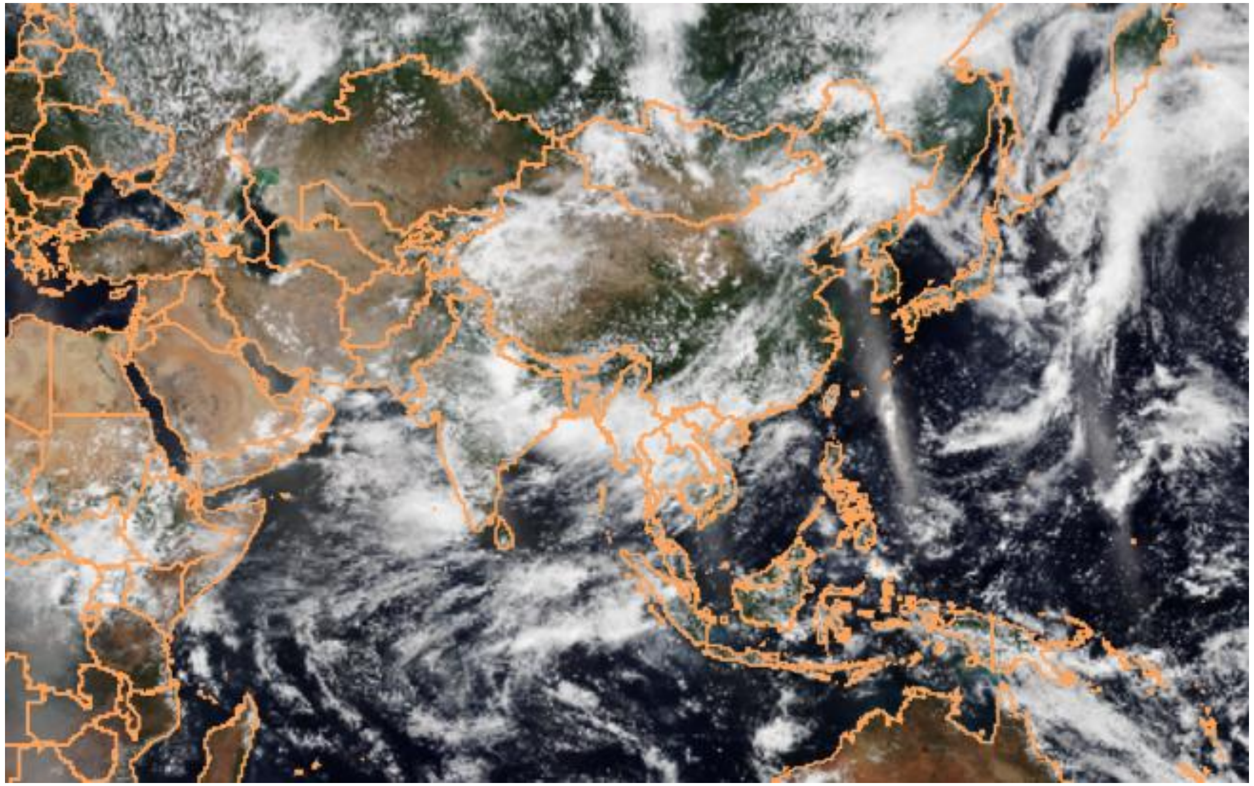
TPCF-3 and meeting of the TPRCC-Network Task Team, New Delhi

# Flood-Causing Precipitation Extremes in the Himalayan Region: Science-Based Insights for Policy Action

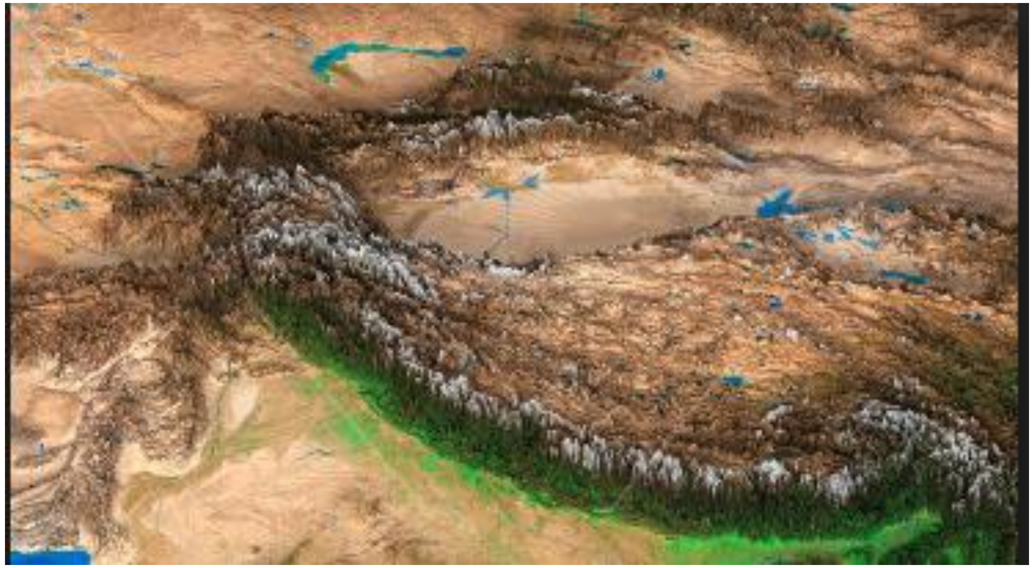



Ayantika Dey Choudhury

Centre for Climate Change Research

Indian Institute of Tropical Meteorology, India

# Why Focus on Himalayan Flood Causing Extremes?

**The Himalayas stretch between eight countries across Asia, is the world's tallest mountain range.**

**This region is the source of the 10 major river systems that provide irrigation, power and drinking water for over 1.5 billion people in Asia – nearly 20% of the world's population.**

**The region is increasingly vulnerable to flood-causing precipitation extremes, due to the diverse geographical settings:**

**Elevated Tibetan Plateau, glaciated high mountains, dry continental regions to the north and west, heavily precipitating monsoon systems to the south, bordered by the Indian and Pacific Oceans**

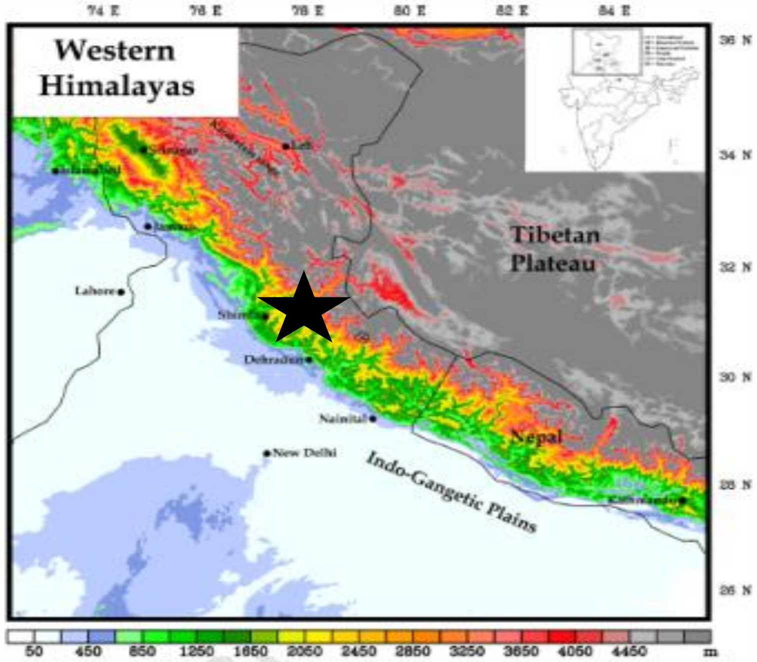
**Climate change intensifies the vulnerability through warming, altered precipitation patterns, and enhanced variability.**

**Recent disasters (eg: 2022 Pakistan floods) expose the limitations of current understanding, planning, and response systems.**

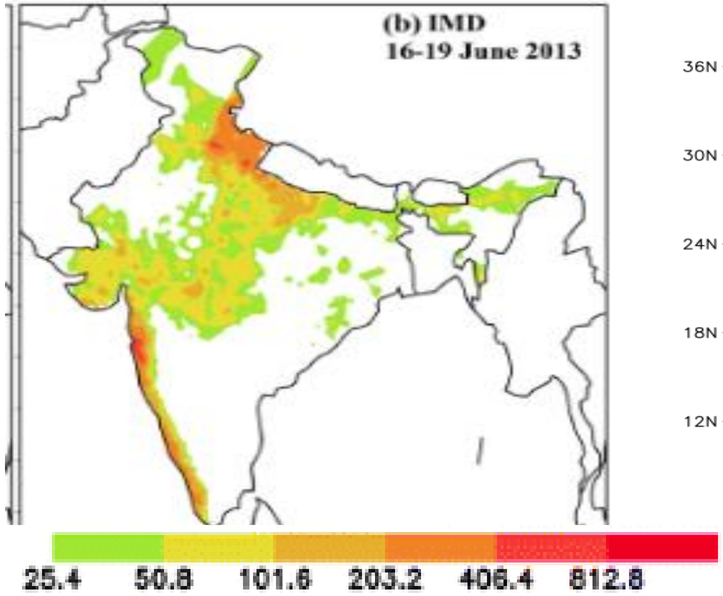
# Recent Precipitation Extremes - Causes, teleconnections, feedbacks, climate change signal, …

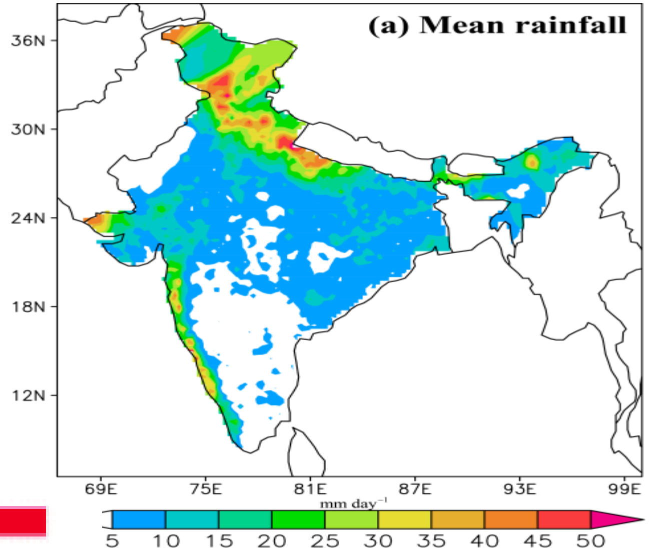
- June 2013, July 2023 Uttarakhand event: Heavy rainfall and floods over Northwest Himalayas – Monsoon and Mid-latitude interactions, moisture transport from north Indian ocean
- July-August 2022, 2010: Widespread and heavy rainfall and devastating floods in Upper Indus basin.
- Leh 2010 flash flood: Mesoscale convective systems over the high terrain
- Gaps in our understanding and Recommendations

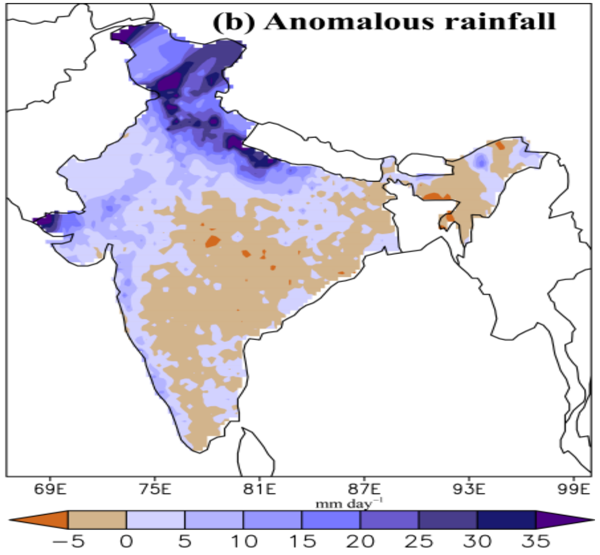
# 2013 Uttarakhand Floods







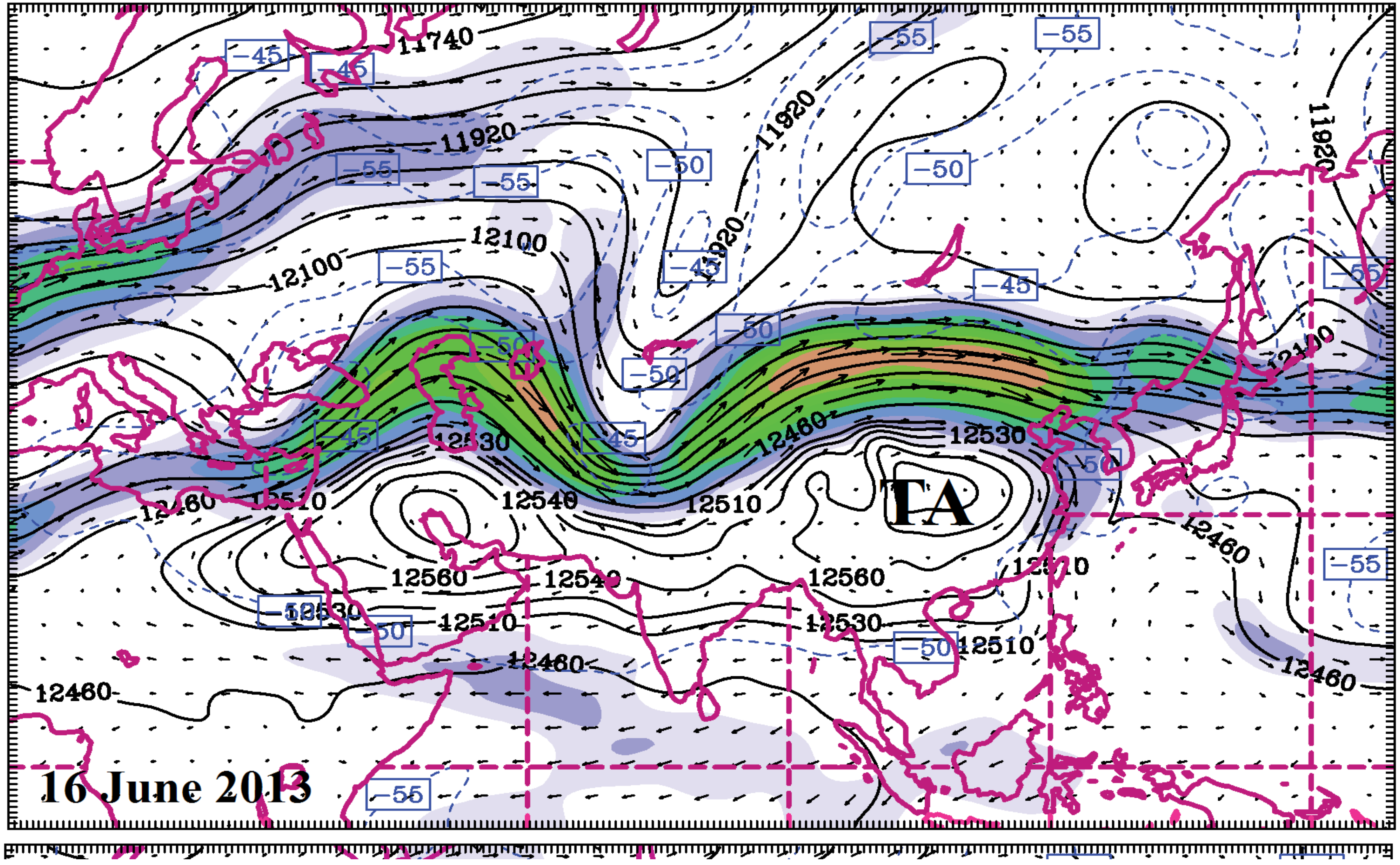




Composite of 34 heavy rain events (WH)

Vellore et al. 2015

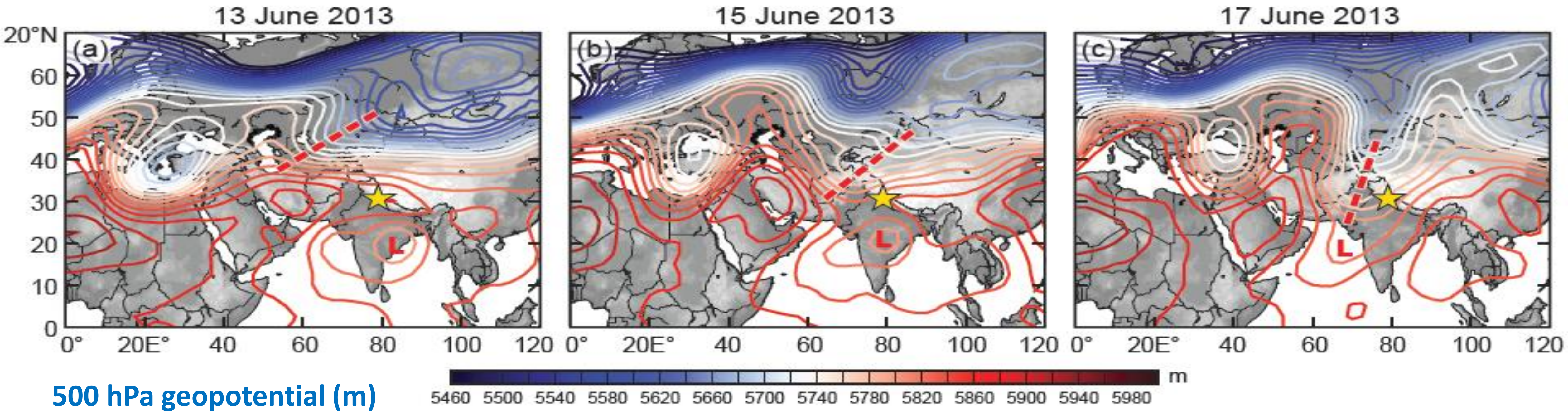
# Monsoon-extratropical circulation interactions in Himalayan extreme rainfall



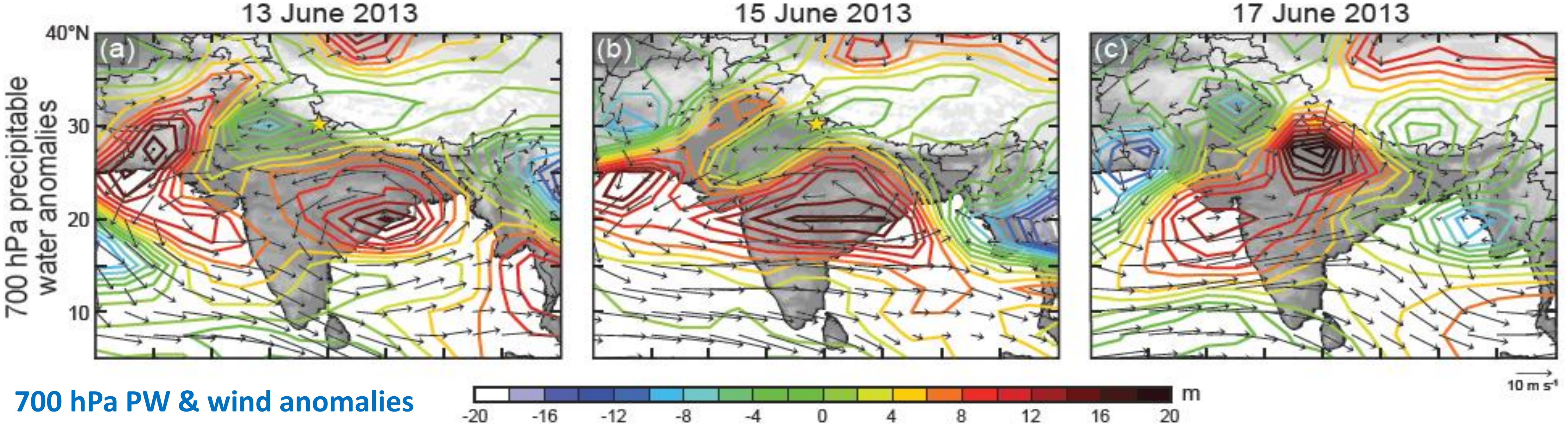

## 16-20 June 2013

Flood producing extreme precipitation (eg., 16-20 June 2013 and many other cases) over NW Himalayas: **Interaction between Monsoon & Extra-Tropical circulation**

Vellore et al. 2015

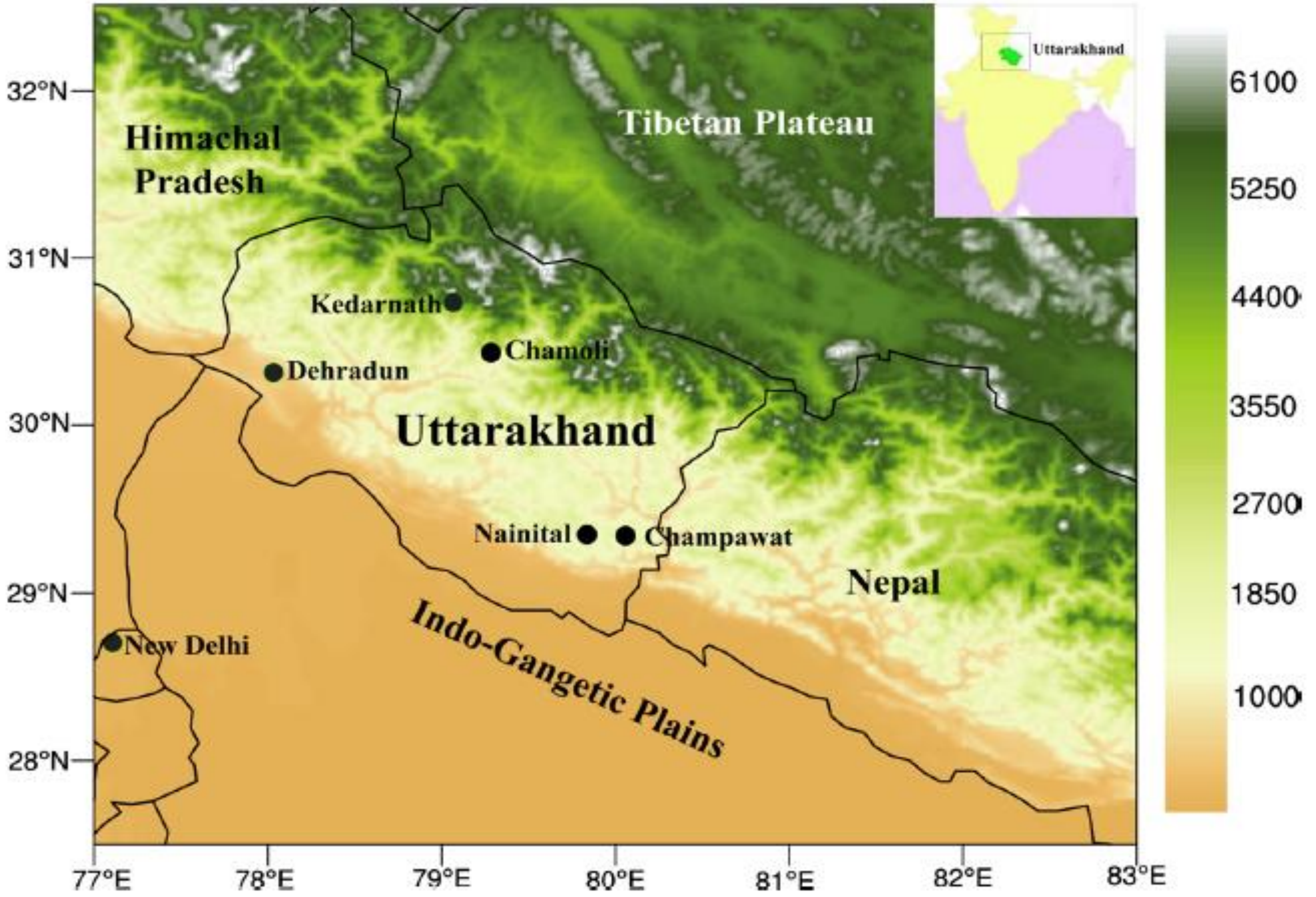



**500 hPa geopotential (m)**




**700 hPa PW & wind anomalies**

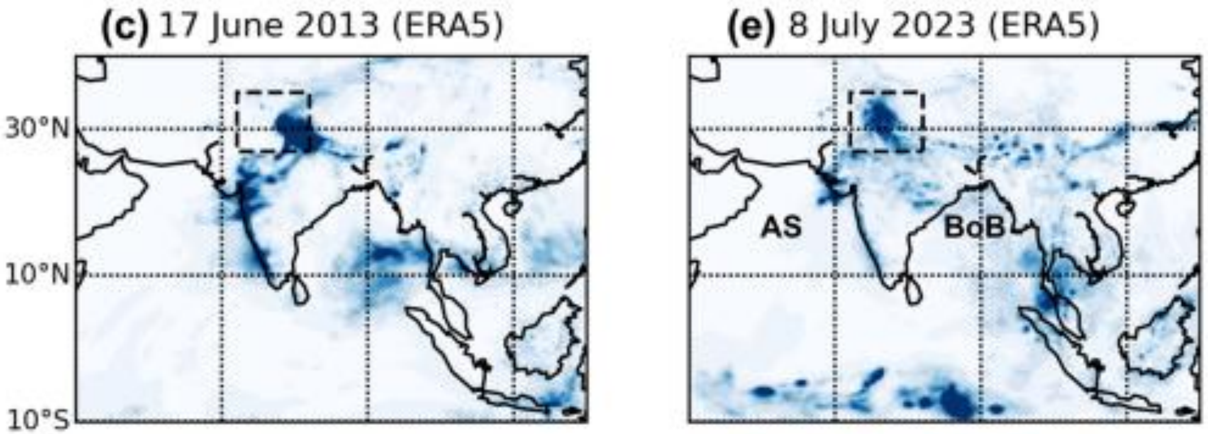
| Station name | Latitude (°N), longitude (°E) | Elevation (m) | Rainfall (mm) |
|---|---|---|---|
| Dehradun | 30.32, 78.05 | 667 | 370 |
| Purola | 30.87, 78.08 | 1503 | 410 |
| Haridwar | 29.92, 78.12 | 276 | 220 |
| Uttarkashi | 30.73, 78.43 | 1297 | 210 |
| Tehri | 30.37, 78.43 | 1672 | 170 |
| Mussorie | 30.46, 78.07 | 1836 | 150 |
| Devprayag | 30.14, 78.60 | 785 | 160 |
| Roorkee | 29.84, 77.92 | 254 | 150 |
| Kirtinagar | 30.21, 78.75 | 748 | 100 |
| Rudraprayag | 30.28, 78.98 | 973 | 90 |
| Karnaprayag | 30.26, 79.22 | 981 | 90 |
| Jollygrant | 30.19, 78.18 | 553 | 224 |
| Ranichauri | 30.20, 78.52 | 1592 | 205 |
| Rishikesh | 30.11, 78.28 | 371 | 145 |
| Kalsi | 30.53, 77.84 | 558 | 391 |
| Srinagar | 30.22, 78.77 | 688 | 133 |
| Mukteshwar | 29.46, 79.66 | 2047 | 240 |
| Kausani | 29.84, 79.60 | 1673 | 210 |
| Haldwani | 29.22, 79.51 | 424 | 200 |
| Nainital | 29.36,79.46 | 1747 | 180 |
| Champawat | 29.34, 80.09 | 1650 | 100 |
| Pithoragarh | 29.57, 80.23 | 1523 | 69 |
| Almora | 29.59, 79.65 | 1432 | 90 |
| Matela | 29.62, 79.62 | 1211 | 97 |
| Pantnagar | 29.02, 79.48 | 232 | 58 |
| Ramnagar | 29.39, 79.11 | 354 | 56 |
| Ranikhet | 29.64, 79.42 | 1700 | 43 |
| Pati | 29.40, 79.93 | 1520 | 206 |
| Lohaghat | 29.40, 80.09 | 1670 | 139 |
| Sitarganj | 28.93, 79.70 | 198 | 75 |
| Gangolihat | 29.65, 80.04 | 1718 | 103 |
| Bageshwar | 29.83, 79.77 | 1020 | 160 |
| Joshimath | 30.55, 79.57 | 2146 | 110 |
| Jakholi | 30.39, 78.89 | 1539 | 110 |
| Chamoli | 30.29, 79.56 | 2199 | 80 |
| Tharali | 30.07, 79.50 | 1458 | 170 |
| Bharsar | 30.05, 79.00 | 2247 | 122 |
| Dhanauri | 29.93, 77.97 | 269 | 151 |
| Mean | | | 157.5 |

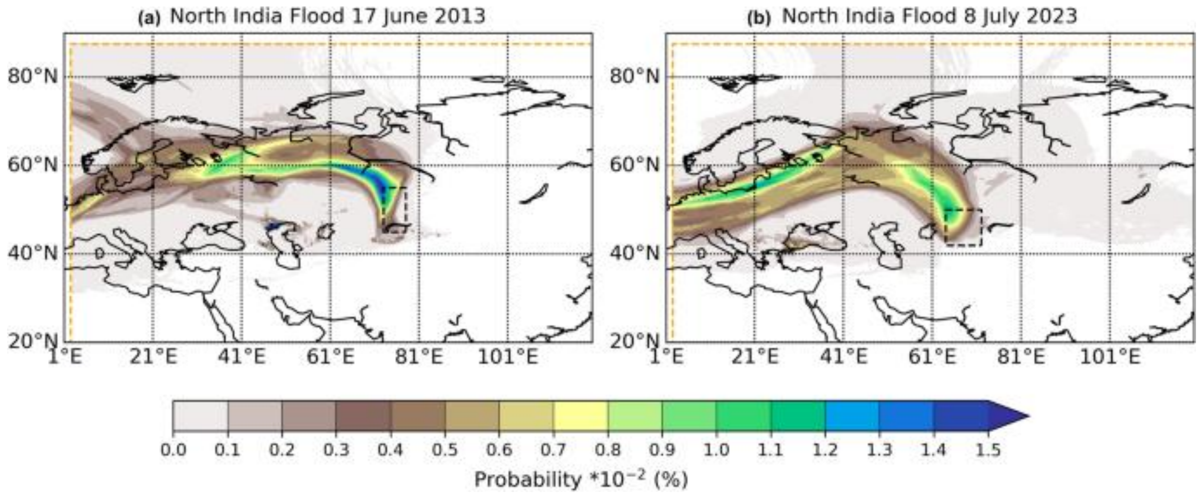



Observed 24-h precipitation accumulations (mm) ending at 0300 UTC 17 June 2013 over the Uttarakhand region (see also Kotal et al. 2014, Ranalkar et al., 2016a, b)

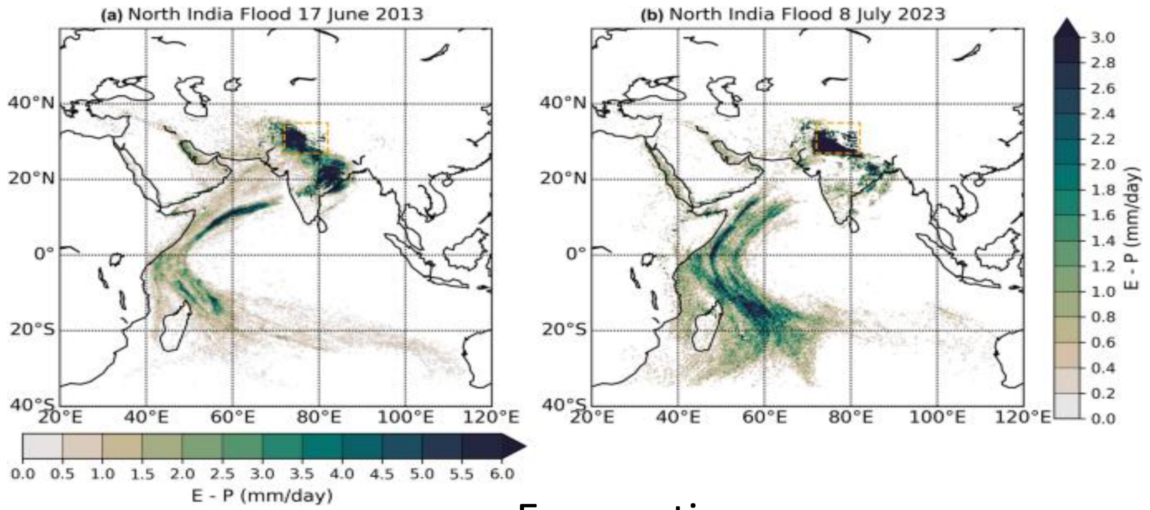
**Vellore et al. 2020**

# Comparing events a decade apart over the same region




Upper level 10-day back trajectory



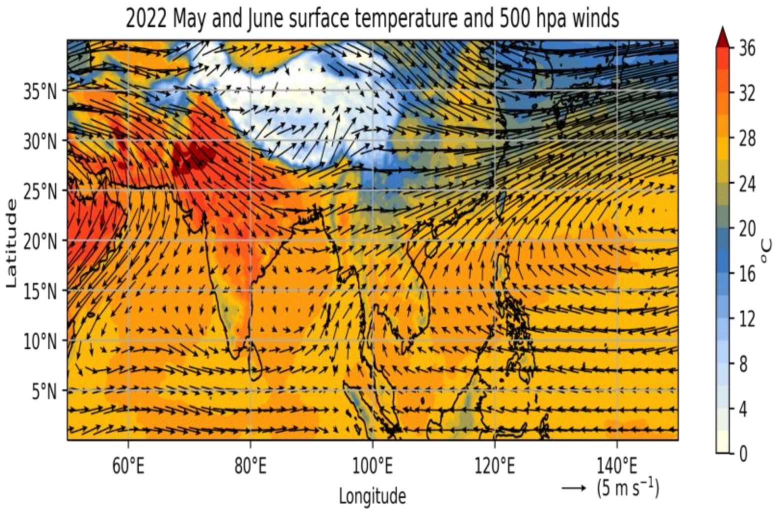

Evaporative sources

- Southward movement of the subpolar jet stream creates a trough in the subtropical jet stream (both years)
- In 2013, inland moisture was transported by two LPS
- In 2023, evaporative sources near Madagascar and the western Indian Ocean were key contributors

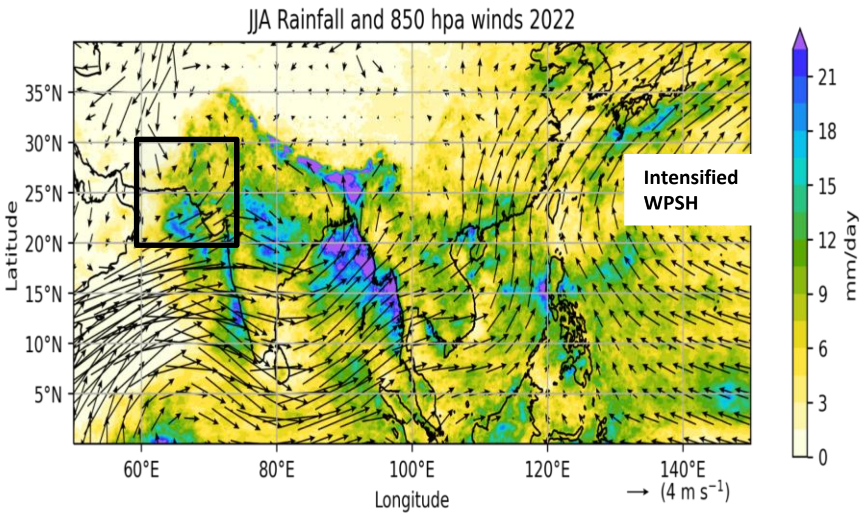
**Dey et al. 2025**

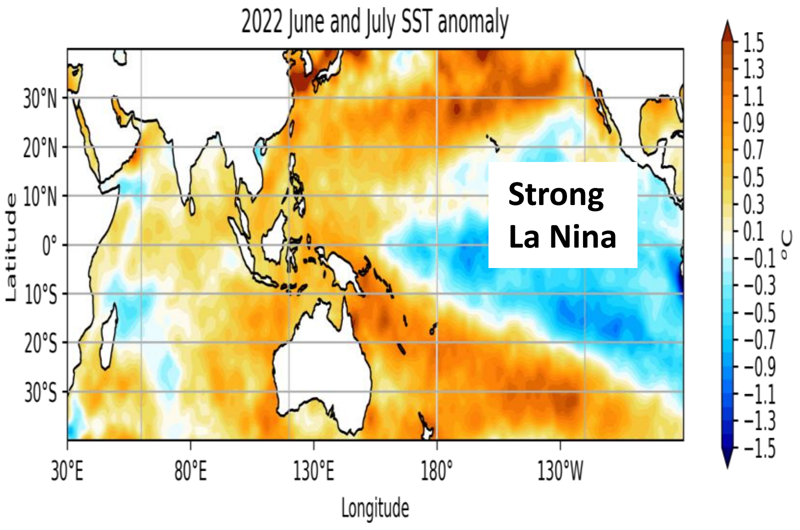
# 2022 Indus Basin Floods : One of the worst disasters in recent years (Compounding extreme)

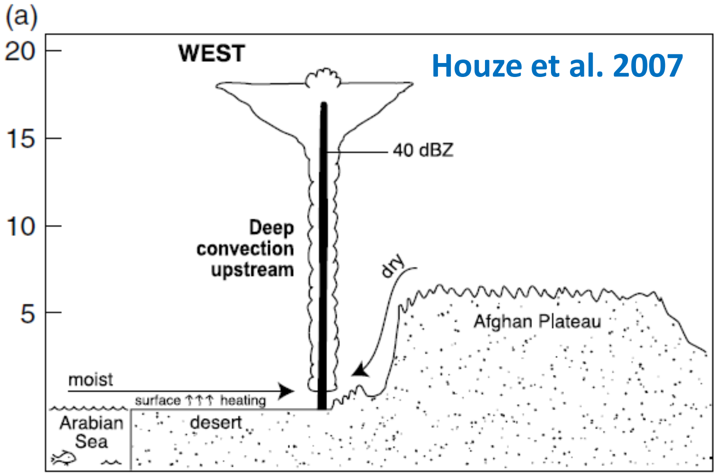
## Pre-Monsoon
## May and June 2022

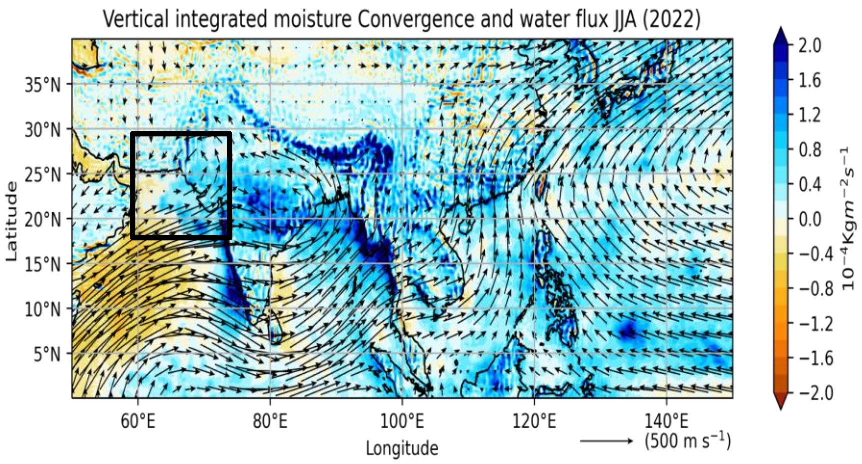


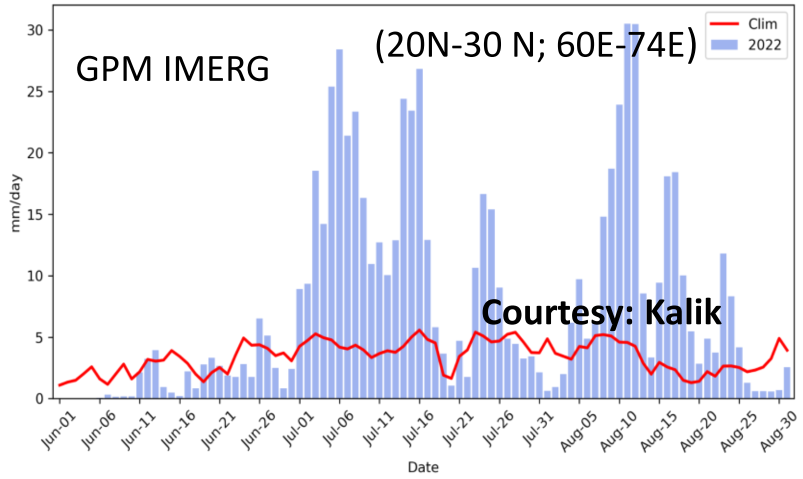

## Summer Monsoon
## June-July-August 2022



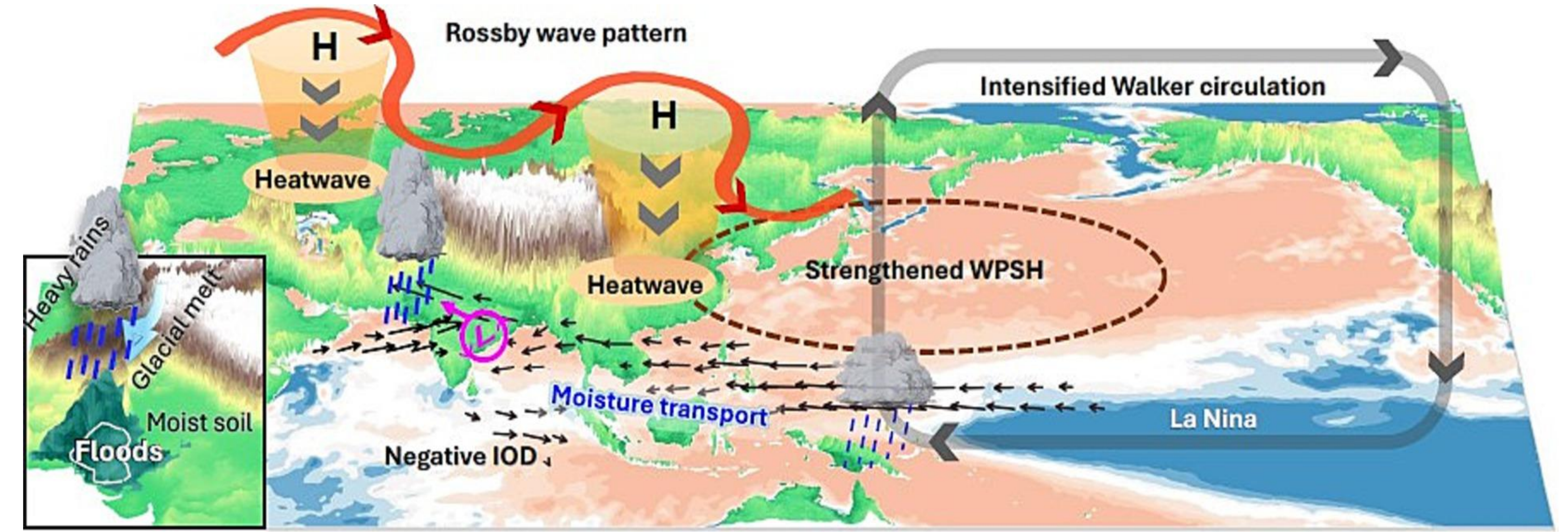



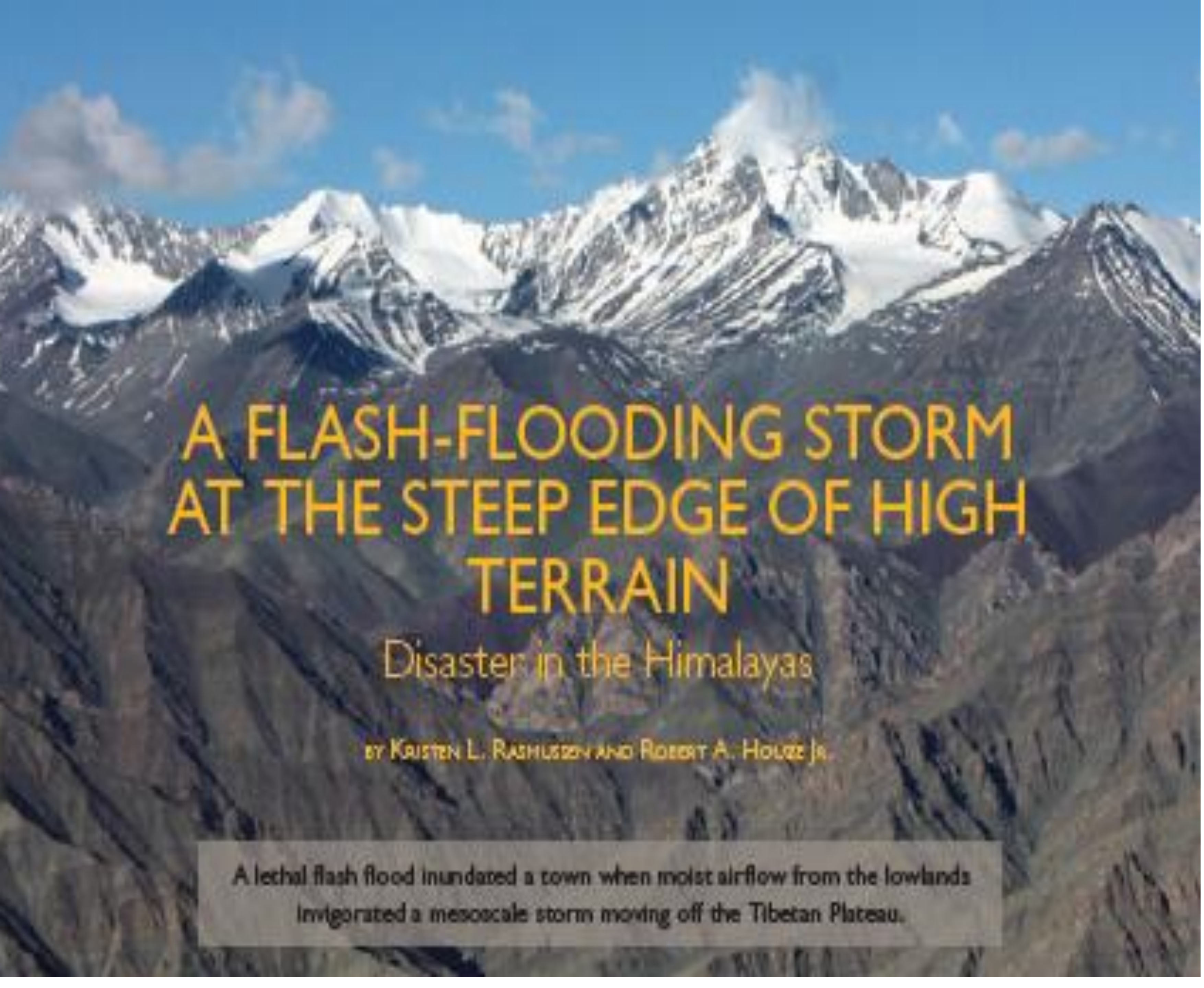
# Drivers of the infamous 2022 Pakistan Floods

Krishnan et al 2025




| Local Preconditioning: | Large-Scale Climate Drivers: |
|---|---|
| •Early heatwaves increased snowmelt and streamflow.<br>•Low-pressure systems formed due to land-surface heating.<br>•Warm Arabian Sea enhanced evaporation and moisture availability. | **•Triple-dip La Niña (2020–2022):**<br>• Westward shift of Pacific Subtropical High<br>• Enhanced moisture transport into the Indus Basin<br>**•Negative Indian Ocean Dipole (IOD):**<br>• Strengthened monsoon currents from the Arabian Sea |
| **Spatial and temporal compounding** | |

# Leh flash floods – 2010




**The Disaster in Leh:** Less than 1 week after the catastrophic slow-rise flooding of the Indus river in Pakistan in late July 2010, flooding of a different, more sudden type produced a disaster in the city of Leh, India, located 500 km to the east. The town of Leh, located in the Ladakh region of the J&K state of India, is a high-altitude cold desert valley, 3,500 m above sea level. Torrential rains delivered to the region by a succession of mesoscale convective systems moving of the region triggered extensive flooding

**Rasmussen and Houze, 2012**

# A flash-flooding storm at the steep edge of high terrain – Rasmussen and Houze, 2012

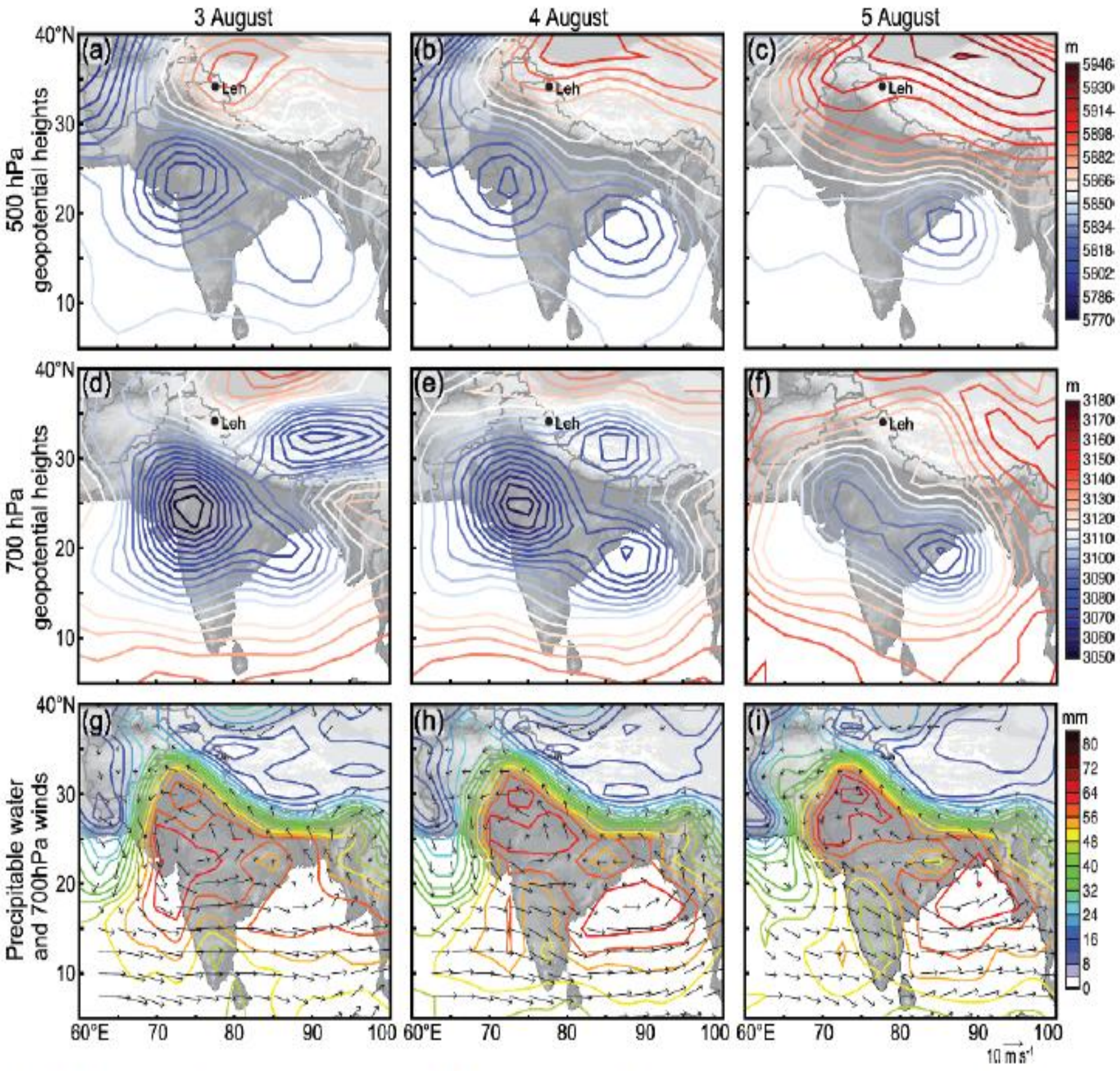



FIG. 2. Sequence of maps showing the evolution of atmospheric structure prior to the Leh flash-flooding event. One-day-average geopotential height field (m) of the (top) 500- and (middle) 700-mb surface. (bottom) Contours of vertically integrated precipitable water (mm) and 700-mb wind vectors. Note that the data source and topographic scale for (a)–(i) are the same as in Fig. 1c.

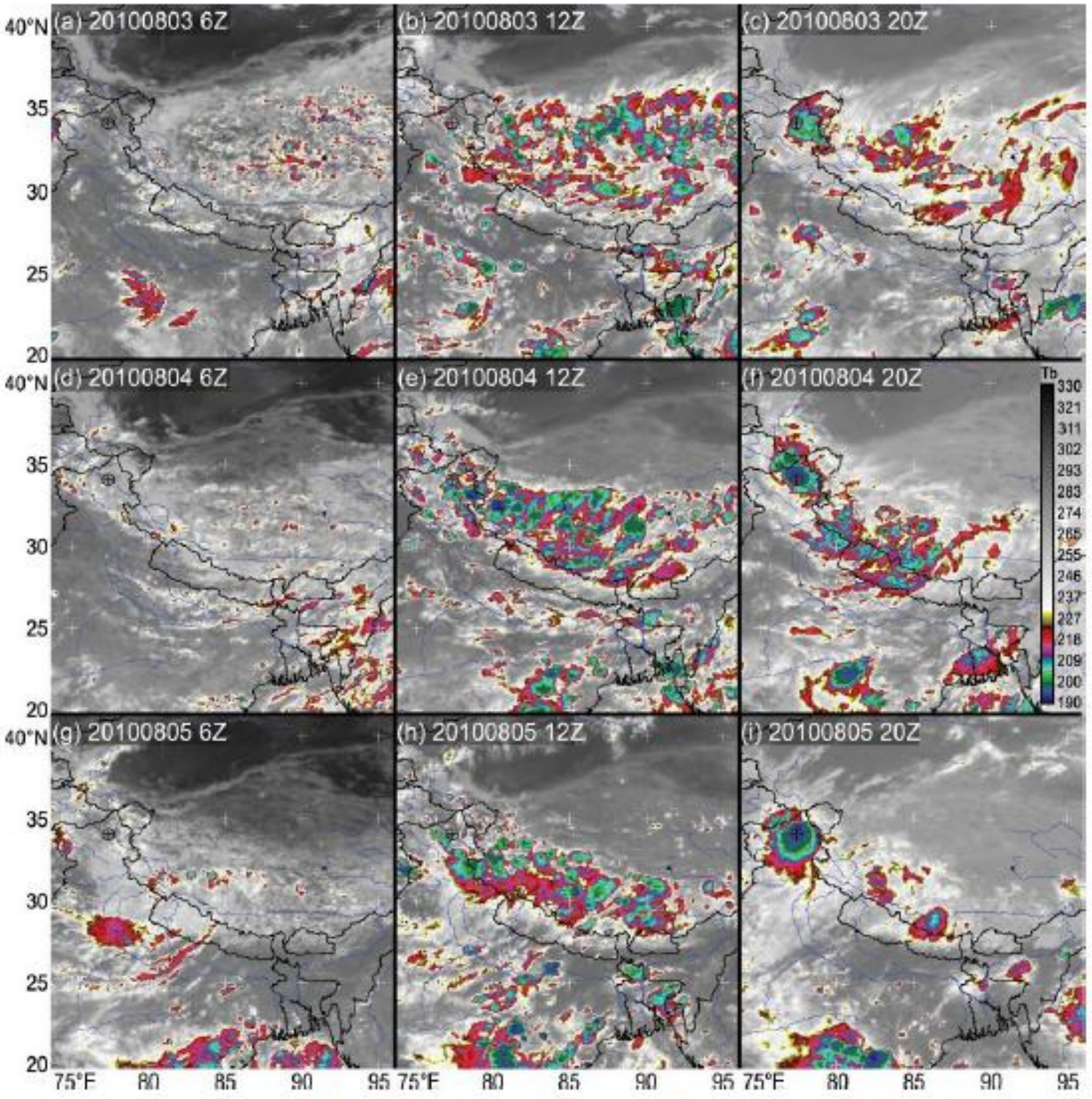
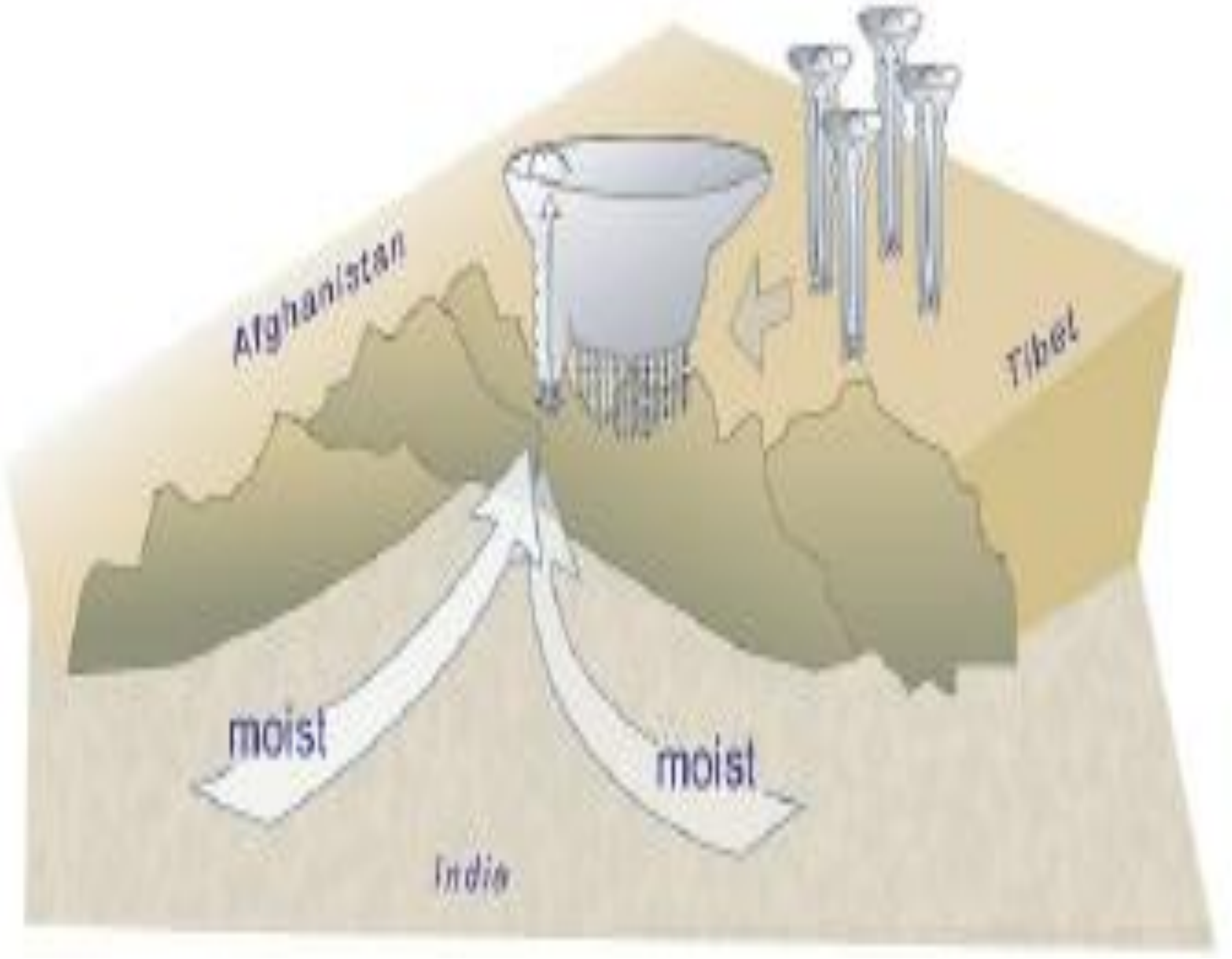



FIG. 5. Sequence of infrared satellite images (K) from *Meteosat-7* showing the diurnal evolution of the storm systems that resulted in the Leh flood. Each row shows data for a different sequential day leading up to the Leh flood (3–5 Aug) and each column shows a different time of day (0600, 1200, and 2000 UTC). The location of Leh is indicated (circled cross) on each map.

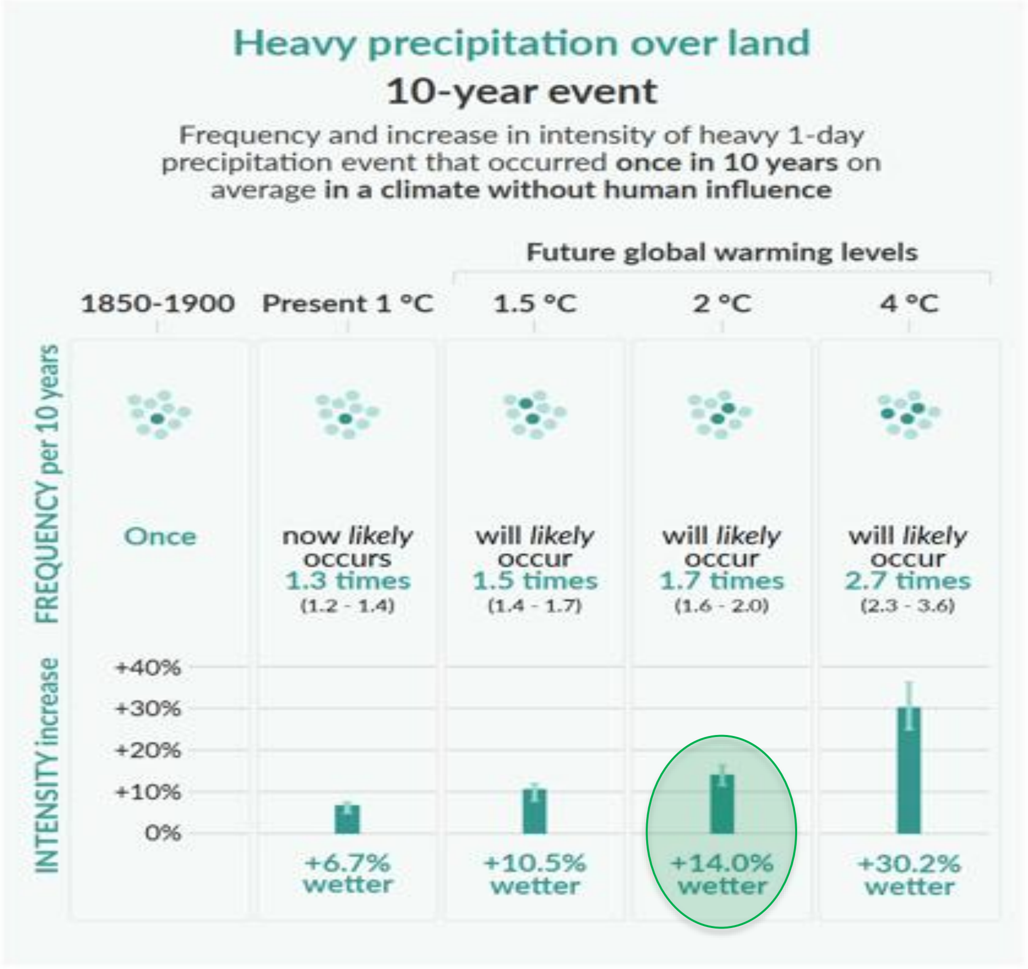


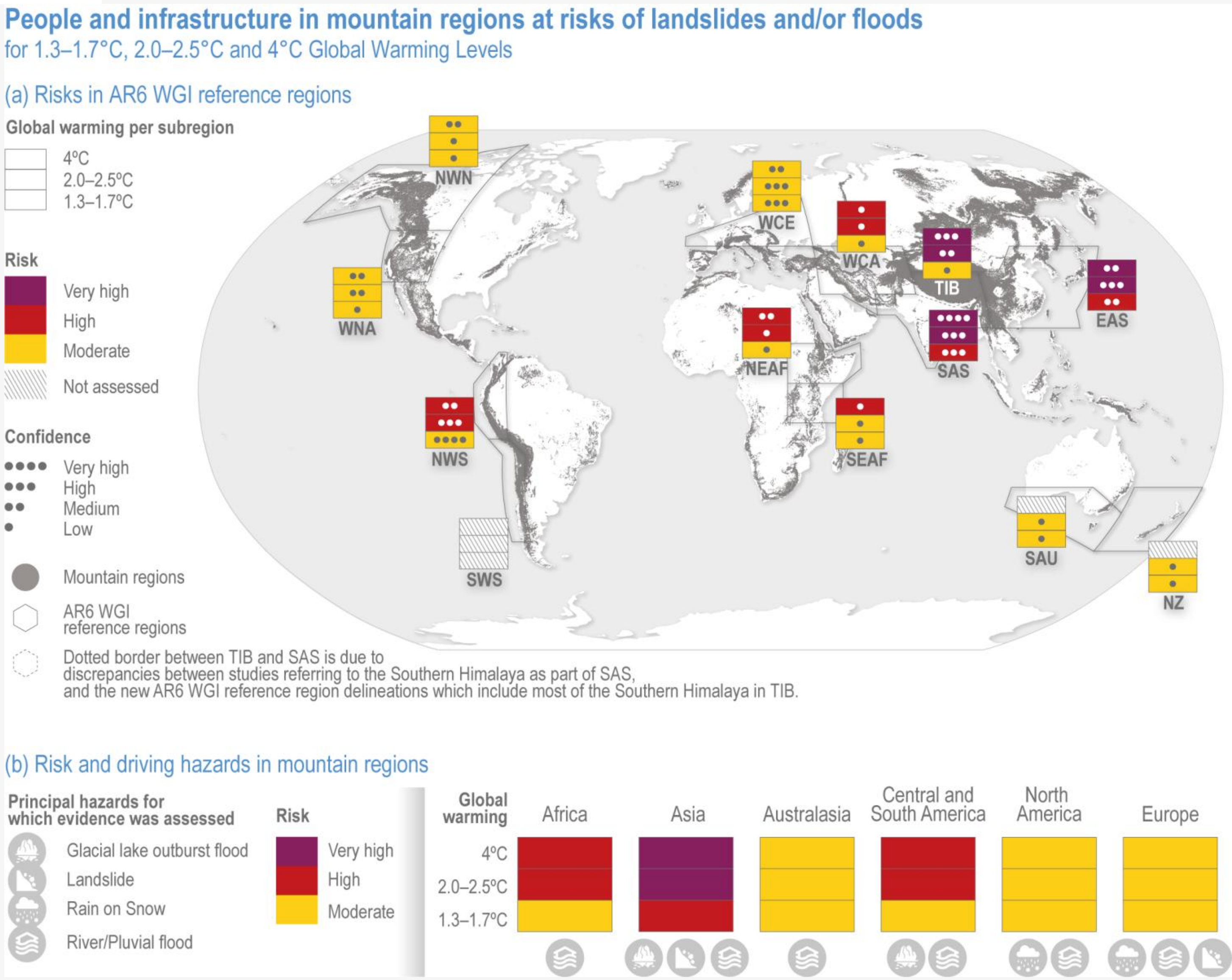

Conceptual model demonstrating key meteorological elements that led to the anomalous flash flooding case in Leh. Convective cells on the Tibetan Plateau organize upscale and propagate to the west. The MCS on the edge of the Himalayas taps into the upslope low-level mositure.

**CONCLUSIONS:** Our investigation into the meteorological setting of the catastrophic flash flood in Leh, India reveals that the event was related to the highly unusual development of **mesoscale convective systems from diurnally generated convective cells** forming over the Tibetan Plateau within the context of a persistent 500-mb flow pattern directing the MCSs over Leh and forcing moisture up the slope of the Himalayas in the Leh region.

**Rasmussen and Houze, 2012**

# Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming




Every additional 0.5°C of global warming causes clearly discernible increases in the intensity & frequency of heavy precipitation (*high confidence*)

# Key Knowledge Gaps and Challenges:

1. Challenges in Modeling & Attribution :

   - Difficulty in attributing extreme events directly to climate change
   - Limitations of climate models: Intensity and location of heavy monsoon rainfall, Convective systems in South Asia, Anomalous SSTs

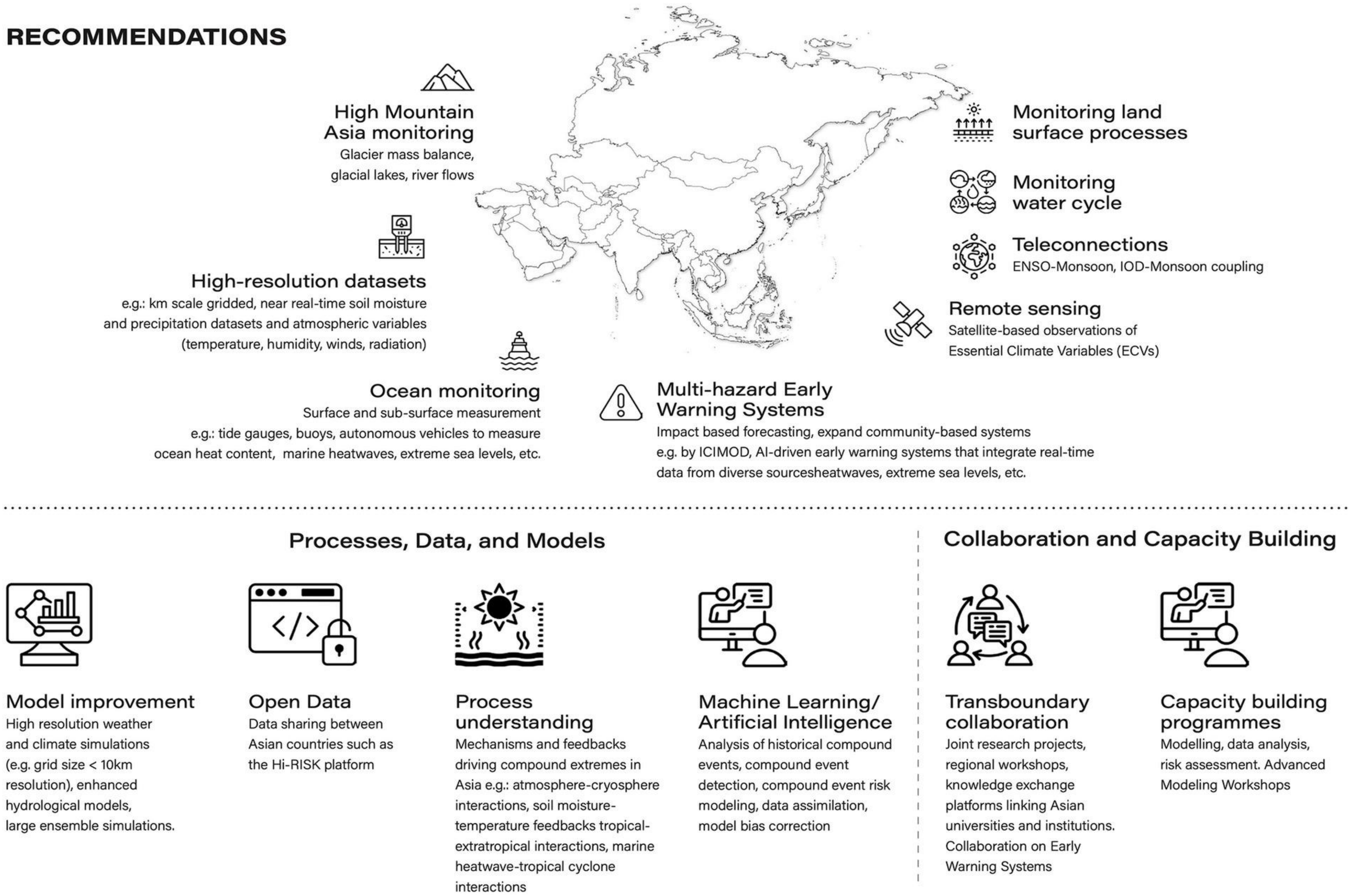
2. Monsoon System Complexity

   - Asian monsoon influenced by multiple climate modes: ENSO, IOD, PDV,
   - High variability across time and space complicates prediction
   - Uncertainty in how modes like El Niño / La Niña respond to global warming.

3. Inadequate Data Coverage

   - Sparse historical and in-situ data in remote areas (e.g., Himalayas).
   - Limited real-time monitoring of: Soil moisture, Glacier melt
   - Gaps in satellite and gridded data for high-mountain regions.

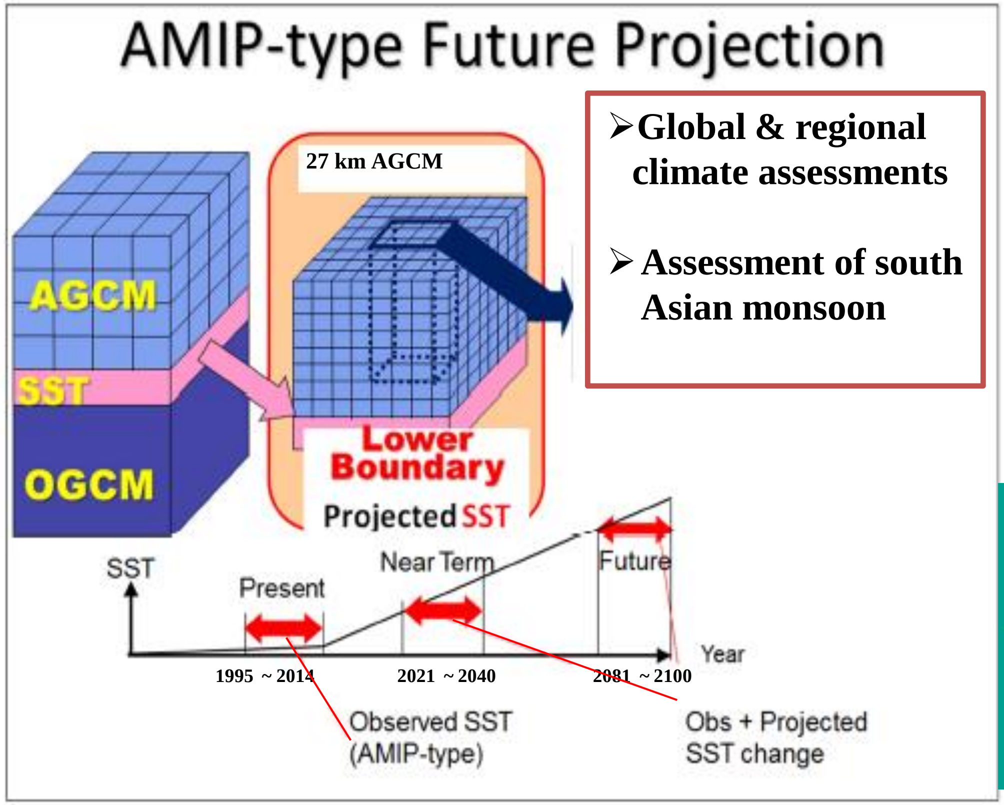
# Recommendations to address scientific and data gaps to improve extreme and compound event prediction and projections over the Third Pole region




Krishnan et al 2025

# High resolution modelling initiatives at IITM to better predict and project weather and climate extremes

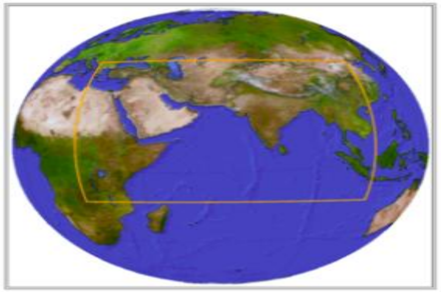
## High resolution climate projections using IITM-ESM AGCM (T574, ~27 Km)




- Dynamical downscaling of IITM-ESM v2 CMIP6 historical simulation using the high-resolution (27 km grid) atmospheric component of IITM-ESM v2
- Spectral model with reasonable good skill in simulating Indian and Pacific oceanic teleconnections with Indian monsoon
- This high-resolution climate simulation will be able to contribute towards various assessments for the country, along with contributing to CORDEX South Asia.

WCRP CORDEX
Coordinated Regional Climate Downscaling Experiment

**Region 6: South Asia**



**The following experiments are completed or underway as part of this programme**

1. Historical 1981-2014
2. SSP 2-4.5 2081-2100
3. SSP 2-4.5Aero 2081-2100
4. SSP 2-4.5GHG 2081-2100

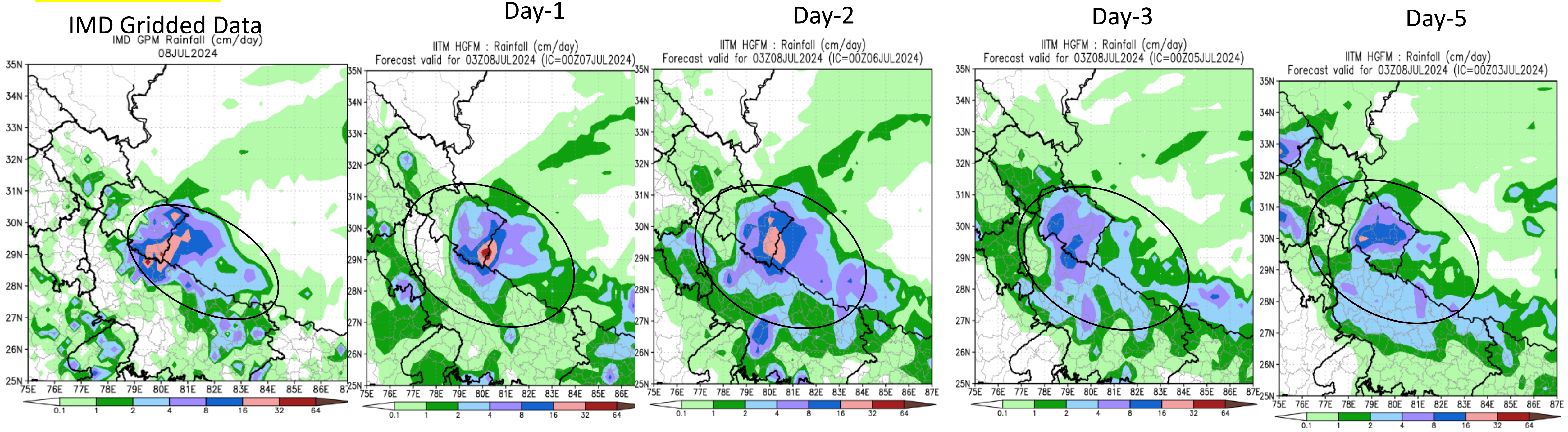
SSP 5-8.5 also will be completed along with this

**Courtesy: Dr Sabin, IITM**

## **Km-scale forecast model:** Bharat Forecast System

- Bharat Forecast System is a triangular-cubic octahedral (TCO) grid based global forecast model developed by IITM
- This grid enhances resolution specifically over the tropics, and the current version of the model runs at the horizontal resolution of about 6 km over the tropics.

**8th July 2024 Exceptionally heavy rainfall Event caused major flash floods West Uttar Pradesh and Uttarakhand**




**BharatFS Exceptionally well predicted the rainfall amount and location**

**Courtesy: Dr Medha Deshpande, IITM**

# Key Message & Way Forward

- Himalayan floods are devastating due to the interplay of monsoon dynamics, mid-latitude systems and cryospheric changes—all worsened by climate change.

- 2022 Indus Basin flood exemplifies compound hazards: heat-induced glacial melt, sustained heavy rainfall, and saturated soils amplified by La Niña and IOD.

- Scientific Gaps:
  - Inadequate model skill in simulating monsoon meso-scale processes and teleconnections.
  - Sparse high-altitude observational data (precipitation, glacier melt, soil moisture).
  - Limited understanding of climate driver interactions (e.g., ENSO, IOD)

- Recommendations:
  - Invest in Km-scale climate models (CORDEX, TPCORDEX)
  - Strengthen Himalayan observation networks and early warning systems.
  - Prioritize regional collaboration and integrated compound risk governance.

**Thank you**