Indian Monsoon
Basic Drivers and Variability

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The Indian (South Asian) Monsoon

Monsoon circulation and rainfall:  *A convectively coupled phenomenon*

Requires a thermal contrast between land & ocean to set up the monsoon circulation

Once established, a positive feedback between circulation and latent heat release maintains the monsoon

The year to year variations in the seasonal (June – September) summer monsoon rains over India are influenced internal dynamics and external drivers
Long-term climatology of total rainfall over India during (1 Jun - 30 Sep) summer monsoon season (http://www.tropmet.res.in)

Interannual variability of the Indian Summer Monsoon Rainfall
Primary synoptic & smaller scale circulation features that affect cloudiness & precipitation. Locations of June to September rainfall exceeding 100 cm over the land west of 100°E associated with the southwest monsoon are indicated (Source: Rao, 1981).
Land/Sea Temperature contrasts

Nov./Dec.

May/June

West African Monsoon
Asian Monsoon
Austral Monsoon

Courtesy: J.M. Slingo, Univ of Reading
Rainfall (mm/day)

DJK

JJA

West African Monsoon

Asian Monsoon

Austral Monsoon

Courtesy: J.M. Slingo, Univ of Reading
Krishnamurti and Bhalme (1976): Schematic diagram of the salient elements of the monsoon system

A quasi biweekly oscillation can be seen in almost all the elements of the Monsoon system.
Planetary scale structure of the northern summer monsoon circulation at 200 hPa (upper troposphere)

Global scale divergent circulation identified by TN Krishnamurti (1971)

Tibetan Anticyclone

Tropical Easterly Jet
Helmoltz decomposition of wind field into rotational & divergent components

Velocity Potential at 200 hPa depicting Divergent component of summer monsoon circulation

Streamfunction at 200 hPa depicting Rotational component of summer monsoon circulation

\[ V = k \times \nabla \psi + \nabla \chi, \]
Seasonal evolution of upper tropospheric anticyclone: Convectively coupled process

Progression of onset and withdrawal of the southwest monsoon – Ananthakrishnan, 1977

Krishnamurti & Ramanathan, 1982: Sensitivity of monsoon onset to differential heating (MONEX)

Large increase in kinetic energy of total flow & rotational flow over Arabian Sea one week prior to onset of monsoon rains over Central India
Monsoon Interannual & Decadal variability
(Links with ENSO, Indian Ocean and PDO)
Observational documentation

Atmospheric Model Simulation Experiments / Coupled Models
(Examples: Keshavamurty, 1982; Shukla and Wallace, 1983; Krishnamurti et al., 1989; Palmer et al., 1992; Webster and Yang, 1992; Nigam, 1994; Chen and Yen, 1994; Ju and Slingo, 1995; Soman and Slingo, 1997; Sperber and Palmer, 1996; Krishnan et al., 1998; Meehl and Arblaster, 1998; Krishna Kumar et al., 2005, 2006; Mujumdar et al., 2007, Krishnamurthy et al. 2011, G. George et al. 2016 and many others)

Monsoon links with other boundary forcing (eg., Eurasian Snow Cover, Soil Moisture etc.)

Atmospheric Model Simulation Experiments
El Niño and Rainfall

El Niño conditions in the tropical Pacific are known to shift rainfall patterns in many different parts of the world. Although they vary somewhat from one El Niño to the next, the strongest shifts remain fairly consistent in the regions and seasons shown on the map below.

For more information on El Niño and La Niña, go to: http://iri.columbia.edu/ENSO


https://www.climate.gov/sites/default/files/IRI_ENSOimpactsmap_lrg.png
K. Krishna Kumar et al. 2006: Unraveling the mystery of Indian monsoon failure during El Nino (Science)

Plot of standardized all-India summer (JJAS) monsoon rainfall and summer NiNO3 anomaly index. Severe drought and drought-free years during El Nino events (standardized NiNO3 > 1) are shown in red and green respectively.

El Nino events with warmest SST anomalies in the central equatorial Pacific are more effective in focusing drought-producing subsidence over India than events with the warmest SSTs in the eastern equatorial Pacific.
Coupled patterns of SST and JJAS ISMR variability estimated by performing maximal covariance analysis (MCA) from 1900 to 2008. The patterns indicated by colored shading are the heterogenous correlation coefficients between the ISMR expansion coefficient time-series and the SST departure field at each grid point and vice versa. (A-D) leading two modes for the global SST domain.
Monsoon seasonal rainfall time-series averaged over the Indo-Gangetic Plain
Indian Ocean - Monsoon Coupled interactions & Droughts over India

Long-standing scientific question
Can the Indian Ocean dynamics influence the occurrence of long-lasting "breaks" in the monsoon rainfall over the Indian subcontinent?


Atmospheric convection intensifies over EEIO
- SST gradient along the equator
- Moisture convergence over EEIO

Decadal pattern: Warm minus cold composite of surface temperature based on 7 warm and 7 cold points of PDO index.

Interannual pattern: Warm minus cold composite of surface temperature based on 15 warm and 15 cold points of ENSO index.

Summary:
- Inverse relationship is noted between the Pacific SST variations associated with the PDO and the Indian monsoon rainfall.
- Majority of dry monsoons have occurred when El Nino events occurred during warm phase of PDO.
- Several wet monsoons have occurred when La Nina events occurred during cold phase of PDO.

Pacific Decadal Oscillation (PDO) and Indian summer monsoon rainfall: Krishnan and Sugi (2003)
Summer Monsoon Sub-seasonal / Intra-seasonal variability

(Active and Break Monsoon Spells)
Spatial map of correlation coefficients of cloudiness with reference point over central India (17.5N, 78E). Values > 0.4 are shaded and those less than -0.4 are dotted.

Power spectra of cloudiness fluctuations over 10N-15N, 72-84E. Units: (Cloudiness values)^2 .day

**10-20 day oscillation:** Westward propagation in the Asian summer monsoon

**30-50 day oscillation:** Slow northward propagation over the Indian monsoon region
Northward propagation of cloudiness fluctuations (30-50 day) over the Indian summer monsoon region: Yasunari (1980)

Westward propagation of sea level pressure at 20N latitude during July 1965: Krishnamurti et al. 1977

Sum of zonal wave numbers 1 & 2

Sum of zonal wave numbers 3 to 12
Meridional propagation of a train of troughs and ridges from near the equator and dissipate near the Himalayas, based on winds at 850 hPa. The meridional scale of this mode is around 3000 km and its meridional speed of propagation is \( \sim 0.75 \) deg latitude per day. The amplitude of wind for this mode is around 3-6 ms\(^{-1}\).

The 30-50 day mode at 850 mb during MONEX: Krishnamurti & Subrahmanyan (1982)

Meridional propagation of a train of troughs and ridges from near the equator and dissipate near the Himalayas, based on winds at 850 hPa. The meridional scale of this mode is around 3000 km and its meridional speed of propagation is \( \sim 0.75 \) deg latitude per day. The amplitude of wind for this mode is around 3-6 ms\(^{-1}\).
Mean rainfall during July & August 1975: Wet monsoon

Monsoon core zone for Active / Breaks

Rajeevan, Gadgil and Bhate (2008)

2002: Monsoon Drought

Mean departure (%) of rainfall during Monsoon breaks: Ramamurthy (1969)

Composite map of rainfall (mm day$^{-1}$) based on active monsoon days. The data is from TRMM 3B42 daily rainfall dataset. The active monsoon dates are from Rajeevan et al. (2008).

Large-scale organization of meso-scale convective systems MCS (3000-4000 km)

**Active Monsoon**

Composite map of rainfall anomaly (mm day$^{-1}$) based on active monsoon days.

South Asian Monsoon Trough

July mean SLP (hPa) & surface wind (knots)
(Sikka and Narasimha 1995)
Dynamical response of monsoon trough during active monsoons

Vertical development of cyclonic circulation well above the mid-troposphere!

Wind anomaly at 500 hPa during active monsoons

Relative vorticity ($x10^{-6}$ s$^{-1}$) profiles averaged over monsoon trough

Large-scale mid-level circulation anomalies extending into the African ITCZ region

TRMM algorithm to separate convective and stratiform echoes:

**Convective**-
- Young, active convection
- $w \sim$ several m/s
- Single mid-tropospheric heating peak

**Stratiform**–
- Older and less active convection
- $w \sim <1-2$m/s
- Heating upper & cooling lower levels

**Vertical profiles of latent heating**

![Diagram showing convective and stratiform heating profiles](image)
Climatological JJAS latent heating derived from TRMM rainfall

Vertically averaged heating

Dry model response to prescribed heating: Control (CTL) experiment

Lower tropospheric circulation

Upper tropospheric circulation

Choudhury and Krishnan (2011)
Sensitivity of circulation response to varying population of convective and stratiform rain anomalies over the monsoon trough zone during active monsoon spells

Stratiform (SF) and convective fractions (CF) of rainfall anomaly is assumed to be fixed at all grid points over the MT zone for any particular experiment.

Total Rain = Clim Rain + Anom Rain

Spatial variation of CF and SF for the total rainfall over the MT zone is allowed.

**Model sensitivity experiments**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Stratiform and convective fractions of rain anomaly during active monsoon period</th>
<th>Active period rain anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stratiform Fraction (SF)</td>
<td>Convective Fraction (CF)</td>
</tr>
<tr>
<td>Exp 1</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Stratiform anomaly</td>
<td>Convective anomaly</td>
</tr>
<tr>
<td></td>
<td>0.0 % of Rain anomaly</td>
<td>100 % of Rain anomaly</td>
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<tr>
<td>Exp 2</td>
<td>30%</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td>30 % of Rain anomaly</td>
<td>70 % of Rain anomaly</td>
</tr>
<tr>
<td>Exp 3</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>50 % of Rain anomaly</td>
<td>50 % of Rain anomaly</td>
</tr>
<tr>
<td>Exp 4</td>
<td>70%</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>70 % of Rain anomaly</td>
<td>30 % of Rain anomaly</td>
</tr>
</tbody>
</table>
Mid-level anomalous circulation response

70% convective clouds

70% stratiform clouds

Streamfunction

Large scale structure of mid-level cyclonic response extending into African ITCZ region

Velocity potential

70% convective clouds

70% stratiform clouds
Evolution of monsoon low pressure system (LPS) from 31 July to 8 August, 2006: Streamlines at 850 hPa and rainfall from TRMM Microwave Imager (TMI) Krishnan et al. 2011

Clustering of synoptic activity by monsoon intraseasonal oscillations: Goswami et al. 2003, GRL

Rainfall anomaly: Active minus Break
Monsoon Breaks: Large-scale structure of anomalies

Mean OLR (June – September) NOAA satellite
Good proxy for tropical convection

Composite OLR anomaly during monsoon Breaks – Krishnan, Zhang, Sugi (2000) JAS

Wind anomaly
850 hPa

Wind anomaly
200 hPa
Sequence of composited OLR anomalies during evolution of breaks (a) Triad -4 (b) Triad -3 (c) Triad -2 (d) Triad -1 (e) Triad 0 (f) Triad +1 (g) Triad +2 (h) Triad +3 (i) Triad +4
C. Ramaswamy (1962): Breaks in the Indian summer monsoon as a phenomenon of interaction between the easterly and sub-tropical westerly jet streams - Tellus

Ramaswamy & Pareekh (1978) Development of westerly circulation in both Hemispheres

500 hPa chart - 05 Aug 1957

500 hPa chart - 26 July 1972: A peak phase of monsoon break
Anomalous southward intrusion of mid-latitude westerly troughs in middle and upper levels during breaks

\[
\frac{\partial \xi}{\partial t} + V \cdot \nabla (\xi + f') = - (\xi + f') \nabla \cdot V + F
\]

Forced divergent barotropic vorticity equation

Simulated Rossby wave response to forcing from upper-tropospheric (200 hPa) divergence anomalies. Note that the simulated circulation response extends from the monsoon region into the midlatitudes.

Divergence anomalies at 200 hPa during monsoon breaks - estimated using OLR: Krishnan et al. 2009
Monsoon-midlatitude interactions during droughts over India

Droughts emanate from prolonged monsoon-breaks

Suppressed monsoon convection over sub-continent forces Rossby wave response extending over sub-tropics and mid-latitudes

Rossby response: Cyclonic anomalies over West-Central Asia and Indo-Pak; with a stagnant blocking ridge over East Asia

Decreases meridional temperature gradient over Indian longitudes; Dry anomalies decrease convective instability, suppress convection and weaken the monsoon

Cold air advection from mid-latitude westerly troughs cools middle and upper troposphere

Krishnan et al. 2009
Changes in monsoon precipitation over India since 1950s
Increasing Trend of Extreme Rain Events over India in a Warming Environment

Goswami et al. 2006, *Science*

Spatial map of linear trend of JJAS rainfall (1951 – 2007)

Time series of count over Central India
Climatological mean density of back-trajectories of monsoon flows reaching Indian region

Interannual variability of JJAS seasonal mean trajectory density (1958 – 2006)

30E-115E; 15S-5N

Krishnan et al. 2013
Long-term climatology of total rainfall over India during (1 Jun - 30 Sep) summer monsoon season (http://www.tropmet.res.in)

Interannual variability of the Indian Summer Monsoon Rainfall
M O N S O O N A L  D R O U G H T S

Surface Boundary Conditions

Land Surface Process
SST
Eurasian Snow Cover

ENSO Cycle

Other Possible Causes
Solar
Volcanic
Anthropogenic

Synoptic Scale <One Week

Low Frequency Intra-seasonal 30-50 day scale

North Ward Moving Episodes
East Ward Moving Episodes

Source: Sikka, 1999

Interactive Dynamics

Source: Sikka, 1999
ABCs (eg. sulfate, organics, black carbon, ash, dust, sea-salt, etc) alter absorption and reflection of solar radiation and influence climate.
Ramanathan et al, PNAS 2005

1970 to 2005: Surface Dimming-India
Trend: about 15 Wm-2

Padma Kumari et al, GRL 2007

1980 to 2004: Surface Dimming-India
Trend 19 Wm-2

R. Krishnan and V. Ramanathan, GRL 2002

Evidence of surface cooling from absorbing aerosols
Observed Trends in Summer Rainfall: 1950 to 2002

Chul Eddy Chung & V. Ramanathan
J. Climate, 2006

The Sahelian Drought

The Weakening Indian Monsoon

N-S Shift in Asian rainfall

Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon
Massimo A. Bollasina et al.
Science 334, 502 (2011); DOI: 10.1126/science.1204994

Bollasina, Ming, Ramaswamy, Science, 2011
The onset of the monsoon in early June brings with it a burst of life across the region — children playing on the streets, blossoming flora, flowing rivers, and sowing of agricultural lands. The monsoon supplies ~80% of South Asia's annual rainfall, supporting the region's primarily rain-fed agriculture and recharging rivers, aquifers and reservoirs that provide water to over one-fifth of the global population. Since the 1950s, the monsoon has weakened and become more erratic, with increased occurrence of extreme rainfall events. This has led to crop failures and water shortages with severe socio-economic and humanitarian impacts across South Asia. Writing in Climate Dynamics, R. Krishnan and colleagues suggest that anthropogenic greenhouse gas (GHG) emissions, aerosol emissions and agricultural land-cover changes are responsible for the observed changes in rainfall patterns. They predict that the monsoon weakening will continue through the twenty-first century, threatening the livelihoods and resources of over 1.6 billion people in the region.

SOUTH ASIAN MONSOON

Tug of war on rainfall changes

Rainfall associated with the South Asian summer monsoon has decreased by approximately 7% since 1950, but the reasons for this are unclear. Now research suggests that changes in land-cover patterns and increased emissions from human activities have contributed to this weakening, which is expected to continue in the coming decades.
Historical (1886-2005):
Includes natural and anthropogenic (GHG, aerosols, land cover etc) climate forcing for the historical period (1886 – 2005) ~ 120 yrs

Historical Natural (1886 – 2005):
Includes only natural climate forcing for historical period (1886– 2005) ~ 120 yrs

RCP 4.5 scenario (2006-2100) ~ 95 yrs:
Future projection includes both natural and anthropogenic forcing based on the IPCC AR5 RCP4.5 scenario. The evolution of GHG and anthropogenic forcing in RCP4.5 produces a global radiative forcing of + 4.5 W m^-2 by 2100

GHG-Only (1951-2005):
Includes GHG only forcing. Other forcing set to pre-industrial values

Aerosol-Only (1951– 2005):
Includes Aerosol only forcing. Other forcing set to pre-industrial values

High-resolution (~ 35 km) modeling of climate change over S.Asia

CO2 concentration in future IPCC AR5 scenarios

Aerosol distribution from IPSL ESM

INCA: INteraction with Chemistry and Aerosol

Runs performed on PRITHVI, CCCR-IITM
JJAS rainfall averaged over Indian region

Count of heavy rain events over central India (R > 100 mm/day)
Mean difference maps (HIST minus HISTNAT) during 1951-2005

JJAS rainfall and 850 hPa winds
Simulation of summer monsoon precipitation & 850 hPa circulation

HISTNAT

GHG only - HISTNAT

HIST - HISTNAT

AERO - HISTNAT
Response of tropospheric temperature and large-scale circulation to Anthropogenic forcing.

Weakening of monsoon Hadley-type overturning circulation.
Simulation of summer monsoon precipitable water response

HISTNAT

GHG only - HISTNAT

HIST - HISTNAT

AERO - HISTNAT

Courtesy: Sabin
Changes in Heavy & Moderate precipitation types (HIST & GHG-only runs)

Central India: 74.5°E – 86.5°E, 16.5°N - 26.5°N

Period: 1951-2000

Frequency counts for both categories are relative to HISNAT
Heavy precipitation events during South Asian summer monsoon

- Flood producing heavy rainfall over the southern slopes of **Northeast Himalayas** during breaks in the Indian monsoon
- **2010 Pakistan floods**
- **Heavy rainfall over** Northwest Himalayas (e.g., June 2013 Uttarakhand floods)
Monsoon update: Normal rainfall in most parts of India, Northeast reels under floods

In the Northeast, Assam, Arunachal Pradesh and Manipur have been witnessing floods and landslides. The mighty Brahmaputra and its tributaries in Assam has so far submerged 2,500 villages, destroyed 1.06 lakh hectares of farmland, damaged infrastructure by breaching embankments and overrunning roads and bridges.

Northeast floods cause unprecedented damage, 80 dead, 17 lakh marooned

Around 80 people died so far due to flooding and landslides in the Northeast, the Centre said on Thursday. The damage due to the flooding has been "unprecedented" and ISRO will be roped in to assess the extent of destruction, the Centre also said.
Flood Inundated Areas in part of Assam State: 8 June 2012 - Analysis of Radarsat SAR data

Flood Hazard Zonation Map of Brahmaputra and Barak Rivers in Assam State – Based on analysis of satellite data during 1998 – 2005 floods

Courtesy: National Remote Sensing Centre, India
Rainfall over the southern slopes of the Himalayas & adjoining plains during monsoon breaks

(Dhar, Soman and Mulye, 1984)

Composite during breaks (Vellore et al., 2014)

Rainfall

Anomalous northward shift of monsoon trough

Vellore et al. 2014
17 June 2013, Uttarakhand heavy precipitation and floods

Shiva statue, Rishikesh, Haridwar

20 June 2013

Composite of 34 heavy rain events (WH)

Monsoon-extratropical circulation interactions in Himalayan extreme rainfall

Ramesh K. Vellore 1, Michael L. Kaplan 2, R. Krishnan 1, John M. Lewis 3, R. K. Madhura 1, Sudhir Sabade 1, Nayan Deshpande 1, Bhupendra B. Singh 1, M. V. S. Rama Rao 1.
Western Himalayan Extreme precipitation events: Vigorous interactions of moisture-laden monsoon circulation and southward penetrating midlatitude westerly troughs – ERA

- Mid-latitude blocking and Rossby wave breaking
- West-northwest propagating monsoon low pressure system
- Eddy shedding of Tibetan High
- Ageostrophic circulations, transverse circulations across Himalayas
- Strong moist convection over Himalayan foothills

Vellore et al. 2015
2010 Pakistan Floods

- Interaction between mid-latitude disturbance and monsoon surges: Hong et al. (GRL, 2011)
- Convection of a more ocean character in a high humid environment: Houze et al. (BAMS, 2011), Rasmussen et al. 2015
- Persistent increase in conditional instabilities: Wang et al. (JGR, 2011)
- Russian heat wave–wildfires and Pakistan flood were physically connected: Lau and Kim (J. Hydrometeor., 2012)
- Westward shift of West Pacific Subtropical High: Mujumdar et al. (Meteo. Appli., 2012)
- Event could have been predicted two weeks in advance: Webster et al. (GRL, 2011)
Closeness centrality: High closeness centrality lies in the northwest subcontinent. This indicates that the information travels fastest to and from these points. Any perturbation occurring in this region can affect the monsoonal rainfall patterns at rapid temporal scales.

Convective instabilities in this region occur due to interactions between the cold/dry subtropical winds with the warm/moisture laden monsoonal winds over a dry and hot region during the peak of the summer with low pressure fields.
Indian Monsoon
Multi-scale Interactive Phenomenon

Internal Dynamics
- Land-sea thermal contrast / Convective coupling / Atmospheric internal variability
- Atmosphere-Ocean-Land-Cryosphere-Biosphere coupling, Carbon and Biogeochemical cycles
- Teleconnections - ENSO, PDO, IOD, MJO, NAO, AMOC, Extra-tropics / Polar, Arctic Amplification, Climate Drivers
- Spatial-scales: Turbulence, CCN Microphysics Aerosols, Clouds, MCS, Meso-scale, Organized Convection, Circulation (Synoptic [lows, depressions, monsoon trough, active/break,], large-scale, planetary-scale..)
- Diurnal, Synoptic (lows, depressions, MTCs), Extremes, Intra-seasonal (10-20 day, 30-60 day modes), Interannual, Decadal & long-term

External forcing
- Greenhouse gases (CO2, CH4, CFCs, ...), Human Induced Climate Change
- Aerosols (Natural - Dust, Sea-Salt, Volcanoes, ...; Anthropogenic: Sulphates, Nitrate, Ash, Black Carbon, Organic Carbon, ...)
- Land-use / Land cover changes (Deforestation, Agriculture, Rivers / Lakes, ...)
- Atmosphere and Ocean Chemistry

Impacts
- Water, Agriculture, Energy, Health, Ecosystems, Environment
- Adaptation Strategies, Policy making, Economy, Mitigation, Sustainable Development, Capacity Building

Methodologies: Computer simulations, Earth System Models / Climate models of varying complexities, Application models (eg. Hydrology, crops, energy, ecosystems ...), Observations and Satellite Data Analysis, Data Assimilation, Ensemble Prediction Tools, Advanced techniques to study behavior of Complex Systems, Networks, etc.