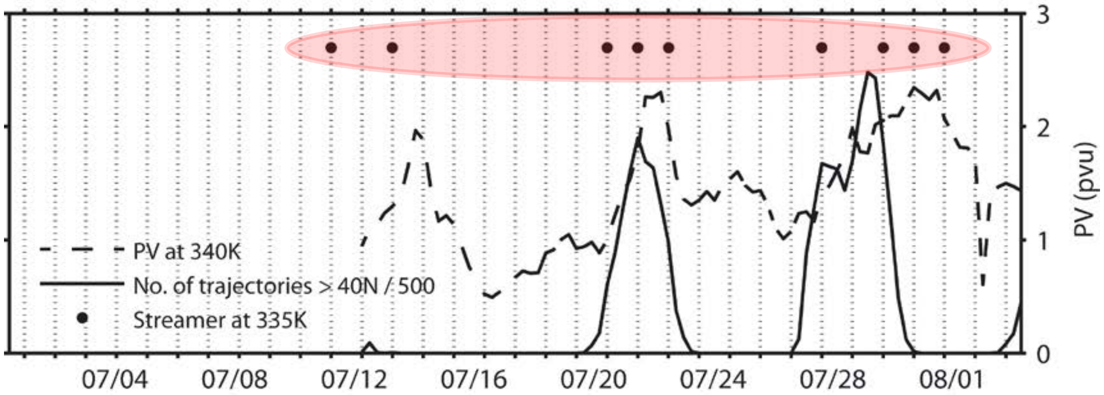








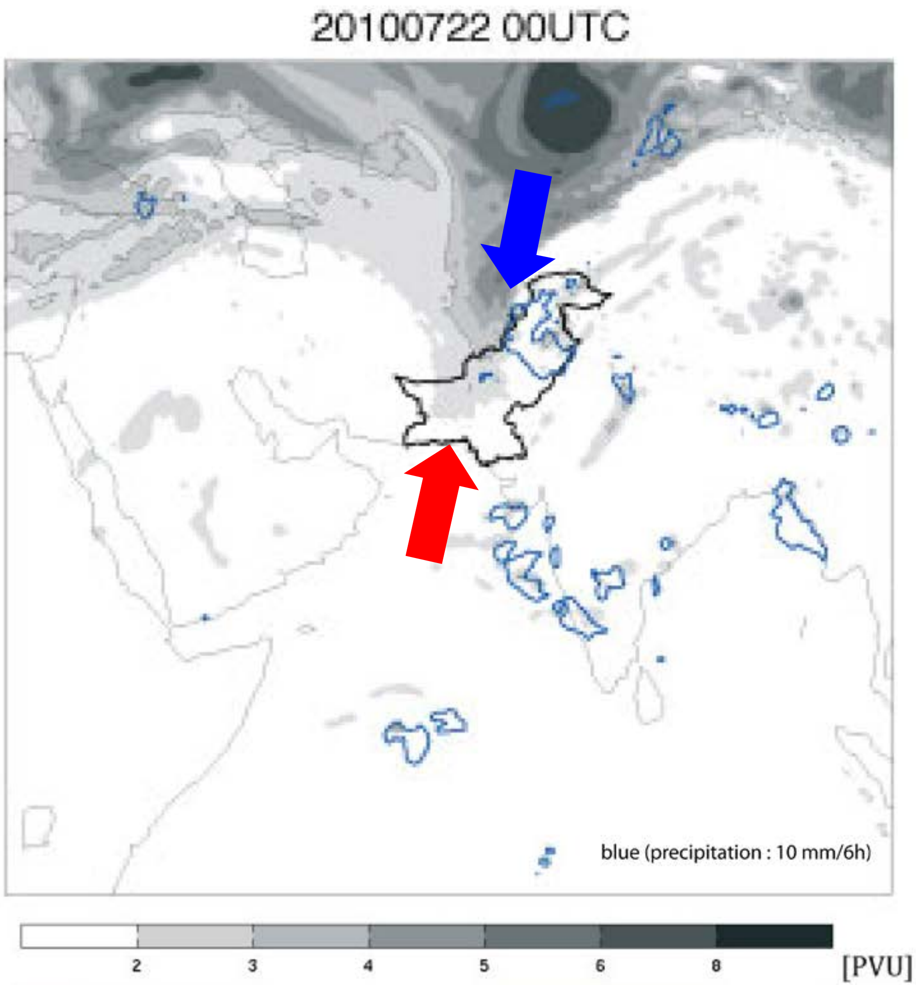
Upper air circulation signals have similarities with extratropical wave breaking and splitting of Tibetan anticyclone



objectively identified wave-breaking events on 335 K (dots)

Area mean PV (60◦E–70◦E, 30◦N–40◦N, dashed line)

Martius et al. (2013)



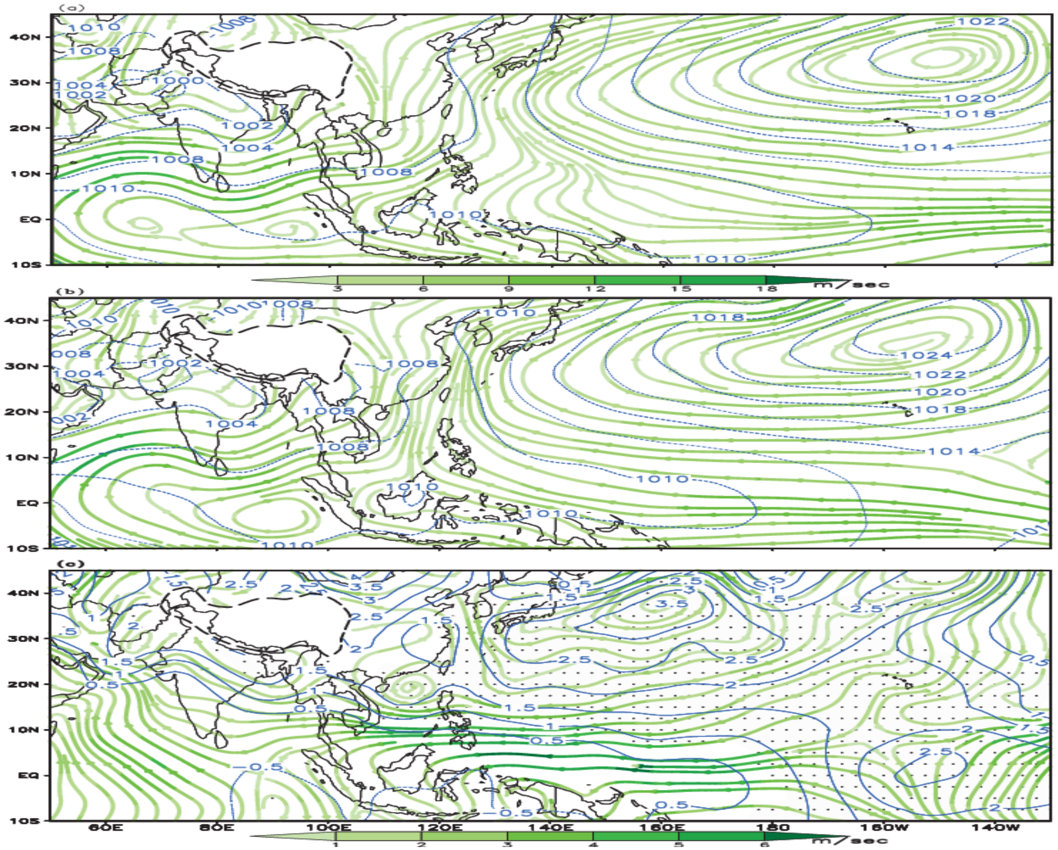
Precipitation was organized and invigorated by upper-level positive PV anomalies that reached Pakistan from the extratropics.

Monsoonal low-level flow features (heat-lows, Indian monsoon depression) were central for the transport and convergence of moist air into northeastern Pakistan

Moisture was transported towards northeastern Pakistan both from the Arabian Sea and the Bay of Bengal.

A long-lived (persistent for about two months) blocking pattern over Europe and Russia and penetration of extratropical PV and concurrent interactions with monsoon surges and La Nina contribution indirectly to the flooding (Hong et al. 2011)

JJAS MSLP (blue contours) and Wind at 850 hPa (Stream-lines)



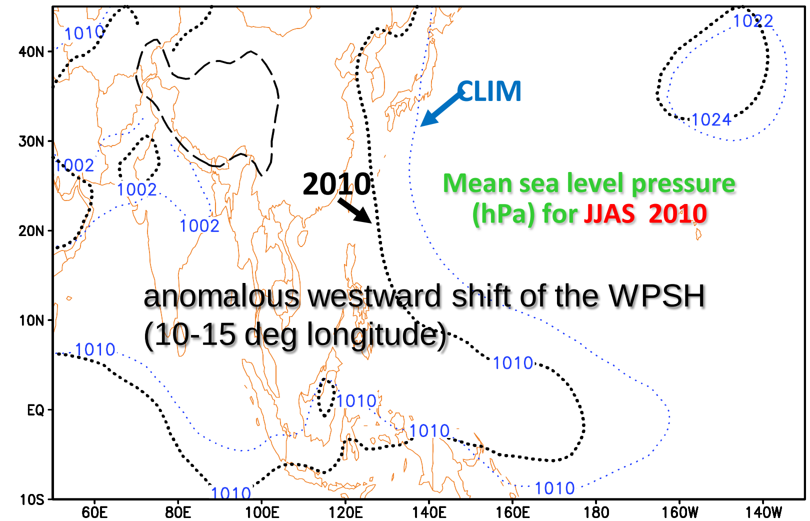
2010 Summer monsoon season observed series of devastating flood events over NW Indo-Pak region.

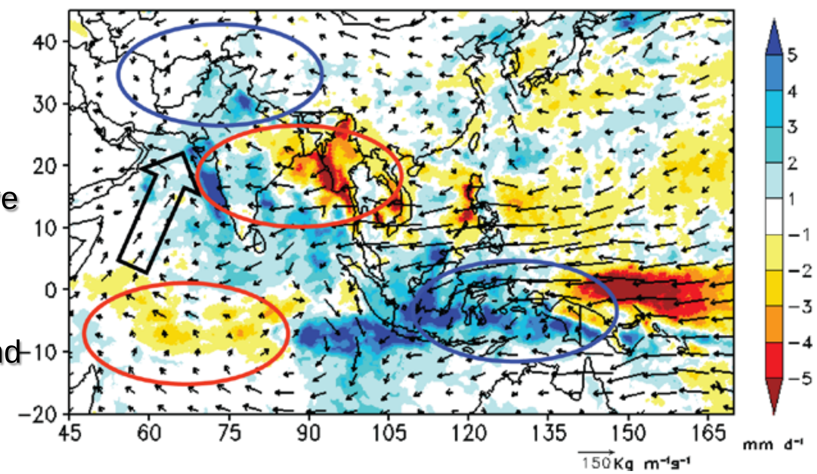
Houze et. al., (2011) attributed these flood events to Mesoscale convective system (MCS) with deep oceanic convection character in a high humid environment with emphasis on cloud systems producing the floods.

Atmospheric blocking events associated with high geopotential heights and surface temperatures over Eastern Europe were present during consecutive flood situations (2010-12) over Pakistan. Quasi-stationary synoptic conditions over the Tibetan plateau allowed for the formation of anomalous easterly mid-level flow across central India into Pakistan (Rasmussen et al. 2014).

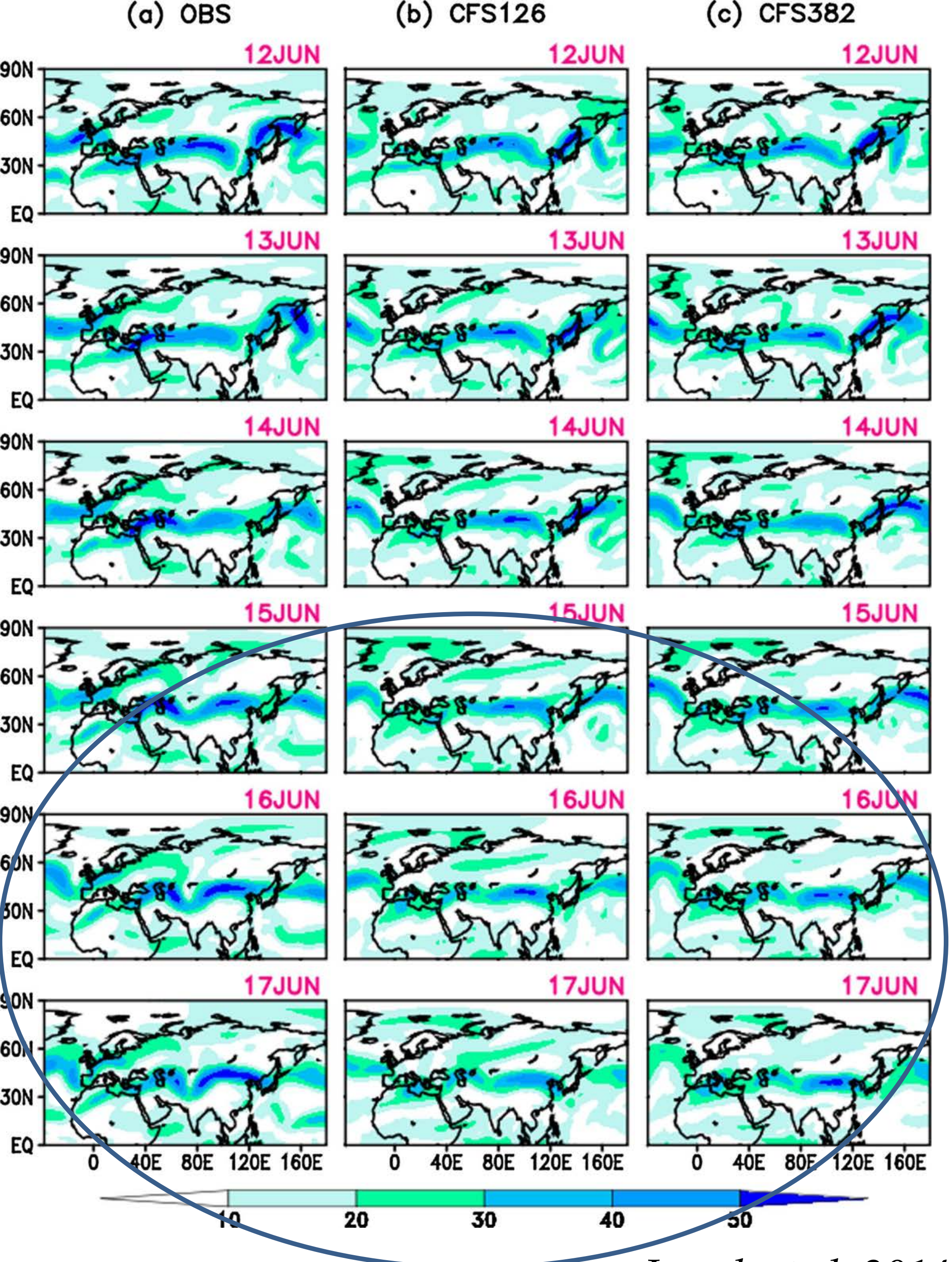
Large-scale seasonal features influencing these north-west Indo-Pak flood events during a typical La Nina year.

Mujumdar et al. (2012) focused on tropical influence in the evolution of extreme events over sub-tropical south-Asia.





Observation
TRMM (Rainfall) & NCEP (Moisture Transport)

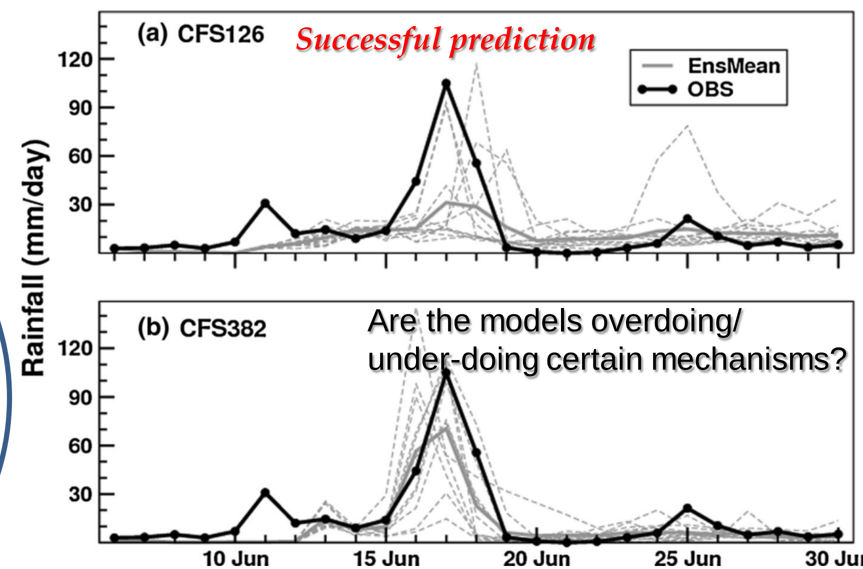


Joseph et al. 2014

Predictability of extreme events:

Upper level wave breaking, trough deepening and jet accelerations at the subtropical/extra-tropical latitudes are rather critical for interaction with the moist-laden monsoon circulation to result in extreme precipitation events over the western Himalayas (in concert with the orographic lift)

Susmitha Joseph, A.K.Sahai, S. Sharmila, S. Abhilash, N. Borah, R. Chattopadhyay, P.A. Pillai, M. Rajeevan, Arun Kumar: North Indian heavy rainfall event during June 2013: diagnostics and extended range prediction, Climate Dynamics (2014)



Extended range prediction of Uttarakhand rainfall event by CFS126 and CFS382 from 05 June initial condition. Rainfall values are averaged is 78°–80°E and 29°–31°N.

Attribution: Orography

Simulations & observations - Inferences

- Monsoon-extratropical interactions understandably provide intense Himalayan rainfall. However, subtleties in the strengths of monsoon and extra-tropical circulations govern the region of intense rainfall over the Himalayas.
- Moderately active monsoon conditions associated with low-pressure system passages provide support to intense rainfall over the western part of the Himalayas. The interactions between monsoon-equatorward penetrating midlatitude circulations provide a closure for deep circulation in the vertical, and further orography also lends a big hand in amplifying the precipitation amounts.
  - Examples: Uttarakhand rain episode in June 2013 and Pakistan floods in July 2010
  - Floods over the Indus Basin.
- Break monsoon conditions provide support to intense rainfall over the central-eastern part of the Himalayas (northeastern states of India) predominantly from the monsoon-extratropical interactions, i.e., not due to orographic effects.
  - During monsoon-breaks, the rain amounts in northeastern part of India is about 3 times the rain amounts obtained during active monsoon conditions in this region.
  - Floods in Assam and over the Brahmaputra River Basin.

Clim Dyn
DOI 10.1007/s00382-013-2024-1

On the anomalous precipitation enhancement over the Himalayan foothills during monsoon breaks

2014

Ramesh K. Vellore · R. Krishnan · Jayant Pendharkar · Ayantika Dey Choudhury · T. P. Sabin

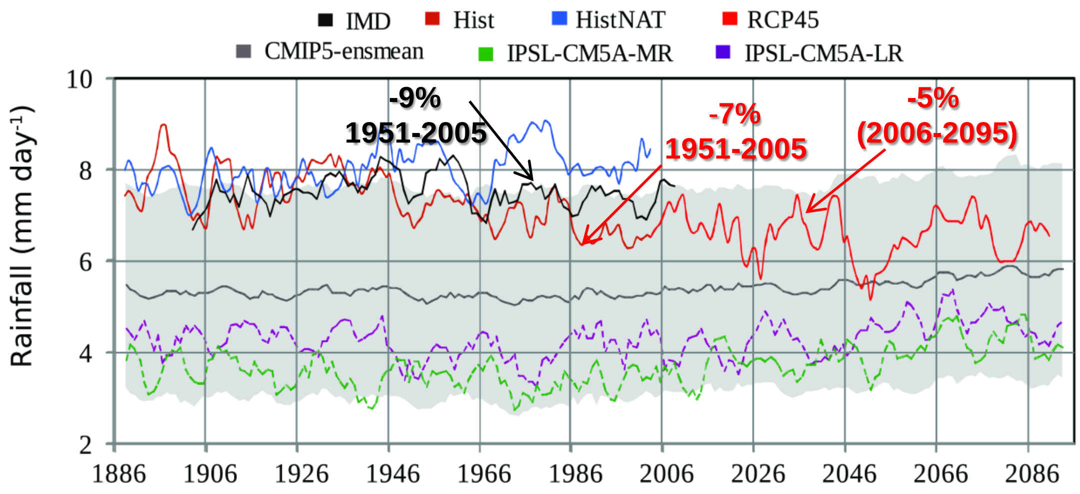
Clim Dyn
DOI 10.1007/s00382-015-2784-x

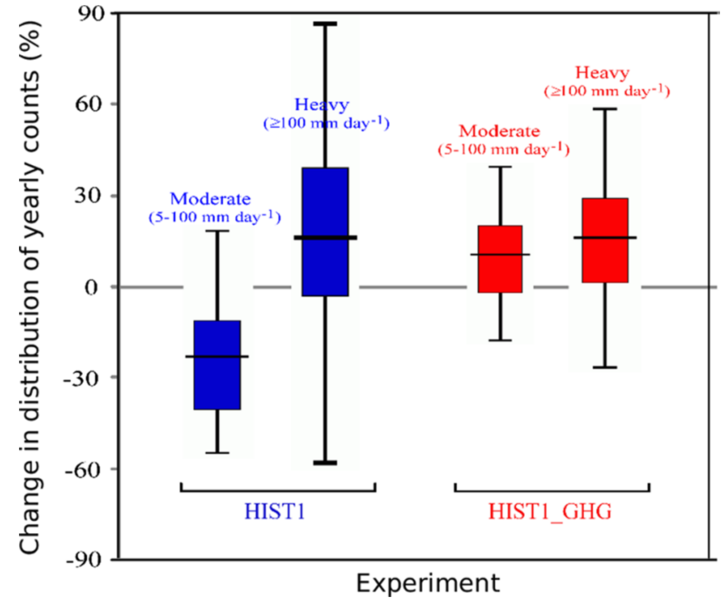
Monsoon-extratropical circulation interactions in Himalayan extreme rainfall

2016

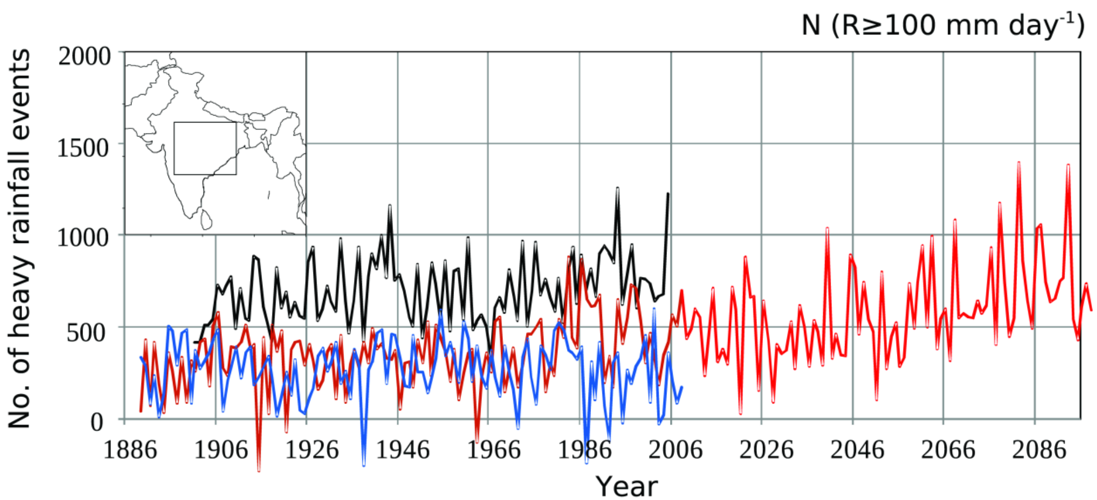
Ramesh K. Vellore [1] · Michael L. Kaplan [2] · R. Krishnan [1] · John M. Lewis [2,3] · Sudhir Sabade[1] · Nayana Deshpande[1] · Bhupendra B. Singh[1] · R. K. Madhura [1] · M. V. S. Rama Rao [1]

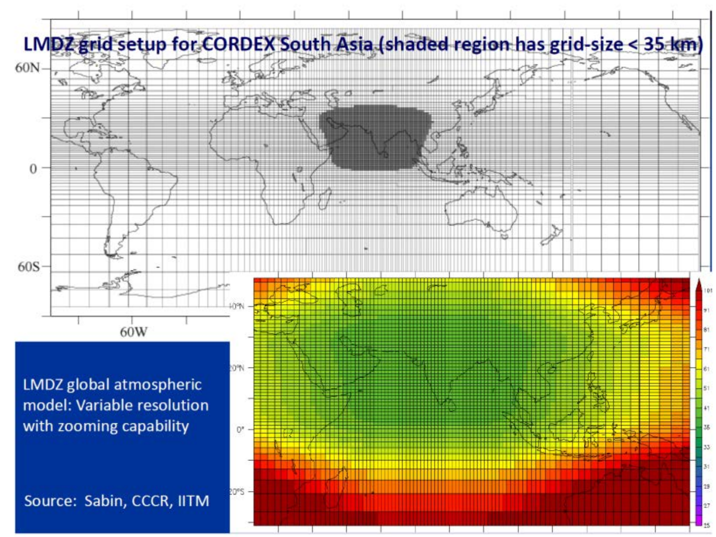
Indian summer monsoon precipitation – Observed and Simulated





Changes with respect to Natural forcing
Blue (all forcing)
Red (Greenhouse forcing)





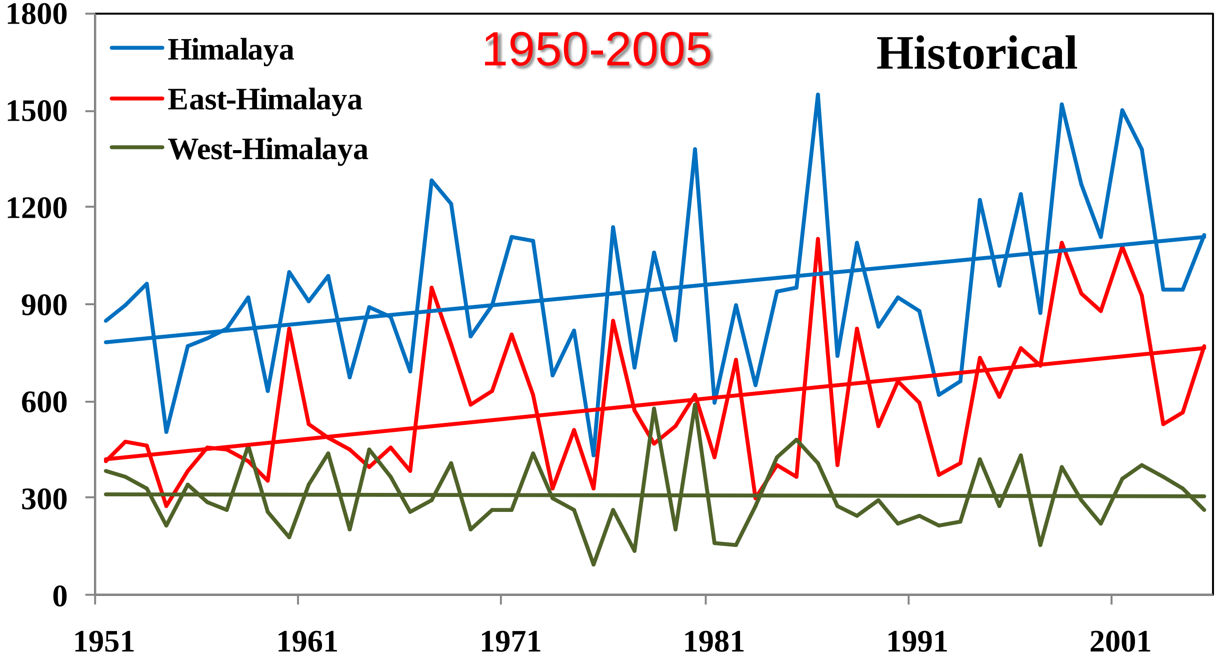
Clim Dyn
DOI 10.1007/s00382-015-2886-5

Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world

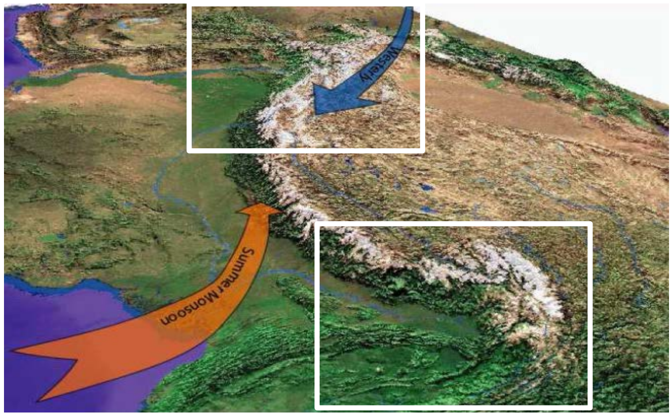
2016

R. Krishnan[1] · T. P. Sabin[1] · R. Vellore[1] · M. Mujumdar[1] · J. Sanjay[1] · B. N. Goswami[1,2] · F. Hourdin[3] · J.-L. Dufresne[3] · P. Terray[4,5]

LMDZ4-simulated over the Himalayas

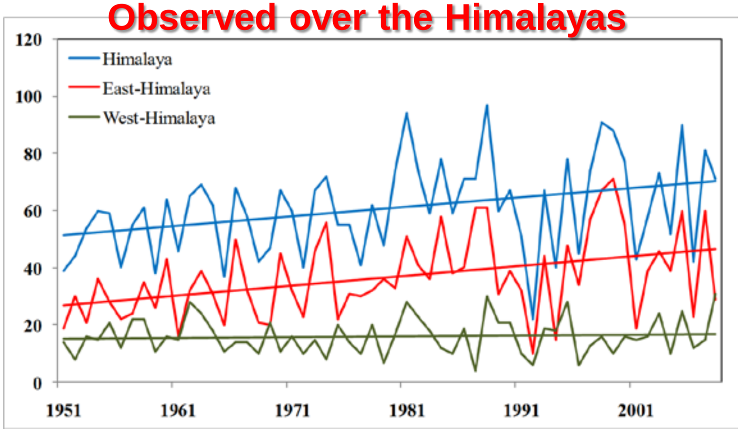


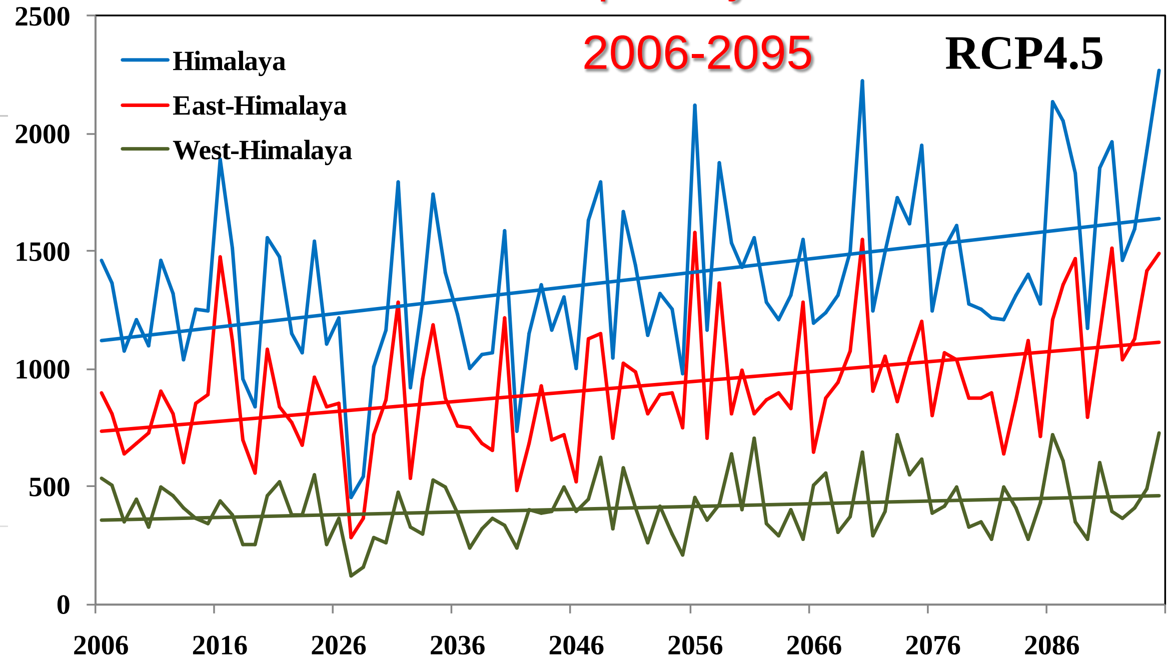
Courtesy:
T. P. Sabin



Propensity of monsoon-breaks

Observed over the Himalayas





Way to future

- **Future changes in precipitation extremes in a warming climate**
  - **Are Uttarakhand and Pakistan type of calamitous floods going to be frequent in future?**
- **Future changes in monsoon circulation and extratropical circulation and their interaction relevance to precipitation extremes in the Himalayas.**
  - **Polar amplification**
- **Changes in the large-scale teleconnections and their relevance to precipitation extremes**

Thank you