Monsoon, where art thou?

The great Indian Drought of 2014?

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The Indian Monsoon

1. Past: History of Monsoon
2. Present: The Monsoon we know/live
   - Driving mechanisms and factors
   - Variability: Interannual, Intraseasonal, etc.
3. Monsoon Modeling
4. Role of Ocean on the Monsoon
5. Future: Changing Climate and the Monsoon
6. Monsoon 2014

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History of Monsoon, 80 Mya
Plate tectonics – factors leading to modern monsoon

Indian plate motion: rate of ~ 15cm/yr – collided with Asia c.20–30 Mya.
History of Monsoon, 30Mya

Rise of the Himalayas and strengthening of the monsoon

The Himalaya–Tibetan plateau uplift during late Tertiary strengthened the Asian Monsoon.

Confinement of African monsoon to a thin band, expanding the subtropical desert is also seen.

Role of Orography:

1. Upward deflection of large scale horizontal flow by orography
2. Uplifted moist air will expand, cool and condense – forming clouds

Fluteau et al. *JGR*, 1999
Variation in the timing and intensity of the monsoon affects lake-water Oxygen isotope and alters relative hydrologic balance between evaporation and precipitation in the lake.

Presence/absence of ostracods confirms this.
History of Monsoon, 1500 AD

Trade Winds – History Changers!

Using the trade wind secret, Indian and Arabian traders were able to dominate the lucrative market by concealing the true source of their cargoes for centuries.

Mediterranean sailors from Egypt and Europe were fearful of open-sea sailing and their ships hugged the coastlines – until 1st century BC when a stranded sailor revealed the secret to Egyptian Officials.
Monsoon, manifested by Winds

Trade Winds

850 hPa wind flow during this week – July 2014
Monsoon, manifested by Surface Temperatures

Seasonal migration of solar insolation
Monsoon, manifested by Thermal Contrast

Land and sea warms at different rates, sp.heat capacity

Tibetan plateau: range of 60° C

Ocean: range of 3 to 5° C
Monsoon, manifested by Pressure Gradient
Monsoon Trough and 120° shift in wind direction

1. Madagascar–Mascarene High/Anticyclone and Monsoon Trough
2. Low-level cross-equatorial Jet: splits in 2 branches at around 10°N, 60°E
Monsoon, Tropical Easterly Jet

Low-level convergence matched by upper level divergence

Tibetan high results in an upper-level anticyclone; located over n. India above the monsoon trough.

Moves in a south-southeast direction following the zone of maximum surface heating and low pressure.
Japanese used the jet stream across Pacific to launch and drop balloon bombs in the US. About 9000 balloons were deployed, and 1000 reached destination after travelling 6000 miles, in 2–3 days!
Monsoon and Coriolis Effect

Earth rotates! and at different speeds at diff latitudes!

add land masses $\rightarrow$ unequal heating and cooling of the Earth
Monsoon, manifested by conducive SST
SST > 28°C conducive for enhanced convective activity

Gadgil et al., *Nature*, 1984; Roxy, *Climate Dynamics*, 2013
SST conducive for Convection

Regions of climatological warm SST ($SST > 28^\circ C$) tend to be collocated with high mean precipitation.
Other Monsoon Systems and TCZ
Seasonal Migration
Interannual Variability of the Indian Monsoon

ENSO is a major driver

Interannual Variability of the Indian Monsoon

ENSO is a major driver

Walker circulation features during summer.
El Niño conditions weaken the monsoon southwesterlies.
Higher frequency of occurrence of active conditions would result in stronger than normal seasonal mean, and vice-versa.
Modeling the Monsoon

Statistical Seasonal Forecasts had poor skill (1988–2010)

Limitations of Indian Seasonal Forecasts:

Too many predictors are used in statistical model (over-fitting)
Method of choosing predictors gives artificial predictability (fishing)
Modeling the Monsoon
Dynamical Seasonal Forecasting, improving gradually

IC = Data for Initial Conditions.
Eg: Ocean Temperature of April for JJAS seasonal forecast

IC of Atmos + IC of Ocean, Land, Atmosphere
- dynamically coupled and consistent IC
- Global ocean (especially upper ocean); sea ice
- Global Atmos. including stratosphere (IC)
- Global GHG (especially CO$_2$, O$_3$)
- Global land (soil moisture, vegetation, snow depth) IC
Modeling the Monsoon
National Monsoon Mission

NCEP Climate Forecast System – CFSv2

- **Atmosphere:**
  NCEP Global Forecast System (GFS)
  - horizontal: spectral T126, ~80 km
  - vertical: 64 sigma-pressure hybrid levels

- **Ocean:**
  GFDL Modular Ocean Model v4 (MOM4p0)
  - 40 levels in vertical, 0.25–0.5 resolution

- **Sea Ice:**
  GFDL Sea Ice Simulator (SIS)
  an interactive, 2 layer sea–ice model

- **Land:**
  NOAH, an interactive land surface model with 4 soil levels

Earth System Model development

HPC: Fastest in India, In the TOP 100
1. Ocean – atmosphere interactions
2. Spatial variability of the interaction
3. Relevance to climate change
and the ocean was in the atmosphere

BBT, 2011
It was thought that …

… **Okeanos** (or Oceanus), was the great equatorial–encircling river, the source of all the earth’s fresh–water: including rivers, wells and rain–clouds. Okeanos’ wife was **Tethys**, was thought to distribute his water to the earth via subterranean streams.


Greek: Ὠκεανός  ->  French: occean -> English: ocean
The oceans’ thermal inertia is communicated to the atmosphere via turbulent and radiative energy exchange at the sea surface. These energy fluxes in turn depend on a single oceanic quantity, the sea surface temperature (SST), as well as several atmospheric parameters including wind speed, air temperature, humidity, and cloudiness. SSTs thus play a key role in regulating climate and its variability.

Where has all the heat gone?

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (high confidence)
SST variability over the monsoon basins

SST and heat flux anomalies associated with monsoon ISV are observed over a large domain, Arabian Sea → s. China Sea → w. North Pacific

Sengupta et al., *GRL*, 2001; Xie et al., *J.GR*, 2007
Webster et al., *JGR*, 1998
Ocean–atmosphere interactions over the monsoon basins

SSTs beyond 26 °C conducive for increased convection

Gadgil et al., *Nature*, 1984; Waliser et al., *J. Climate*, 1993
Over “Bay of Bengal”: Intraseasonal SST influence the atmospheric variability, eg: Precipitation

Negative SST lead monsoon break by 10 days ($r = 0.67$).

Step by step process on the SST− precipitation relationship?

Vecchi and Harrison, *J. Climate*, 2002

Fu et al., 2008
Ocean–atmosphere interaction over Indian/w.Pacific
- positive SST anomalies enhance convection

Positive SST anomalies
=> destabilize lower atmos. column
=> convective activity

Wu et al., *GRL*, 2008
Ocean–atmosphere interactions over the monsoon basins

Atmospheric soundings between June 2–14

Mean profile of virtual potential temperature $\theta_v$, for 0600 GMT on 2 June (pre–monsoon) and 11–14 June (onset) from MONEX 79 ship data over Arabian Sea.

Holt and Raman, 1987
Ocean–atmosphere interactions over the monsoon basins

Matsuno, 1996; Gill 1980; Roxy and Tanimoto, *Climate Dynamics*, 2010
Spatial variability of SST–precipitation relationship

The SST–precipitation relationship have different lead–lags over the Arabian Sea and the Bay of Bengal/South China Sea Ocean -> Atmosphere | Atmosphere -> Ocean

Spatial variability: response time difference of 1 week!

Roxy et al., *Climate Dynamics*, 2012
The SST–precipitation relationship have different lead–lags over the Arabian Sea and the Bay of Bengal/South China Sea.
Why is the response time different over the basins? — ocean–atmosphere interaction?

SSTa → $\theta_e$: instantaneous over all the basins, $\theta_e$ → precipitation response is different.

Convective max located south of SST max.

Roxy et al., *Climate Dynamics*, 2012
Why is the response time different over the basins?

- role of surface convergence

Relatively stronger surface convergence over the Arabian Sea accelerates the uplift of the moist air, resulting in a relatively faster response in the local precipitation anomalies.

Roxy et al., *Climate Dynamics*, 2012
Why is the response overestimated in CFSv2 model?

Is it the MLD bias?

For the same magnitude of fluxes, change in SST is different:
Shallow MLD $\rightarrow$ ISV amplified
Deep MLD $\rightarrow$ ISV weakened
$r = 0.5$, significant at 95% levels
Ocean-atmosphere interactions over the monsoon basins

Roxy et al., Climate Dynamics, 2012
SST–precipitation relationship over Tropics

Gadgil et al., *Nature*, 1984
Waliser et al., *J. Climate*, 1993
Does high SSTs have an active role on Monsoon?
- mean SSTs above 28.5 over basins
SST–precipitation relationship over Tropics – the upper threshold and CAPE

![Graphs showing SST-precipitation relationship](image)

Earlier studies: Precipitation increases monotonously at SSTs beyond 26 °C, but limited to: **Upper threshold of 28 – 29°C**

Explanation given: Precipitation tends to occur where positive convective available potential energy (CAPE) exists

→ the occurrence of deep convection will tend to squelch CAPE?

Gadgil et al., *Nature*, 1984; Waliser et al., *J. Climate*, 1993
SST–precipitation relationship over Indian Ocean – where SSTs above upper threshold!

Figure 2. Over north Indian ocean (a) mean TMI SST in °C of 16 April to 15 May of 8 years 1998 to 2005. (b) Mean GPI rain fall of the same area and period. The SST–convection relation for data averaged over 1° lat × 1° long squares. (c) In monthly data and (d) in daily data. Length of the vertical bars represents the standard deviation on either side of the mean. The right vertical axes specify the number of parameter pairs used [in (c) and (d), the linear correlation coefficient and number of observational pairs are marked at top left]. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Sabin et al., Int. J. Climatology, 2012
Rajendran et al., J. Earth System Science, 2012
SST–precipitation relationship over west Pacific

− negative relationship at SSTs $> 29^\circ\text{C}$?

Rajendran et al., *J. Earth System Science*, 2012
The Clausius–Clapeyron relation implies that specific humidity and hence atmospheric moisture would increase roughly exponentially with temperature — 7%\(^/\ ^\circ\mathrm{C}\) — substantially smaller than the sensitivity change documented.

C–C also controls how “wet gets wetter, and dry gets drier”.

Observations suggest that precipitation and total atmospheric water have increased at about the same rate over past 2 decades.

\[ \frac{de_s}{dT} = \frac{L_v e_s}{R_v T^2} \]

\[ \text{with SST, moisture has increased} \]

\[ \text{with moisture, rainfall has increased} \]


Wentz et al., *Science*, 2007
Rich gets richer

- poor gets poorer

IPCC, *AR5*, 2013
Ocean–atmosphere interaction over Indian/w. Pacific
- positive SST anomalies enhance convection

- positive SST anomalies
  - destabilize lower atmosphere column
  - convective activity

Wu et al., *GRL*, 2008
Temporal & Spatial variability to be considered – response time difference of 1 week!

The SST-precipitation relationship have different \textit{lead-lags} over the Arabian Sea and the Bay of Bengal/South China Sea. The magnitude of the correlation refers to the intensity of the driving force, and the corresponding lag (lead) time denotes how quickly the atmosphere responds to the SST anomalies and vice versa.

Roxy et al., \textit{Climate Dynamics}, 2012
What is the change in perspective we are looking at?
- lag, domain w.r.to air sea interaction, isv

1. There is a lag between SST and Precip., from 5 days to 2 weeks.
2. This lag has a spatial variability

3. Calendar months not useful due to:
   (a) the above lag (in days) and spatial variability
   (b) SST change might be in one month and corresponding precipitation change might be in next month.
   Eg: Lag over BoB can be up to 2 weeks!

4. Averaging over large domains not useful:
   Intraseasonal variability over Arabian Sea and Bay of Bengal are at different phases at a time.

5. Simultaneous analysis gives the effect of SST on precipitation and the effect of precipitation on SST, making it difficult to separate them.

Hence an analysis considering the time lag, over different domains is necessary

Wu et al., *GRL*, 2008
Roxy et al., *Climate Dynamics*, 2012; Roxy, *Climate Dynamics*, 2013
SST – Precipitation relationship with/without lags
- in observations

Quantified: 1°C rise in SST $\rightarrow$ 2 mm/day in rainfall

Roxy et al., *Climate Dynamics*, 2013
SST – Precipitation relationship with/without lags – in model simulations

Quantified: 1°C rise in SST $\rightarrow$ 2 mm/day in rainfall
Monsoon precipitation in a changing climate – in CFSv2 climate projections

Increase in Monsoon Precipitation with increasing SST

Regions of maximum precipitation tends to be located at the ascending branches of the tropical circulation (Lau et al. 1997)
Revised SST – Precipitation relationship

Remember…

…the ocean was in the atmosphere

Roxy, *Climate Dynamics*, 2013
A new paradigm for SST-precipitation relationship – and its relevance to climate

1. SST – precipitation relation has a spatial variability over the monsoon basins, with a lag of:
   ~ 5 days over the Arabian Sea
   ~ 12 days over the Bay of Bengal and South China Sea

2. Considering this lag, a quantifiable relationship can be deduced between SST (above 26°C) and precipitation:
   1°C rise in SST \(\rightarrow\) 2 mm/day in rainfall

3. Relationship holds for a changing climate.
Changing Climate and Monsoon

Extreme Events

Goswami et al. Science, 2006
Indian Ocean in a Changing Climate

Indian Ocean warming: 1.2°C in the western Indian Ocean

Monsoon in a Changing Climate
Weakening Trend in Rainfall over central South Asia

Monsoon in a Changing Climate
Warm Ocean, Weak Monsoon?

Monsoon in a Changing Climate
Model response to warm western Indian Ocean

Monsoon 2014

- what went wrong?

June–July: deficient rains
Monsoon 2014
– what went wrong?

June–July: deficient rains, weak monsoon winds
June–July: deficient rains
weak monsoon winds
weak jet stream

AT LAST, 30 HOURS; 30 MINUTES AND 30 SECONDS FROM ZERO HOUR...

HERE WE ARE! THE RIVER GANGES!

ITLY
Greece
Athens
Persia
Mesopotamia
Valley of the Ganges
Valley of the Indus

GAUL
Rome
Tyre

LOOKS A BIT GUNGY, AS RIVERS GO!
WHAT ARE ALL THOSE PEOPLE DOING, SQUELCHING ABOUT IN THE MUD?
The Ganges is a sacred river. Even in this drought, the people still come here to wash, thus purifying their souls and bodies. See?

CLEAR AS MUD! THESE INDIANS ARE CRAZY!

TAP! TAP! TAP!

Monsoon 2014
– weak jet stream?
Monsoon 2014
- El Nino? Developing El Nino?

Great Famine of 1877–79

SST anomalies of DJF 1877

All India Monsoon Rainfall: −29%; Drought Area: 670,000 km²; Estimated Deaths: 5.5 – 8.2 million (?)

Governance: British Rule, exported food from India to England despite famines.
Monsoon 2014

- Pacific conditions similar to 2009

Ascending air in Pacific has to subside somewhere...
Ashok et al., *GRL*, 2012
Monsoon 2014
anomalous land–sea contrast?

Does the changes in thermal contrast have a role?
Mid-latitude incursion? Atlantic conditions – jet stream??
The wind and SST anomaly pattern developed in June tend to persist through out the season. To develop such type of anomaly some global scale feature (like El Nino this year) must be responsible

Kothawale and Kulkarni, 2014, Under Review
Monsoon 2014, this week
- super cyclone Neoguri pulling away the monsoon?

ERPAS IITM-Forecast: Enhanced cyclonic activity over West Pacific will hamper the intensification of monsoon over central India for next few days. Monsoon will intensify once the system over West Pacific move northwards. The central and peninsular India will receive good amount of rainfall after 10 July. Large scale MISO forecast suggests that monsoon activity will be strong over central India from 10–20 July and gradually shifting towards foothills.
Monsoon 2014

will cacofonix sing? will monsoon revive?

FOR THE RAIN IT RAINETH EVERY DAY...

DON'T BE SO WET!!!

THE GAULISH MIRACLE!

AND THE GAULISH MIRACLE HAS BROUGHT THE MONSOON ON AT LAST. THE CROPS ARE SAVED, THE WATERS OF THE GANGES HAVE RISEN AGAIN AND ALL THE INDIANS ARE HAPPY...

...WITH A FEW EXCEPTIONS!

SHEER SCIENCE FICTION, THAT IDIOT SAID!

GOING TO BE RAJAH INSTEAD OF THE RAJAH. THAT CROOK SAID!

Thank You