On the Decreasing Trend of the Number of Monsoon Depressions in the Bay of Bengal

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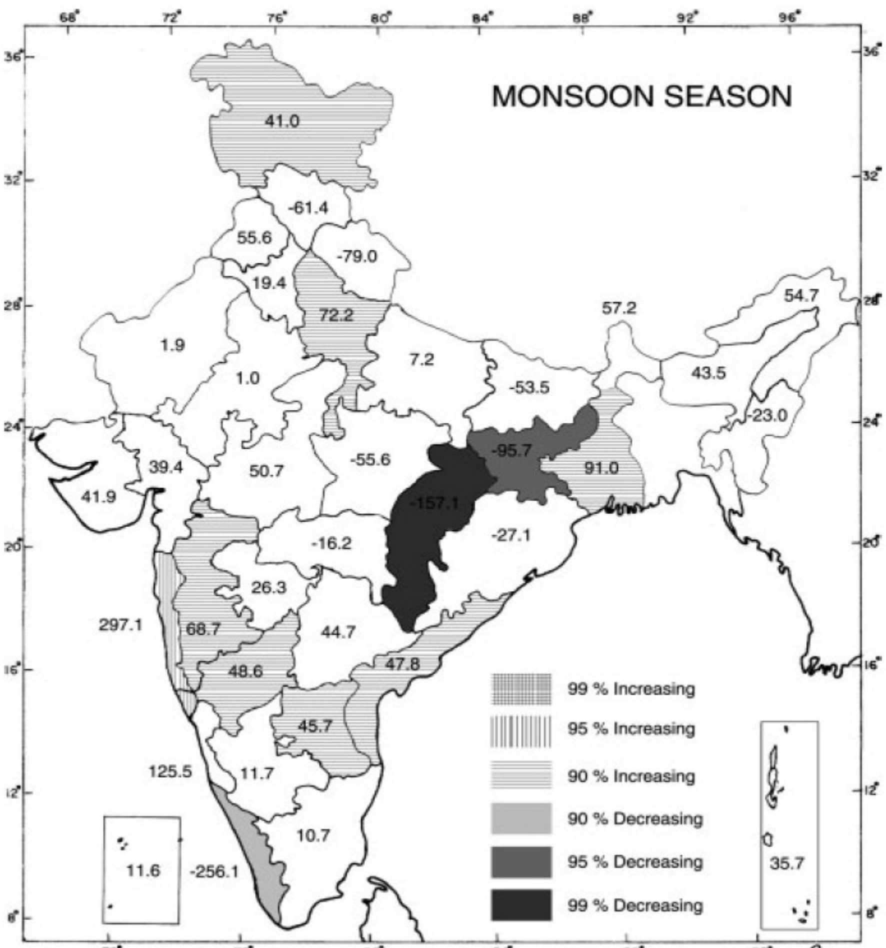
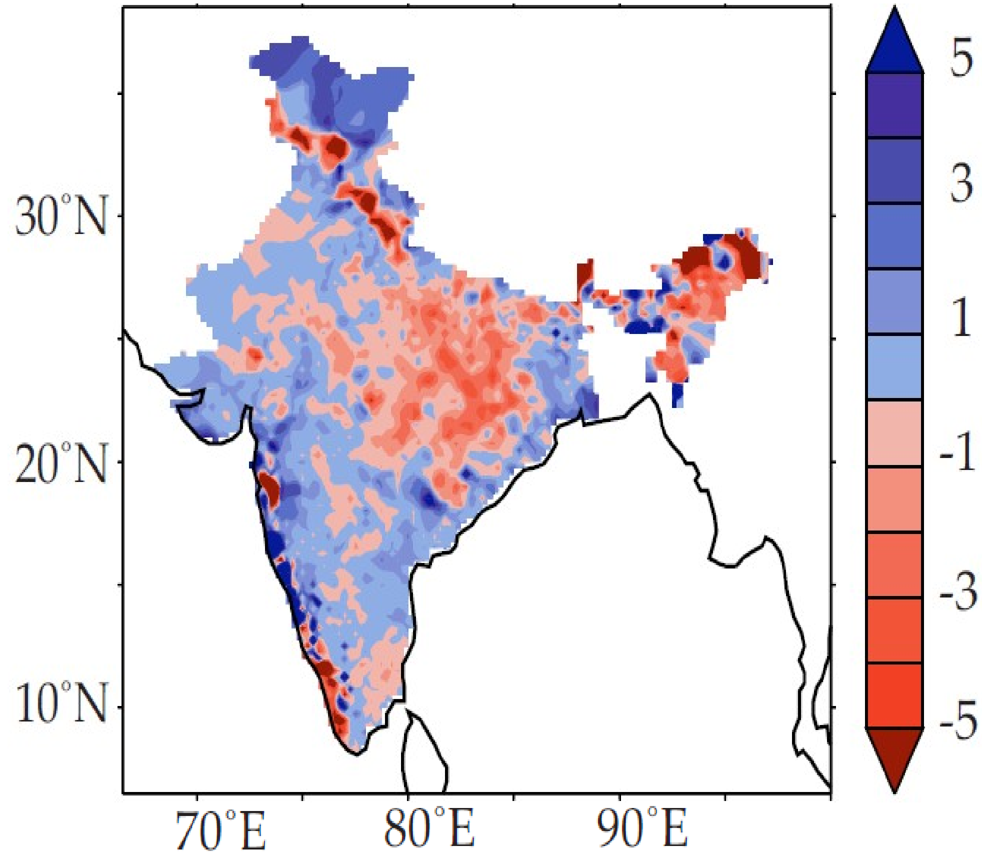
Long term variation in the summer monsoon rainfall



Spatial distribution in the rate of change of rainfall during summer monsoon season.



Guhatakurta and Rajeevan (2008) also had shown earlier that even though there are no long term trends in the ISMR, there is a significant decreasing (increasing) trend in three (eight) meteorological subdivisions.

In a recent study, using long term gridded rainfall data, Roxy *et al* (2015) reported that there is a significant decreasing trend in the rainfall over the central-eastern Indian region.

Background

The rainfall over the Indian region during the monsoon season can be attributed to

- **Lows and depressions move from Bay of Bengal/Arabain Sea to the mainland**
- **Northward movement of the Tropical Convergence Zone (TCZ).**

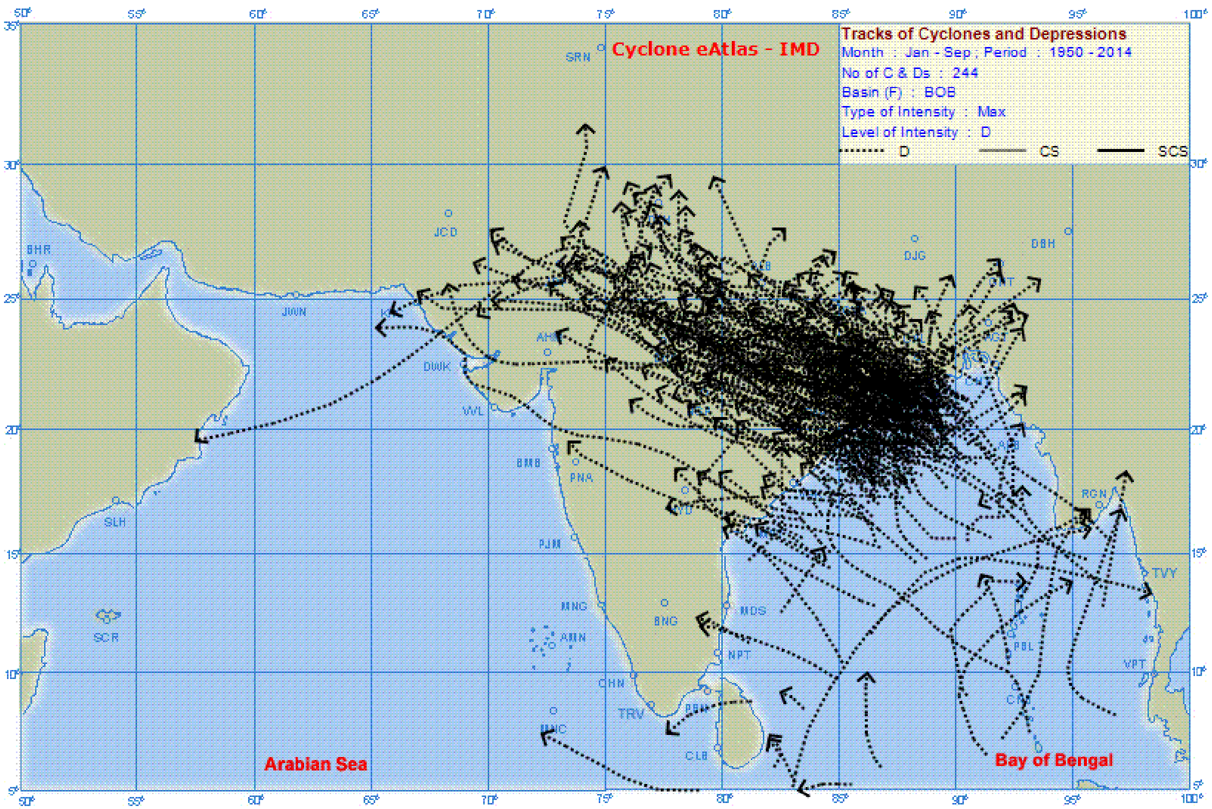
Both are linked to the oceans surrounding us.

(Sikka 1980, Pant and Parthsarathy 1981, Gadgil *et al* 2004, Pottapinjara *et al* 2014, etc)

In this study we focus on the variation in the number of Monsoon Depressions only.

Monsoon depressions

MD form over the Bay of Bengal (BoB) or cross over to the BoB from Western Tropical Pacific and south-China Sea (WTC-SCS) and propagate westward/northwestward to the mainland (Ding and Sikka 2006).

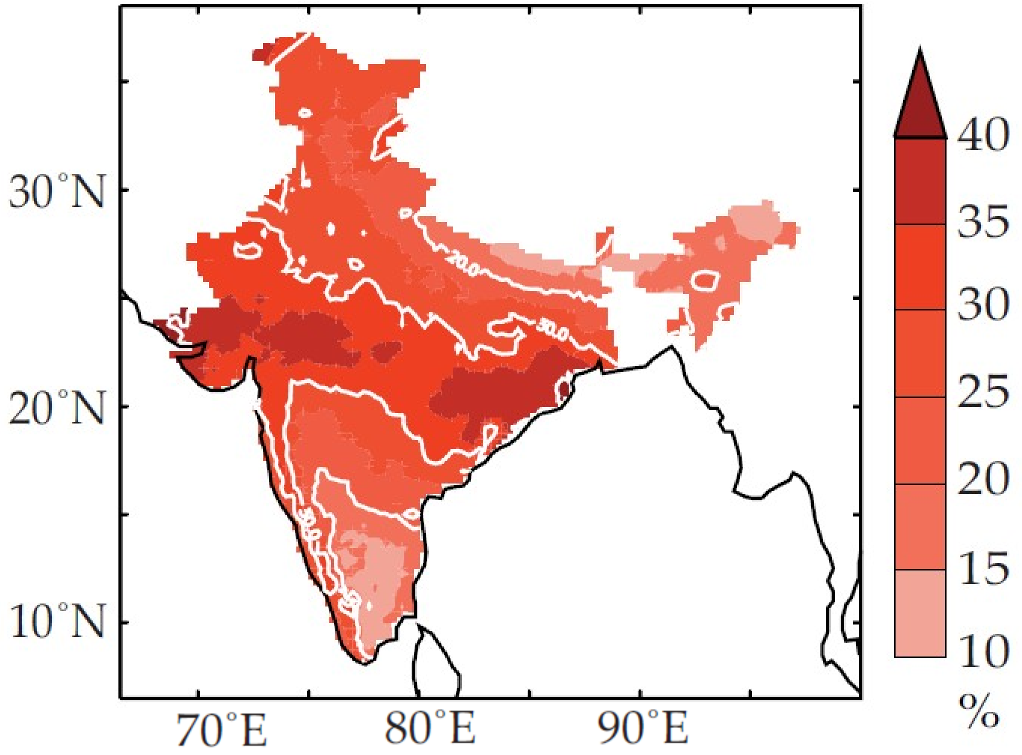


Tracks of Monsoon Depressiosn in the period 1951-2014

MD move north-westward along the monsoon trough and reach as far as northwestern India/Pakistan and produces large rainfall totals (some times up to 300-400 mm) along its track (Sikka 1977).

Influence of MD on the seasonal total rainfall

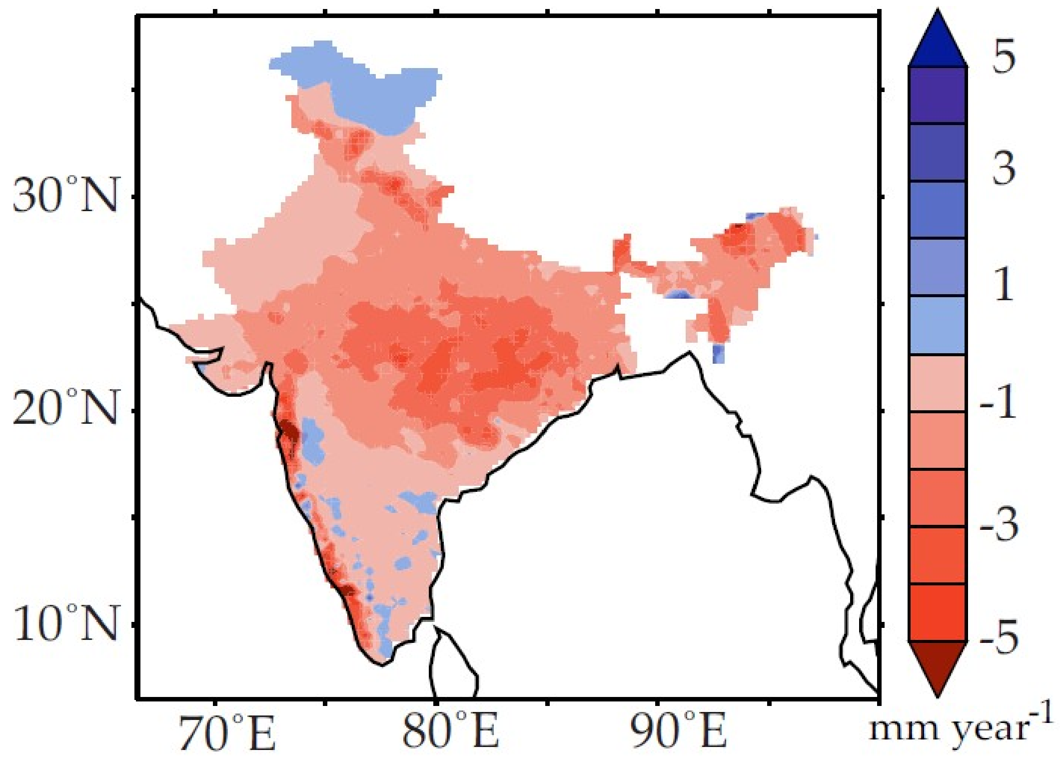
Percentage of rainfall during the occurrence of MD in the seasonal rainfall.



The ratio of rainfall in the monsoon core region during the occurrence of MD to the seasonal mean rainfall varies in the range of 35-45%, which is quite substantial.

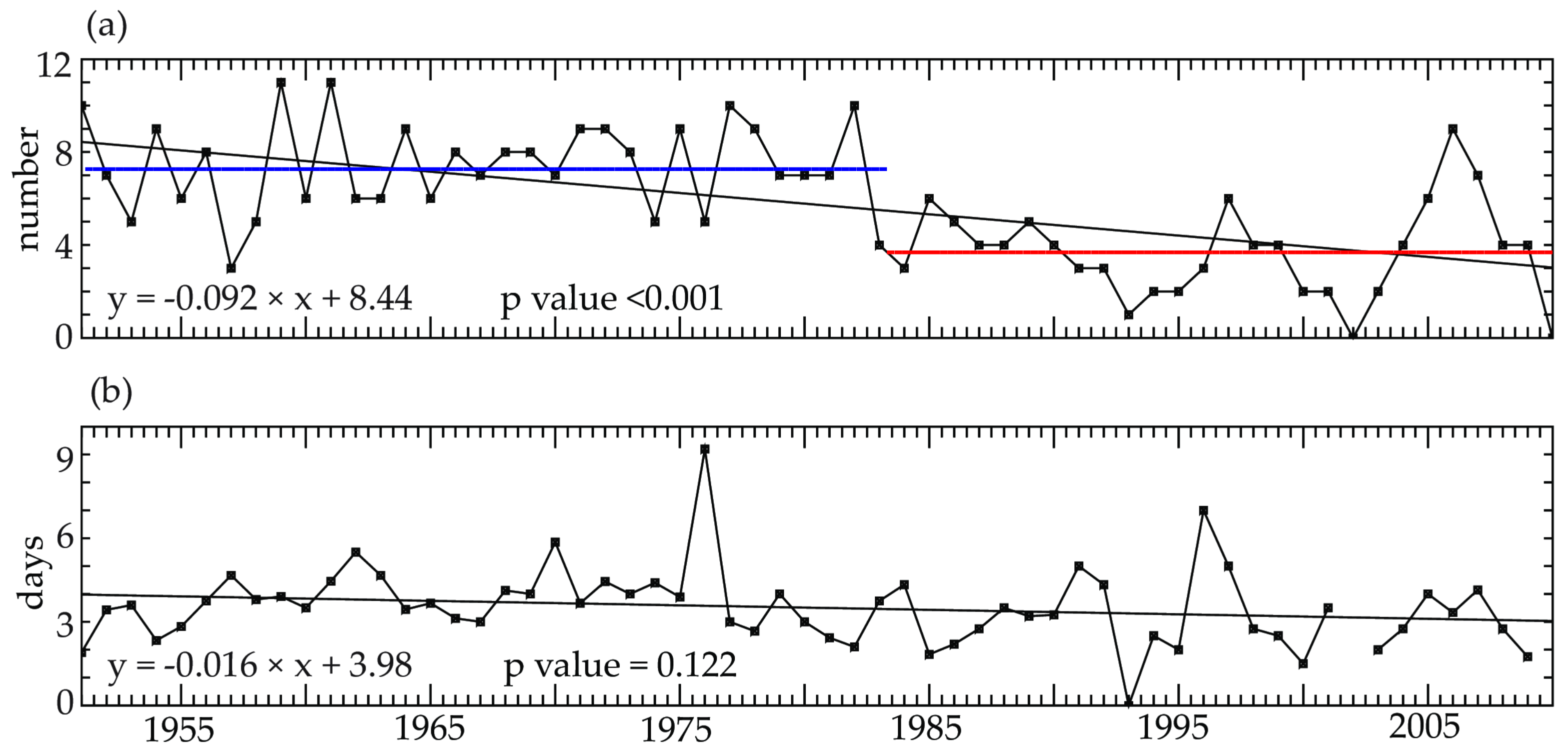
Even West coast of India receives significant amount of rainfall during the occurrence of MD over the BoB.

It is interesting to note that the decreasing trend in the "rainfall associated Monsoon Depressions" also is significant over the eastern edge of the core monsoon region, and the west coast of India.

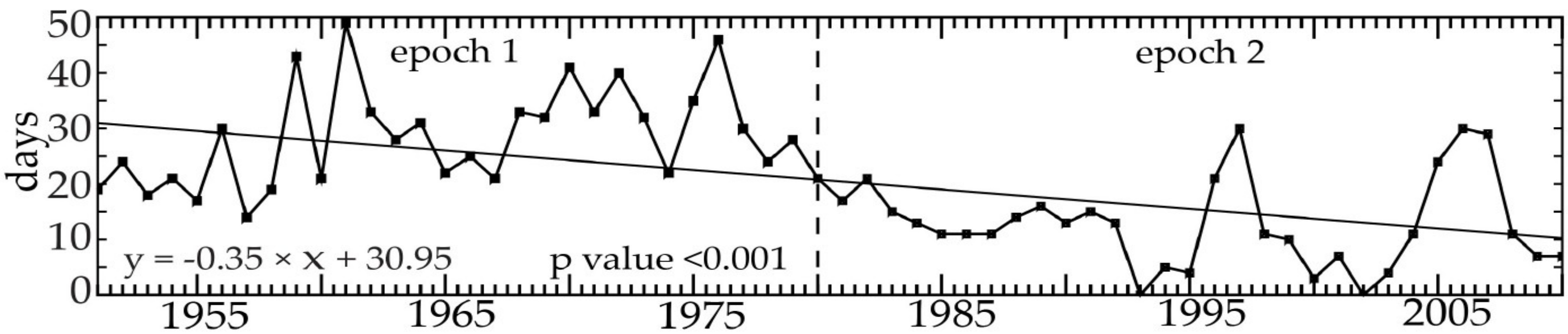


Trend in rainfall during the occurrence of monsoon depressions

Variation of the number and life span of Monsoon Depressions



Variation of the (a) number and (b) averaged life span (in days) of monsoon depressions during the period 1951 to 2010.

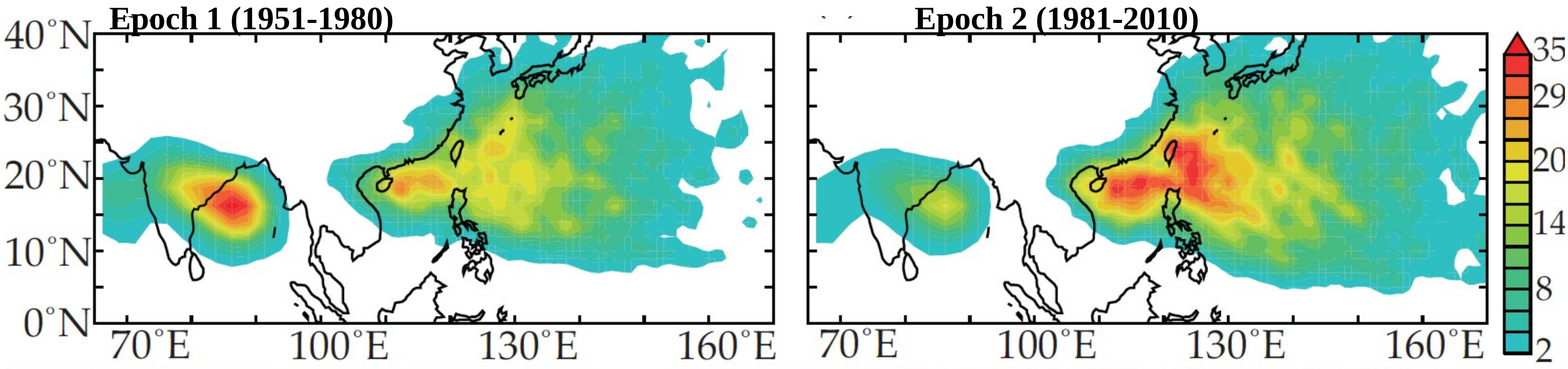


Variation in the number of monsoon depression days

This decrease is essentially due to decrease in the number of monsoon depressions rather than changes in the life span of the systems

In fact, there is a strong discontinuity in the number of monsoon depressions in early 1980s

Spatial distribution of the density of cyclonic storms over theBoB and the western Pacific-south China Sea during June- September.



The number of monsoon depressions over the BoB had decreased even though more cyclonic storms moved westward from the WTP-SCS after 1980 compared to the earlier epoch.

This suggests that either these systems are not reintensifying after they cross over to the BoB or there is considerable decrease in the number of monsoon depressionss form within the BoB basin

Parameters influences the trend in Monsoon Depressions

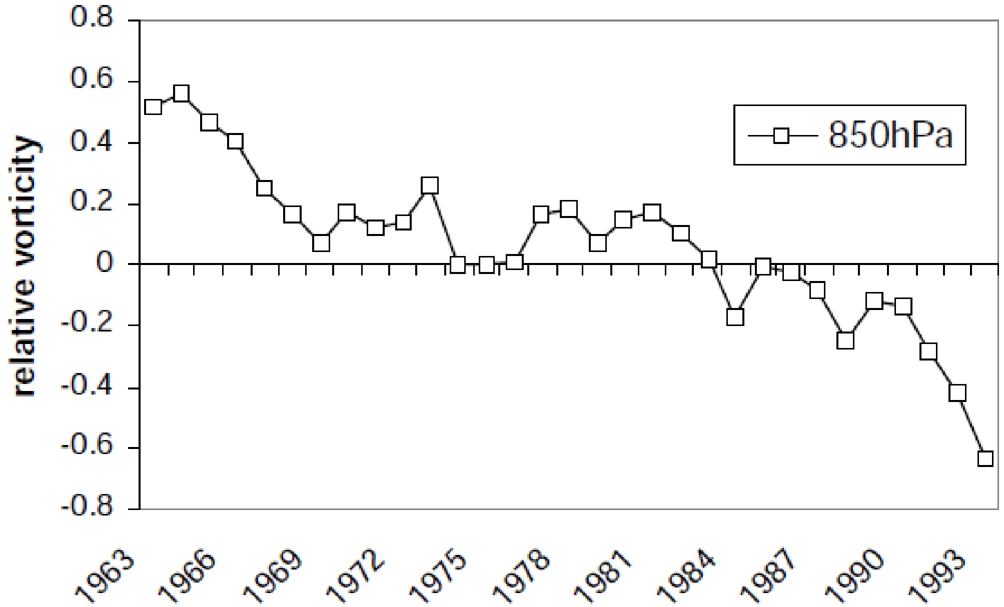
The essential environmental conditions for the formation of Monsoon Depressions (Sikka 1977) are

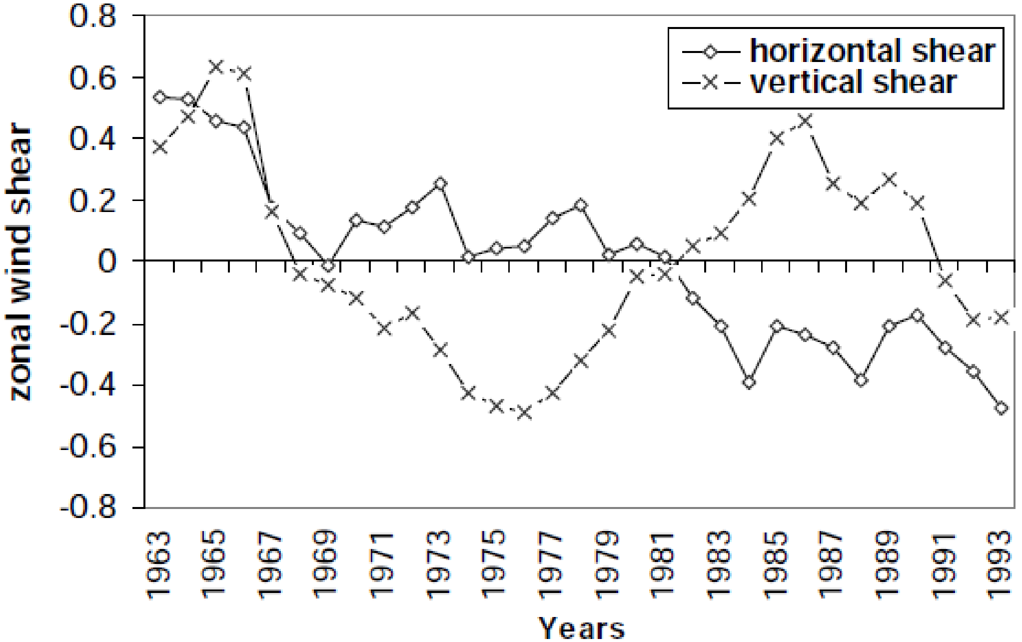
- **High Sea Surface Temperature (SST),**
- **Presence of low level (850 hPa) cyclonic vorticity,**
- **High mid-tropospheric humidity and**
- **Weak vertical wind shear**

These are the same essential criteria for the genesis of tropical cyclones(Gray 1968).

The strong wind shear over BoB in one of the factors that limit the Monsoon Depressions to intensifing into tropical cyclone.

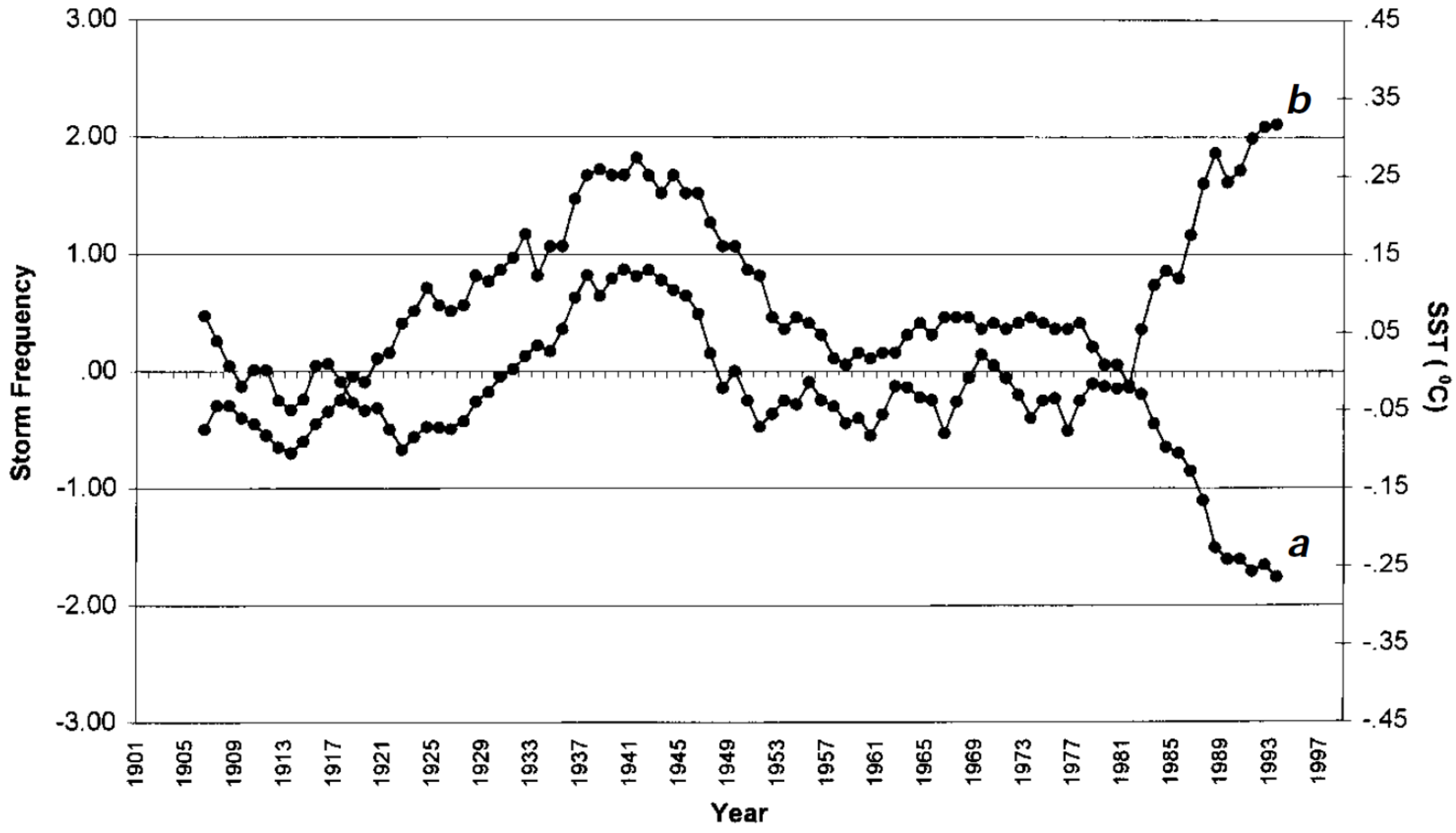
11 year running mean of relative vorticity at 850 hPa (top) and wind shear (bottom) over the Bay of Bengal during monsoon season.



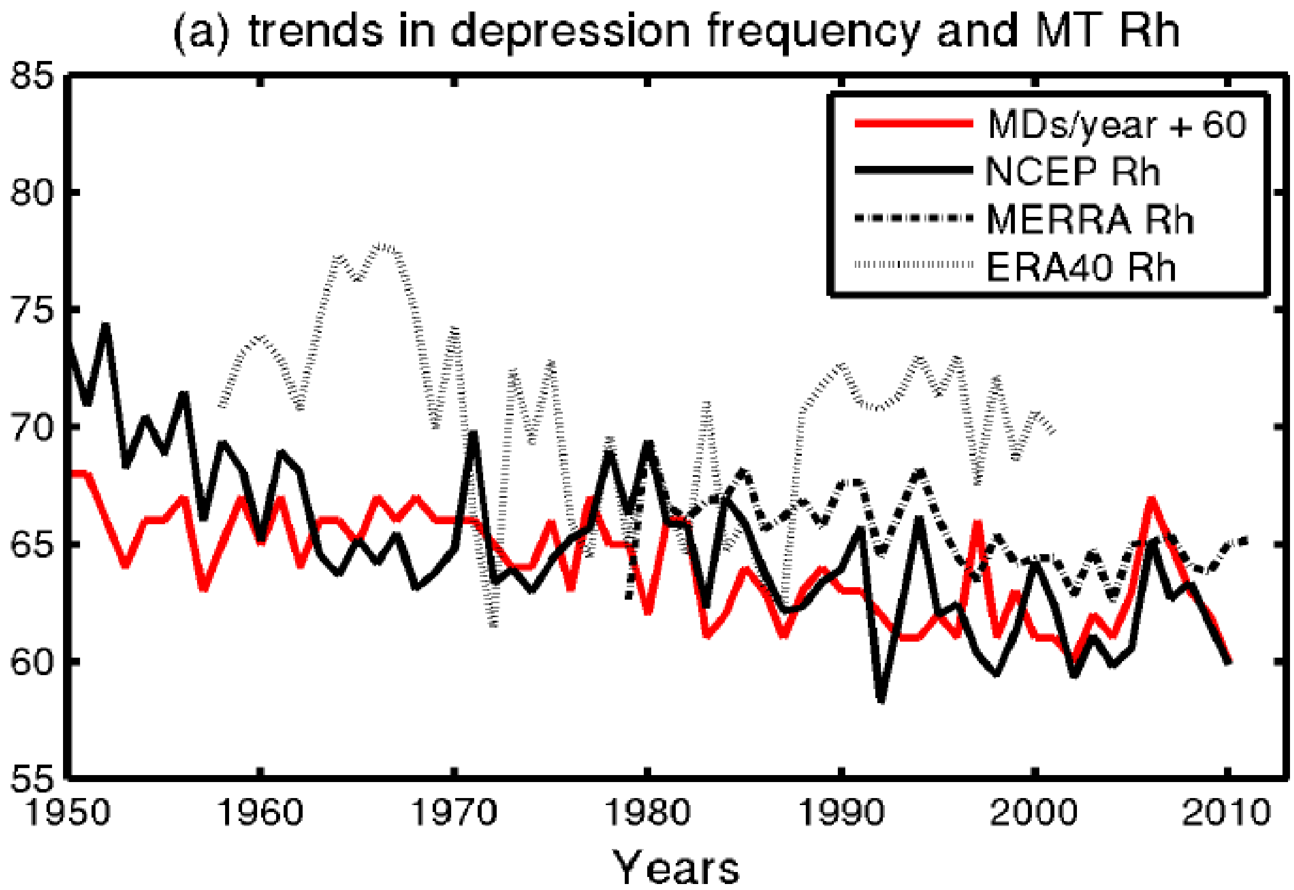


Unfavaourable phase in low-level vorticity and vertical and horizontal wind shear of zonal wind [Mandke and Bhide 2003].

11 year running means of Bay of Bengal (10°N–25°N, 80°E–100°E) storm frequency (standardized anomalies; a) and SST anomalies (b) during the period 1901 to 1998.



Rajeevan *et al* [2000] reported that SST in the BoB and frequency of Monsoon Depressions had shown similar decadal variations till early 1980s, however the monsoon depressions have been decreasing in-spite of increasing SST since mid-1980s.



Declining trend in mid-tropospheric relative humidity [Prajeesh *et al* 2013]

In this study, we make quantitative estimates of the relative contributions of each of the environmental variables responsible for the variation in the number of monsoon depressions

Data Used

- **The information of monsoon depressions is taken from the website of India Meteorological Department (IMD) (http://www.rmcchennaieatlas.tn.nic.in).**

- **Daily high resolution (0.25° x 0.25°) gridded rainfall data (Pai *et al* 2014)**

- **Monthly mean profiles of atmospheric temperature, horizontal wind, specific humidity, relative humidity, precipitation and evaporation (derived from latent heat flux) from**

  - **National Centre for Environmental Prediction (NCEP) Reanalysis (Kalnay *et al* 1996)**
  - **ERA-20C reanalysis data obtained from European Centre for Medium-Range Weather Forecasts (ECMWF, http://apps.ecmwf.int/datasets/data/era20cm-edmm)**

- **Monthly mean SST from the Hadley Centre Global Sea Ice and Sea Surface Temperature version2 (HadISST2) (Rayner *et al* 2003)**

Quantitative analysis of large scale environmental factors

To find the changes in the environmental parameters which are responsible for the development and intensification of the monsoon depressions occurred in the recent epoch (1981–2010, epoch 2) compared to the previous one (1951–1980, epoch 1), we used an emperical index known as Genesis potential Index (GPI).

The GPI formulated by Emanuel and Nolan (2004) is a useful tool to quantitatively describe the influence of large-scale environmental factors on the genesis of the tropical cyclones.

The GPI has been successfully used to analyze the seasonal, intra-seasonal and inter-annual modulation of tropical storm activity in various tropical basins (Camargo *et al* 2007; Camargo *et al* 2009; Yanase *et al* 2012; Li *et al* 2013; Girishkumar *et al* 2014)

Genesis Potential Index

Following Emanuel and Nolan (2004) and Li *et al* (2013), we have used the following expression in order to understand the relative contributions of the changes in individual environmental conditions in the changes of number of monsoon depressions

$$\delta GPI = \alpha 1 \times \delta \left(\frac{H}{50}\right)^3 + \alpha 2 \times \delta |10^5 \eta|^{\frac{3}{2}} + \alpha 3 \times \delta \left(1 + 0.1 V_{shear}\right)^{-2} + \alpha 4 \times \delta \left(\frac{V_{pot}}{70}\right)^3$$

Where $\alpha 1 = \overline{|10^5 \eta|^{\frac{3}{2}}} \times \overline{\left(1+0.1 V_{shear}\right)^{-2}} \times \overline{\left(\frac{V_{pot}}{70}\right)^3}$

$\alpha 2 = \overline{\left(\frac{H}{50}\right)^3} \times \overline{\left(1+0.1 V_{shear}\right)^{-2}} \times \overline{\left(\frac{V_{pot}}{70}\right)^3}$

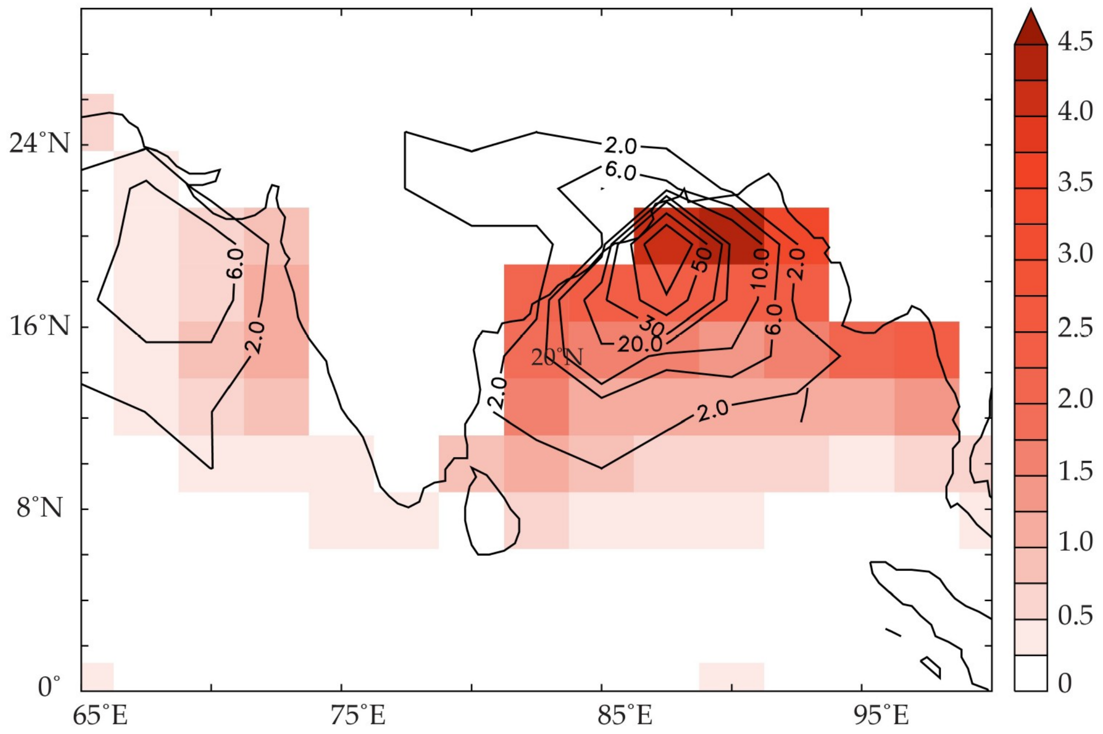
$\alpha 3 = \overline{\left(\frac{H}{50}\right)^3} \times \overline{|10^5 \eta|^{\frac{3}{2}}} \times \overline{\left(\frac{V_{pot}}{70}\right)^3}$

$\alpha 4 = \overline{\left(\frac{H}{50}\right)^3} \times \overline{|10^5 \eta|^{\frac{3}{2}}} \times \overline{\left(1+0.1 V_{shear}\right)^{-2}}$

Where H is the relative humidity (%) at 600hPa, η is the absolute vorticity at 850 hPa (s^{-1}), V_{shear} is the magnitude of the vertical wind shear (ms^{-1}) between 850 hPa and 200 hPa, and V_{pot} is the maximum tropical cyclone potential intensity.

GPI and Monsoon Depressions

Seasonal (June-September) climatology of the GPI (shaded) and total number of tropical storm (contour) formed over north India during 1951-2010.



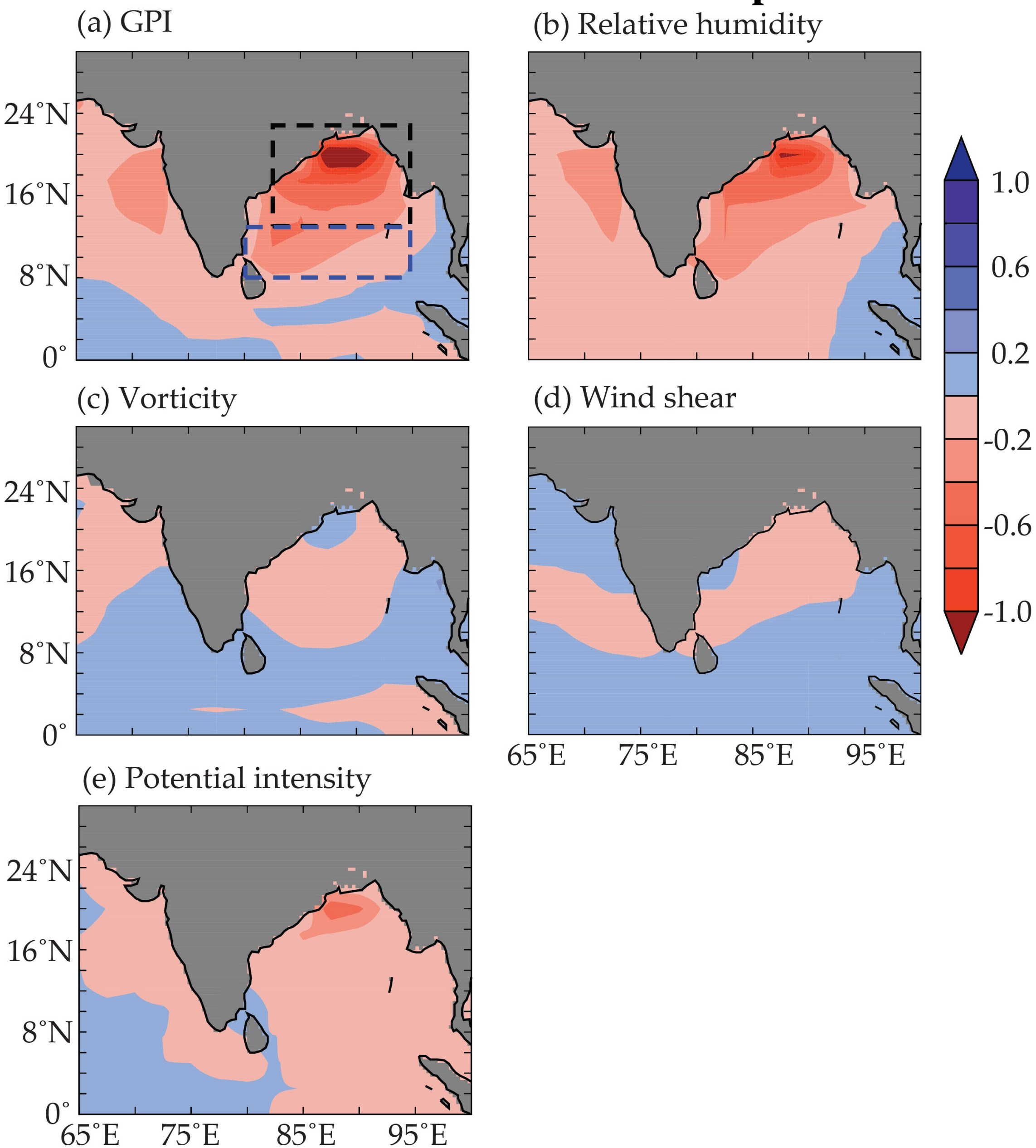
Spatial distribution of the GPI is consistent with genesis of monsoon depressions.

Decadal mean frequency of Monsoon Depression (MD; wind speed 17-33 kt), Cyclone (CS; wind speed 34-47 kt) and Severe Cyclone(SCS; wind speed 48-63 kt) formed in the BoB along with the mean GPI.

Decades	Frequency of formation of			GPI
	MD	CS	SCS	
1951–1960	5.90	0.80	0.10	1.88
1961–1970	5.50	0.70	0.10	1.41
1971–1980	4.70	1.10	0.70	1.51
1981–1990	3.00	0.70	0.20	1.08
1991–2000	2.00	0.30	0.00	1.06
2001–2010	2.50	0.60	0.10	1.14

The frequency of formation of tropical storms and the GPI over the BoB decrease from earlier decade (1951 – 1960) to the recent decade (2000 – 2010)

The epochal difference in the GPI and relative contribution of each environmental parameters



The in recent period (1981–2010) is considerably lower than the earlier period (1951–1980 (δGPI= -0.4 to -1.0) over the BoB.

The mid-tropospheric humidity (primary contribution) and Potential Intensity (PI; secondary contribution) are mainly responsible for the decrease in the GPI over BoB during recent years.

The relative humidity term contributes around 62% and 72% of the total GPI reduction over the head BoB and the central BoB respectively

GPI terms	Head BOB	Central BoB
Relative Humidity	62.48	72.40
Vorticity	9.32	5.90
Wind Shear	7.75	-2.89
Potential Intensity	20.73	24.53

Table: Seasonal estimate of relative contributions of the terms (in %), averaged over the head BoB (12.5°N–22.5°N, 82.5°E–95°E) and the central BoB (7.5°N–12.5°N, 80°E–95°E), on the right-hand side of GPI Eq. to the epochal difference in the GPI (δGPI) between recent (1981-2010) and earlier epoch (1951-1980).

An important question that arise is whether this reduction of relative humidity is due to changes in local evaporation or due to the changes in the advection of moisture into the BoB.

To understand the reason behind the “dryness” over BoB, the moisture budget is assessed

$$\frac{1}{g}\frac{\partial}{\partial t}\int_S^T q\,dp + \underbrace{\frac{1}{g}\int_S^T \vec{V}\,.\nabla q\,dp + \frac{1}{g}\int_S^T q\,\nabla\,.\vec{V}\,dp}_{MFD} = E - P$$

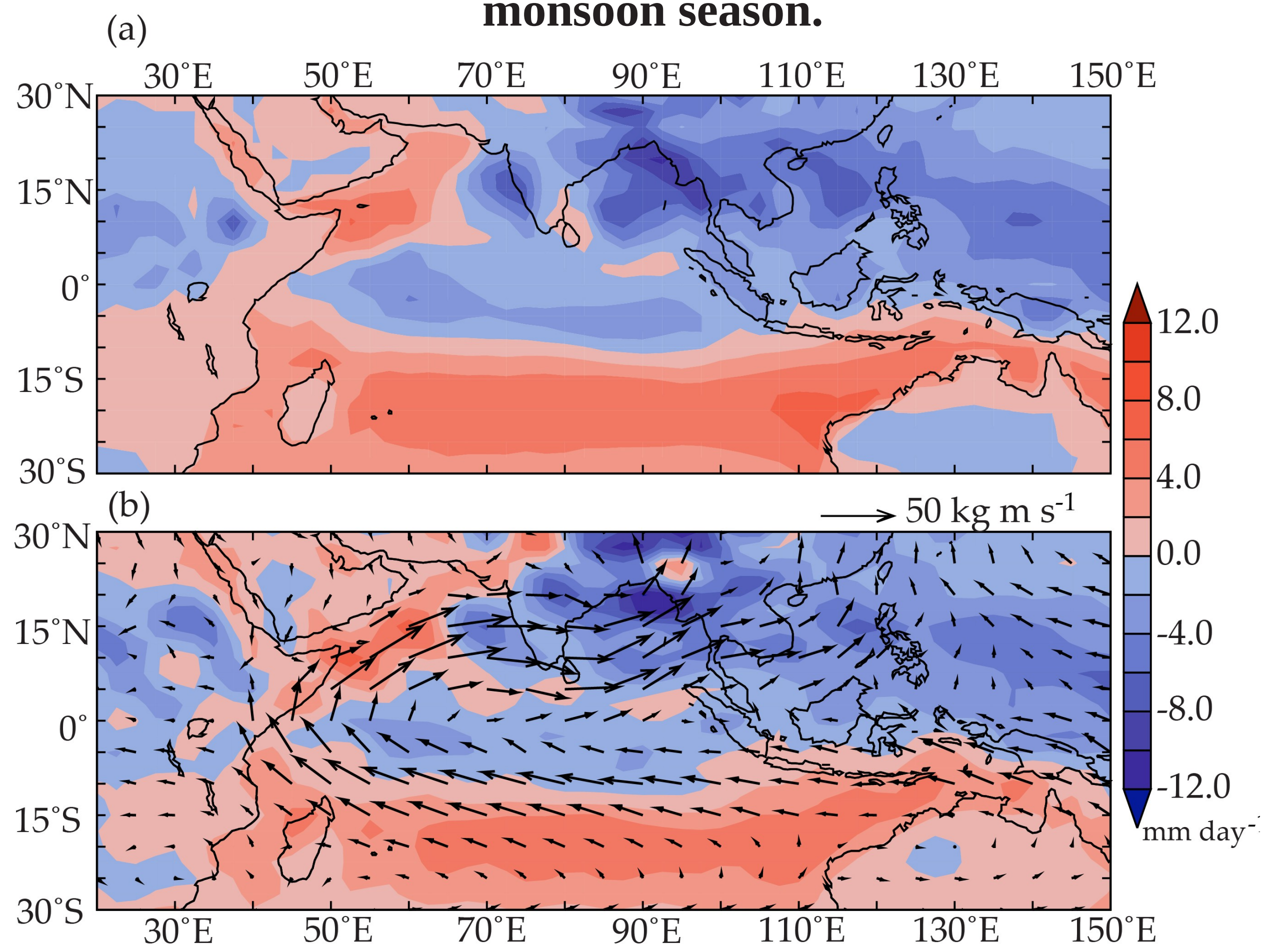
where, *g* is the acceleration due to gravity, *S* and *T* represents the surface and top level of atmosphere, and *E* and *P* are the surface evaporation and precipitation rate respectively.

The second and third terms are the horizontal water vapor advection and horizontal velocity divergence.

The sum of second and third term is named as moisture flux divergence.

Regions with excess precipitation (where P is greater than E) are seen over the western India, the BoB, and the southeast Asia.

Climatology of (a) the E-P term and (b) the MFD term in MBE; vectors represent the VIMT during summer monsoon season.



It is noticed that in the moisture convergent areas, moisture is supplied by the strong monsoon wind that originate from the moisture divergent (also *E* greater than *P*) regions of the southern hemisphere and the Arabian Sea.

Hence moisture transport from remote regions is the key process for the maintenance of the moisture over the BoB during summer monsoon season

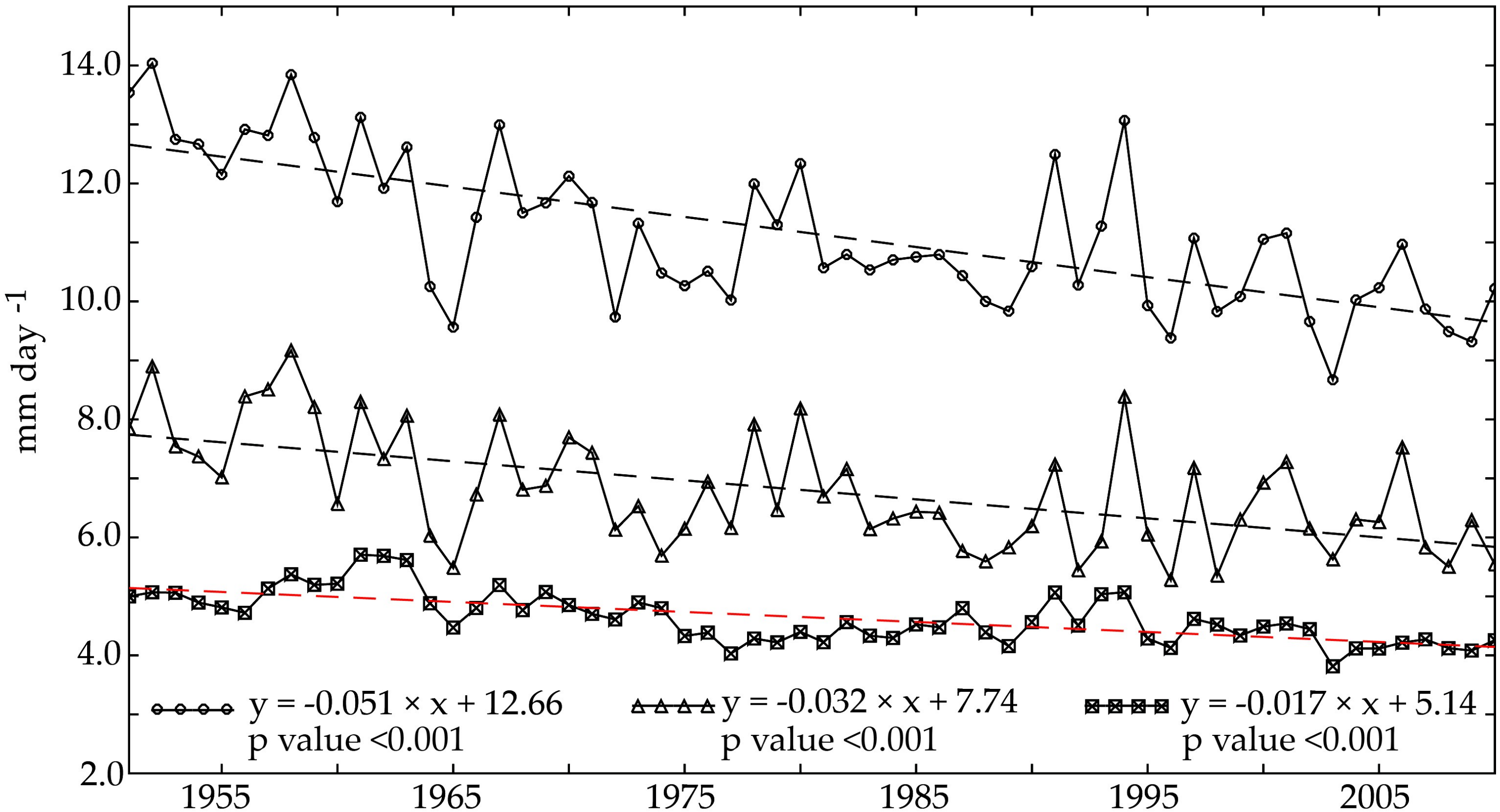


Fig: Time series of precipitation (circle), evaporation (square), and the MFC term (triangle) in MBE over head BoB [12.5°N–22.5°N, 82.5°E–95°E]. unit: mm day^{-1} $year^{-1}$

The percentage contribution of the Moisture Flux Convergance (MFC) term is higher (65%) than local evaporation (E) (35%) to the decreasing trend in the total moisture flux.

The decrease in the MFC should be either due to the decrease in the moisture advected into the region or due to the increase in the moisture advected out of the region or a combination of the both.

Zangvil *et al* (2004) estimated the outflow and the inflow of the moisture of the head BoB by modifying the MFD term in the MBE as

$$\frac{OF}{A}-\frac{IF}{A}$$

where as OF, IF and A represent the outflow, inflow and the surface area respectively.

Total inflow (TIF) and total outflow (TOF) over the head BoB are decreasing, with TIF decreasing at a higher rate (0.10 mm day^{-1} year^{-1}; p value <0.001) than the TOF (0.04 mm day^{-1} year^{-1}; p value 0.005)

The advection terms (TIF and TOF) have higher epochal difference (-2.3 mm day^{-1} and -1.15 mm day^{-1}) compared to evaporation (-0.46 mm day^{-1}).

The recycling ratio does not show any significant change (remains ~ 0.15) for both epochs.

As the local evaporation contribute only 15% to the net moisture content, the variation in the TIF is the major factor for the increasing trend of dryness over the head BoB.

Moisture budget components calculated over the head BoB (12.5°N–22.5°N, 82.5°E–95°E) during recent (1951–1980) and earlier (1981–2010) epoch and their differences.

		1951–1980 (Earlier)	1981–2010 (Recent)	Difference (Recent–Earlier)
West	Inflow	15.240	14.280	-0.960
	Outflow	0.046	0.011	-0.035
East	Inflow	0.004	0.000	-0.004
	Outflow	12.230	10.810	-1.420
South	Inflow	12.010	10.350	-1.660
	Outflow	0.000	0.000	0.000
North	Inflow	0.413	00.745	0.332
	Outflow	7.388	07.690	0.302
Total Inflow (TIF)		27.670	25.370	**-2.300**
Total Outflow (TOF)		19.670	18.520	**-1.150**
TIF-TOF		8.001	6.854	-1.147
Avg Precipitation (P)		11.960	10.490	-1.470
Avg Evaporation (E)		4.879	4.418	-0.461
P-E		7.076	6.076	-1.000
Recycling ratio (R)		**0.151**	**0.150**	**-0.001**

The inward moisture transport over the head BoB is mostly through western (14.74 mm day^{-1}) and southern boundaries (11.18 mm day^{-1})

The outward moisture transport is mainly through eastern (11.52 mm day^{-1}) and northern (5.54 mm day^{-1}) boundaries

The decrease in the inflow of moisture through southern and western boundaries and increase in the outflow through northern boundary cause the decrease in moisture over BoB.

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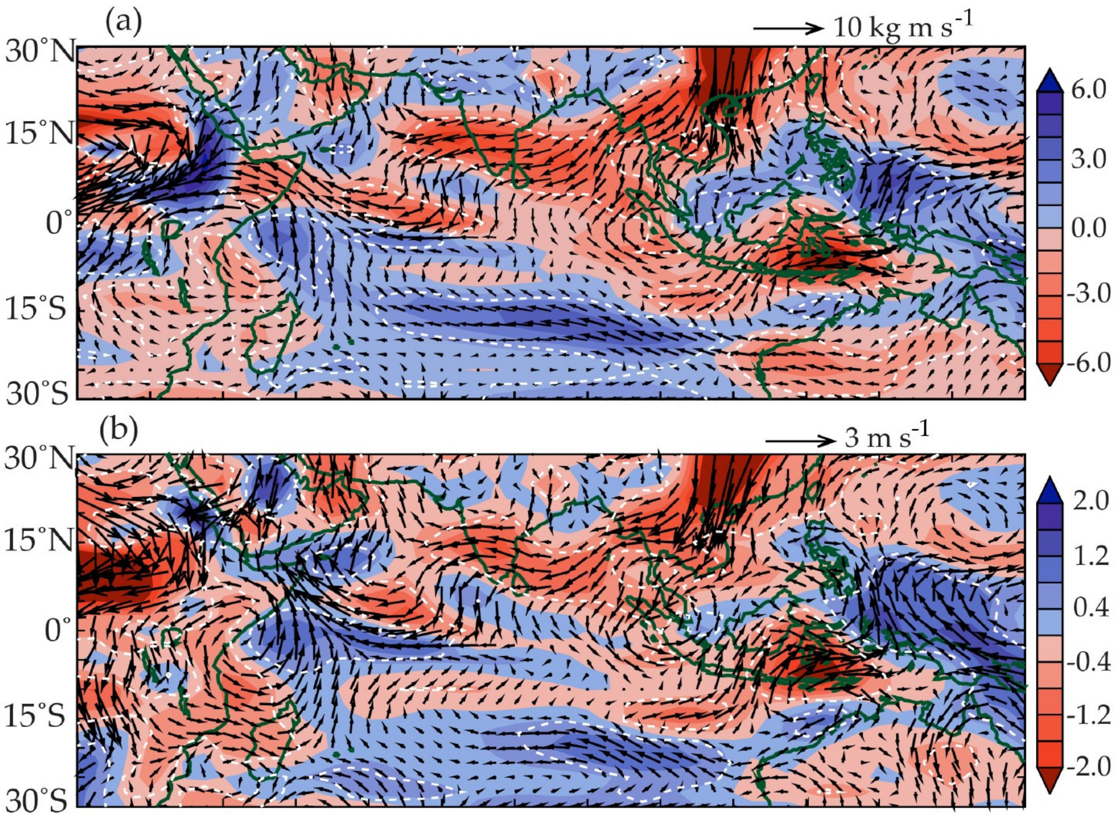
The epochal difference in (a) VIMT and (b) wind at 850 hPa.



Vertically Integrated Moisture Transport (VIMT) shows a decreasing trend in moisture transport to the BoB.

The epochal changes in VIMT and Low Level Jet (LLJ) show strong spatial correspondence.

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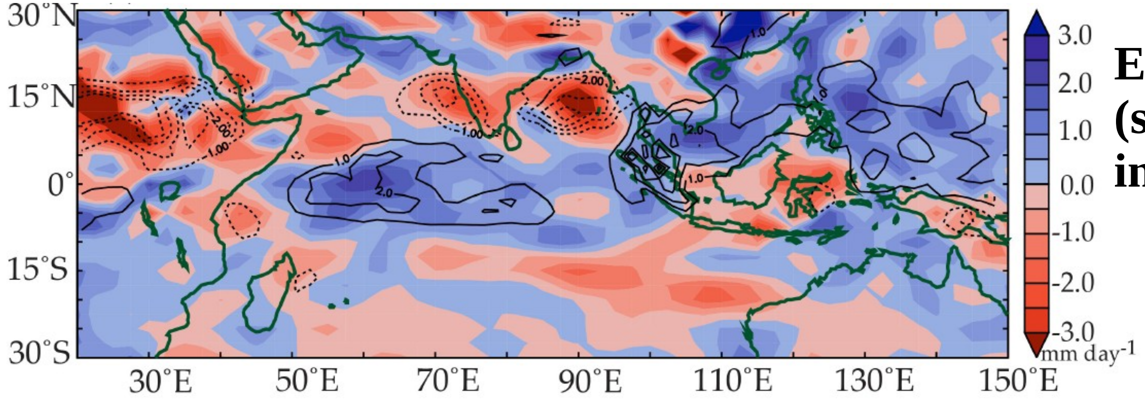
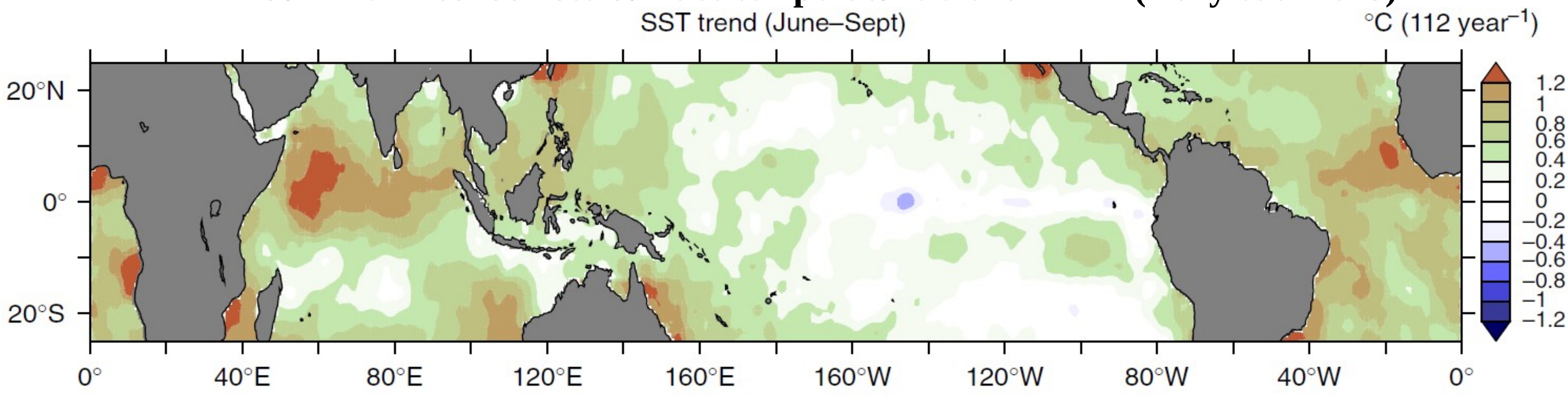
Shades represent the epochal difference in the magnitude of respective vectors. The white contours enclose the regions where the difference is significant at the 95% confidence level.

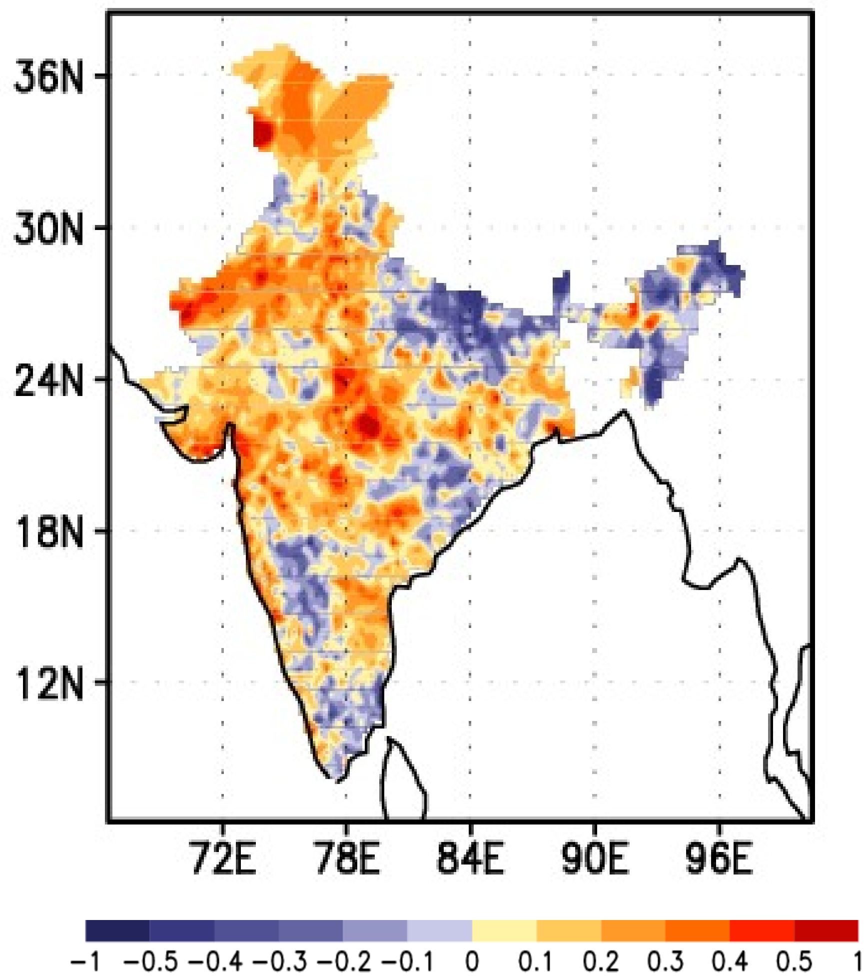


Epochal difference in the MFC term (shaded) and the precipitation (contour) in mm day^{-1}.

Summer mosnoon sea surface temperature trend (Roxy et al 2015)



Spatial distribution of the correlation between OLR over the WEIO and the gridded rainfall over India



While there is a strong positive correlation between the western parts of the country, and the convection over the WEIO, the correlation over the eastern side of the monsoon zone is not very strong.

This could be due to the negative relationship between convection/convergence over the WEIO and the formation/strengthening of monsoon depressions.

Conclusion

- Reduction in the mid-tropospheric humidity is the most important environmental factor that is responsible for the decrease in MDs in the recent period.

- This decrease in the moisture flux convergence (negative of moisture flux divergence) is mainly due to the weakening of moisture advection into the BoB which in turn is associated with the weakening in monsoon flow.

- Further, anomalous moisture atmospheric convergence over the western equatorial Indian Ocean which could be associated with the rapid warming of the sea surface, might be reducing the moisture advection into the Bay of Bengal.