Seminar Name
Venue
Date

India's Climate Risks: Monsoon Shifts, ENSO & State-Level Extremes

Speakers name : Dr. Anil Kumar Singh

Designation : Remote Sensing & Climate Scientist

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Outlines

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- Introduction: Why climate risk matters for India (vulnerability, sectors).
- Observed trends: Historical monsoon patterns & recent 2023–2025 diagnostics.
- Climate drivers: ENSO, IOD & land-use .
- Monitoring tools: Earth Engine dashboards, SPI, radar flood mapping.
- Projections: CMIP6 & SSP scenarios — extremes and regional shifts.
- Adaptation pathways & policy actions.
- Conclusions .

Understanding Climate Risk: A Multi-Dimensional Challenge

Climate risk arises from the interaction of **climate hazards**, **exposure**, and **vulnerability**. It reflects how societies and ecosystems are affected by both extreme events and gradual climate changes.

❖ **Physical Risks**

•Result from **direct climatic hazards** such as floods, droughts, heatwaves, and cyclones.
•Cause **immediate damage** to crops, infrastructure, and ecosystems.
Example: Rising sea levels threaten coastal cities and agricultural deltas.

❖ **Socioeconomic Risks**

•Affect **livelihoods, food security, and public health**.
•Poor and marginalized communities face the **highest vulnerability** due to limited adaptive capacity.
Example: Heat stress reduces farm labor productivity in South Asia.

❖ **Environmental Risks**

•Long-term degradation of ecosystems and biodiversity.
•Disturbs the **natural balance** of land, water, and atmosphere.
Example: Shifts in rainfall patterns alter forest and crop ecosystems.

❖ **Systemic Risks**

•Interconnected impacts that **cascade across sectors** (e.g., food, water, energy).
•Can amplify crises — such as droughts leading to food insecurity and migration.
Example: Crop failure triggering rural economic losses and urban migration.

Why Climate Risk Matters for India

India ranks **6th globally** in the Climate Risk Index, facing unprecedented challenges from climate-induced disasters. With over 400 extreme weather events recorded and economic.

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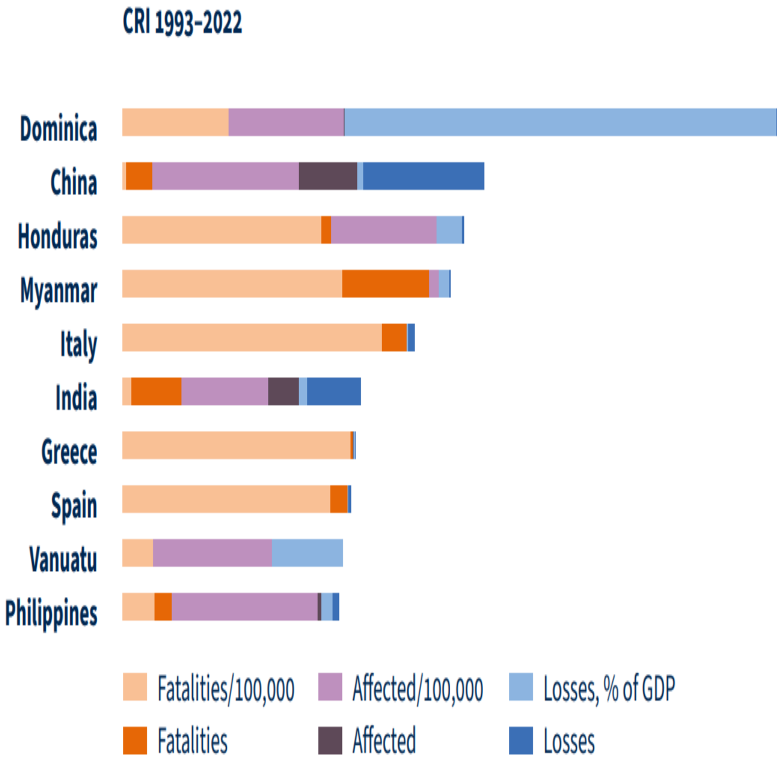

Statistic Highlights:

- 🧑‍🌾 **58% of workforce** depends on climate-sensitive agriculture.
- 🌊 **More than 75% of districts** are vulnerable to extreme weather events.
- 🌆 **Urban floods & heat stress** increasing in frequency and intensity.

Key Points

Economic Impact: Climate extremes cost **$87 billion annually** (World Bank).
Agriculture: Rainfall variability affects crop yield and food security.
Health: Heatwaves, vector-borne diseases, and air pollution risks rising.
Infrastructure: Coastal cities and transport networks face severe flood damage.

India's Climate Vulnerability Index

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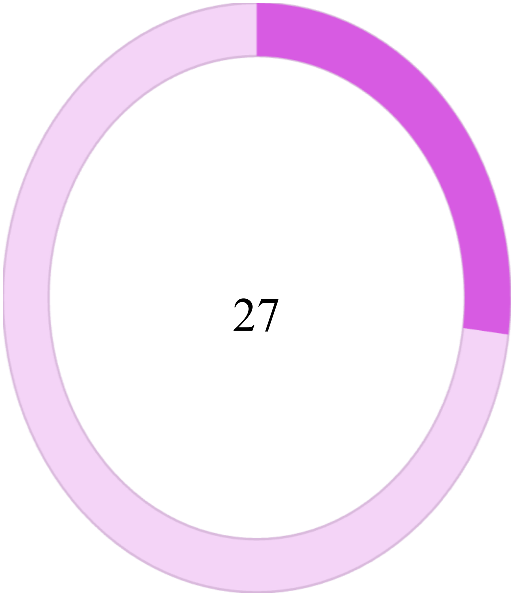
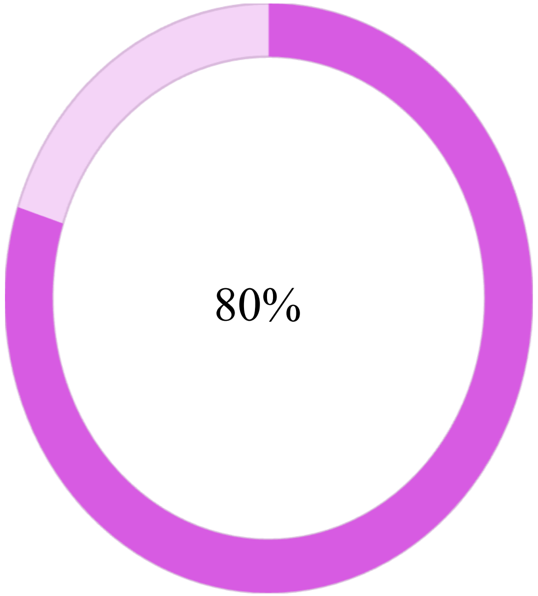
The CEEW Vulnerability Index reveals stark regional disparities in climate risk exposure. States in eastern and coastal regions face the highest vulnerability due to recurring floods and cyclones, while western and central regions grapple with water scarcity and extreme heat.



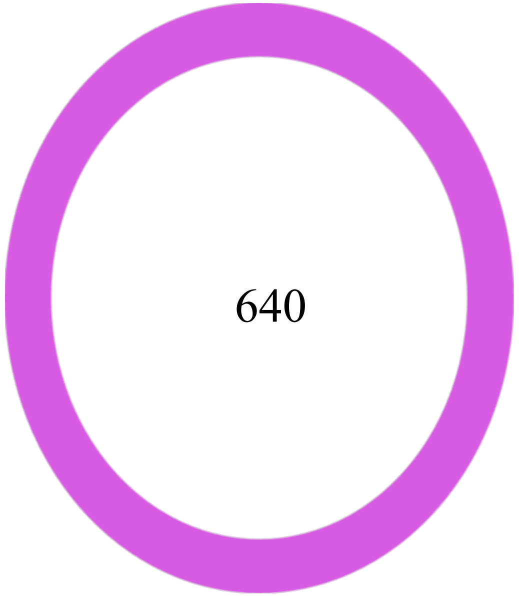
High-Risk States

States classified as extremely vulnerable to climate impacts



Population Exposed

Share of Indians living in climate-vulnerable districts



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Comprehensive coverage across all Indian states and territories

Source: CEEW Climate Vulnerability Index, 2024

Global Risk Landscape – India’s Position (IPCC AR6, 2021)

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India: High-Risk Climate Zone

- Ranked 7th globally in climate vulnerability
- Climate risks: floods, cyclones, droughts, heatwaves, glacial melt

Key Risks Identified

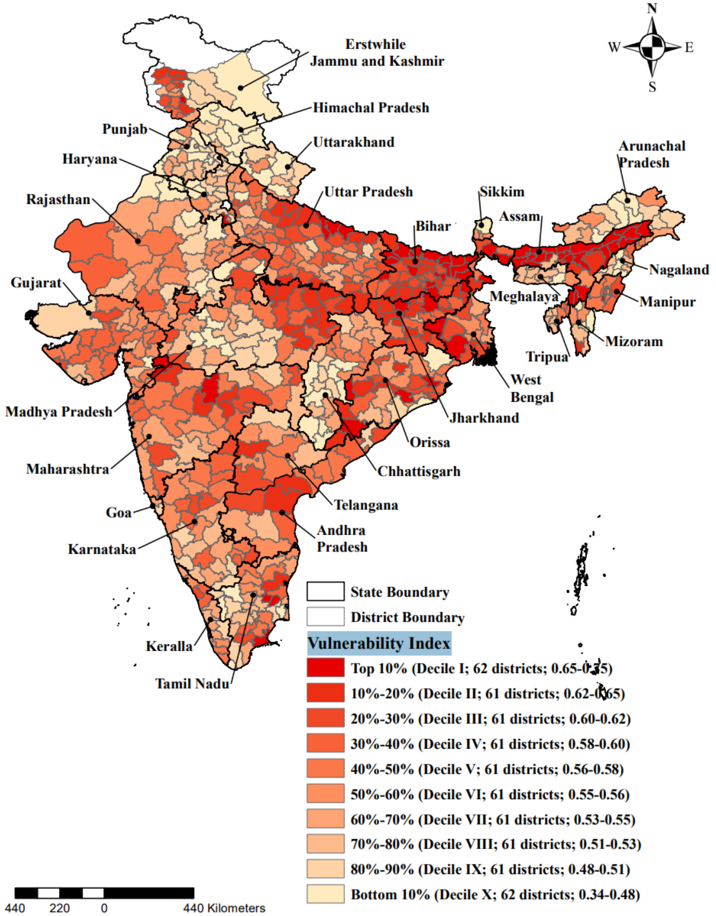
- Extreme Heat: More intense and frequent heatwaves
- Heavy Rain & Floods: 20% increase in extreme rainfall events
- Cyclones & Coastal Threats: Intensified storms, rising sea levels
- Drought: Increased water stress in key agricultural zones
- Glacial Retreat: Himalayan glaciers could lose up to 100% volume

Sectoral Vulnerabilities

- Agriculture: Monsoon changes, yield loss in rain-fed areas
- Urban Areas: Rising flood and heat stress in megacities
- Mountains: Glacial melt, landslides, river flow disruption

IPCC AR6 Recommendations

- Climate-risk mapping and infrastructure planning
- National coordination for systemic resilience
- Strengthening disaster risk infrastructure



Summary:
India stands at the epicenter of multi-hazard climate risk, requiring urgent national action for adaptation and resilience.

Key Climate Terms Explained

ENSO

El Niño-Southern Oscillation: Pacific Ocean temperature fluctuations that influence monsoon strength and timing across India.

IOD

Indian Ocean Dipole: Temperature differences in the Indian Ocean affecting rainfall distribution and intensity.

JJAS

June-July-August-September: India's critical monsoon season delivering 70-80% of annual rainfall.

Drought

Drought is a prolonged period of abnormally low rainfall, leading to water scarcity and dry conditions.

Runoff

Surface water flow occurring when soil infiltration capacity is exceeded, leading to flooding risks.

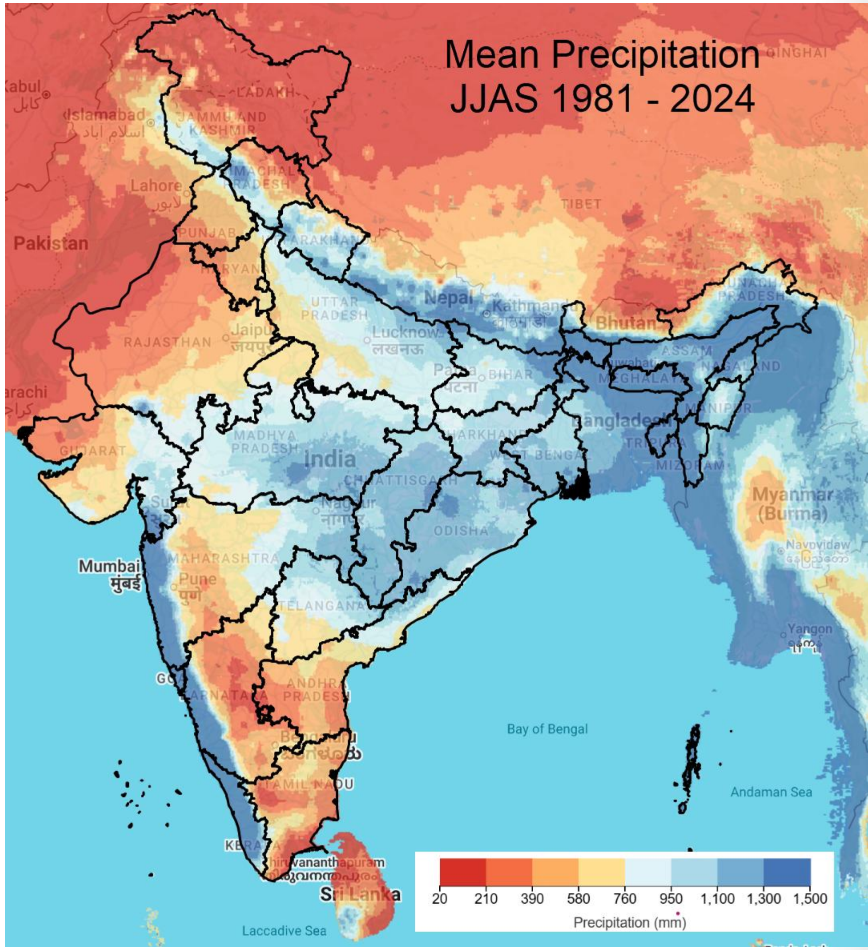
North-East Monsoon (OND):

Occurs during October–November–December (OND) when retreating monsoon winds blow from the northeast, bringing rainfall mainly to Tamil Nadu, coastal Andhra Pradesh, Kerala, and parts of Sri Lanka. It contributes significantly to winter-season water availability and rabi crop irrigation in southern India.

Historical Monsoon Rainfall Patterns

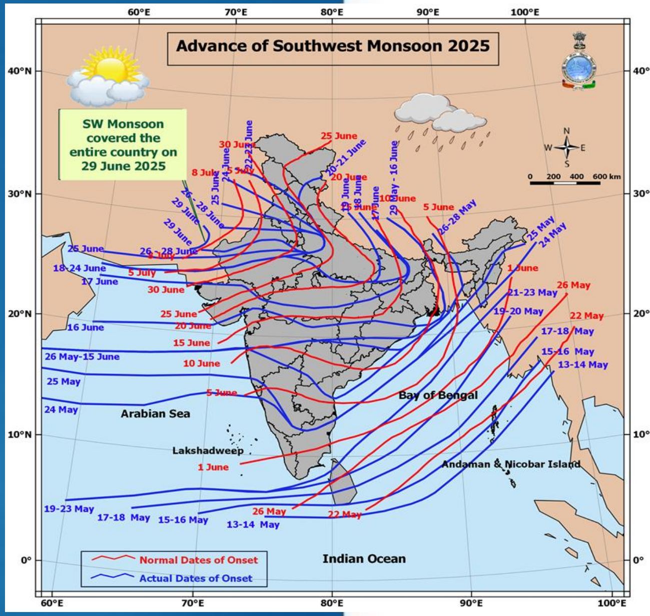
For decades, India's monsoon followed a predictable pattern: onset in early June, withdrawal by September. This consistency was the foundation of agricultural planning and water resource management across the subcontinent.

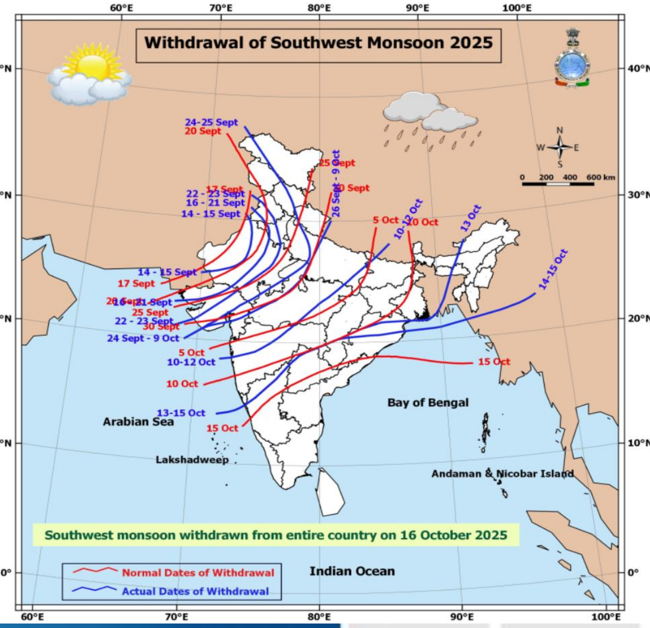
The monsoon delivers 70-80% of India's annual rainfall, supporting 600 million farmers and replenishing critical water reservoirs. Any deviation from normal patterns creates cascading impacts on food security and economic stability.



Source: India Meteorological Department (IMD) Monsoon Data

Recent Trend: Changing Onset & Withdrawal





Delayed Onset

Monsoon arrival increasingly delayed, with notable instances in 2019 and 2022 disrupting planting schedules and causing water stress in key agricultural zones

Earlier Withdrawal

Premature monsoon retreat observed across several states, shortening the growing season and reducing reservoir recharge capacity in critical watersheds.

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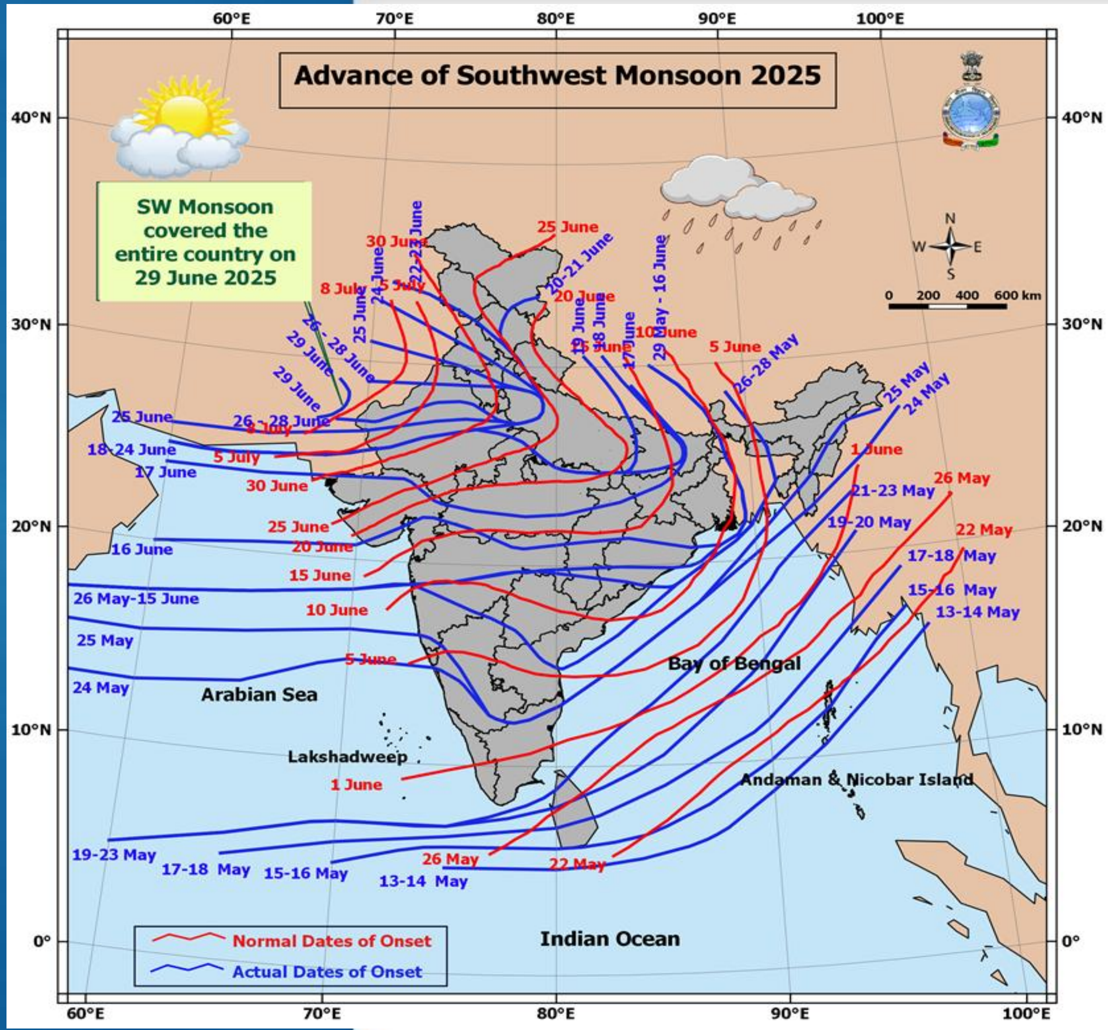
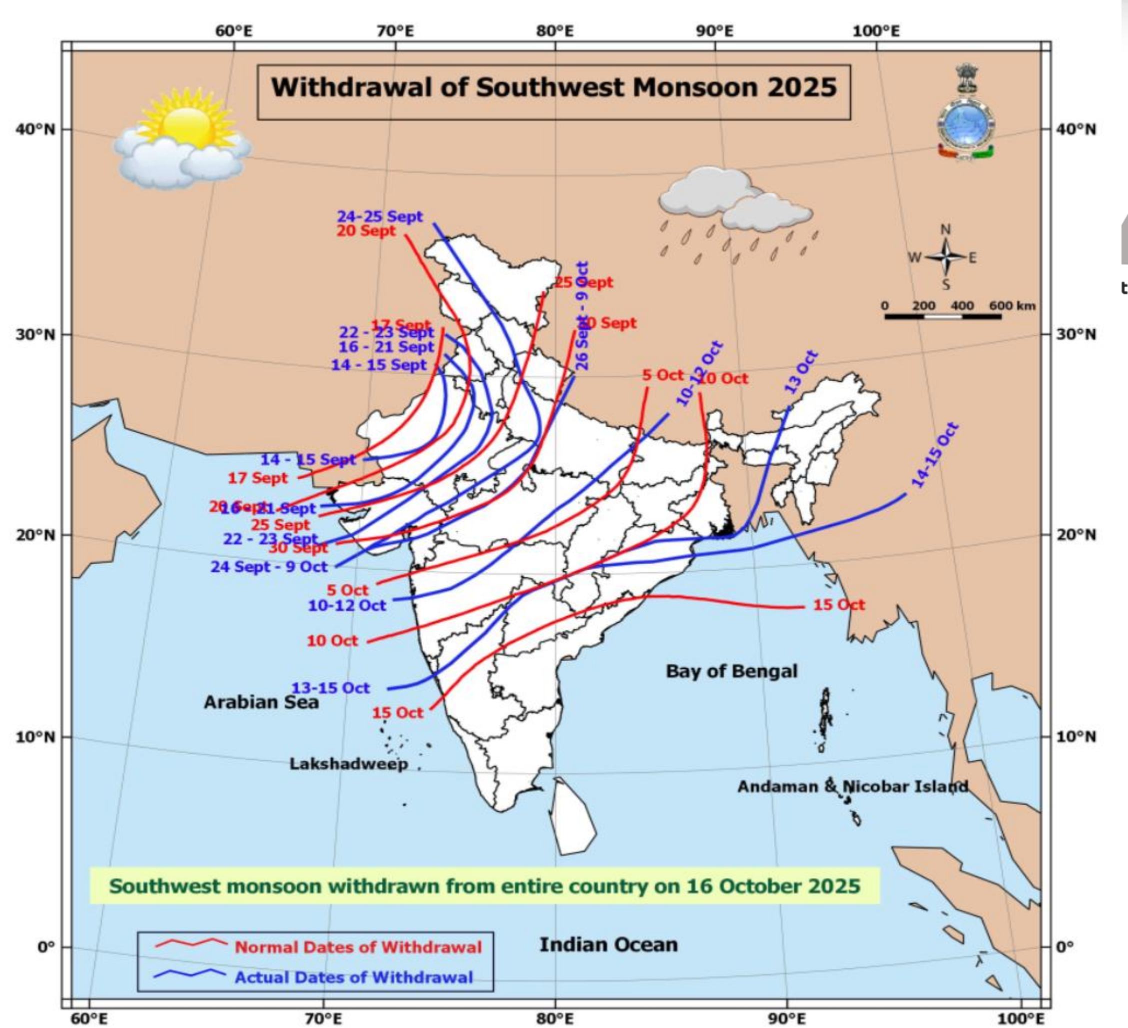
Increased Uncertainty

Seasonal predictability declining, making traditional forecasting methods less reliable and challenging long-term planning for farmers and water managers.

Rainfall Extremes in 2025

- Above-Normal Rainfall: India received 108% of the Long Period Average (LPA), with Northwest India recording its highest rainfall since 2001.
- Regional Contrasts: While Northwest and Central India saw surpluses, East & Northeast India had the 2nd lowest rainfall since 1901, highlighting spatial imbalance.





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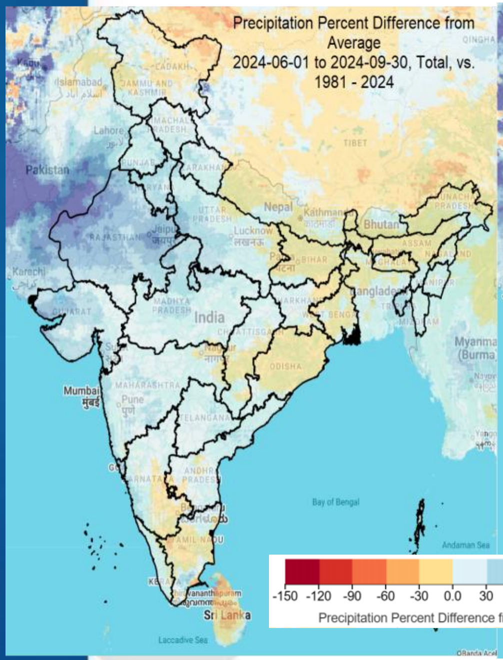
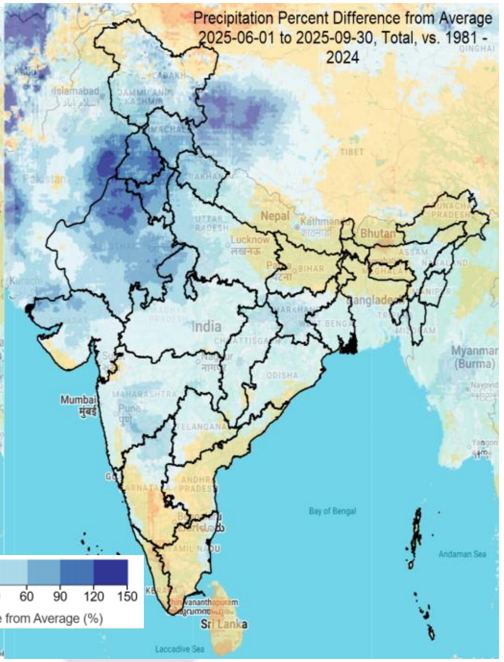
Rainfall Intensity & Distribution Changes

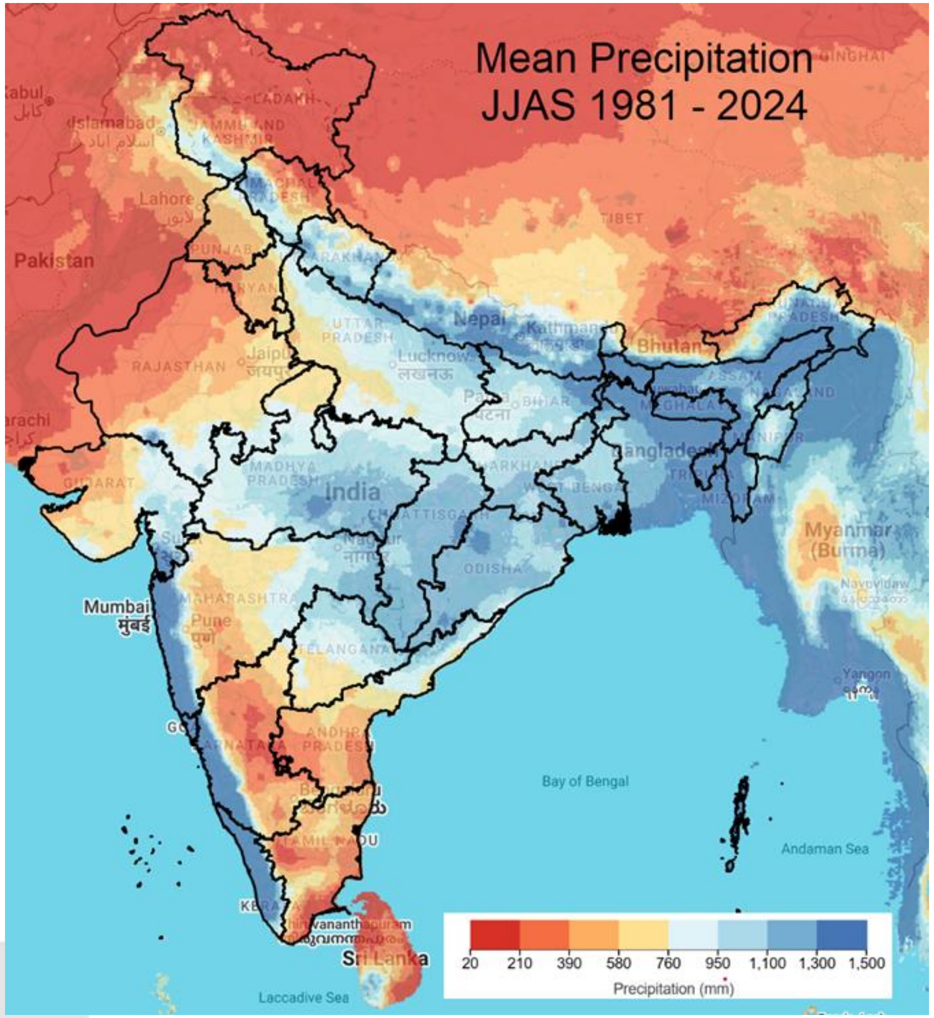
Rising Intensity

June-September (JJAS) rainfall intensity has increased by approximately 2 mm/day over recent decades. Heavy rainfall events are becoming more frequent, particularly across North and Northeast India.

Paradoxically, dry spells are also lengthening in some regions—creating a dangerous pattern of floods alternating with droughts within the same season







Monsoon Shifts & Future Projections

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Historical Trends
- Indian Summer Monsoon (ISM) delivers ~75% of annual rainfall.
- Increasing variability in **onset (±7 days)** and **withdrawal (5–10 days delay)**.
- Declining rainfall over Indo-Gangetic plains; rising trends in peninsular & NE India.
- Rise in **extreme rainfall events**, decline in moderate rains.

Observed Shifts (Past 50 Years)
- Northward & westward displacement of the monsoon trough.
- Weakened land–ocean thermal gradient due to aerosols & land use change.
- Regional disparity in rainfall distribution and intensity.

Future Projections (CMIP6, IPCC AR6 – SSP2–4.5 & SSP5–8.5)
- **SSP2–4.5:** 6–12% increase in monsoon rainfall by 2100.
- **SSP5–8.5:** 15–25% ↑ in total rainfall; more **intense short-duration downpours**.
- Shorter monsoon period with **longer dry breaks** between heavy spells.
- Higher monsoon variability linked with stronger ENSO & IOD phases.
- More frequent **flash floods, urban flooding, and droughts** in the same season.

Implications
- Shift in sowing & harvesting windows across major crops.
- Increased irrigation & groundwater stress.
- Urgent need for **climate-smart agriculture** and **AI-based early warning systems**.

Sources: IPCC AR6 (2021), IMD & IITM Pune (2024), MoES Climate Projections.

Role of ENSO & IOD in Monsoon Dynamics

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India's monsoon is increasingly influenced by complex interactions between global climate oscillations, making rainfall patterns less predictable and more extreme.

El Niño Southern Oscillation (ENSO)

El Niño events suppress monsoon rainfall, often triggering severe droughts across India. The warming of Pacific Ocean waters disrupts normal atmospheric circulation, reducing moisture delivery to the subcontinent.

Indian Ocean Dipole (IOD)

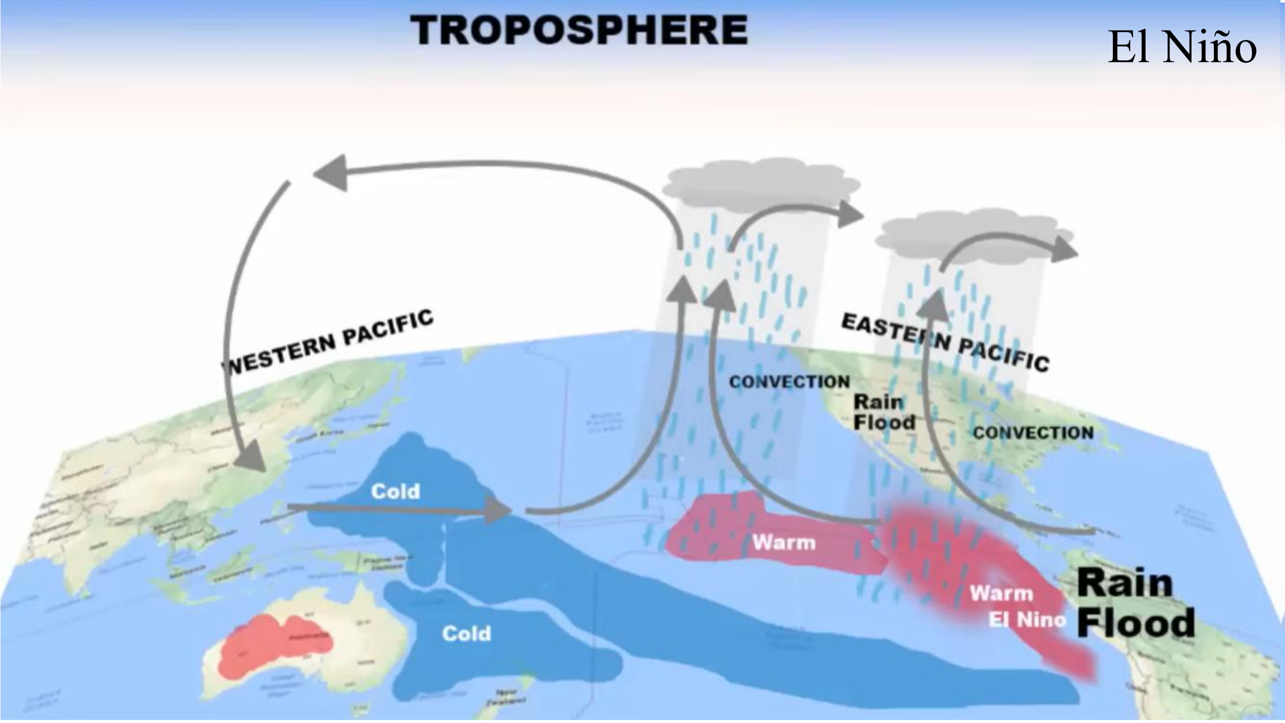
Positive IOD phases drive erratic flooding patterns. When western Indian Ocean waters warm relative to the east, it intensifies rainfall variability and can cause devastating floods in vulnerable regions.

Recent Examples

2015 Chennai Floods: Positive IOD contributed to extreme rainfall, causing catastrophic urban flooding and economic losses exceeding $3 billion

2019 Bihar Drought: El Niño conditions led to severe rainfall deficit, affecting 13 million people and decimating agricultural output

ENSO Phase	IOD Phase	Monsoon Outcome
El Niño	Neutral	Weak, drought risk
El Niño	Positive	Impact softened, normal rainfall possible
El Niño	Negative	Severe drought, widespread deficit
La Niña	Neutral	Strong, abundant rainfall
La Niña	Positive	Excess rainfall, possible floods
La Niña	Negative	Moderated rainfall, less intense

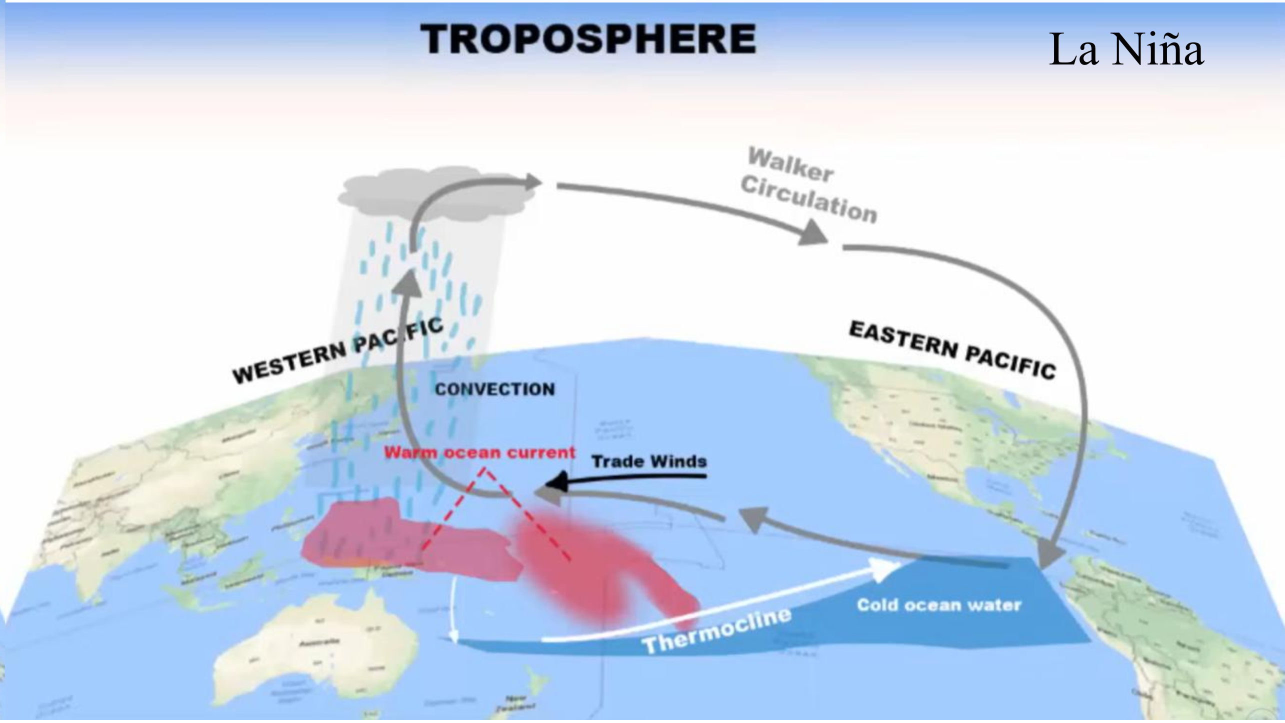


El Niño is a climate phenomenon where the Eastern Pacific Ocean becomes unusually warm, disrupting the normal flow of winds and weather across the tropics.

❖ Eastern Pacific:
• The ocean surface is warm, triggering strong convection—warm air rises, forming clouds and causing heavy rainfall and floods.
• This region is labeled "El Niño" and "Rain Flood", showing the intense precipitation linked to the warm waters.

❖ Western Pacific:
• The ocean surface is cold, and the air is dry and descending, leading to less cloud formation and drought.
• Convection is minimal here, meaning less rainfall and more dry spells.

❖ 🔁 Atmospheric Circulation:
• Air flows from west to east in the upper troposphere, reversing the usual Walker Circulation.
• This shift weakens the trade winds and allows warm water to pile up in the east.

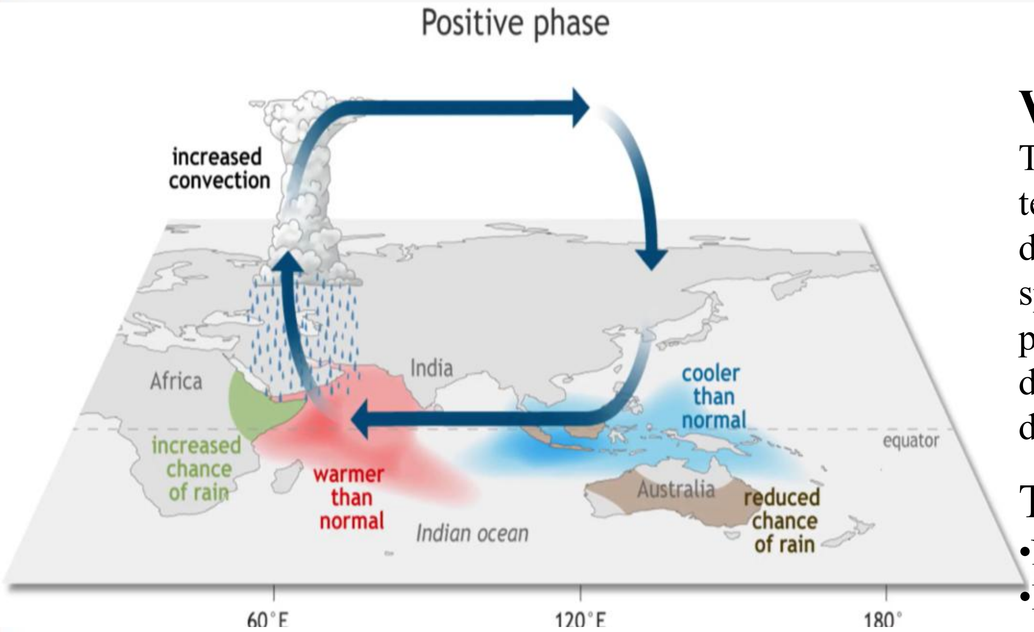


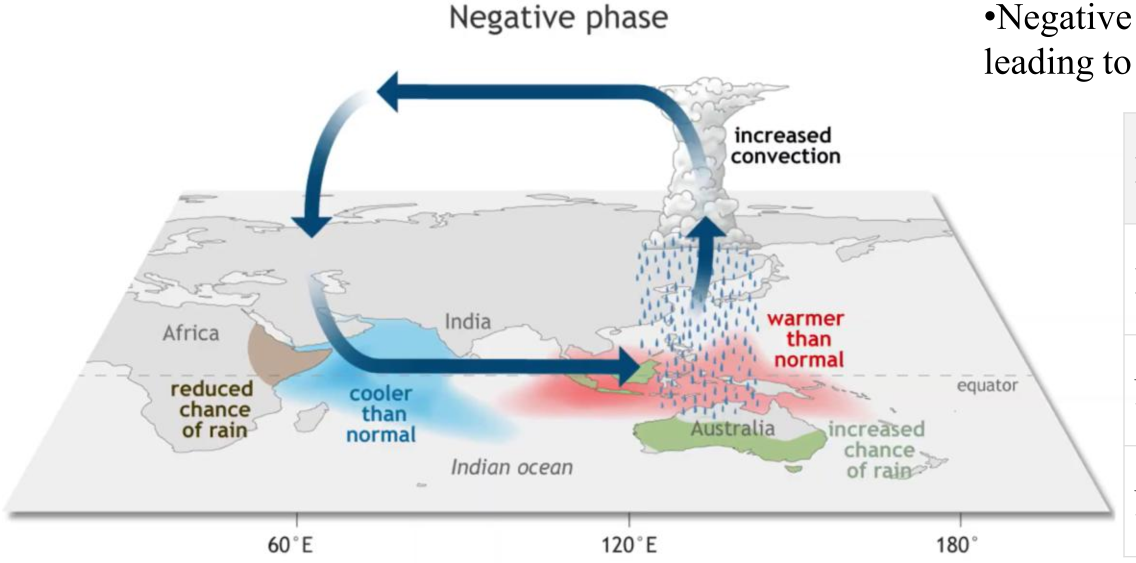
La Niña is a climate pattern where the Eastern Pacific Ocean becomes unusually cold, while the Western Pacific becomes warmer and wetter. This strengthens the normal atmospheric and oceanic circulation across the tropical Pacific

❖ Walker Circulation intensifies:
• Warm, moist air rises over the Western Pacific (Indonesia, Australia), causing heavy rainfall and convection.
• Cooler, dry air sinks over the Eastern Pacific (South America), leading to dry conditions and drought.

❖ Trade Winds strengthen:
• Surface winds blow more forcefully from east to west, pushing warm water toward Asia.
• This enhances upwelling of cold water in the Eastern Pacific, cooling the ocean surface.

❖ Thermocline tilts more steeply:
• The boundary between warm and cold water deepens in the west and rises in the east, reinforcing the temperature contrast.





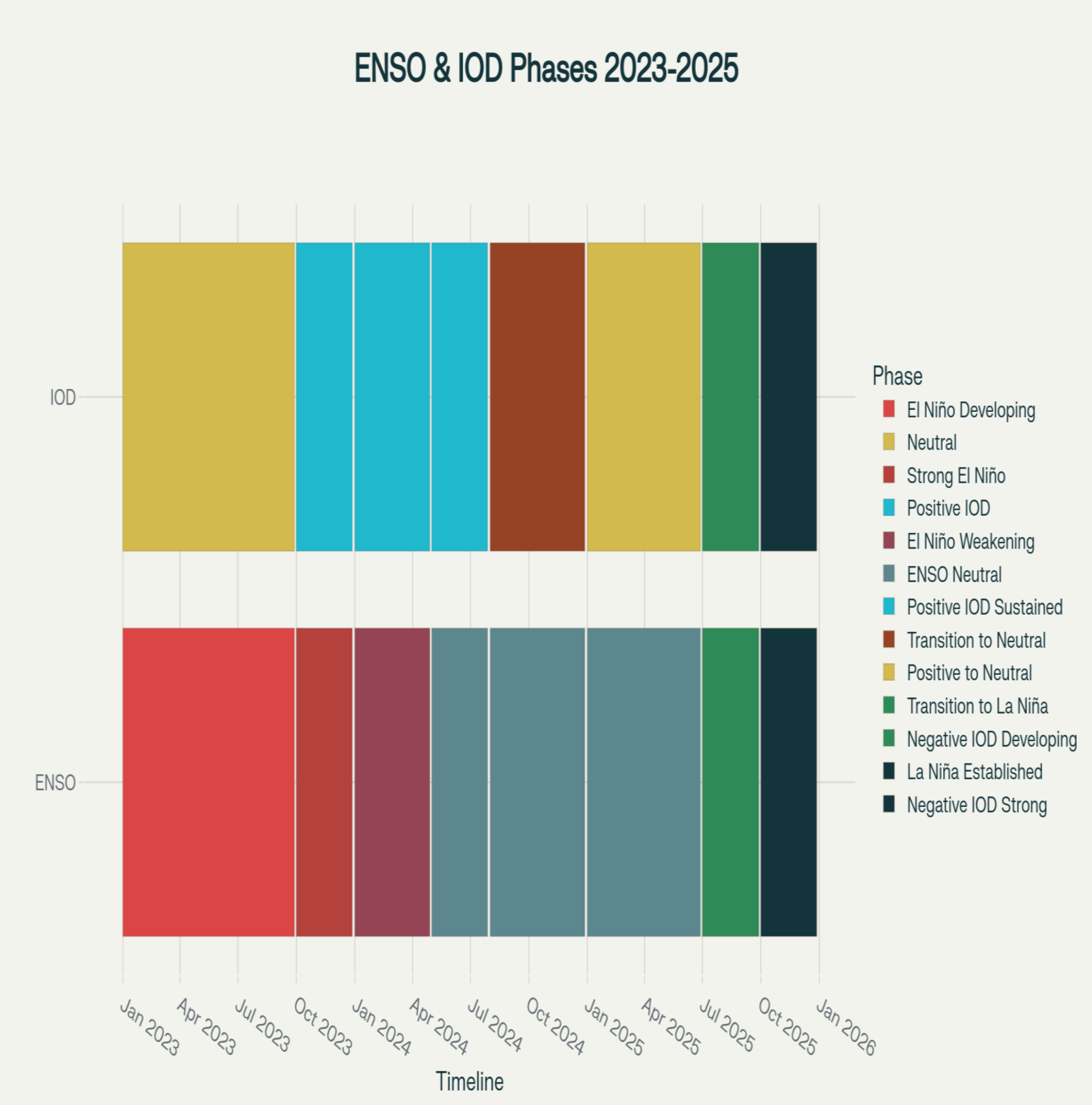
What is the Indian Ocean Dipole?

The IOD is an irregular oscillation of sea surface temperatures in the Indian Ocean, characterized by differences between the western and eastern regions—specifically, warmer waters near the Arabian Sea (western pole) and cooler waters near Indonesia (eastern pole) during its positive phase. The phenomenon typically develops between April and May, peaking in October

There are three IOD phases:

•Neutral: Sea surface temperatures are roughly equal east and west.
•Positive IOD: Warmer waters in the western Indian Ocean and cooler waters in the eastern part. This phase often brings increased rainfall to India.
•Negative IOD: Cooler in the west and warmer in the east, usually leading to drier conditions over the subcontinent.

IOD Phase	SSTs (West/East)	Monsoon Impact in India
Positive	Warm west, cool east	Enhanced rainfall
Neutral	SSTs roughly equal	Average conditions
Negative	Cool west, warm east	Reduced rainfall



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Key Insights (2023–2025)

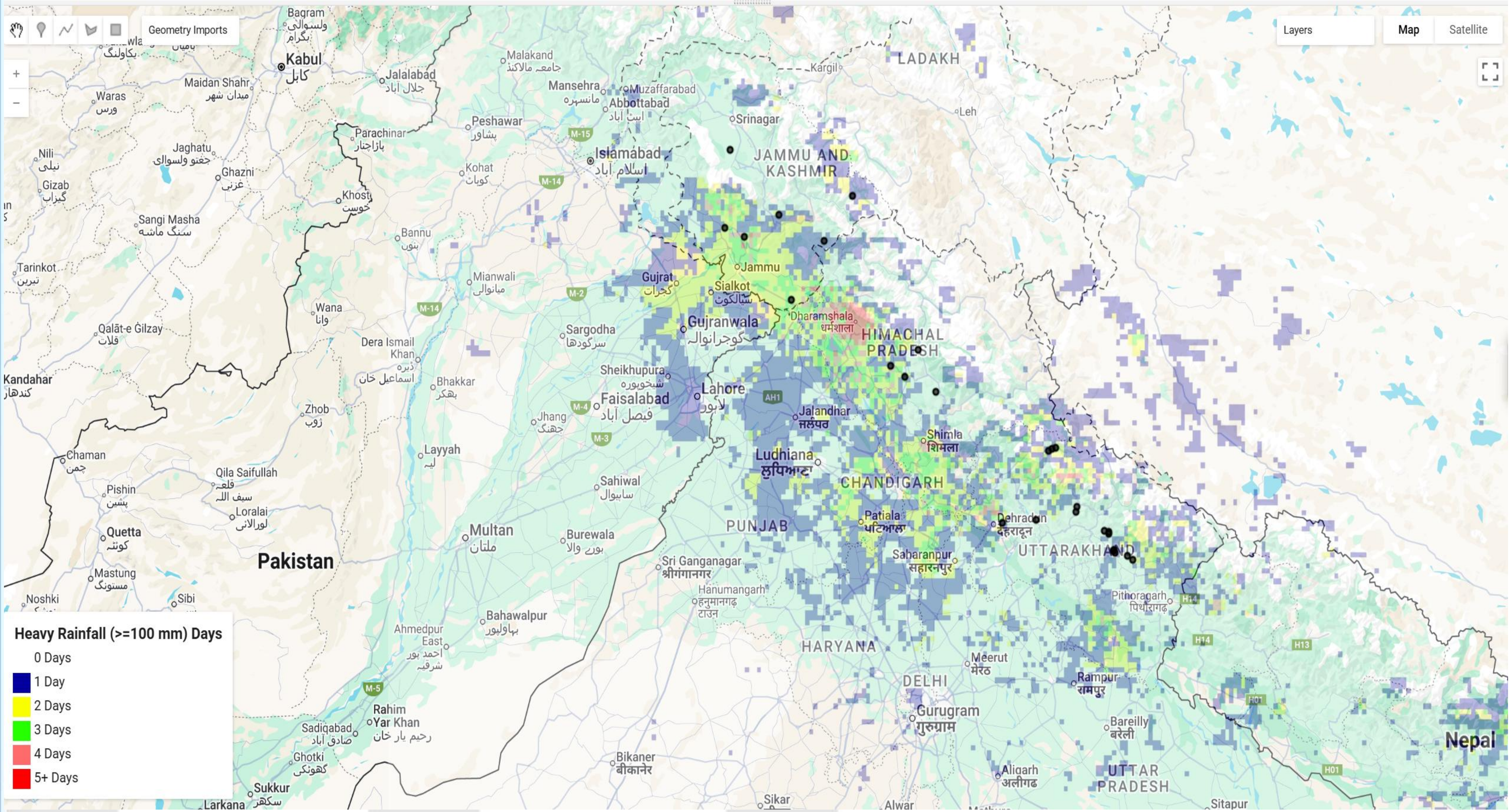
- 2023: A strong El Niño developed mid-year, peaking by October—causing suppression of monsoon rainfall in north and central India, while a positive IOD partly offset deficits in the south.

- 2024: ENSO transitioned to neutral by April; a sustained positive IOD supported above-normal rainfall in peninsular India during the monsoon period.

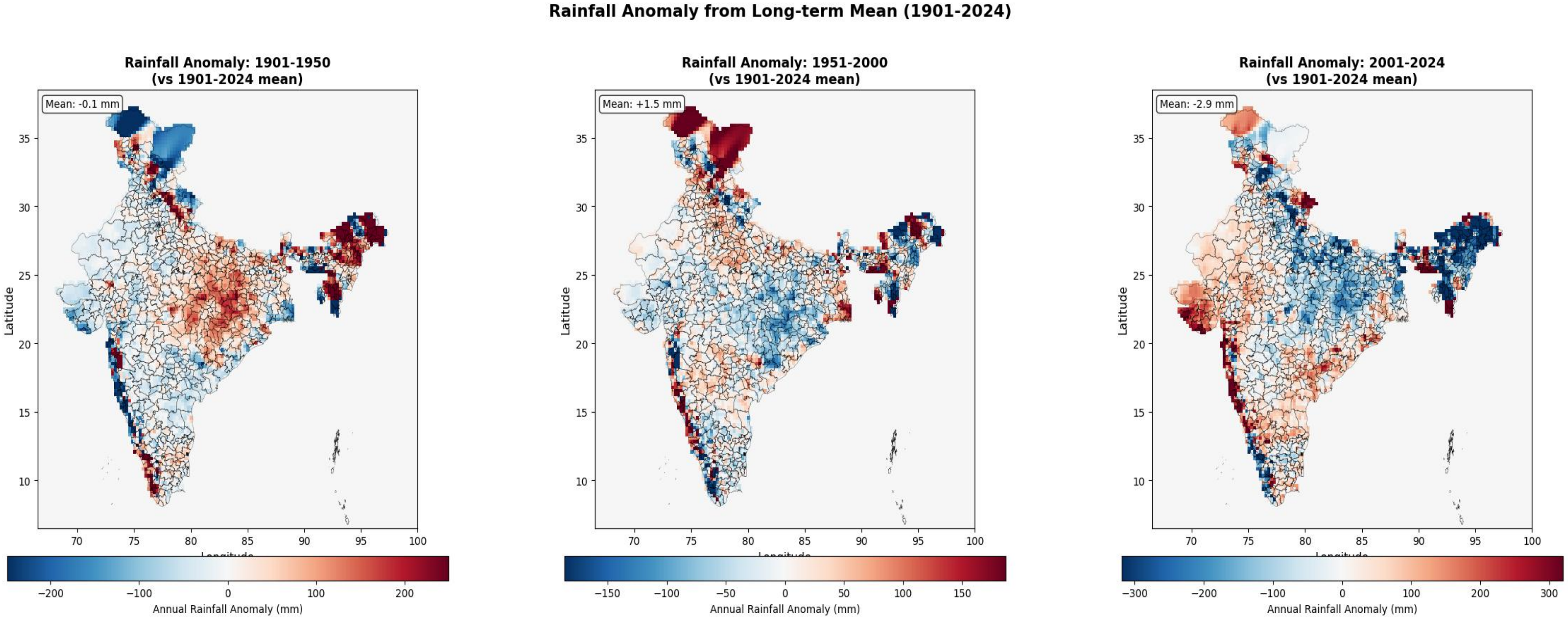
- 2025: Conditions flipped—ENSO shifted from neutral to developing La Niña by July, while a negative IOD strengthened, reducing rainfall over northwest India and enhancing totals in southern and eastern regions.

This timeline captures how the interaction between ENSO and IOD phases modulated rainfall distribution, marking a cycle from El Niño → Neutral → La Niña alongside alternating positive and negative IOD events.

Extreme Rainfall Events 2025



Rainfall Anomaly Trends in India (1901–2024)
Based on IMD Gridded Rainfall Data (0.25° x 0.25° resolution)



Three time-sliced anomaly maps compare regional rainfall deviations against the 1901–2024 mean:

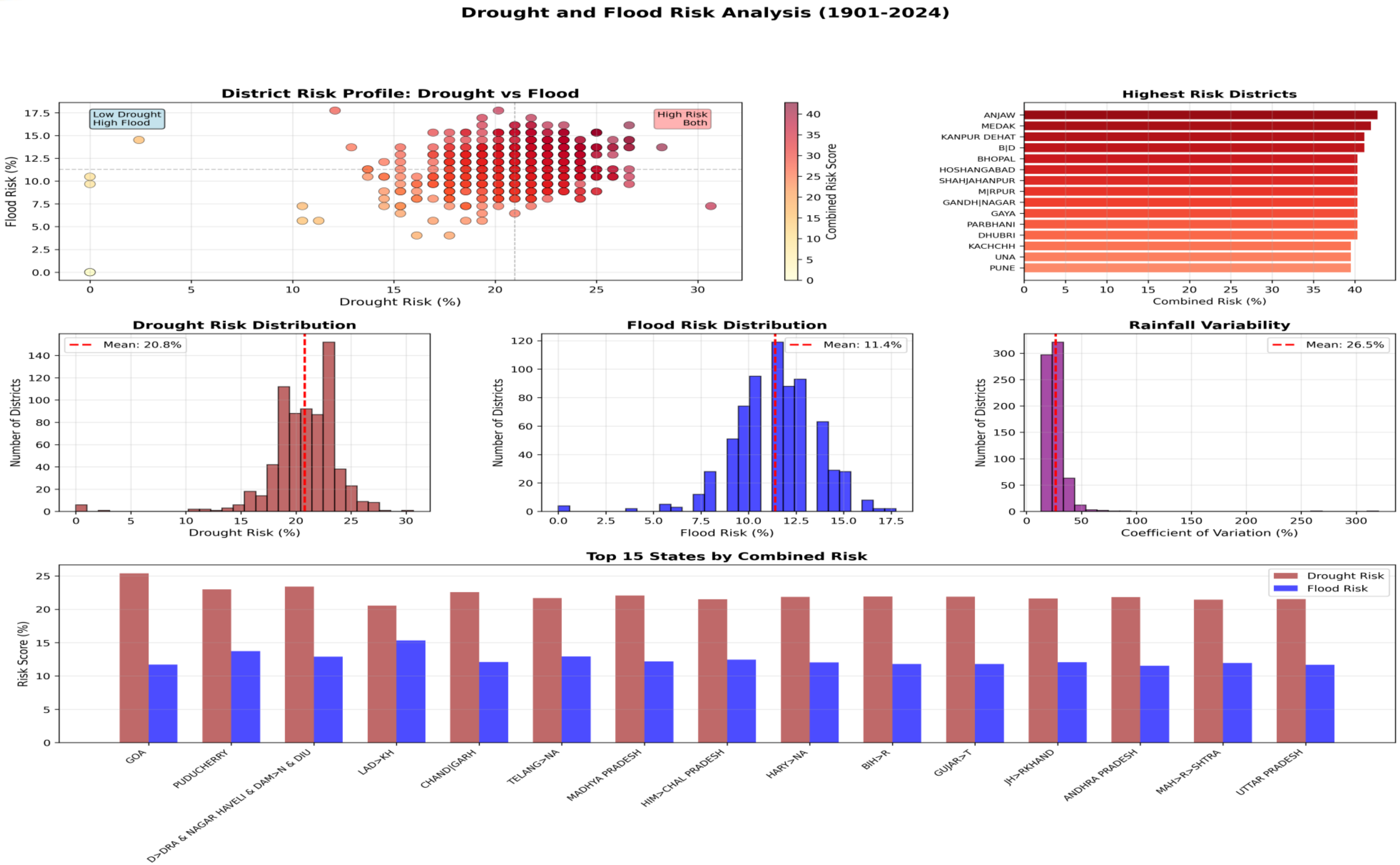
Period	Mean Anomaly (mm)	Key Observations
1901–1950	−2 mm	Northern and central India show below-average rainfall (red zones); pockets of surplus in the south and northeast.
1951–2000	−4.15 mm	Intensified deficit in northern India; southern and northeastern regions show moderate positive anomalies.
2001–2024	+2 mm	Widespread positive anomalies (blue zones), especially in central and southern India, indicating a recent wetting trend.

Interpretation

• Historical Deficit: Early 20th century and mid-century periods show persistent rainfall deficits in agriculturally critical zones.

• Recent Recovery: Post-2000 period reflects a shift toward wetter conditions in many regions, possibly linked to changing monsoon dynamics and climate variability.

• Policy Relevance: These trends are vital for climate adaptation, water resource planning, and agro-climatic zoning.



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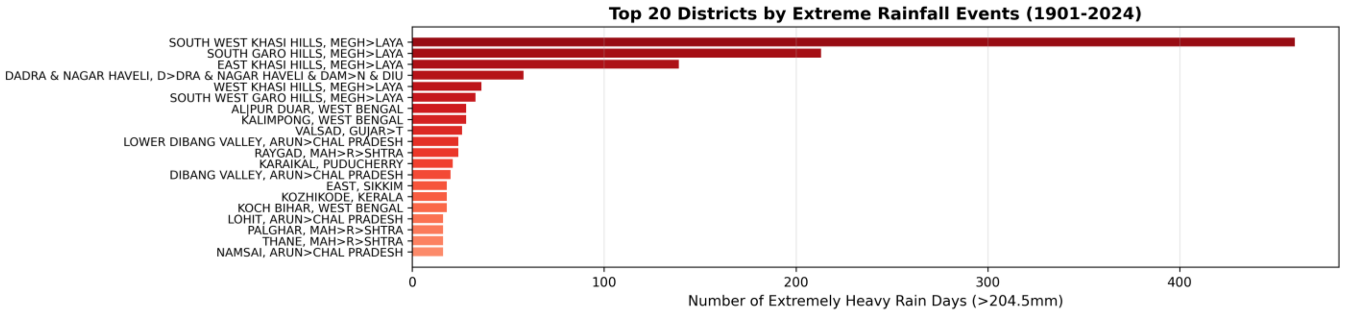
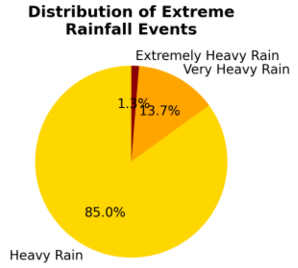
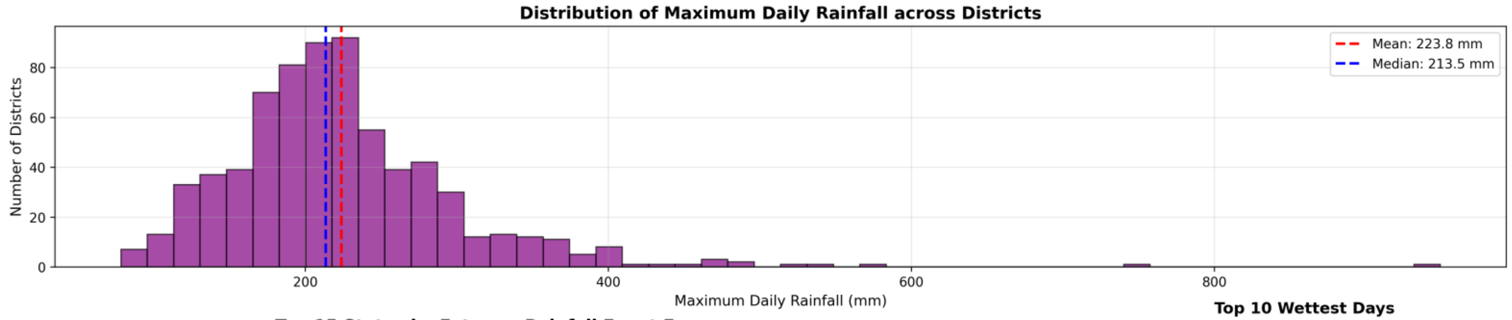
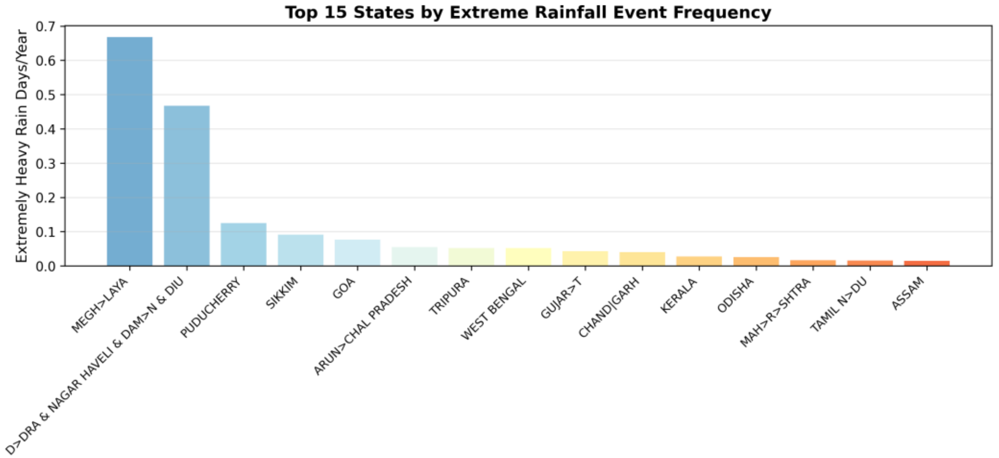
Extreme Rainfall Events Analysis (1901-2024)



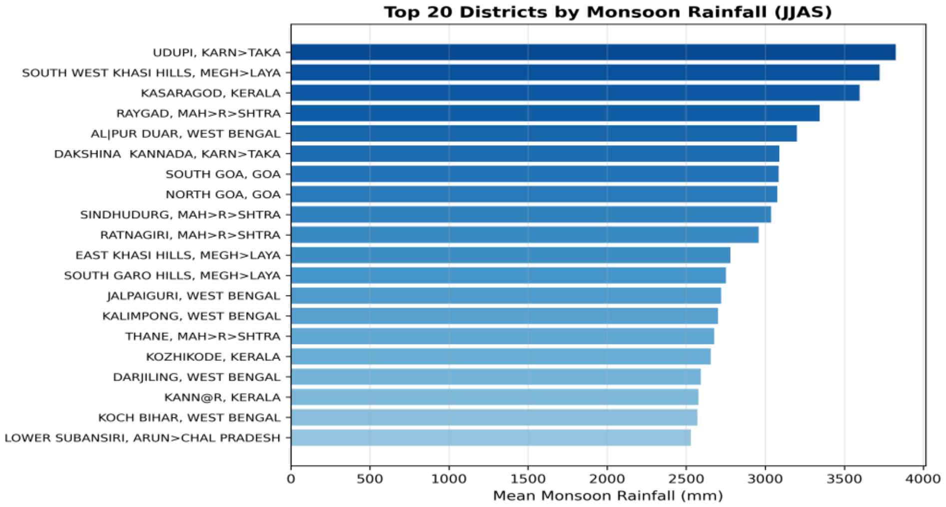


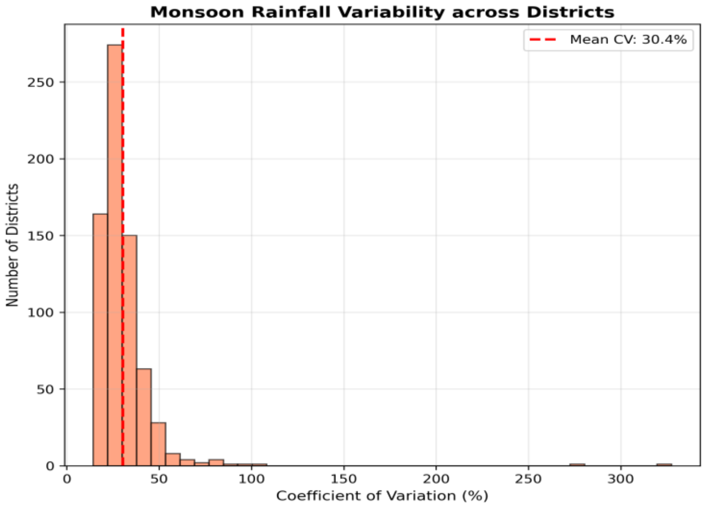


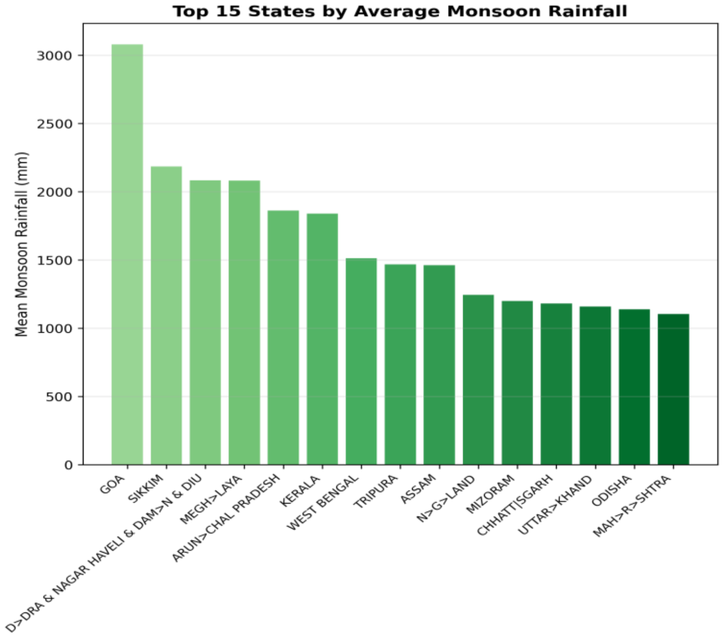


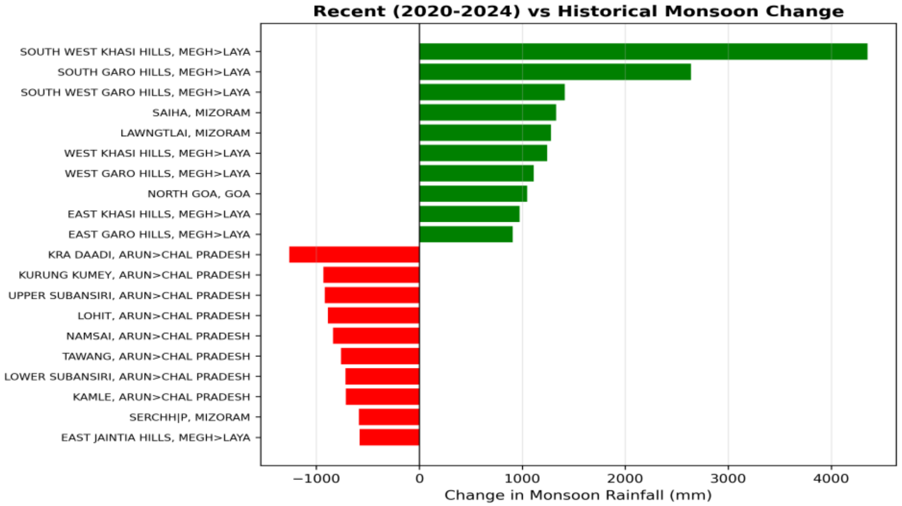
Top 10 Wettest Days

#	District	State	Max Rain
1	SOUTH WEST KHA	MEGH>LAYA...	949 mm
2	SOUTH GARO HIL	MEGH>LAYA...	742 mm
3	LOWER SUBANSI	ARUN>CHAL ...	569 mm
4	VALSAD...	GUJAR>T...	544 mm
5	EAST KHASI HILL	MEGH>LAYA...	525 mm
6	KALIMPONG...	WEST BENGA...	493 mm
7	ALIPUR DUAR...	WEST BENGA...	488 mm
8	DADRA & NAGAR	D>DRA & NA...	479 mm
9	LUNGLEI...	MIZORAM...	466 mm
10	SEPAHIJALA...	TRIPURA...	464 mm









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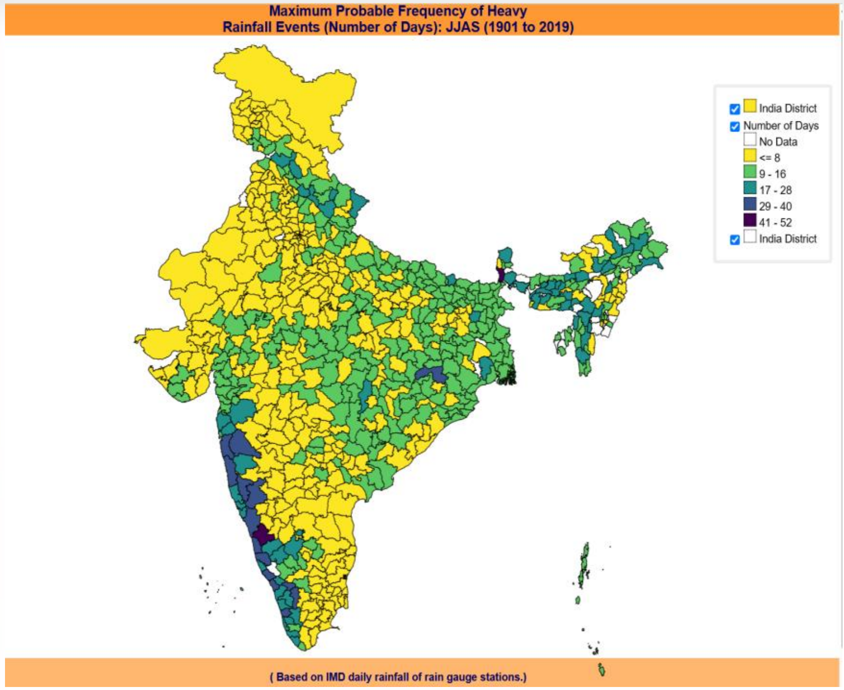

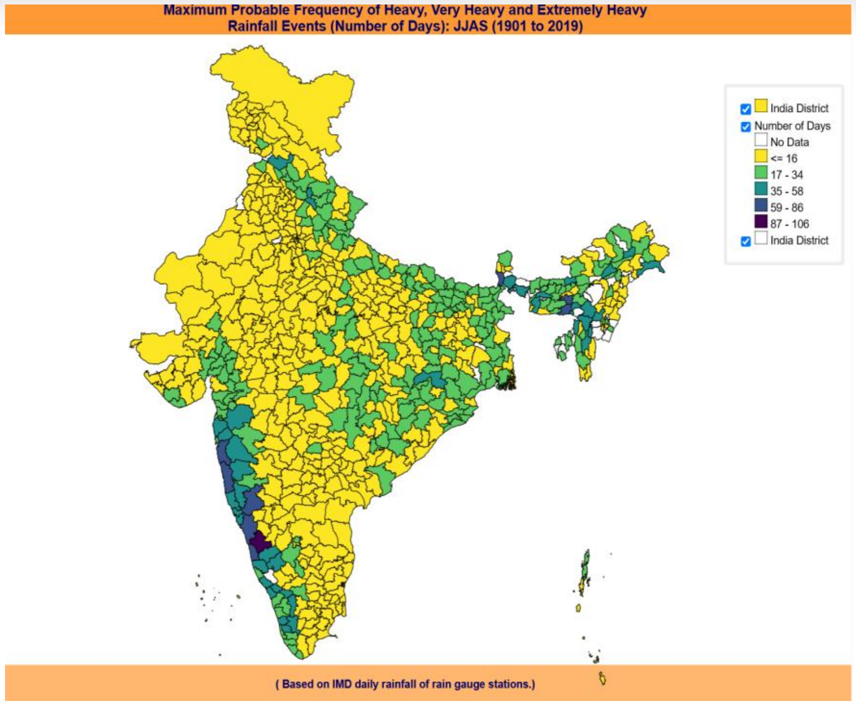

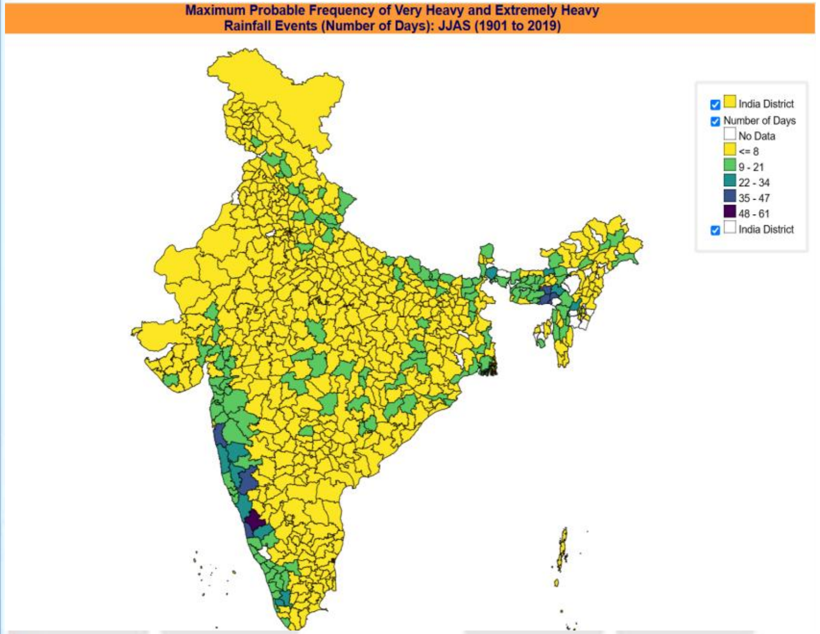

Terminology	Rainfall range in mm
Heavy Rainfall	64.5- 115.5
Very Heavy Rainfall	115.6-204.4
Extremely Heavy rainfall	Greater or equal to 204.5

Source: https://imdpune.gov.in/hazardatlas/extr_rainfallnew_p2011_2020.html

CMIP6 Climate Projections: SSP2–4.5 vs SSP5–8.5 Scenarios

CMIP6 (Coupled Model Intercomparison Project Phase 6): A global climate modeling framework coordinated by the World Climate Research Programme (WCRP) to compare and improve climate models across research institutions worldwide.

- It provides multi-model ensembles of global climate projections for different emission and socio-economic pathways (SSPs).
- Model examples used in CMIP6:MIROC6, MPI-ESM1.2, IPSL-CM6A-LR, CESM2, NorESM2, GFDL-ESM4, UKESM1-0-LL, among others.
- SSP2–4.5 (Intermediate scenario):Shared Socioeconomic Pathway with medium mitigation. Global temperature rise of ~2.1–3.5°C by 2100.
- SSP5–8.5 (High-end scenario):Fossil-fueled development pathway with high emissions; projected warming ~4–5°C by 2100.

❖ Key Projections for India (2050–2100):

- ↑ Temperature by 2.5–4°C across North-Central India.

- ↑ Frequency of extreme rainfall events over Central & Western India.

- Spatially uneven precipitation — drying in Indo-Gangetic plains, wetter over coasts and highlands.

Climate Projection Visualization

Future Projections of the Indian Monsoon and Impacts

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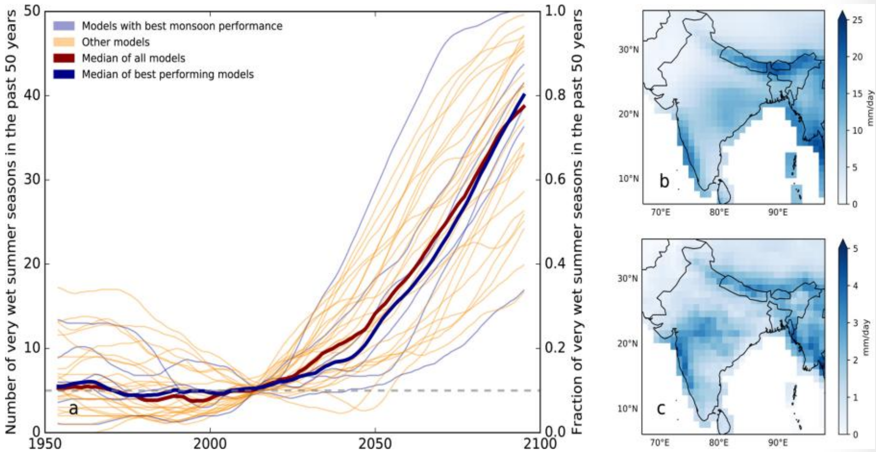
- ❖ Monsoon Rainfall Projected to Increase:
  - Total JJAS rainfall may rise by 8–14% by 2100 under high-emission scenarios.
  - Regional extremes: More intense wet years, with "very wet" monsoon seasons expected to become 8 times more frequent by late century.



- ❖ Explosive Growth in Extreme Events:
  - *Heavy rainfall events* (short bursts of intense rain) expected to increase by 21% or more.
  - Monsoon will be more volatile and unpredictable—with swings between droughts and floods.

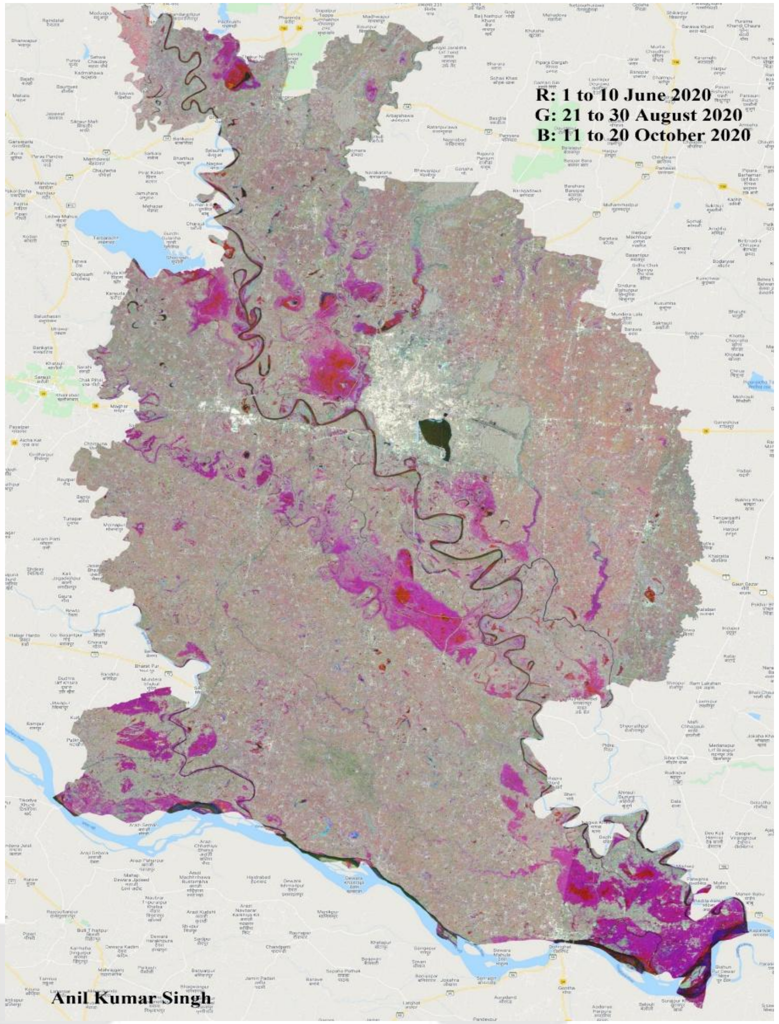
- ❖ Socioeconomic & Environmental Impact:
  - *Agriculture at risk*: Shifting crop zones, waterlogging, and more crop failures due to erratic rain.
  - *Water security threatened*: Dry and wet years will stress reservoirs and flood infrastructure.
  - *Migration and Disasters*: Rural-urban migration, heightened vulnerability in coast/Himalaya.

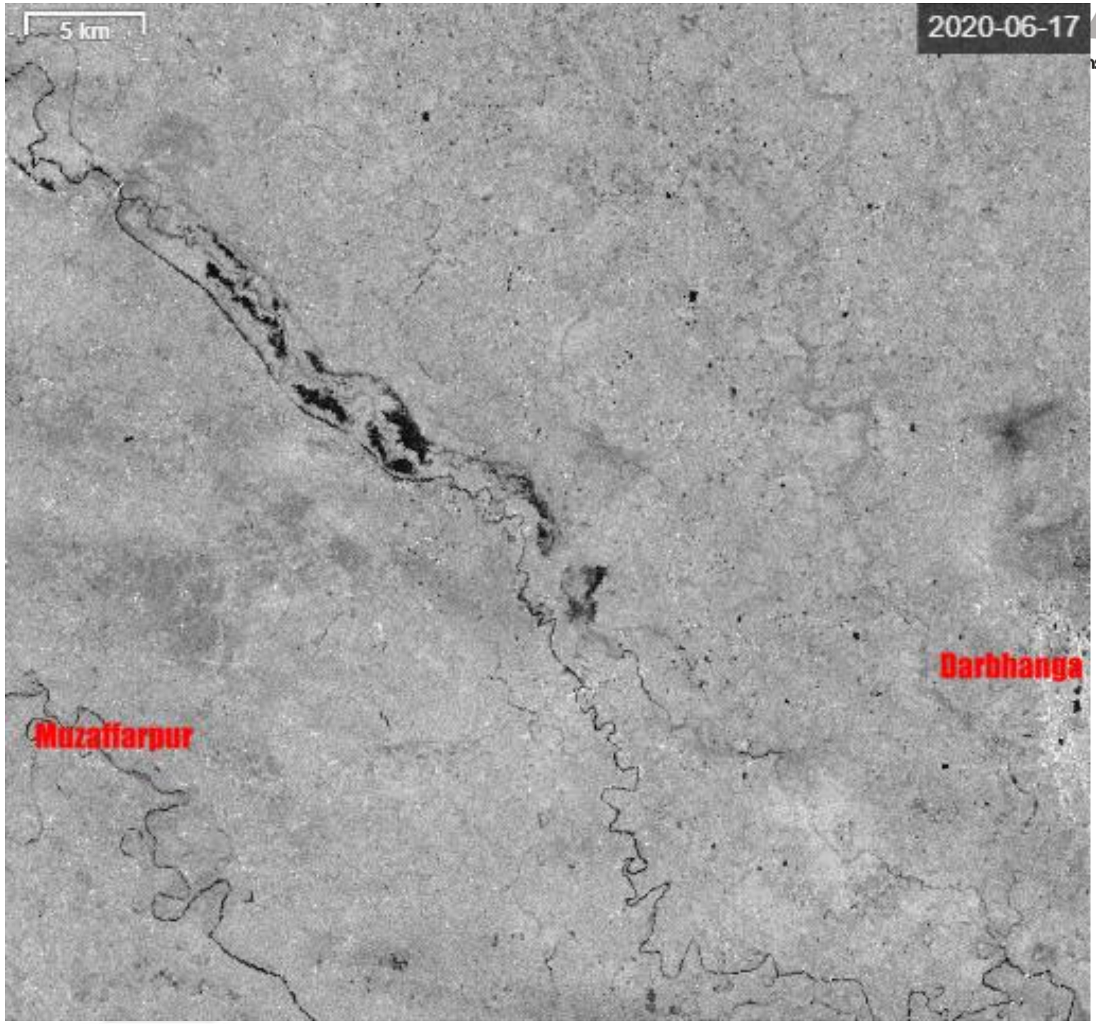
Climate Adaptation — Priority Actions

- **Early Warning & Forecast-to-Action**
  - Operationalize sub-seasonal & seasonal ENSO–IOD signals into district advisories.
  - Use radar + satellite flood alerts
- **Climate-Smart Agriculture**
  - Dynamic sowing calendars, drought-tolerant & short-duration varieties, staggered planting.
  - Promote micro-irrigation + on-farm water harvesting.
- **Integrated Water Management**
  - Use seasonal forecasts to operationalize reservoir release rules and conjunctive use.
  - Scale watershed recharge.
- **Urban & Infrastructure Resilience**
  - Green-blue infrastructure, strengthen drainage & flood-proof transport corridors in metros.
  - Heat-action plans and canopy/roof cooling in cities with rising WBGT exposures.
- **Nature-based Solutions & Land Use**
  - Reforestation, riparian buffer protection, and agroforestry to restore ET and reduce runoff.
  - Incorporate LULC change into local projection models
- **Finance, Institutions & Community Capacity**
  - Mainstream climate-risk into state budgets; expand index insurance & contingent finance.
  - Co-produce advisories with local extension services; farmer training on heat and flood safety.

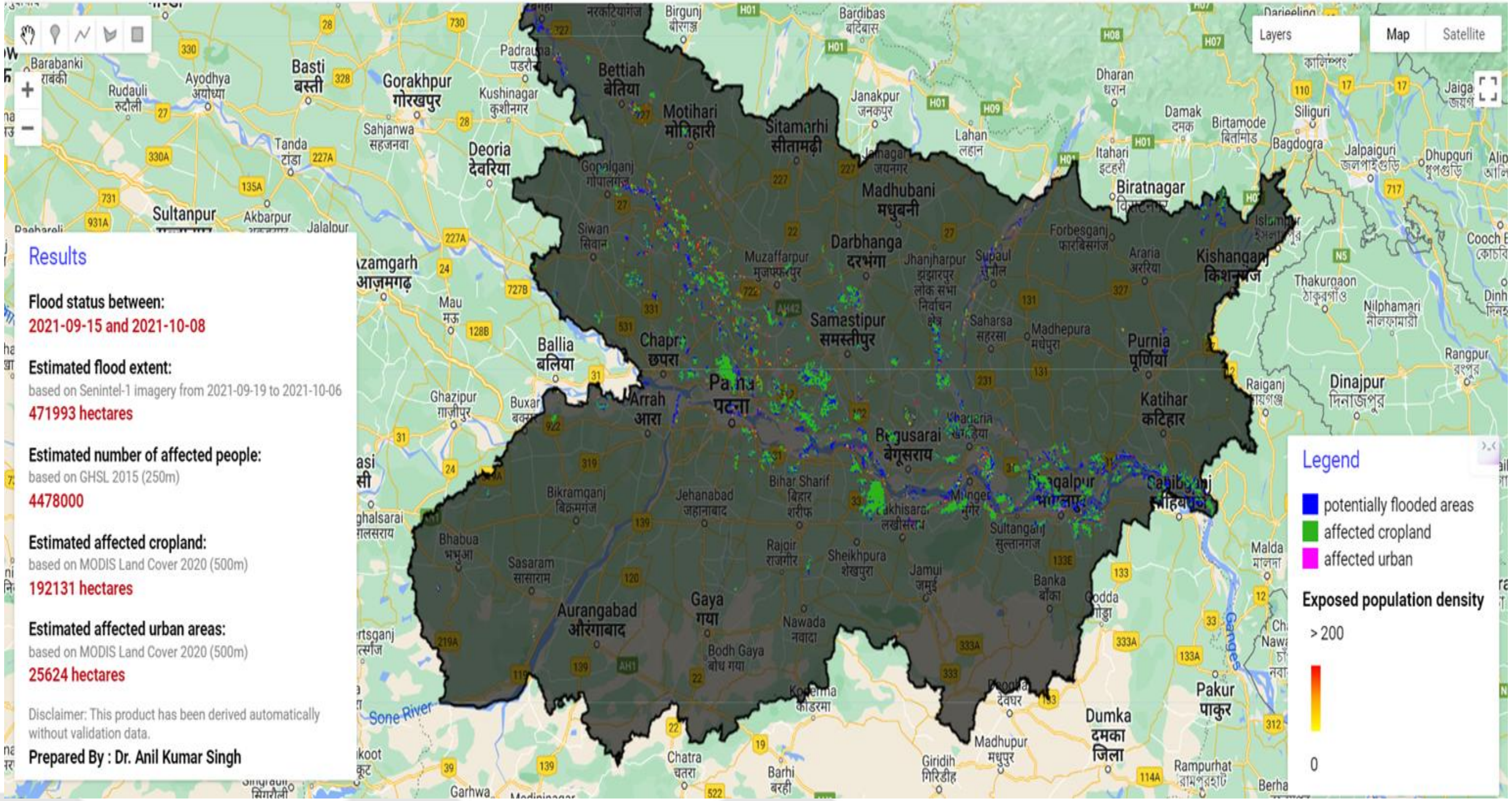
Some Recent Natural Disasters Due to ENSO
And
Tools and application to monitor and Tracking disaster

Flood in North India



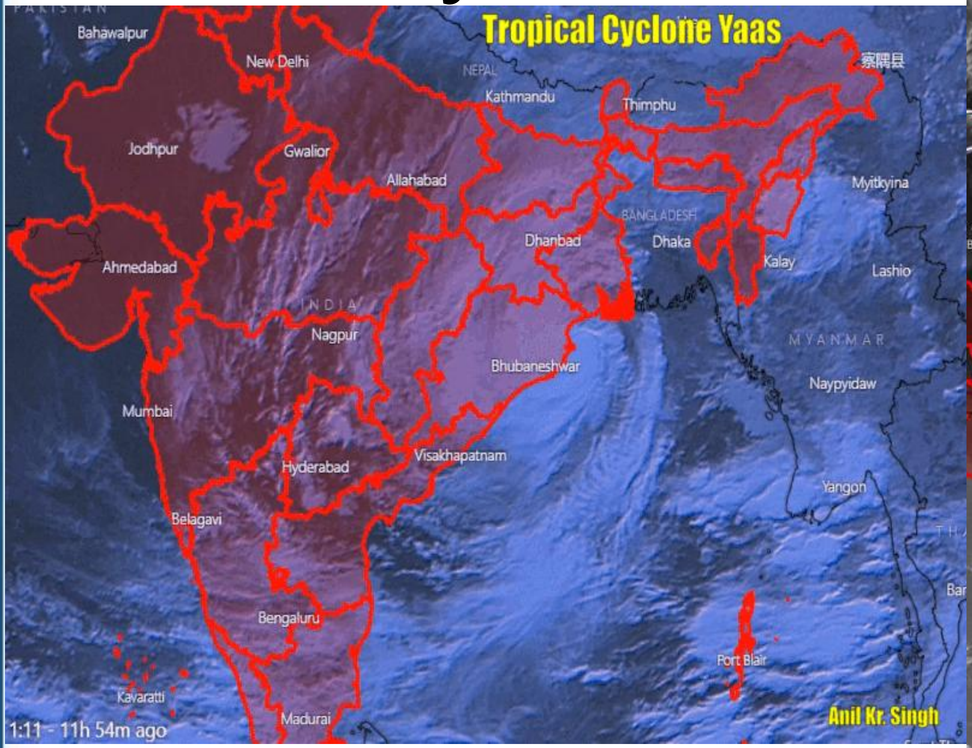


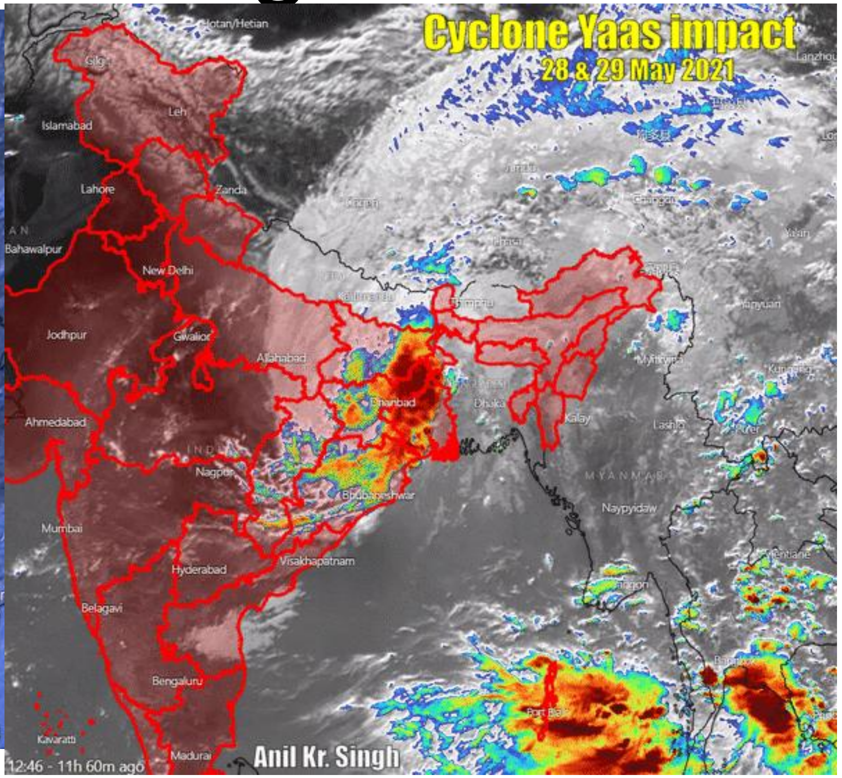
Flood Monitoring from Radar satellite



https://singhanil854.users.earthengine.app/view/biharfloodmap-monitoring

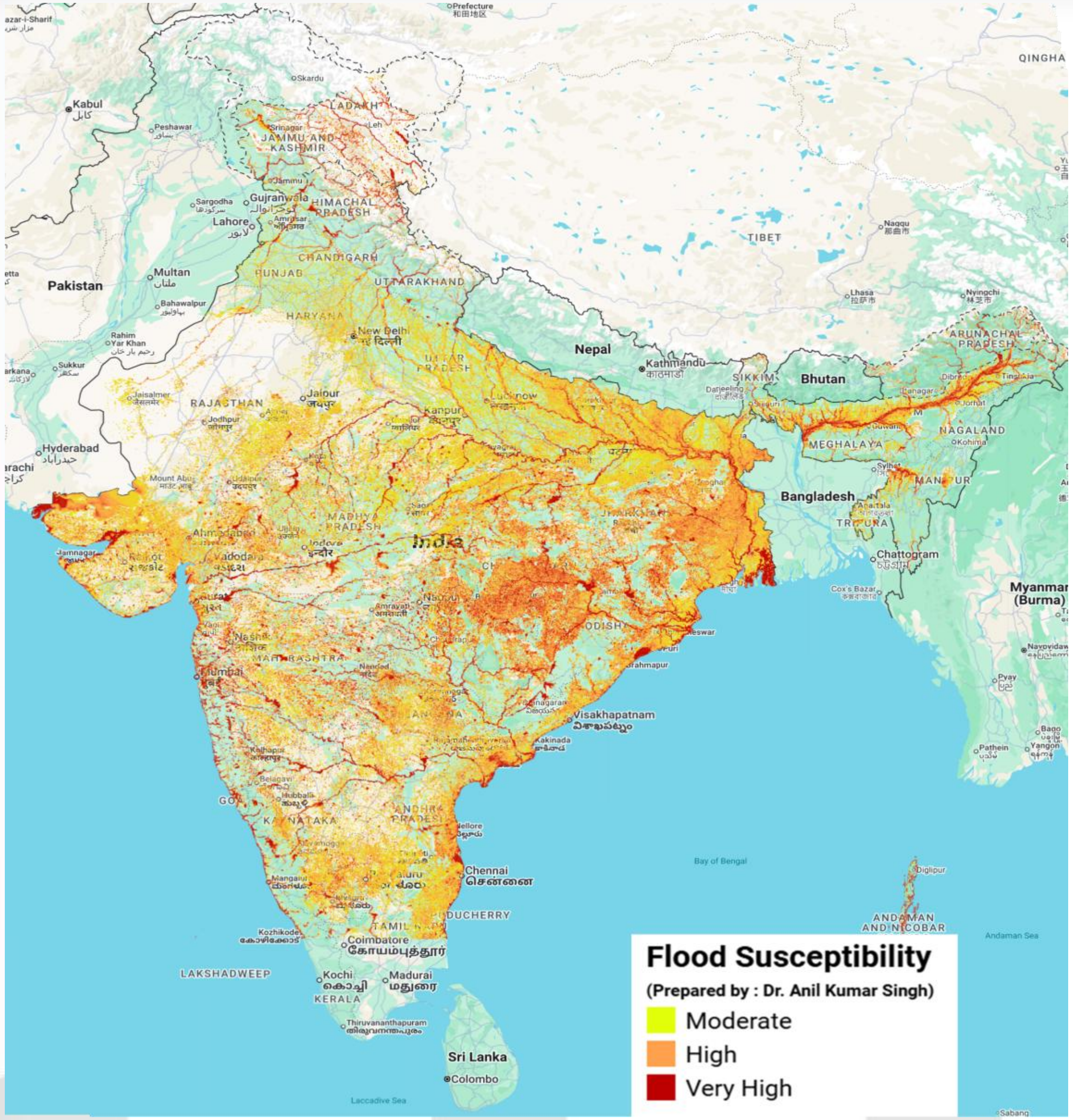
Cyclone monitoring





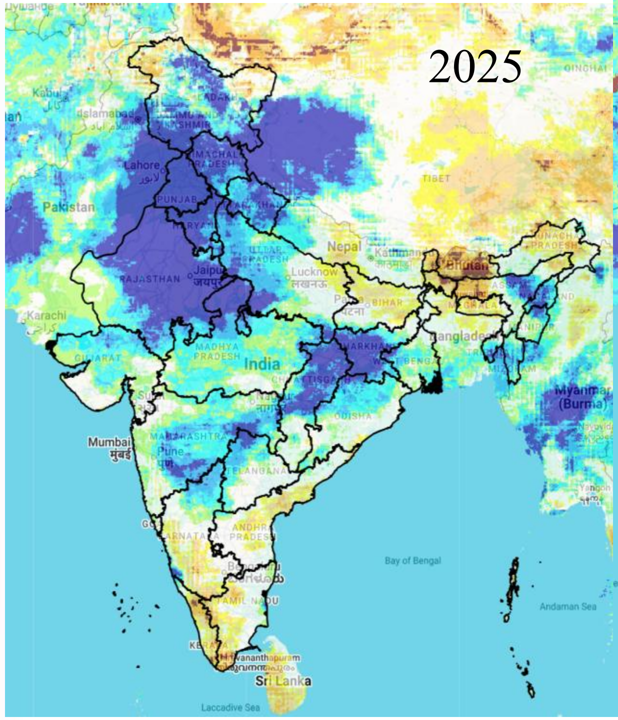
Land fall of Yaas cyclone

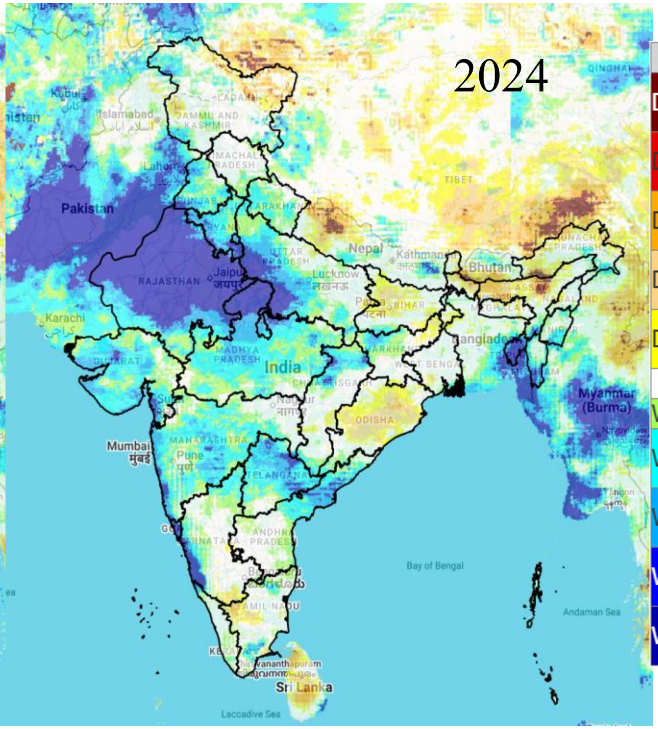
Fatalities	20 total
Damage	$2.07 billion (2021 USD)
Areas affected	Andaman and Nicobar Islands, India (West Bengal, Odisha, Jharkhand, Bihar, Uttar Pradesh, Madhya Pradesh), Bangladesh, Nepal



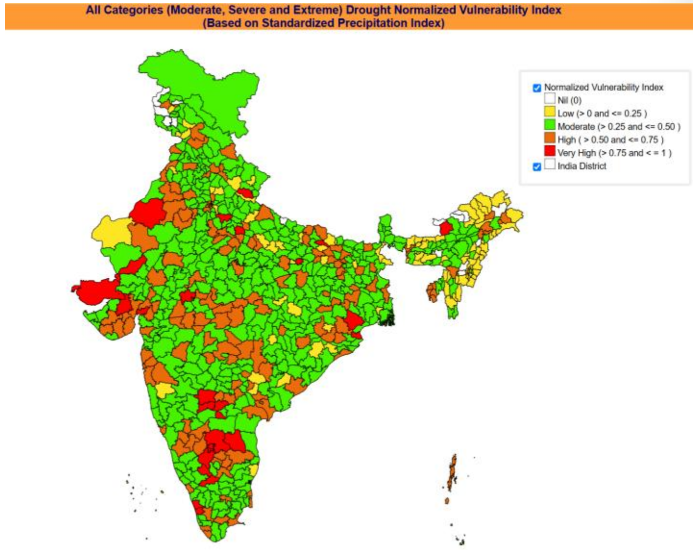
https://ee-singhanil854.projects.earthengine.app/view/allindiafloodrisk

Drought: Drought occurs due to deficiency of rainfall for an extended period of time, resulting in meteorological drought and causing lack of soil moisture leading to extensive damage to crops, loss of yield, resulting in a water shortage causing adverse impacts on vegetation, animals, and people. There are various indicators for monitoring drought in different temporal scales. In our present analysis, we have considered the Standardized Precipitation Index (SPI) for identifying the drought. SPI is computed for the cumulative period of four months (June-September) southwest monsoon season. It is computed for each year for the period 1901-2020 for all the districts using monthly rainfall data of districts and frequency of droughts of each category viz. moderate, severe, extreme drought and combination of all categories are computed.

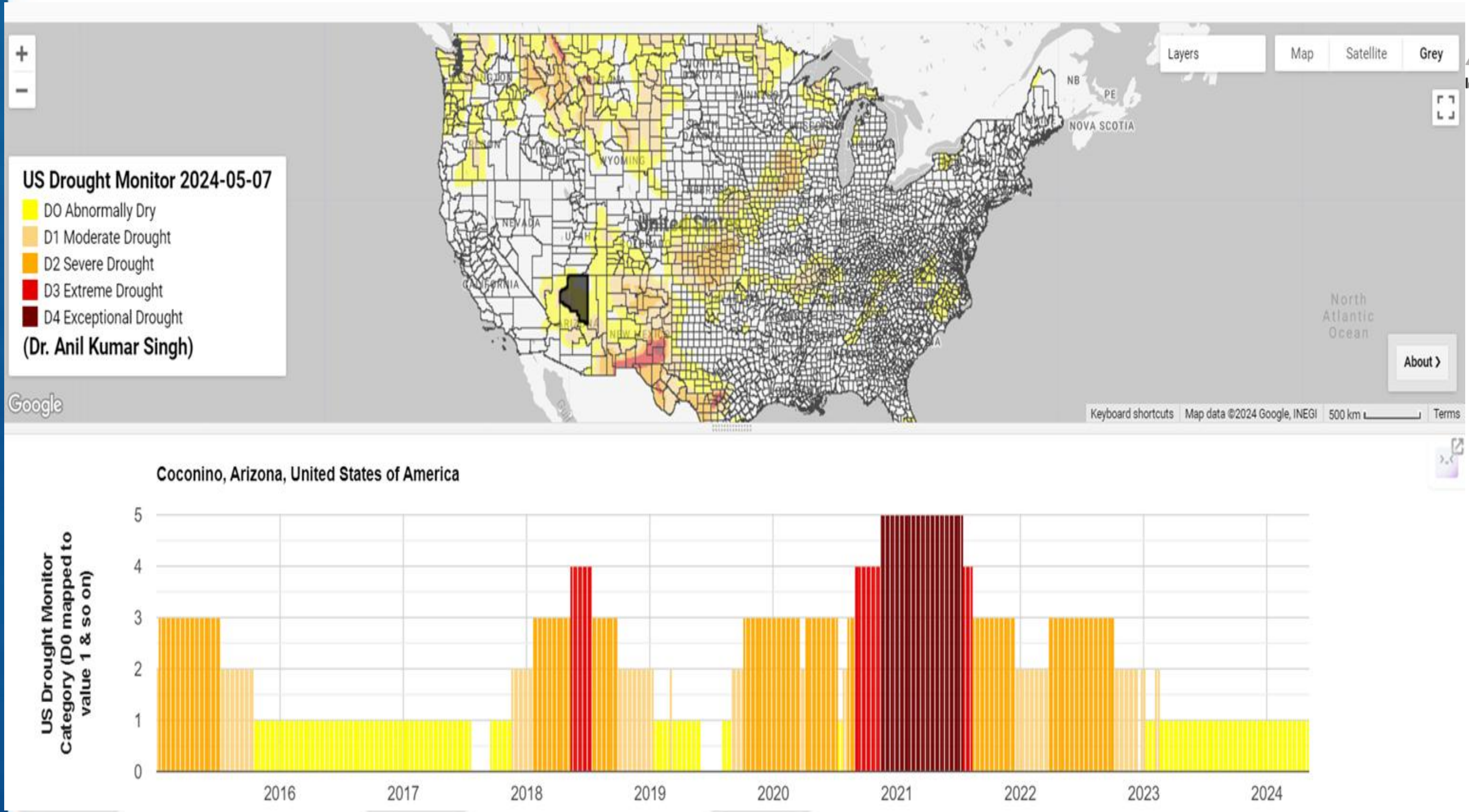




	USDM Category
D4	Exceptional Drought
D3	Extreme Drought
D2	Severe Drought
D1	Moderate Drought
D0	Abnormal Dry
	Neutral
W0	Abnormal Wet
W1	Moderate Wet
W2	Severe Wet
W3	Extreme Wet
W4	Exceptional Wet



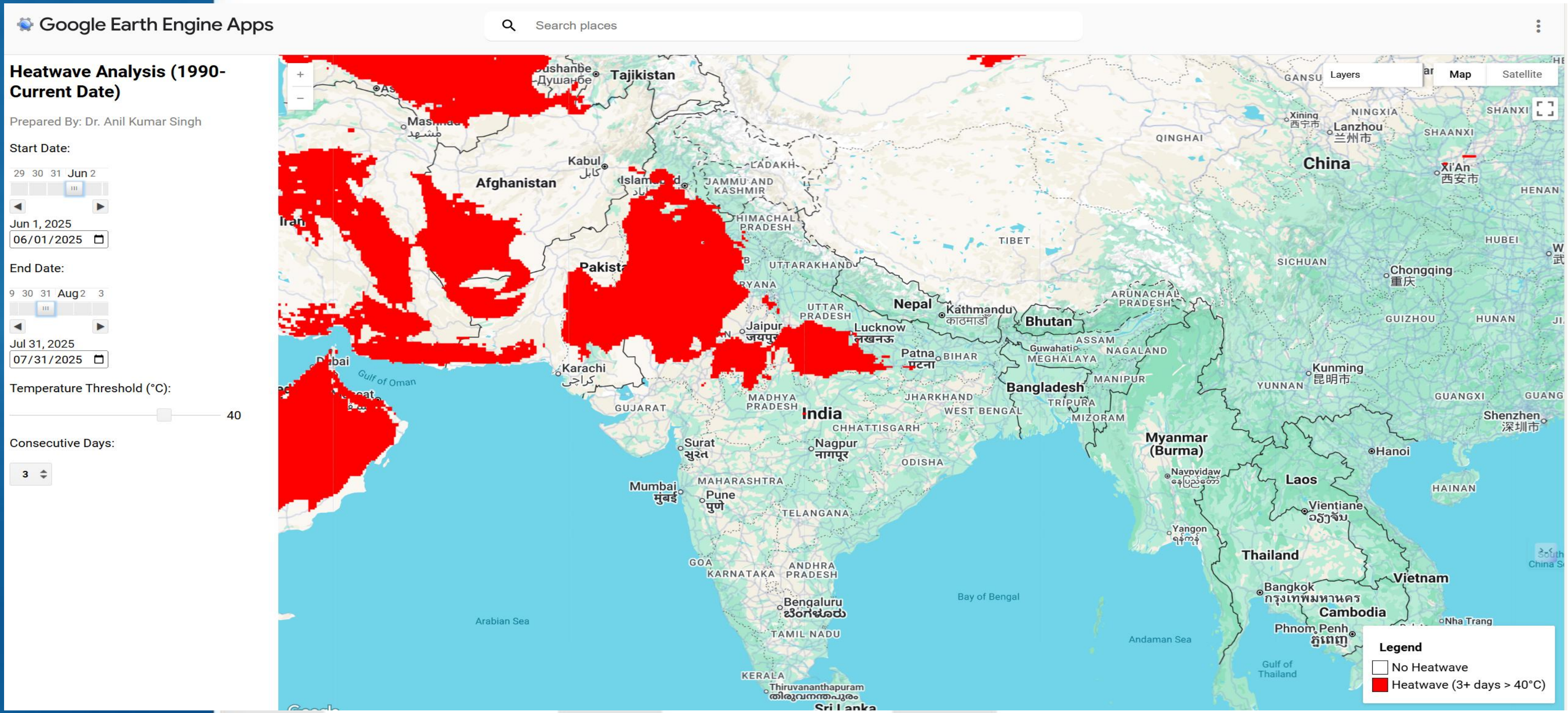
Drought Monitoring over USA



https://singhanil854.users.earthengine.app/view/usadrought-monitoring#lat=39.829;lon=-97.441;zoom=4

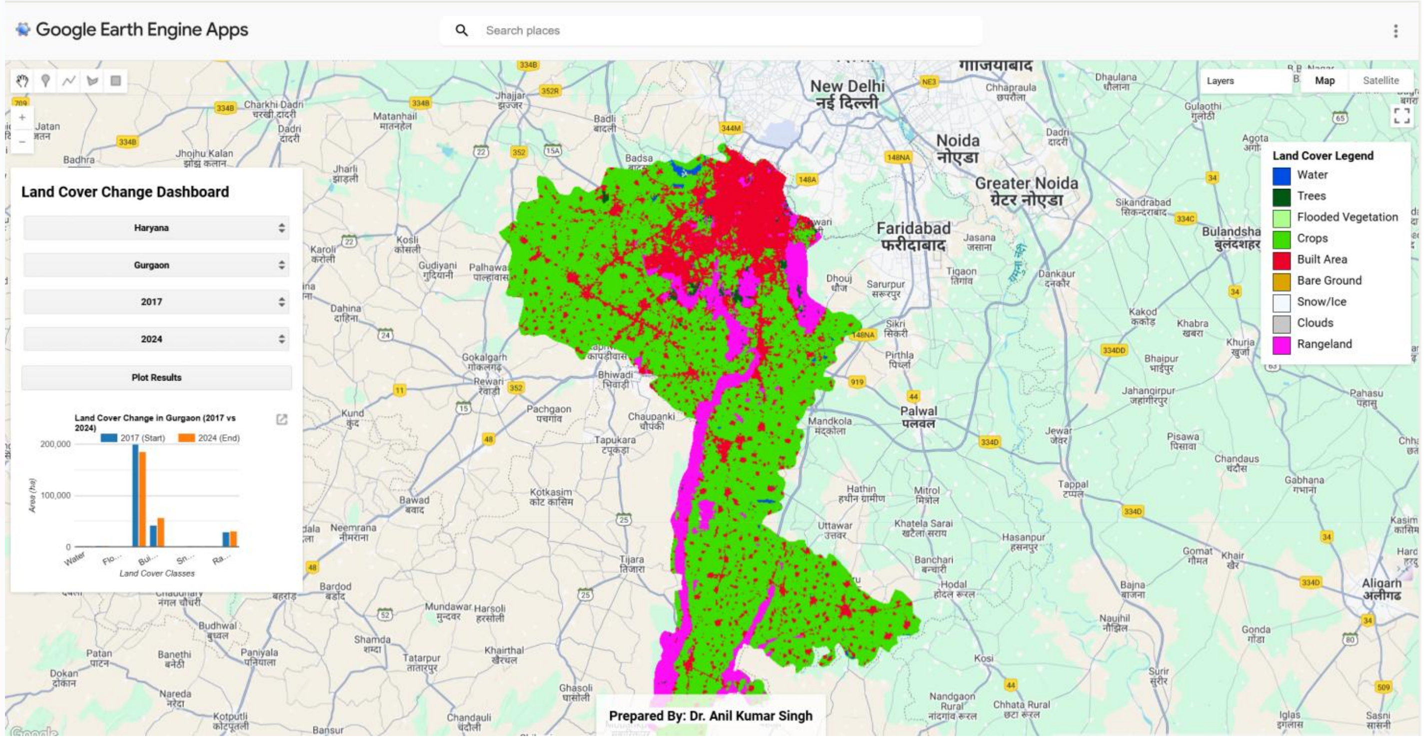
Institute of Actuaries of India

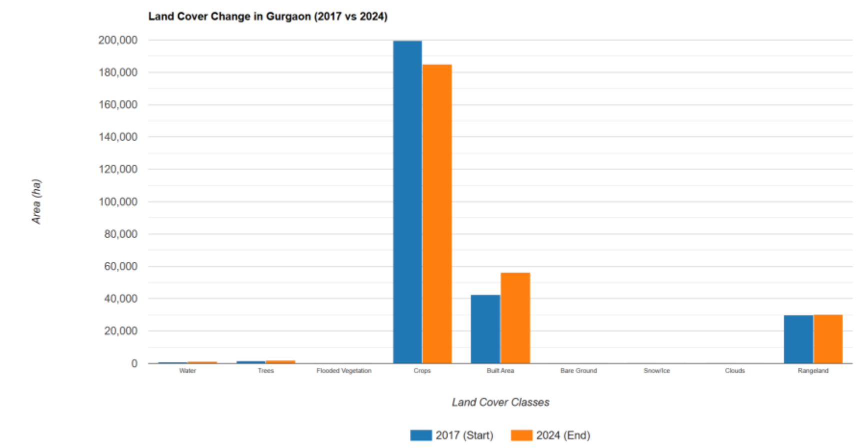
Heat wave Monitoring



https://ee-singhanil854.projects.earthengine.app/view/heatwavemonitoring

Landcover Monitoring





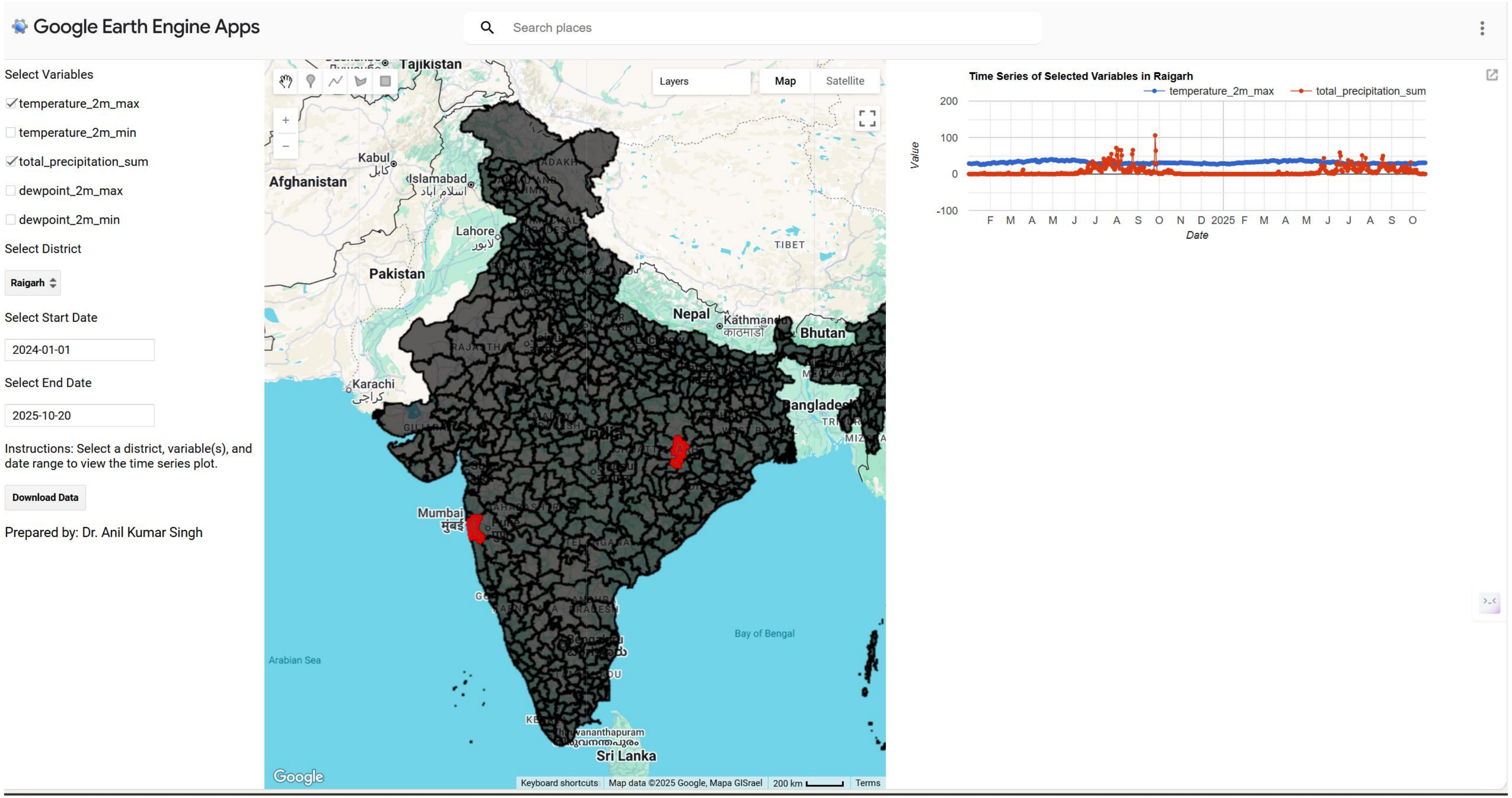
Weakening of Indian Summer Monsoon Rainfall due to LULC Changes

- Observed a statistically significant decline in Indian Summer Monsoon Rainfall (ISMR) since 1950.
- Large-scale deforestation and conversion of forest land to cropland in India has contributed to weakening ISMR.
- Mechanism: Deforestation decreases evapotranspiration (ET), reducing recycled rainfall and thus overall monsoon precipitation.
- Ganga Basin and Northeast India are most impacted, showing greatest declines.
- Implications: Climate models must include recent land use/cover changes for accurate monsoon projections; essential for sustainable water resources and agricultural adaptation strategies.

https://ee-singhanil854.projects.earthengine.app/view/landcoverchange

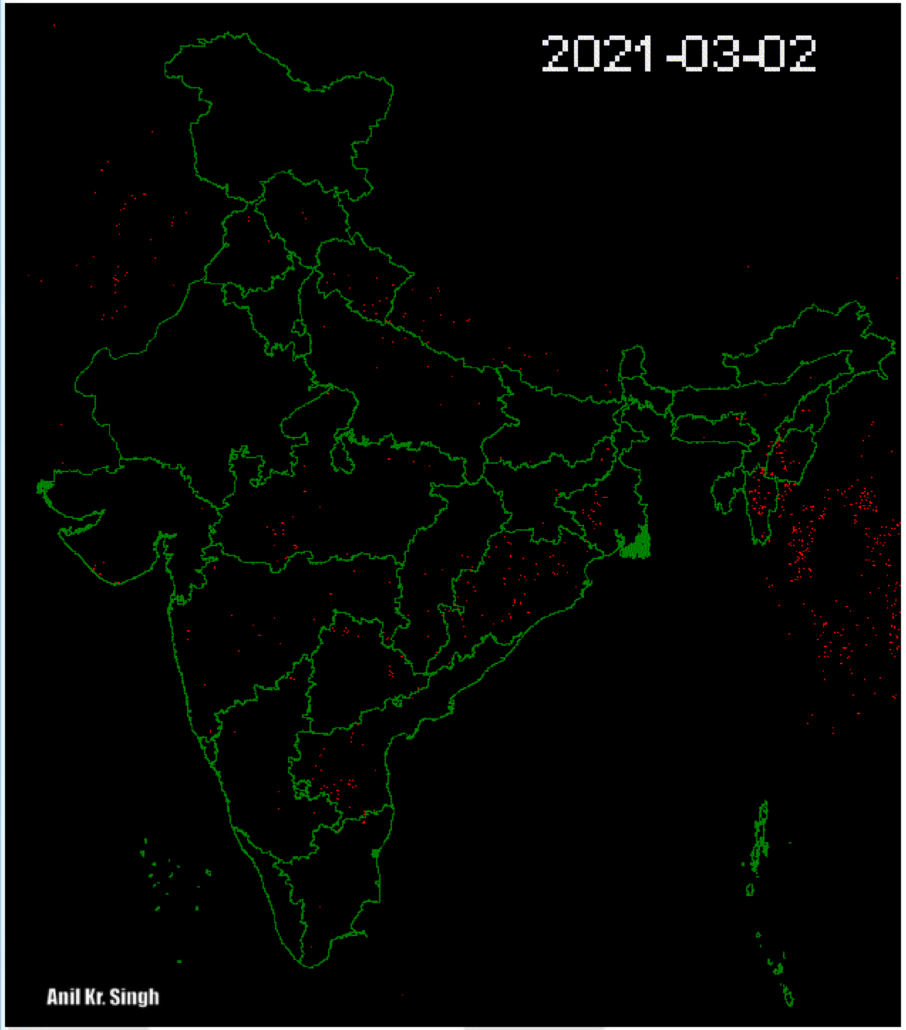
https://www.nature.com/articles/srep32177.pdf

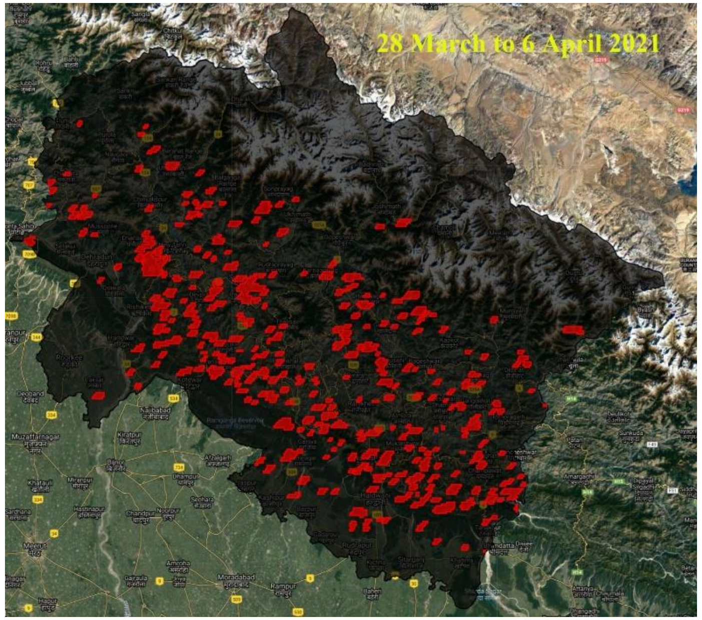
Climate Data Visualization and download

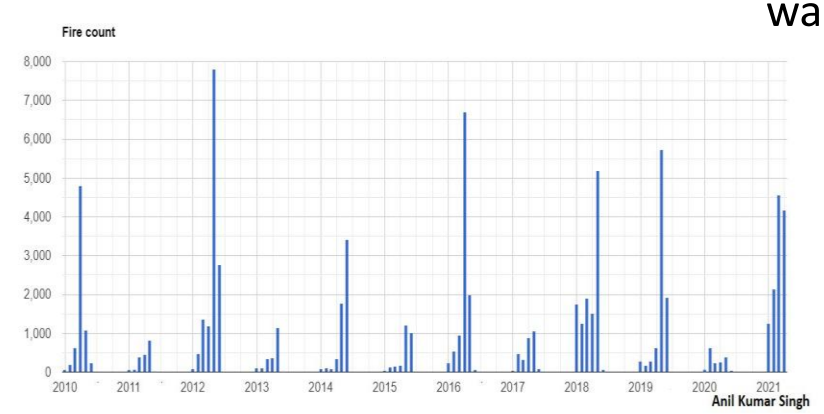


https://ee-singhanil854.projects.earthengine.app/view/era5data-downloader

Institute of Actuaries of India

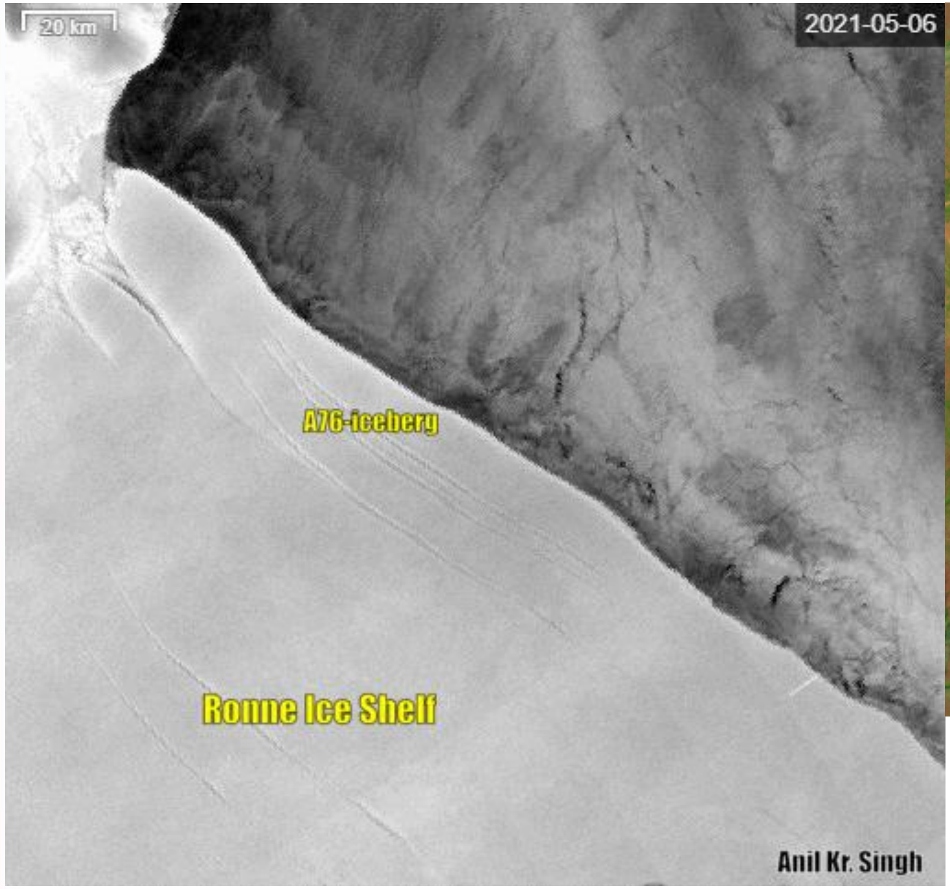






Jan to June (2011 to 2020) for 2021 Jan to 6 April. Compared to 172 hectares last year, 1290 hectares of forest area was affected this year

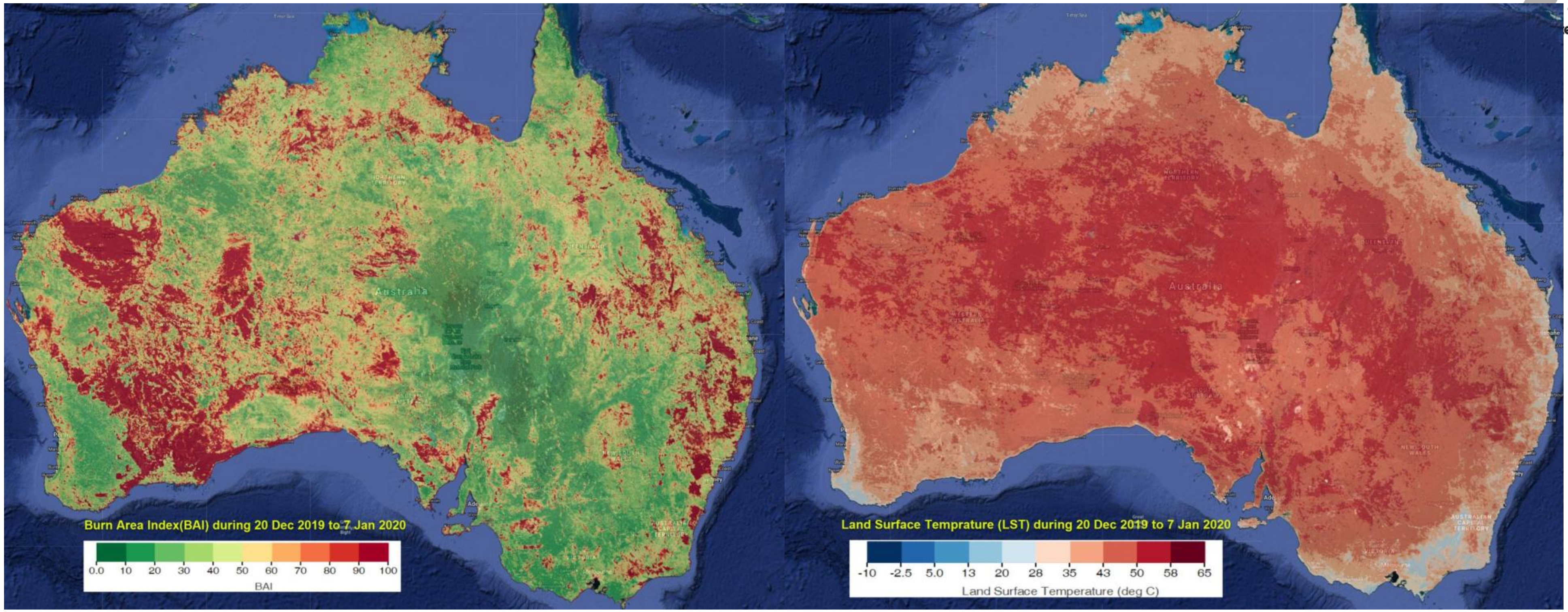
https://nasafirms-uiavab7s5czognrmjfidgb.streamlit.app



#Wildfires destroyed 10 acres of tiger habitat in the #Amrabad tiger reserve in #Hyderabad. capture from Sentinel2 satellite.

The #world's largest #iceberg has calved from #Antarctica

Australia bush Fire



ENSO was neutral, a **strong positive IOD combined with weak El Niño–like Pacific conditions** created one of the **driest and hottest summers** in Australia's history, triggering the catastrophic 2020 bushfires.

Conclusions & Key Messages

- **Monitor**: Strengthen real-time Earth observation and model integration (radar, GPM, ERA5, SPI) for district-level alerts.
- **Plan**: Use CMIP6 scenario maps (SSP4.5 / SSP8.5) to inform crop zoning, water infrastructure, and urban climate planning.
- **Act**: Implement climate-smart agriculture, watershed recharge, urban green-blue measures, and targeted finance.
- **Science** → Policy: ENSO–IOD predictive signals must feed into actionable triggers for reservoir operations and advisories.
- **Urgency & Equity**: Prioritize high-vulnerability districts and safeguard livelihoods of smallholders and urban poor.

"From Monitoring to Action — Align observations, forecasts, and policy to protect livelihoods."

Thank You