Climatology of Tropical Cyclones over North Indian Ocean (NIO)

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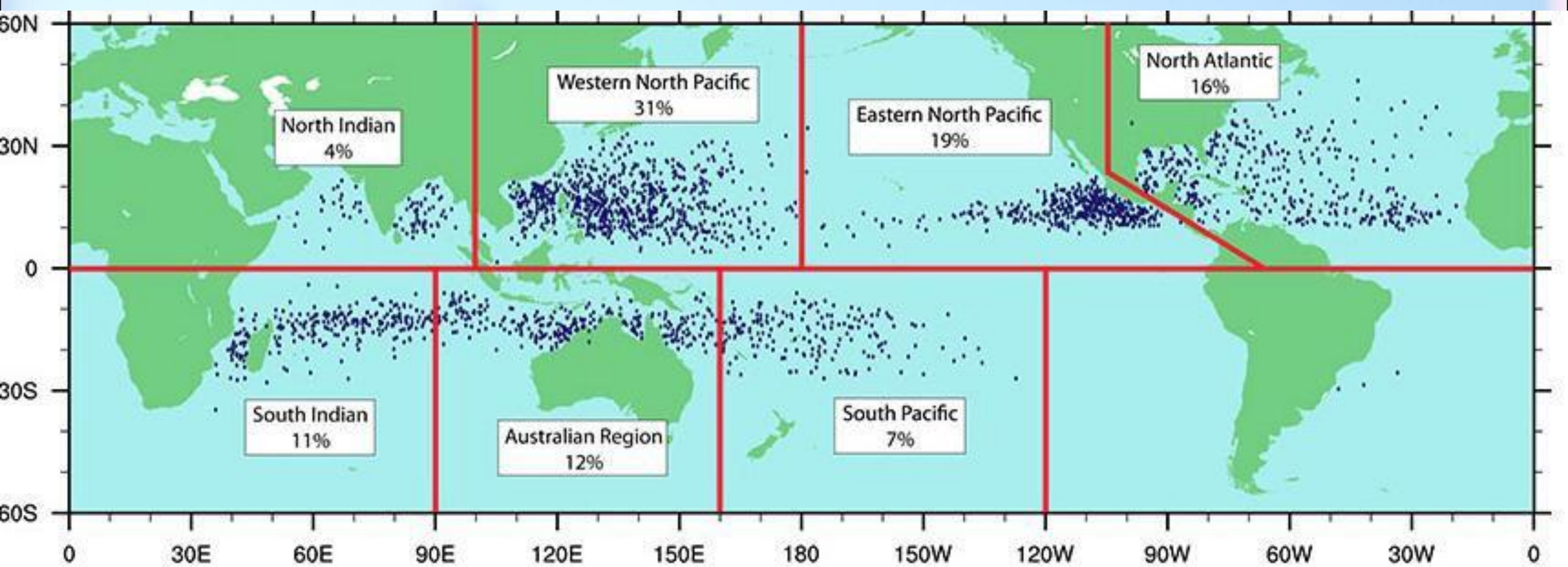
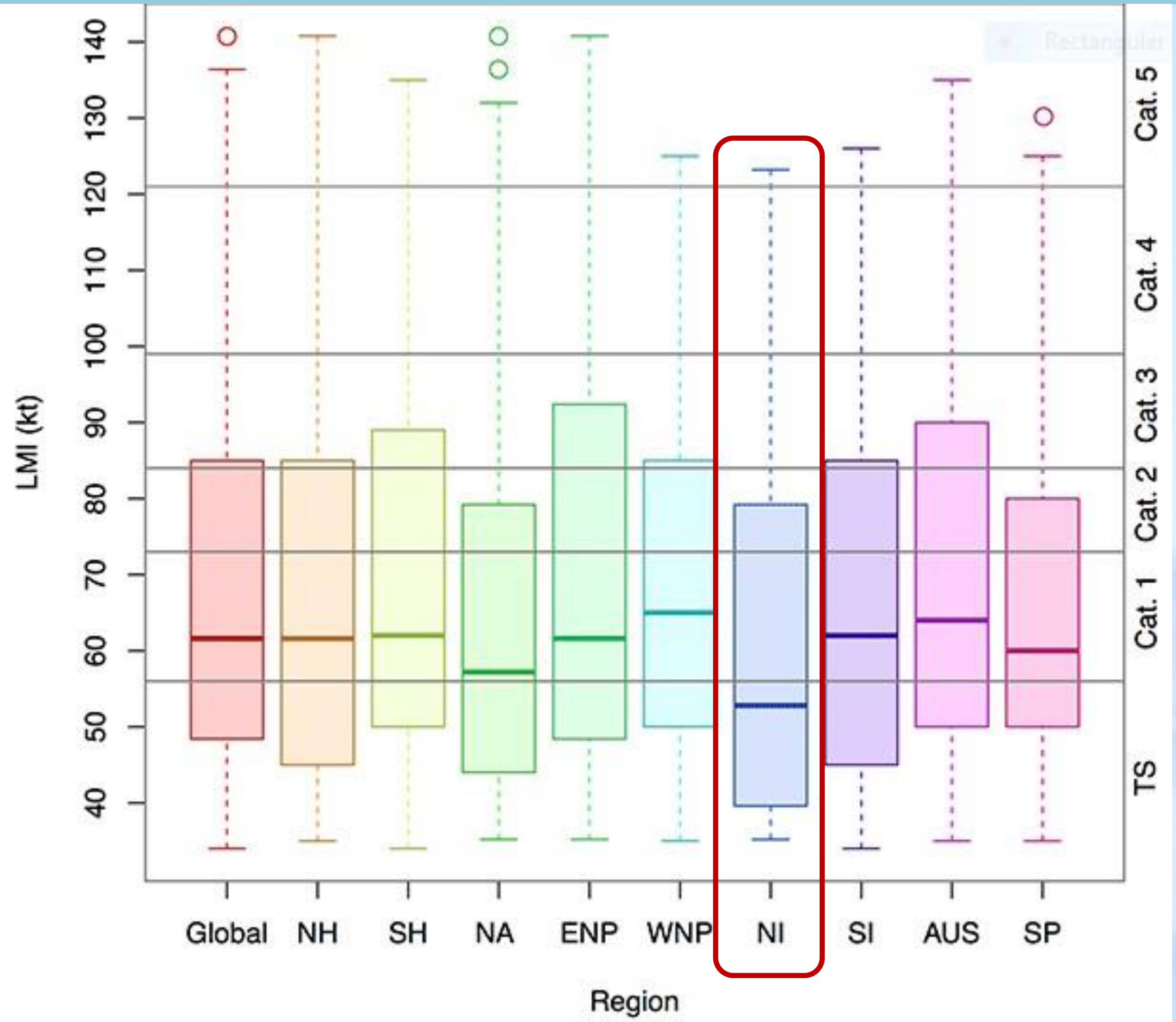
Global climatology of Tropical cyclones



The global distribution of tropical cyclone formation points for the period of most reliable global best track data. The percentage of tropical cyclones occurring in each basin (relative to the global total) is also shown based on data from 1990 to 2014 – Reproduced from Ramsay (2017)
https://doi.org/10.1093/acrefore/9780199389407.013.79

Intensity of tropical Cyclones over the Globe



Courtesy: Ramsay (2017)

Distribution of Lifetime Maximum Intensities (LMI) of Tropical Cyclone (Global, Northern Hemisphere, Southern Hemisphere and individual Basins)

Shaded rectangles show the inter quartile range of LMIs, with the corresponding Median value indicated by the thick horizontal line

The extreme upper & Lower horizontal lines indicate the minimum & maximum LMI for each region, excluding the outliers which are shown as open circles.

Major Basins of Cyclone Formation

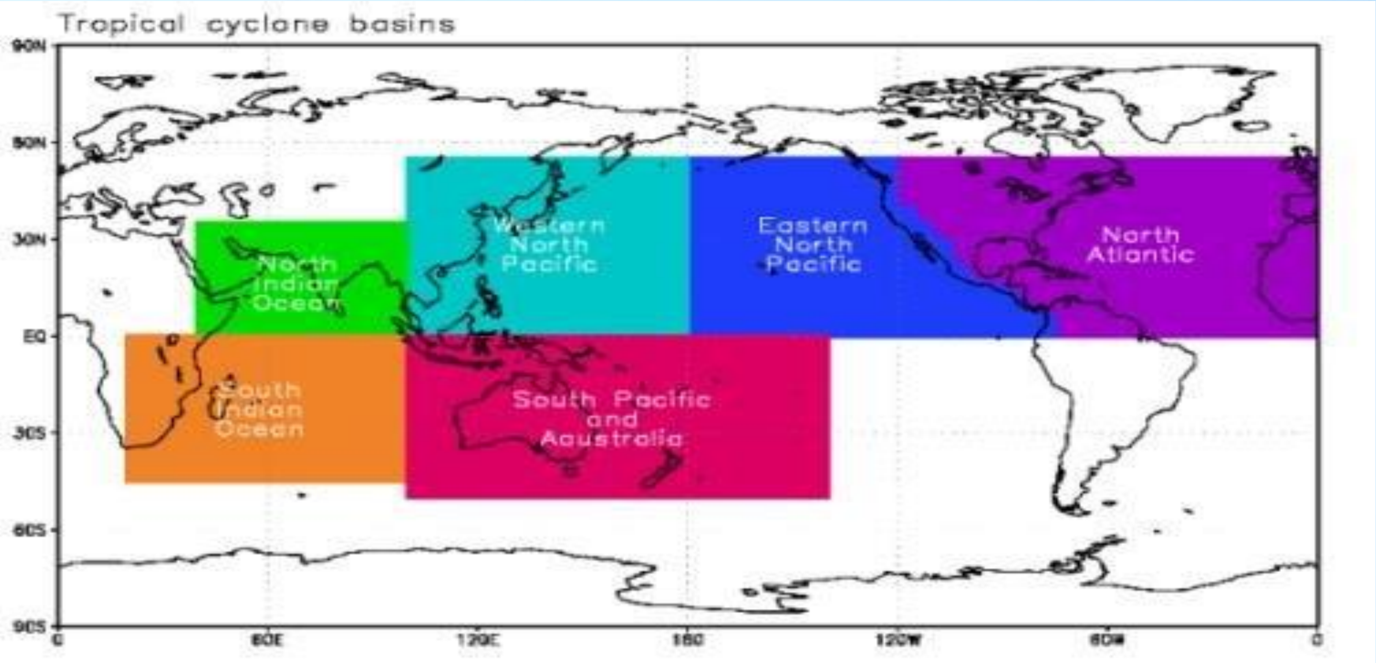


Fig. Courtesy : JMA

1. Atlantic basin (including North Atlantic Ocean, Gulf of Mexico and Caribbean Sea)
2. Northeast Pacific basin (from Mexico to about the dateline)
3. Northwest Pacific basin(from the dateline to Asia including South China Sea)
4. North Indian basin (including Bay of Bengal and Arabian Sea)
5. Southwest Indian basin(from Africa to about 100^0 E)
6. Southeast Indian/Australian basin (100^0 E to 142^0 E)
7. Australian/Southwest Pacific basin(142^0 E to about 120^0 W)

Movement of Tropical Cyclones Globally

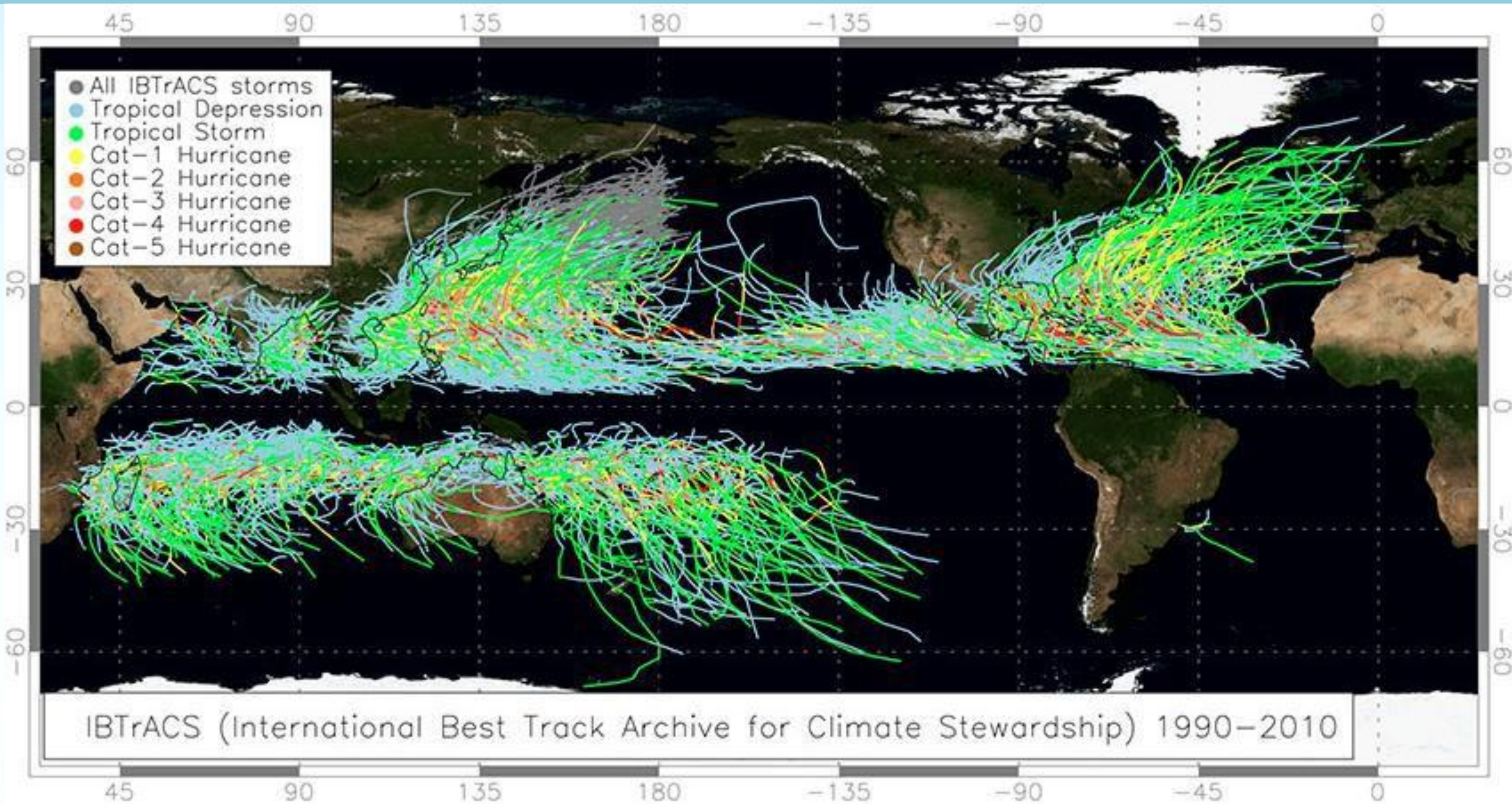
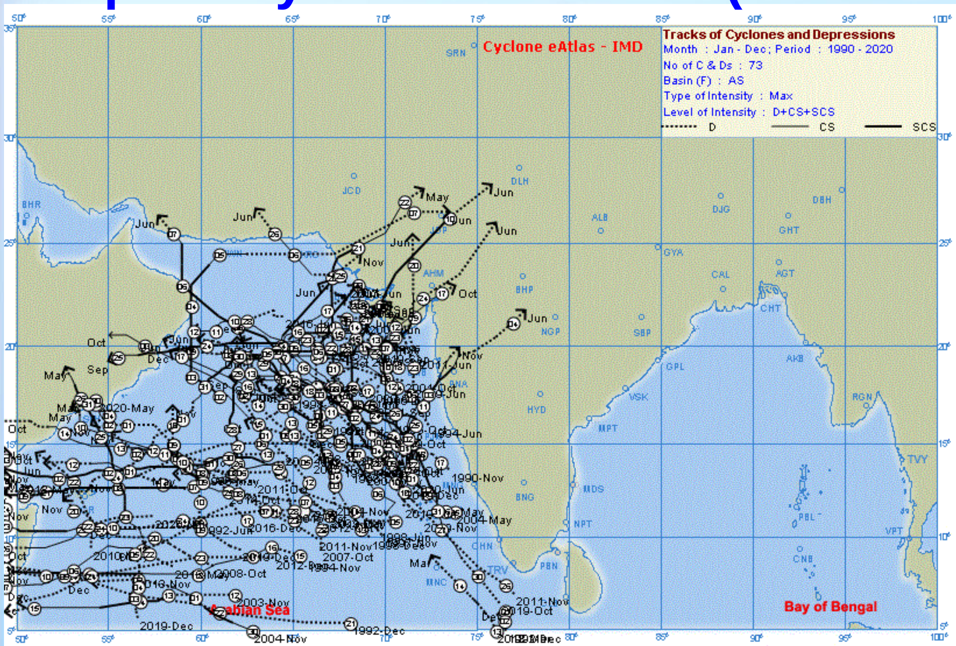


Image re-produced from Knap et al., 2010

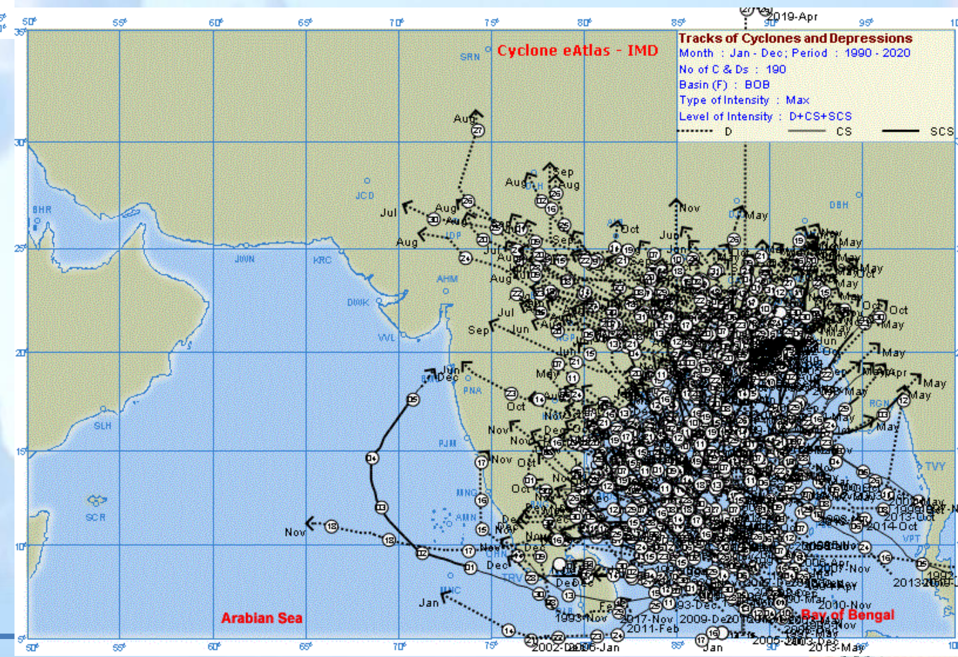
Global Tropical Cyclone tracks for the period 1990- 2010 colour coded by intensity on the Saffir – Simpson wind Scale. Tracks are from the IBTrACS-ALL best track data set (ie., both WMO & non-WMO data)

Tropical Cyclones over NIO (Arabian Sea & Bay of Bengal) [1990-2020]



Total Over Arabian Sea: 73
Dissipated over land: 20
Dissipated over sea:41

Total Over Bay of Bengal: 190
Dissipated over land: 157
Dissipated over sea:31



Classification of Low Pressure Systems over the north Indian Ocean

Low Pressure System	Abbreviation	Wind Speed Associated (Knots)	T. No.
Low Pressure Area	LOPAR	< 17	1.0
Depression	D	17-27	1.5
Deep Depression	DD	28-33	2.0
Cyclonic Storm	CS	34-47	2.5, 3.0
Severe Cyclonic Storm	SCS	48-63	3.5
Very Severe Cyclonic Storm	VSCS	64-89	4.0,4.5
Extremely Severe Cyclonic Storm	ESCS	91-119	5.0, 5.5,6.0
Super Cyclonic Storm	SuCS	≥120	>6.5

Importance of Climatology in Tropical Cyclone Forecasting

- **Climatological data of TCs are fundamental inputs in most of the Tropical Cyclones forecasting schemes and can provide preliminary forecasts on the movement, intensification and landfall of TCs.**

- **CLIPER (Climatology + Persistence) forecast scheme utilizes TC climatology.**

- **CLIPER forecasts also serve for evaluating the skill of forecasts of movement of TCs based on other techniques such as those based on NWP.**

- **To know the extremes so far, on a monthly / seasonal basis.**

- **Climatological analysis helps to understand the response of Tropical Cyclones to Climate Variability & Change**

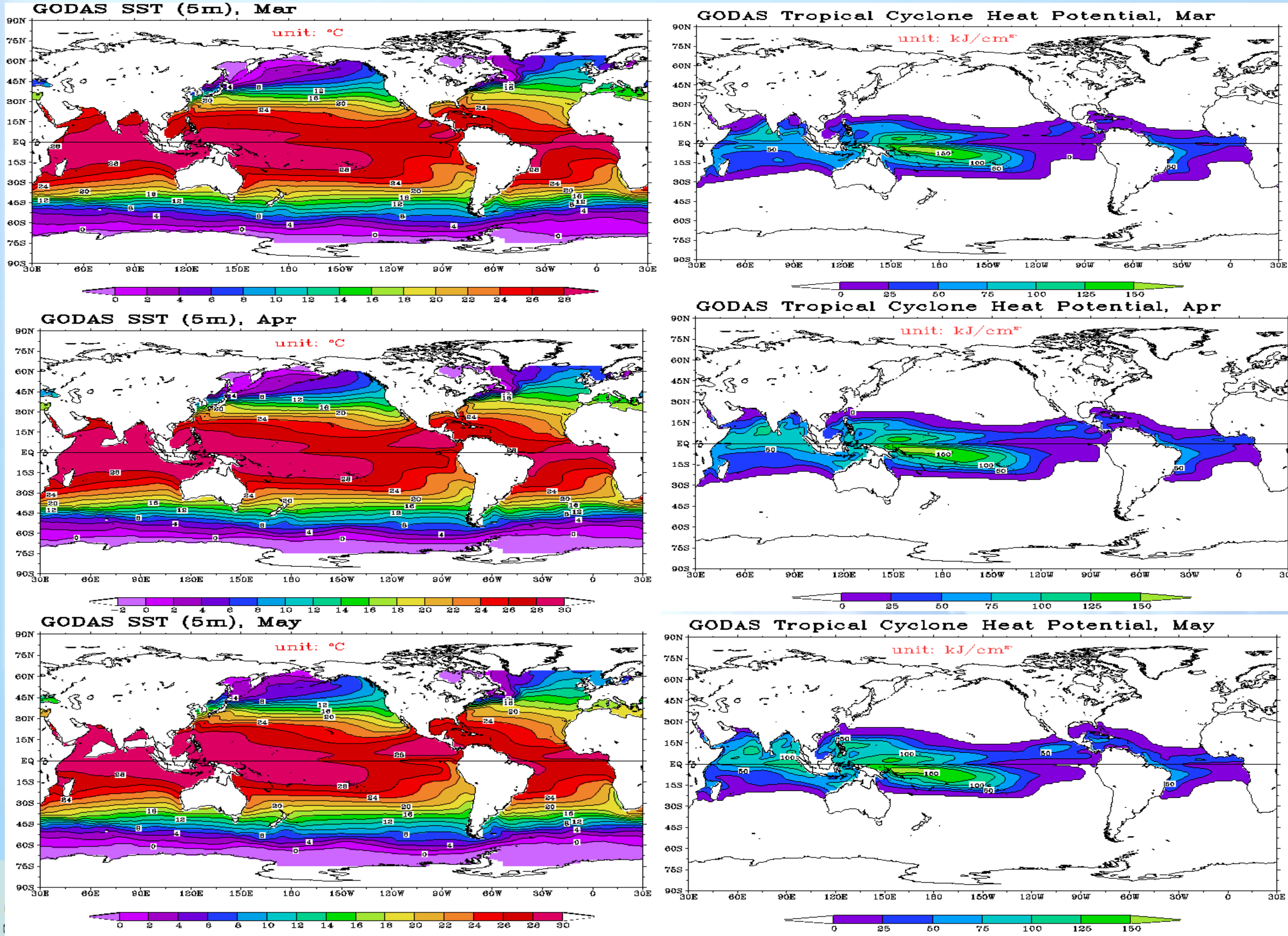
Global annual frequency of tropical cyclones

S.No.-	Basin	Season / Period	Average annual frequency of TCs	
			(MWS ≥ 34 knots)	(MWS ≥ 64 knots and above)
1	Atlantic	June-November	9.7	5.4
2	Northeast Pacific	May-November	16.5	8.9
3	Northwest Pacific	April – January	25.7	16.0
4	North Indian	April-December	5.4	2.5
5	Southwest Indian	October-May	10.4	4.4
6	Australian Southeast Indian	October-May	6.9	3.4
7	Australian Southwest Pacific	October-May	9.0	4.3
	Global		83.7	44.9

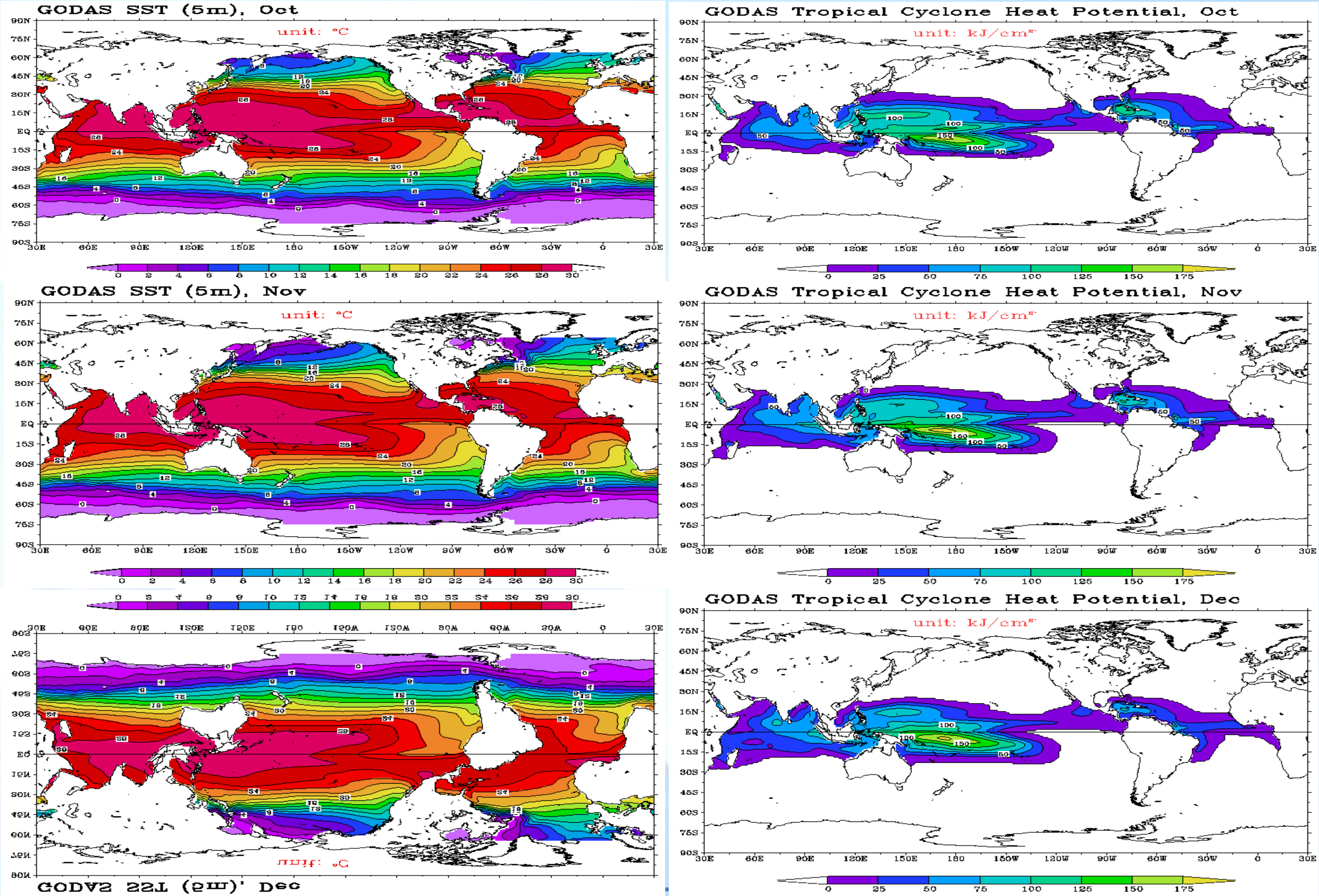
Gray's Parameters for Cyclogenesis

- **Sea surface temperature (>or = 26.5^{0}C)**
- **Middle tropospheric relative humidity**
- **Degree of convective instability**
- **Existence of a pre requisite system**
- **Low level absolute vorticity**
- **Minimum Vertical shear of the horizontal wind**

Necessary Condition for TC Development: Warm Sea Surface Temperature $\gtrsim 26^{o}$C

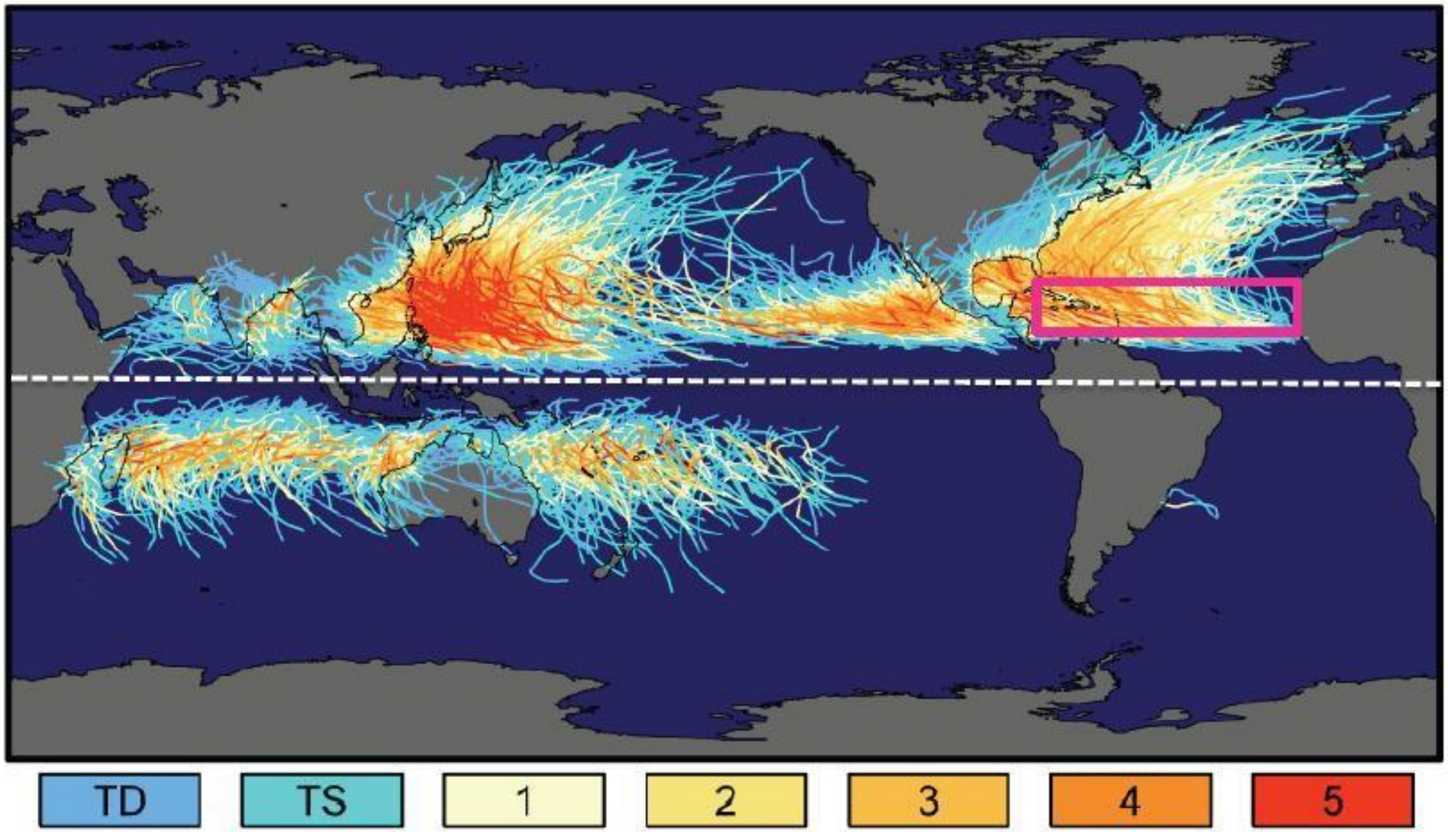


Necessary Condition for TC Development: Warm Sea Surface Temperature $\gtrsim 26^{o}$C



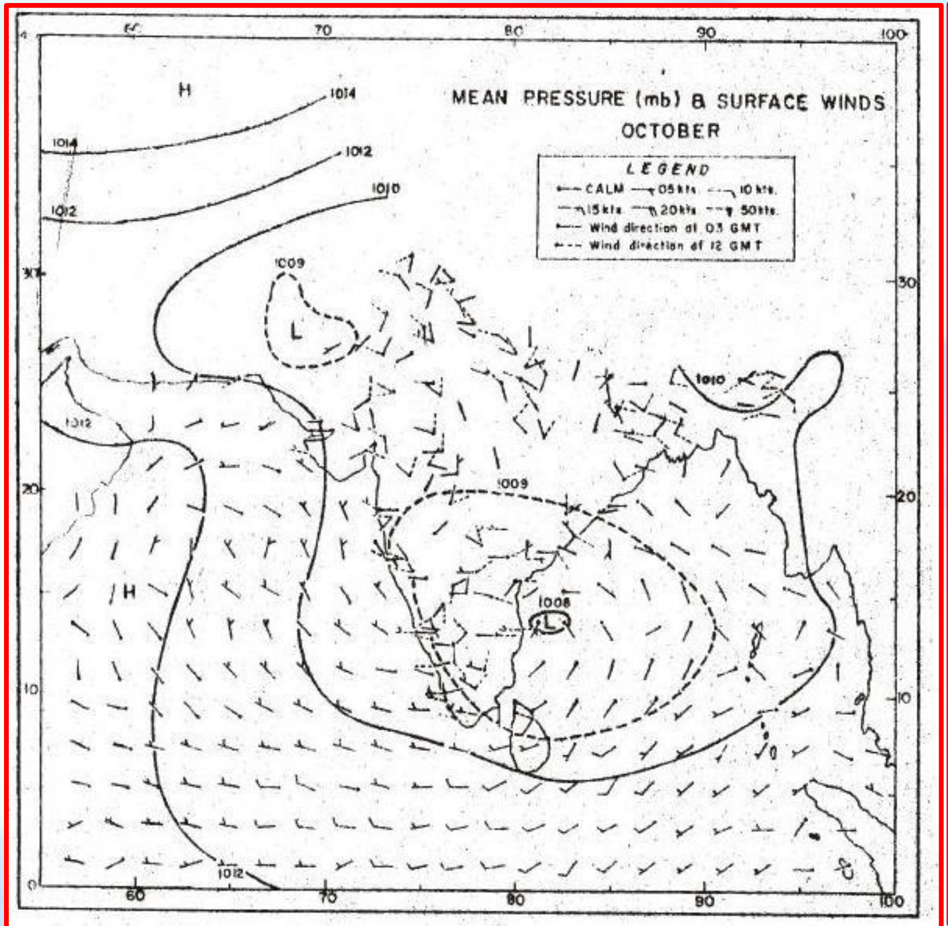
Necessary conditions for TC development:
2)Off equatorial location (Coriolis effect)

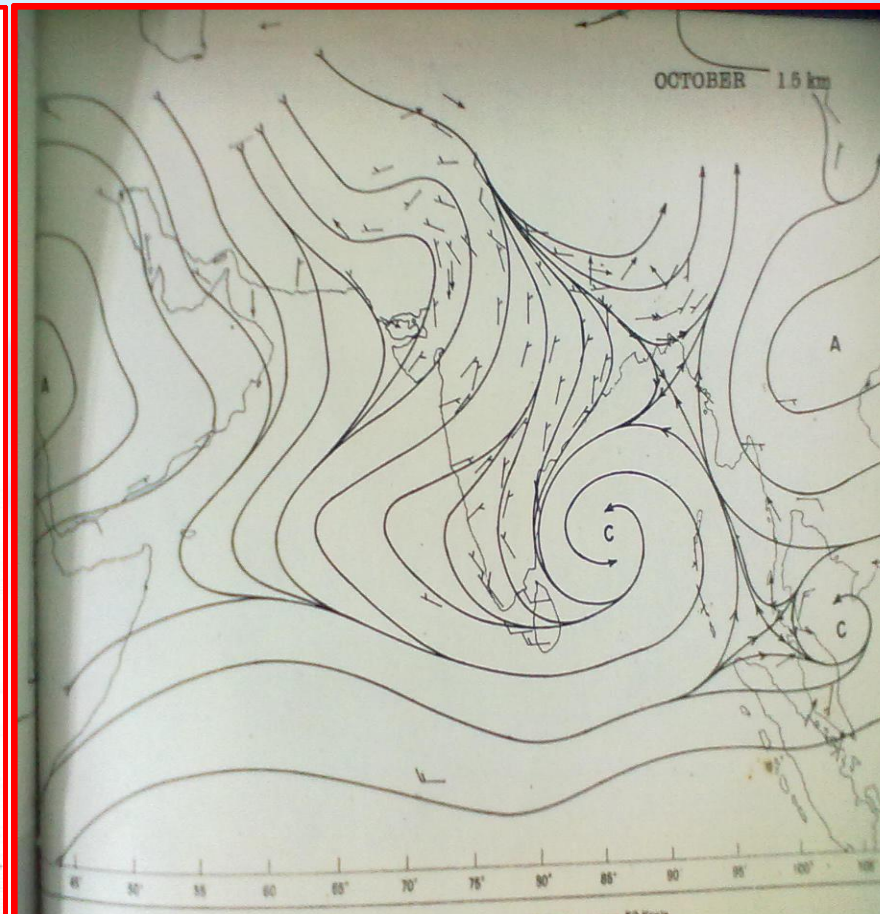
Tracks and Intensity of All Tropical Storms



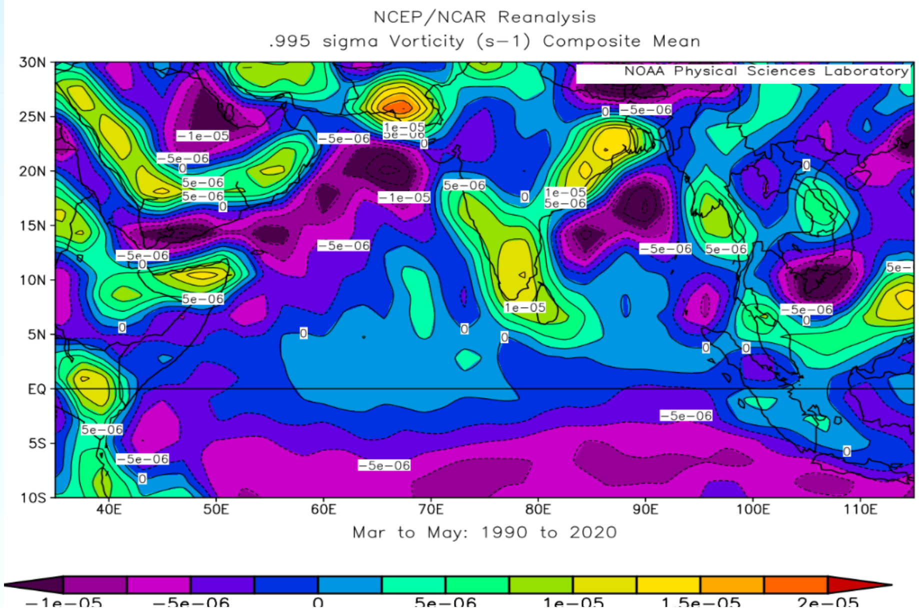
Saffir-Simpson Hurricane Intensity Scale

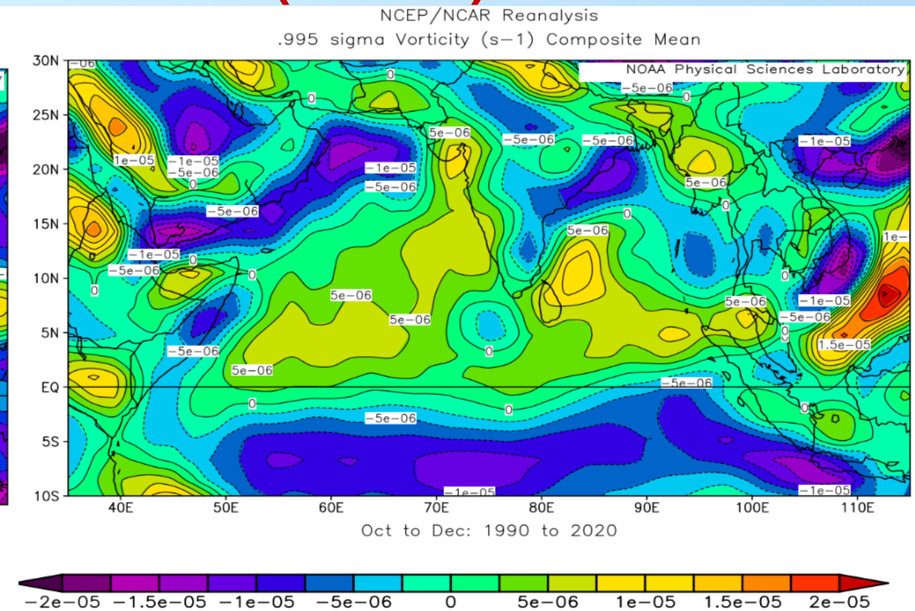
pre-existing systems & associated low level vorticity

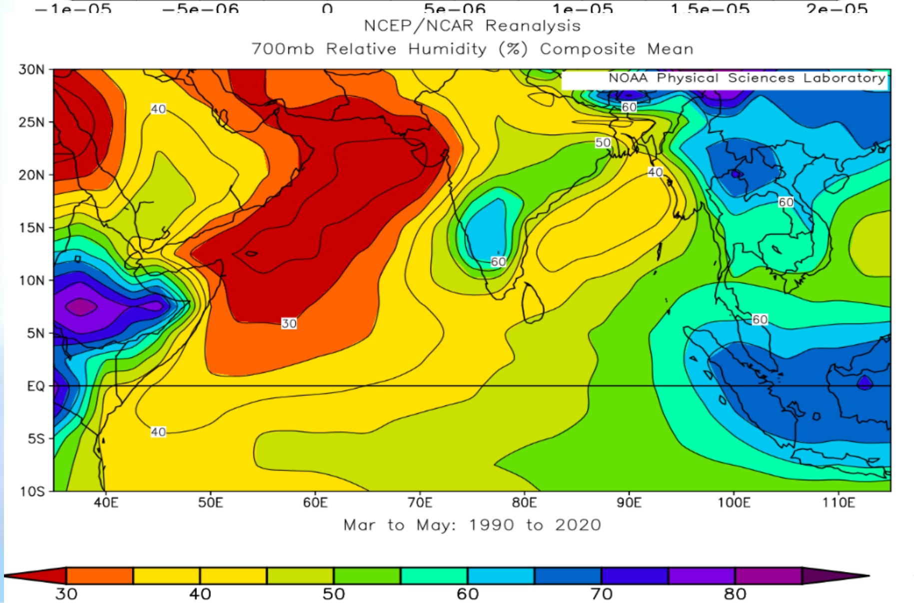


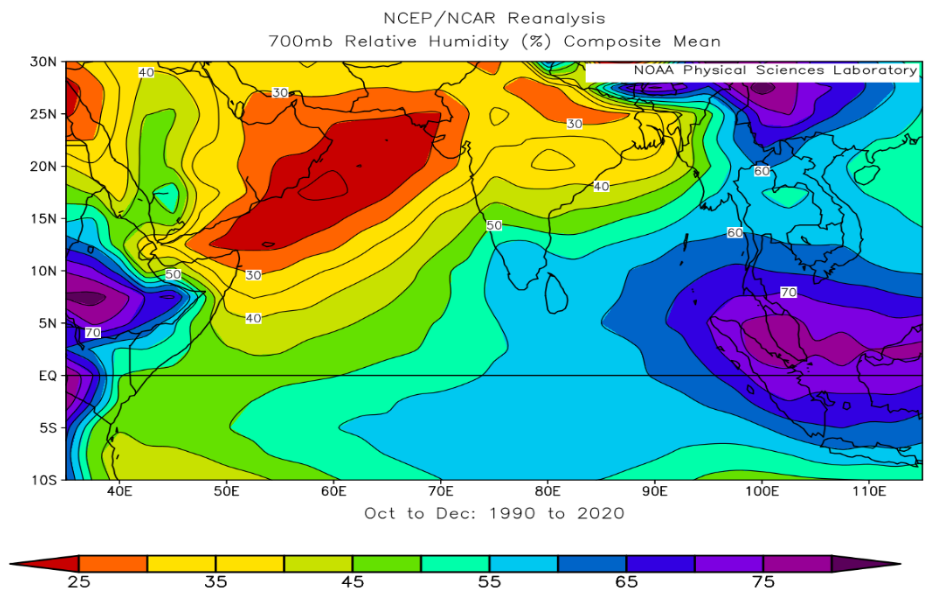


Necessary Condition for TC Development:
Low Level (850 hPa) vorticity & Mid-Level (700 hPa) Moisture

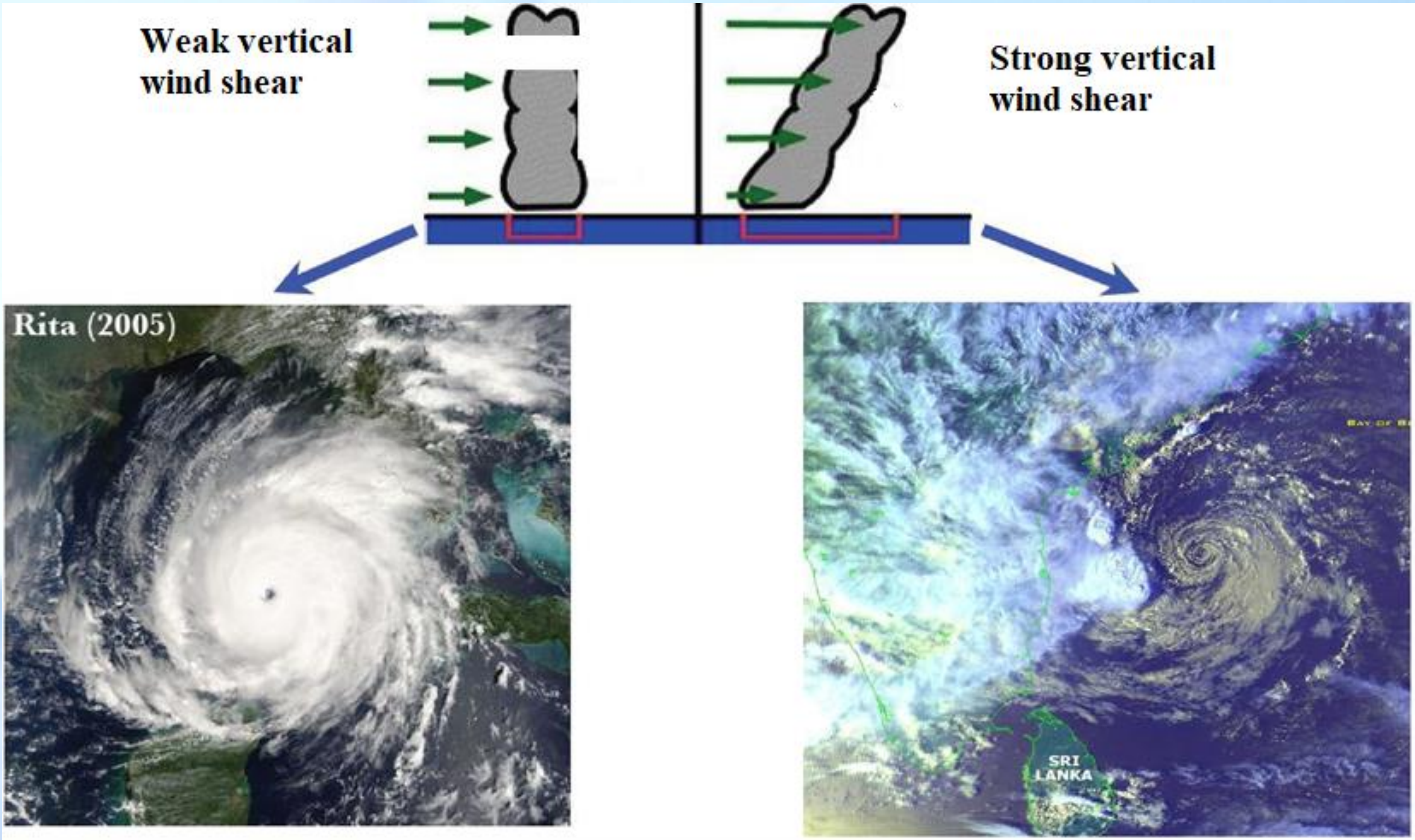




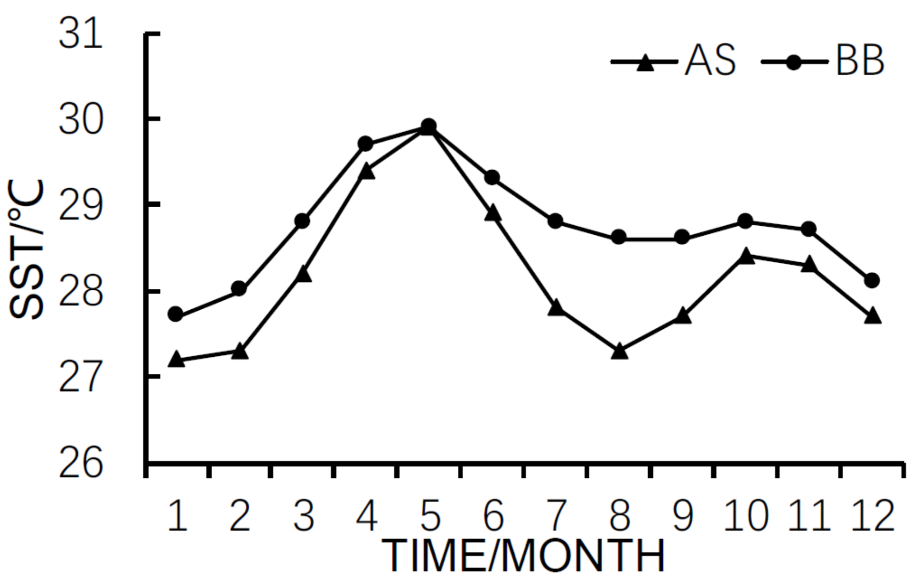


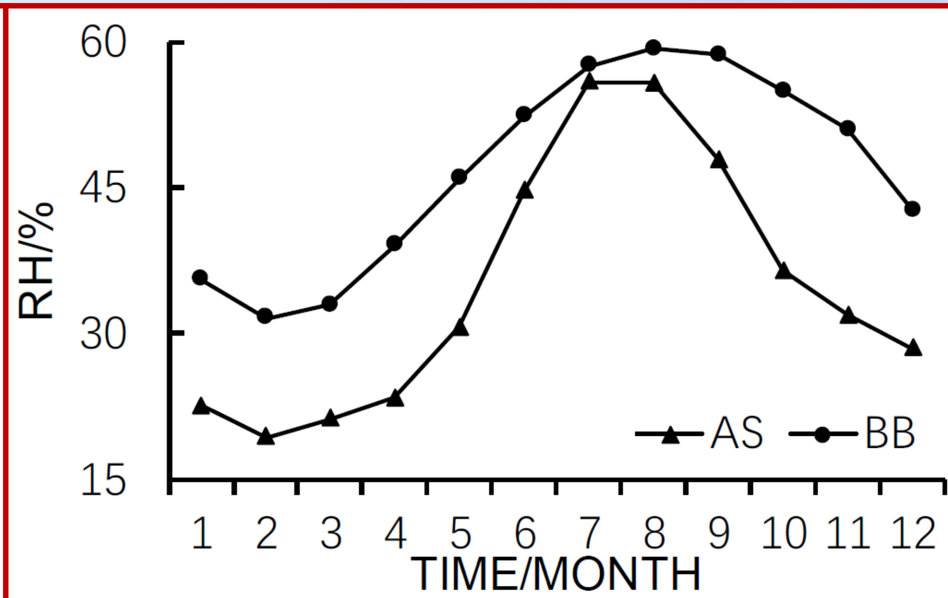


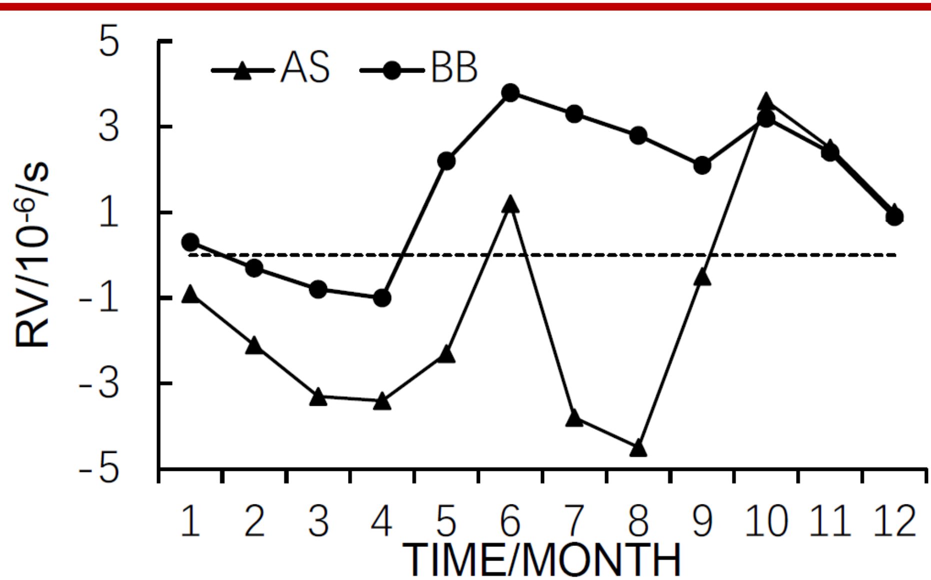
Necessary Condition for Tropical Cyclone Development:
Relative weak vertical wind shear

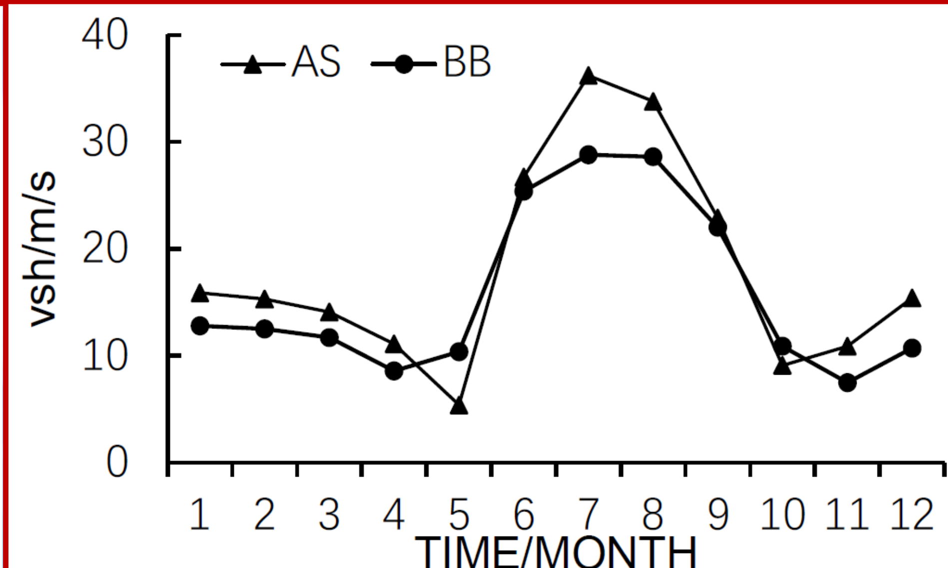


Necessary Condition for TC Development: Climatology of various Parameters



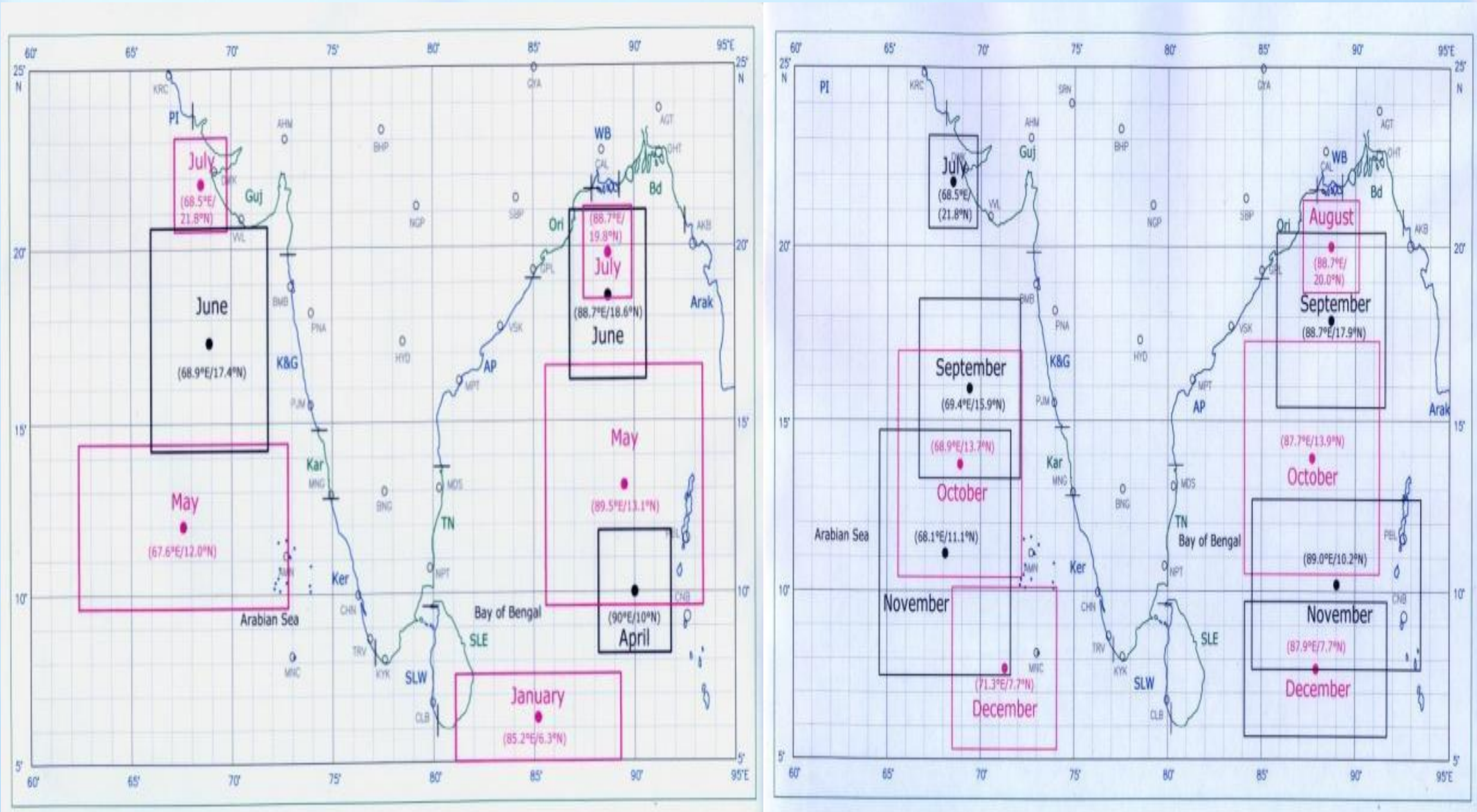




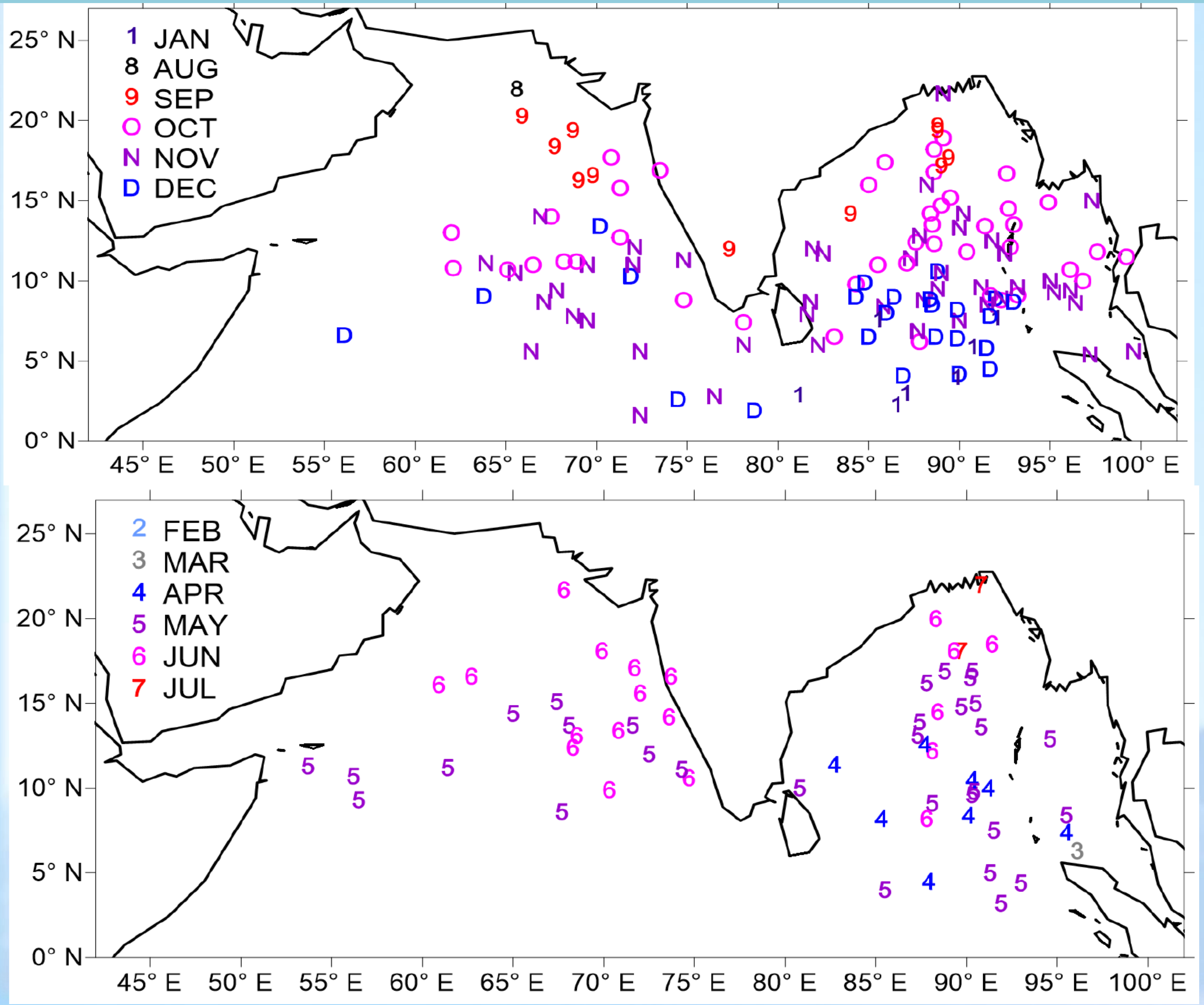


Genesis of Cyclonic Disturbances

Normal Genesis Areas of Systems During Different Months



Genesis Point Of Systems During Different Months (1980-2019)

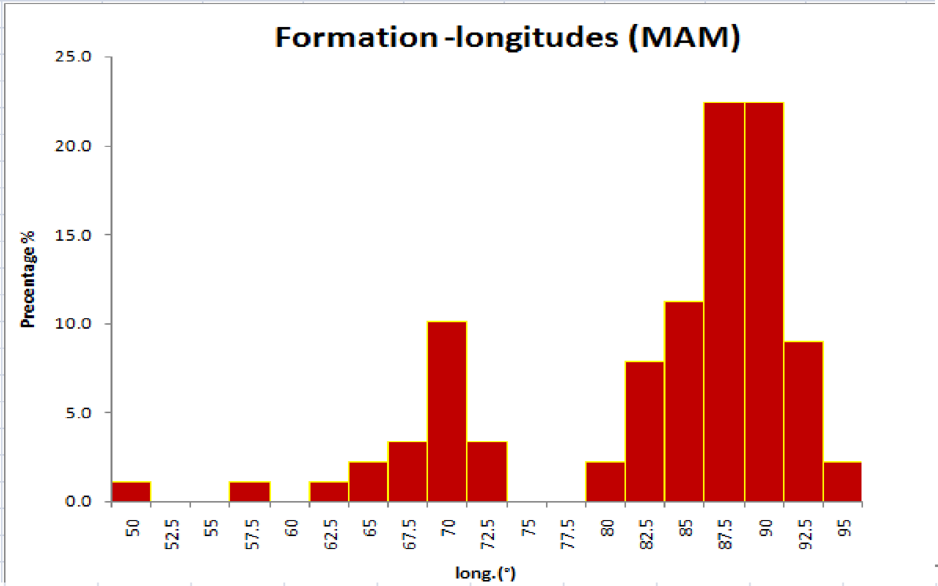


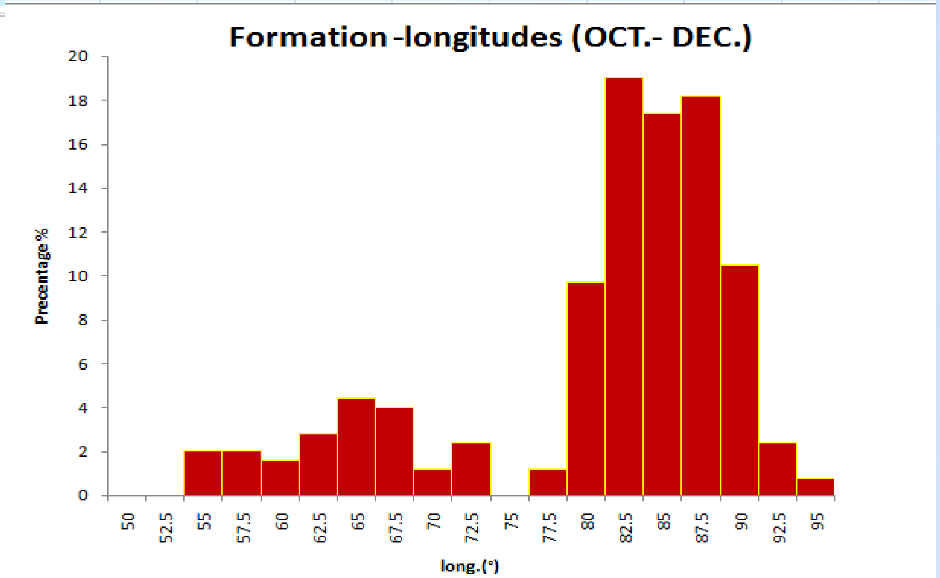
Monthly distribution of the initial positions of North Indian Ocean (NIO) tropical cyclones

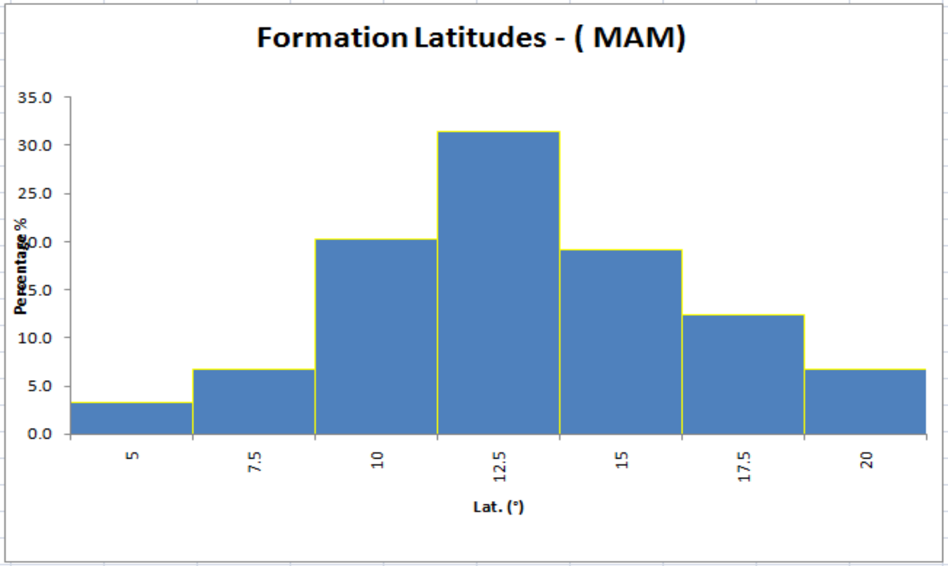
Duan et al. (2021)

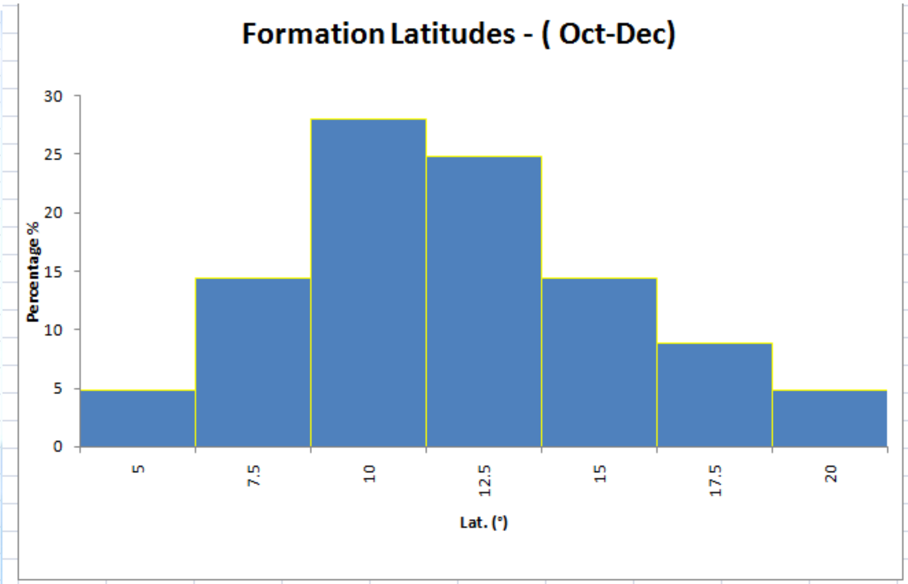
Formation of longitudes / latitudes CS/SCS over BOB and AS (MAM)

Formation of longitudes /latitudes CS/SCS over BOB and AS (OND)

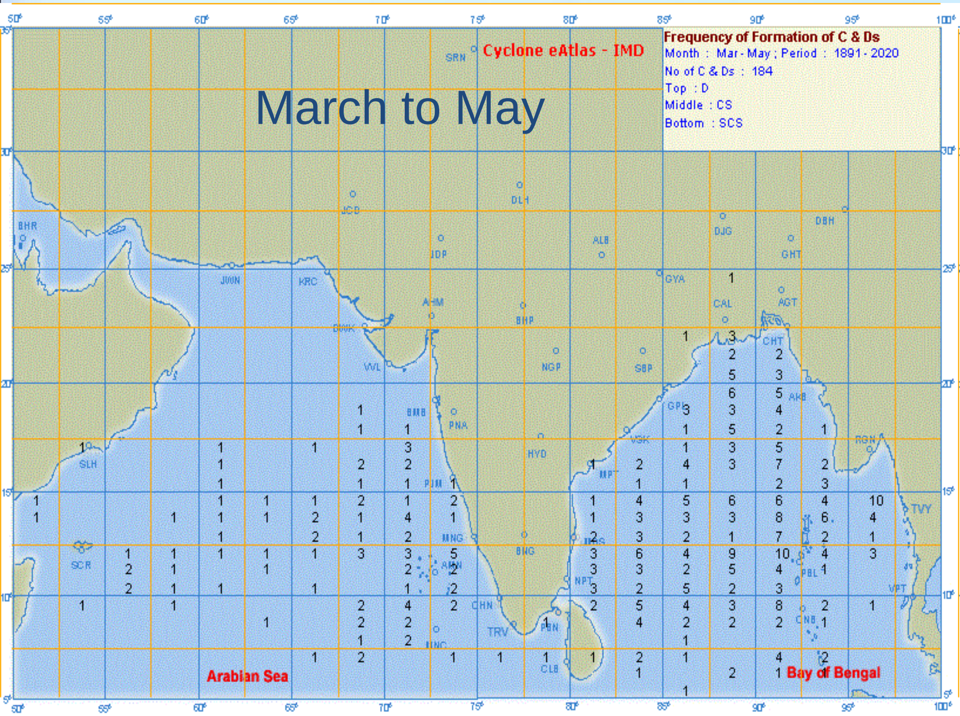


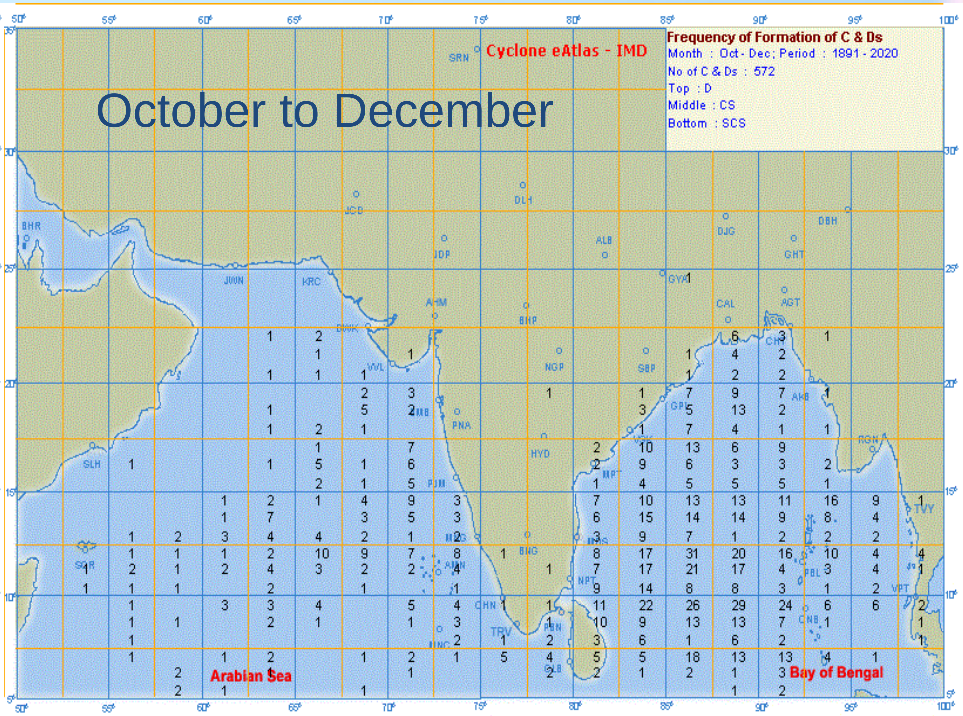


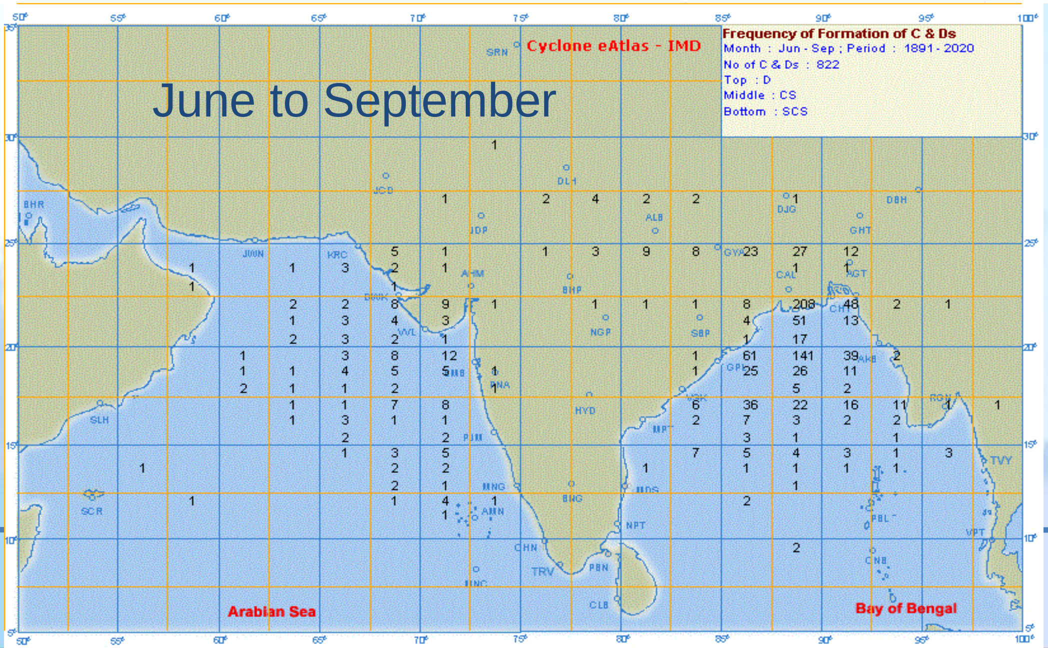




Frequency of Cyclonic Disturbances


Cyclone eAtlas - IMD
Frequency of Formation of C & Ds
Month : Mar - May ; Period : 1891 - 2020
No of C & Ds : 184
Top : D
Middle : CS
Bottom : SCS
March to May
Arabian Sea
Bay of Bengal


Cyclone eAtlas - IMD
Frequency of Formation of C & Ds
Month : Oct - Dec ; Period : 1891 - 2020
No of C & Ds : 572
Top : D
Middle : CS
Bottom : SCS
October to December
Arabian Sea
Bay of Bengal


Cyclone eAtlas - IMD
Frequency of Formation of C & Ds
Month : Jun - Sep ; Period : 1891 - 2020
No of C & Ds : 822
Top : D
Middle : CS
Bottom : SCS
June to September
Arabian Sea
Bay of Bengal

Climatology - Rapid Intensification

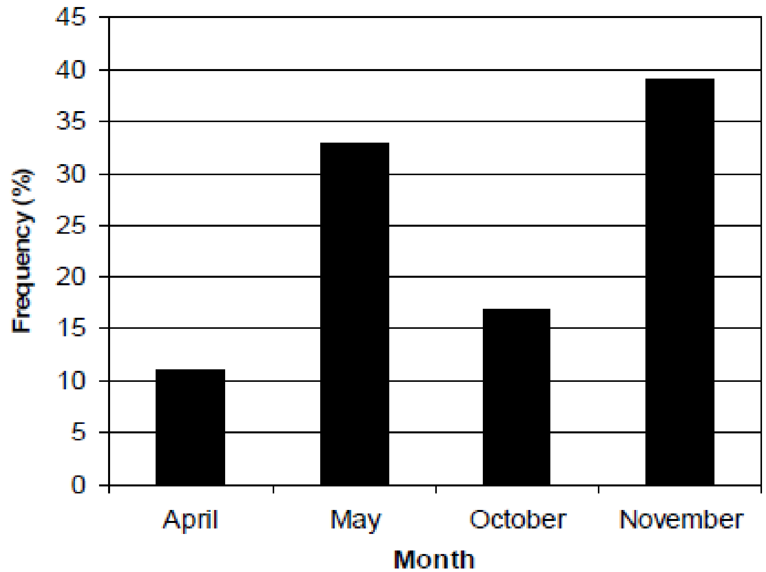


Fig. 4. The percentage distribution of the RI cases by month

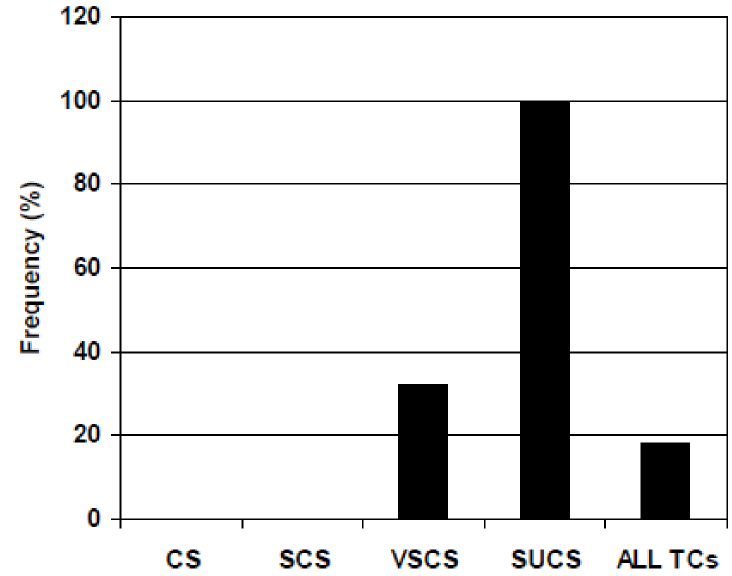
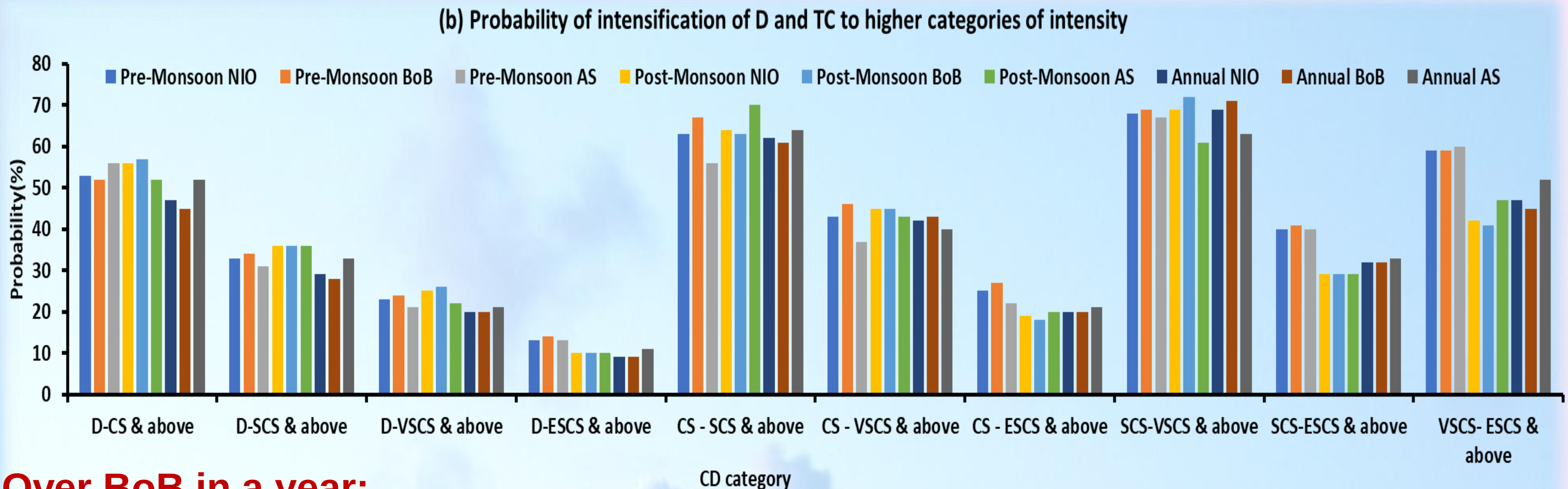


Fig. 2. The percentage distribution of systems that underwent RI at least once during their lifetime as a function of the maximum intensity attained by each system

- **RI cases generally occur at higher latitude**
- **No cyclonic storms (CS) and severe cyclonic storm (SCS) underwent RI during their lifetime.**
- **It is found that 32% of all very severe cyclonic storms (VSCS) and all super cyclonic storms (SUCS) underwent RI phase at least once during their lifetime.**



Over BoB in a year:

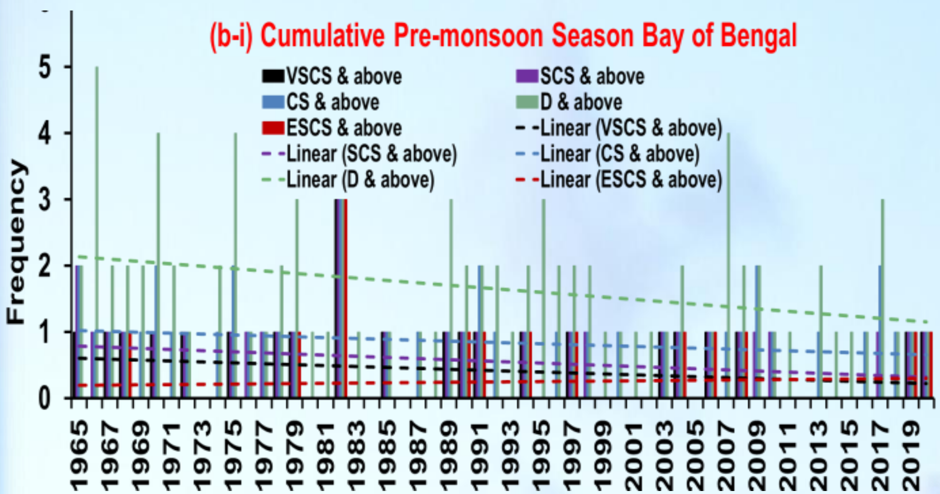
- About 8 CDs develop, out of which 3-4 (45%) become the TCs. About 61% of TCs become severe, 43% become very severe and 20% become extremely severe or above intensity storms.
- There is 71% and 32% probability for an SCS to intensify into a VSCS and ESCS respectively and 45% probability for a VSCS to intensify into an ESCS

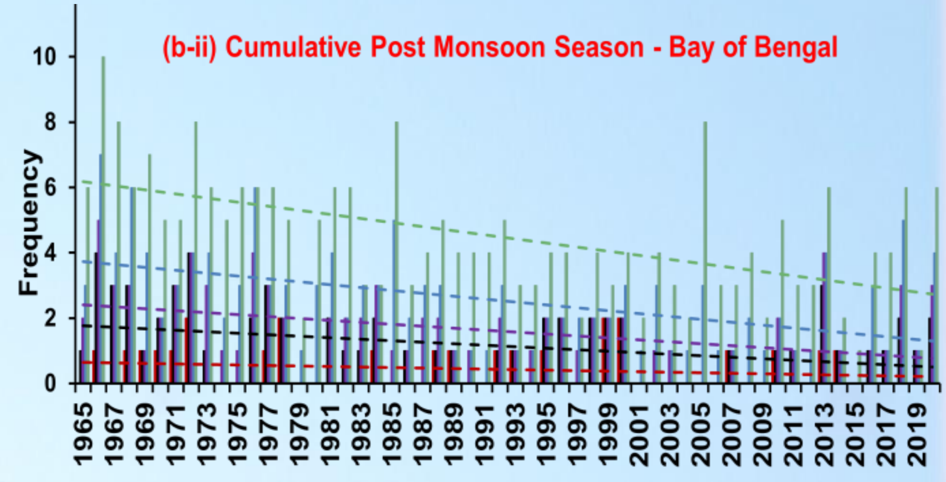
Over AS in a year:

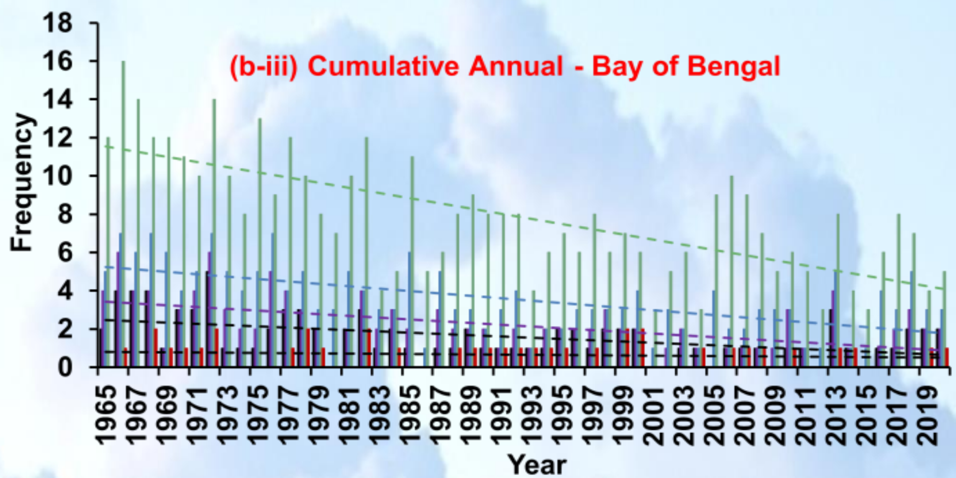
- The average frequency of D, CS, SCS, VSCS and ESCS is 2.2, 0.4, 0.3, 0.2, 0.2 respectively. About 52% of CDs intensify into TC. The probability of a TC becoming severe is 64%, becoming very severe is 40% and extremely severe is 21%.
- There is 63% and 33% probability for an SCS to intensify into a VSCS and ESCS respectively and 52% probability for a VSCS to intensify into an ESCS. (Mohapatra etal 2021)

Super Cyclonic Storms over the north Indian Ocean during 1965-2019: Mohapatra etal (2021)

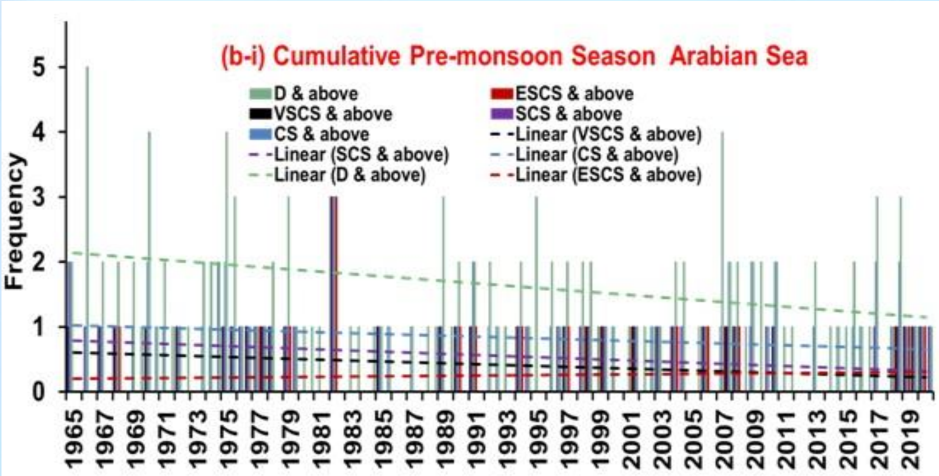
S. No.	Period	Basin	T.No.	Peak Intensity (knot)	Landfall Point	Landfall Intensity (knot) & category
1.	14-20 Nov, 1977	BOB	T6.5	125	AP, Chirala	125 (SuCS)
2.	01-09 Nov, 1989	BOB	T6.5	130	AP, Kavali	115 (ESCS)
3.	4-10 May, 1990	BOB	T6.5	130	AP, Machilipatnam	102 (ESCS)
4.	24-30 Apr, 1991	BOB	T6.5	130	Bangladesh, Chittagong	127 (SuCS)
5.	25-31 Oct, 1999	BOB	`T7.0	140	Odisha, Paradeep	140 (SuCS)
6.	1-7 June 2007, Gonu	AS	T6.5	130	Oman, Muscat	77 (VSCS)
7.	24 Oct-2 Nov 2019, Kyarr	AS	T 6.5	130	Weakened over sea	Weakened over sea
8.	16-21 May, 2020, Amphan	BoB	T 6.5	130	West Bengal, Sunderbans	85 (VSCS)

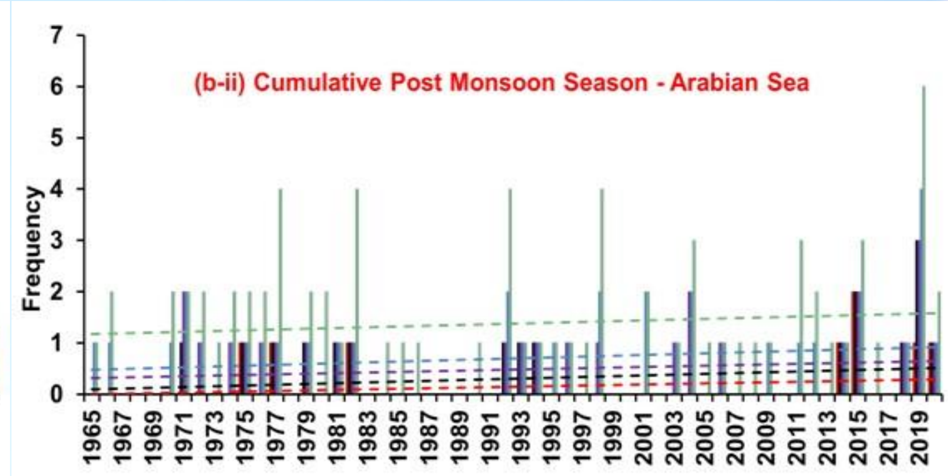


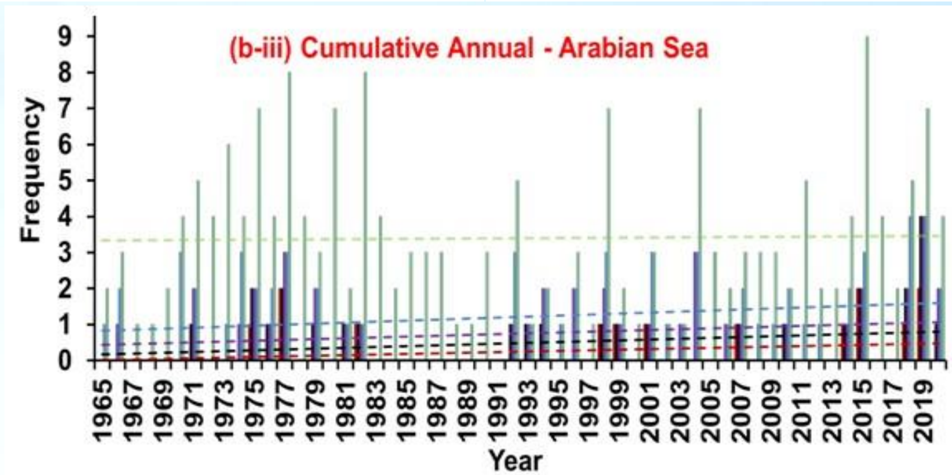




There is a decreasing trend in frequency of D & above, CS & above, SCS & above, VSCS & above and ESCS & above over the BOB and all the above except ESCS & above over the NIO during the year as a whole. (Mohapatra etal 2021)



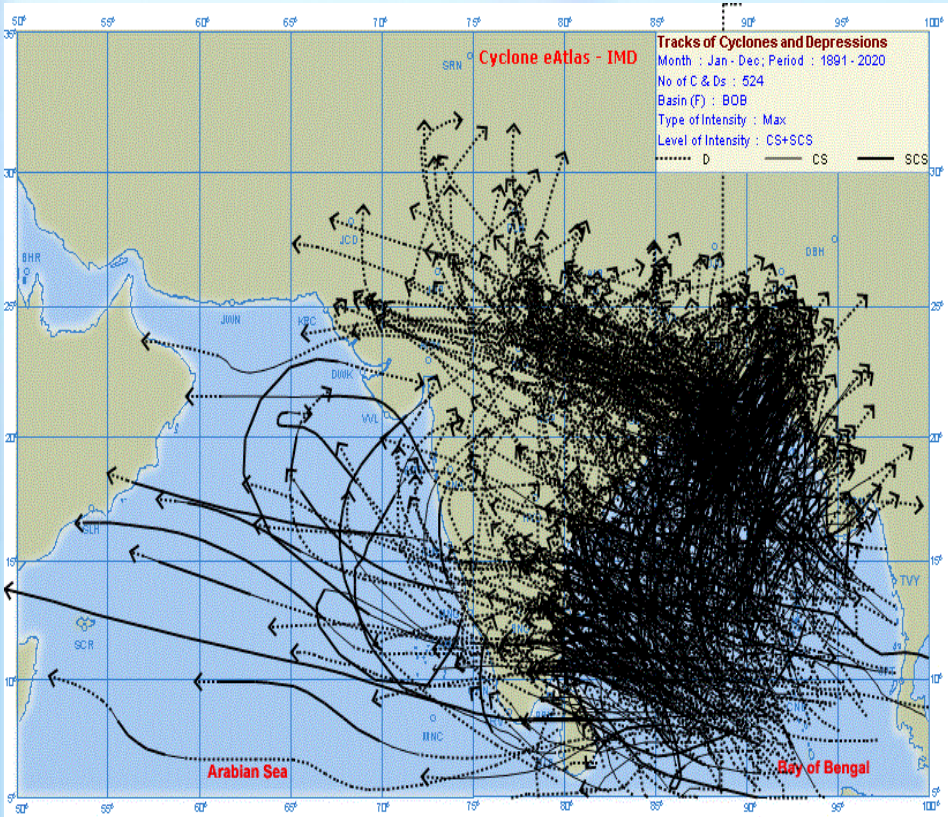




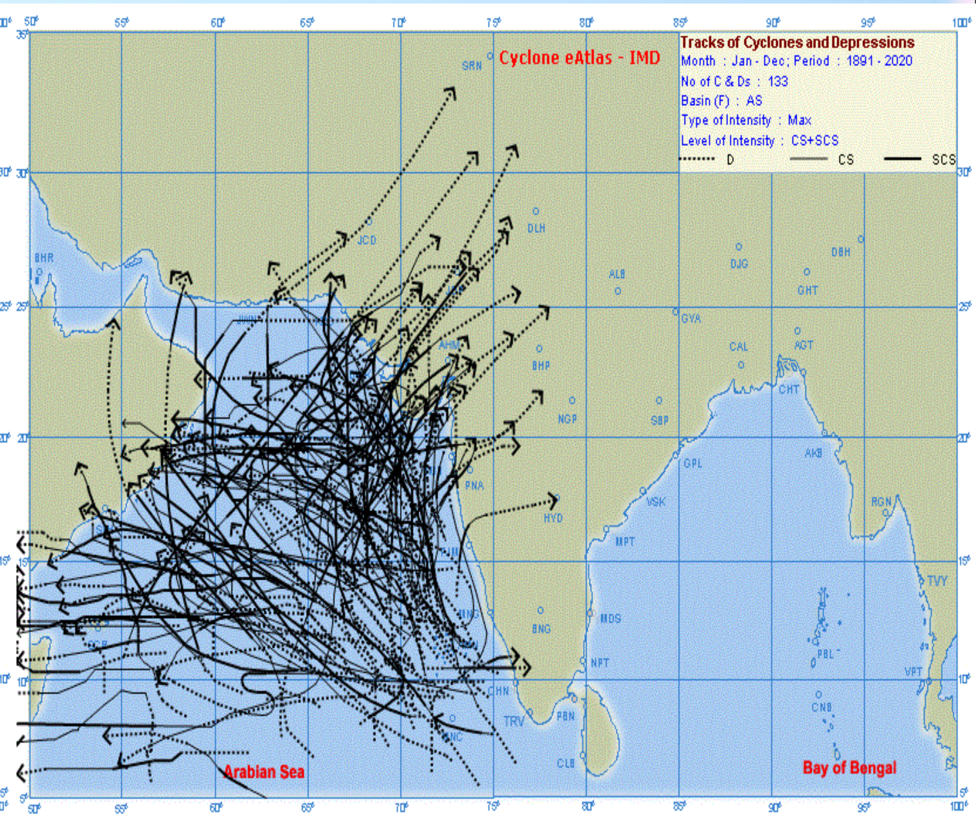
There is no significant trend in frequency of any such category of storms over the AS during the period except that there is increasing trend in the frequency of ESCS. There is an increasing trend in the frequency of CS & above, SCS & above, VSCS & above and ESCS & above over the AS during the year as a whole .(Mohapatra etal, 2021)

Movement of Cyclonic Disturbances

Tracks of Cyclonic Disturbances (Bay of Bengal)



Tracks of Cyclonic Disturbances (Arabian Sea)



Mean direction of movement, distance travelled and time taken by a CD formed over Bay of Bengal during intensification from D to CS and CS to SCS for various months / seasons

Month	D to CS				CS to SCS			
	Vector movement		Scalar movement		Vector movement		Scalar movement	
	Dir (°)	Distance (km)	Distance (km)	Time taken (hrs)	Dir (°)	Distance (km)	Distance (km)	Time taken (hrs)
Jan	--	--	--	--	--	--	--	--
Feb	--	--	--	--	--	--	--	--
Mar	--	--	--	--	--	--	--	--
Apr	321	248	292	30	345	124	146	15
May	348	243	313	30	356	238	309	25
Jun	342	345	496	38	--	--	--	--
Jul	--	--	--	--	--	--	--	--
Aug	282	116	129	21	--	--	--	--
Sep	306	337	393	33	26	253	358	26
Oct	311	346	418	30	326	169	255	16
Nov	304	378	463	32	312	192	247	17
Dec	314	296	456	44	326	163	219	22
JF	328	297	493	47	--	--	--	--
MAM	343	252	321	30	355	214	275	23
JJAS	313	272	357	31	003	187	305	26
OND	308	350	447	34	318	179	244	18
Annual	314	308	408	33	332	184	262	20

Normal monthly speed of movement of CDs over BOB, AS and Land

Month	BOB				AS				Land			
	No. of CDs	No. of positions	Normal speed (kmph)	Distance travelled in 24 hrs (km)	No. of CDs	No. of positions	Normal speed (kmph)	Distance travelled in 24 hrs (km)	No. of CDs	No. of positions	Normal speed (kmph)	Distance travelled in 24 hrs (km)
Jan	10	95	10.0	241	--	--	--	--	--	--	--	--
Feb	--	--	--	--	--	--	--	--	--	--	--	--
Mar	--	--	--	--	--	--	--	--	--	--	--	--
Apr	8	150	12.5	300	--	--	--	--	6	33	13.4	321
May	45	415	12.9	309	18	180	12.4	297	41	146	12.7	305
Jun	44	174	11.6	278	29	236	12.7	335	60	229	12.3	314
Jul	38	118	9.8	235	6	43	10.8	259	48	282	13.2	318
Aug	66	187	10.7	257	6	28	11.1	266	75	434	13.0	311
Sep	56	252	13.3	319	13	109	11.7	280	72	529	11.8	284
Oct	82	524	13.9	334	25	231	13.3	320	67	226	13.4	322
Nov	78	692	13.7	328	32	283	13.5	324	53	165	13.9	334
Dec	42	421	11.7	280	11	85	12.1	290	25	63	12.3	295
JF	12	110	10.1	241	--	---	--	--	--	--	--	--
MAM	51	509	12.8	307	19	189	12.5	299	43	151	12.7	306
JJAS	192	684	11.8	284	53	405	12.5	300	239	1346	12.7	306
OND	191	1541	13.4	321	63	557	13.2	316	137	434	13.4	322
Annual	435	2743	12.9	308	131	1086	12.8	308	409	1881	13.1	313

Translational Speed of Cyclonic Disturbances

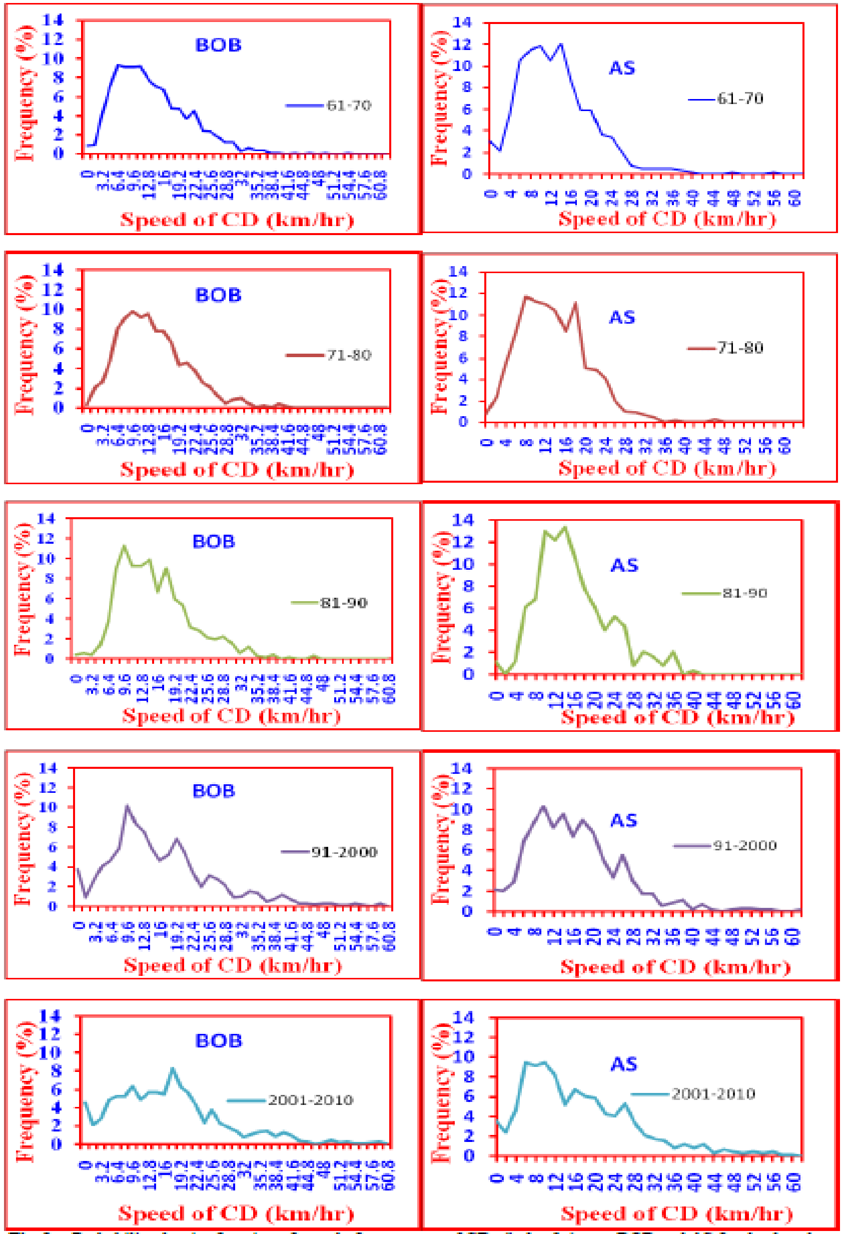


TABLE 2

Decade-wise mean speeds of movement and standard deviations

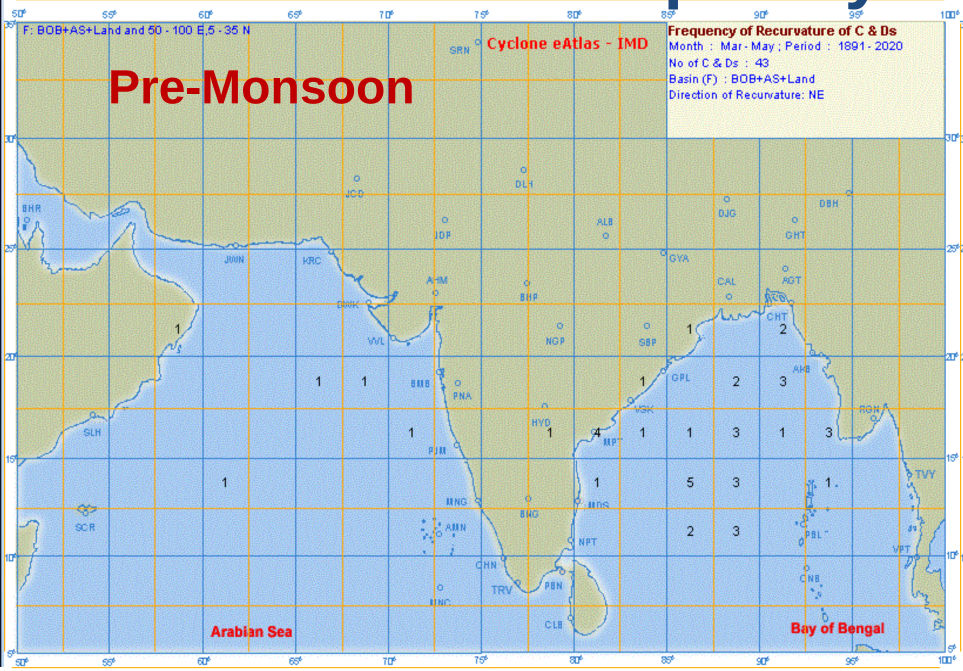
Decade	BOB			AS		
	N	Mean (km/hr)	S. D. (km/hr)	N	Mean (km/hr)	S. D. (km/hr)
1961-70	2005	12.64	7.55	659	12.03	7.56
1971-80	1367	12.86	7.7	798	12.55	6.84
1981-90	655	14.74	7.18	246	14.82	7.46
1991-00	1254	16.3	12.4	691	15.86	11.8
2001-10	1379	16.64	12.3	752	16.32	14.3

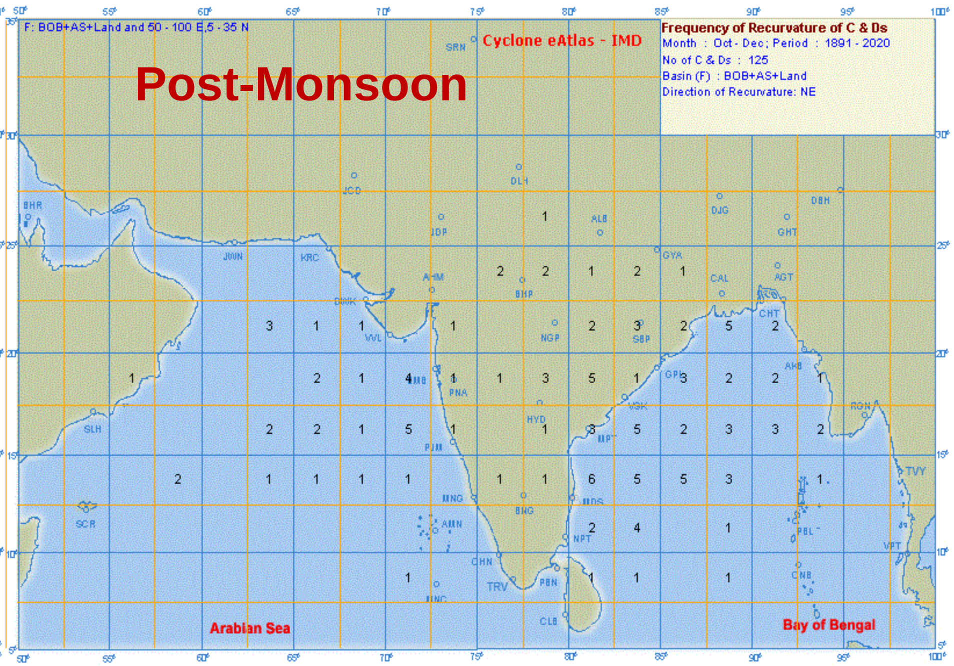
Recurvature

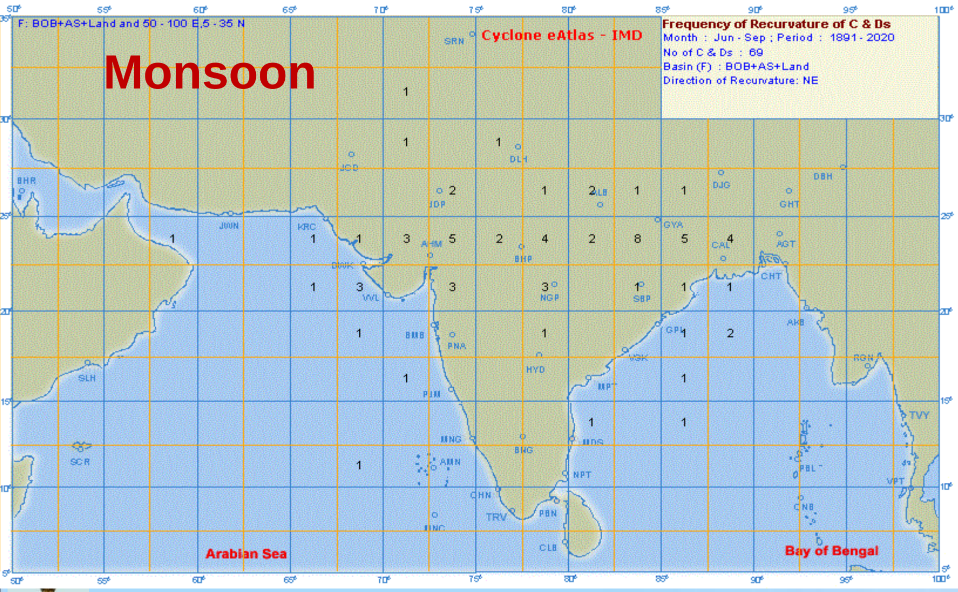
Salient points of Recurvature

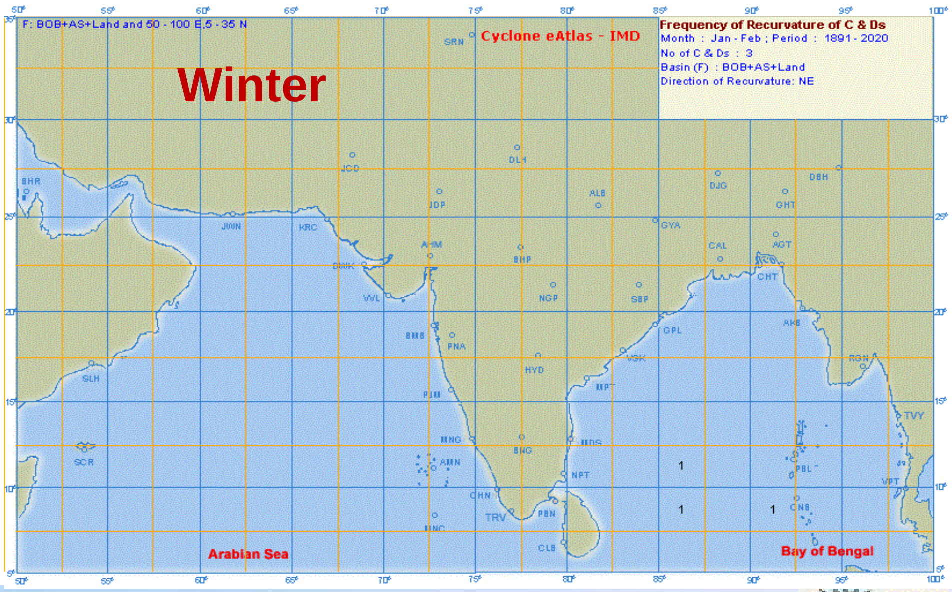
- Recurving CS/SCS → important feature over NIO
- In BOB, recurving CS/SCS move away from east coast of India
- Over AS, recurving CS/SCS move towards west coast of India

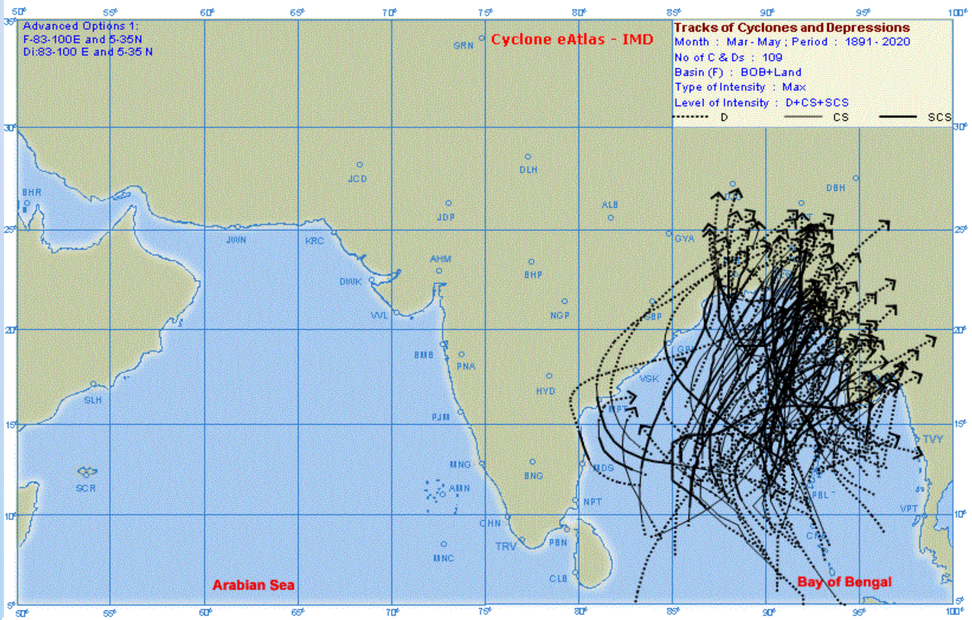
Frequency of Recurvature

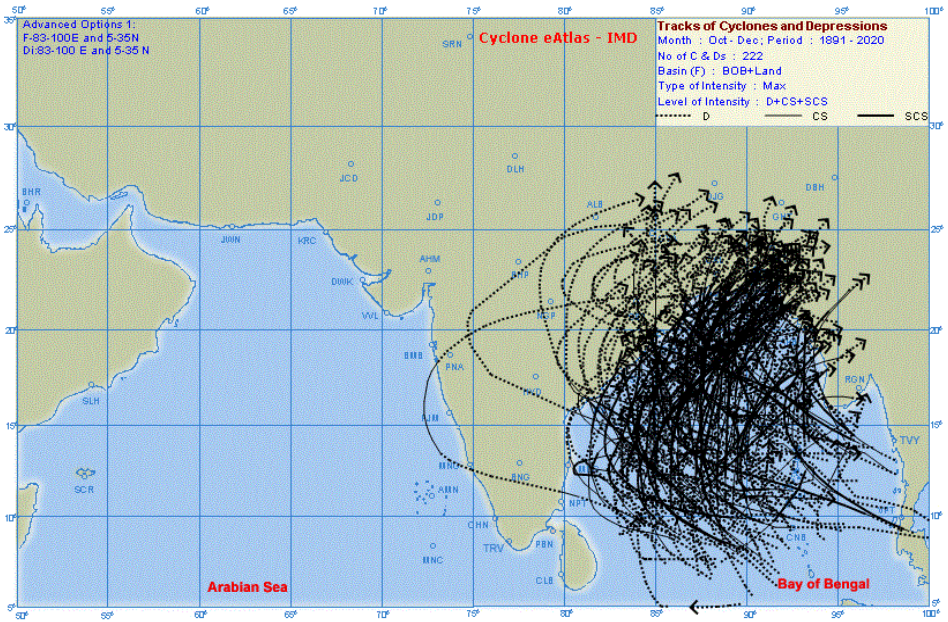


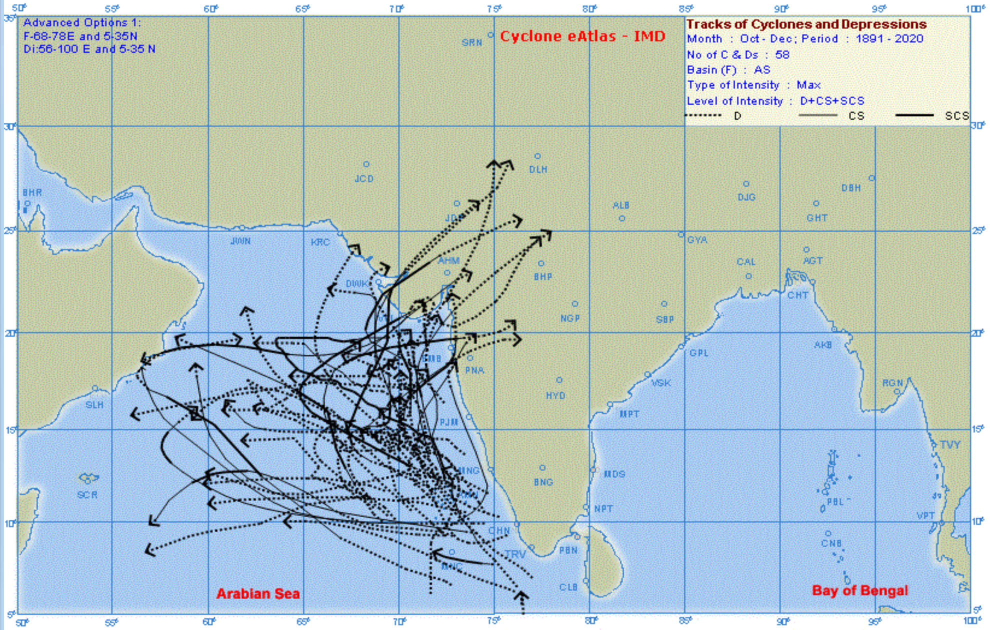


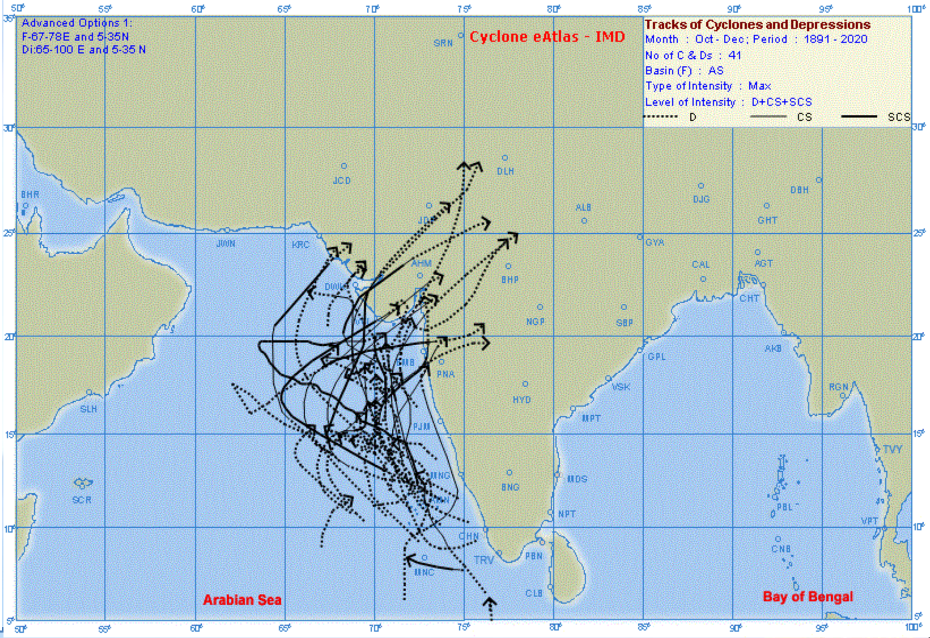





Advanced Options 1:
F-83-100E and 5-35N
Di:83-100 E and 5-35 N
Cyclone eAtlas - IMD
Tracks of Cyclones and Depressions
Month : Mar - May ; Period : 1891 - 2020
No of C & Ds : 109
Basin (F) : BOB+Land
Type of Intensity : Max
Level of Intensity : D+CS+SCS
D
CS
SCS
Arabian Sea
Bay of Bengal


Advanced Options 1:
F-83-100E and 5-35N
Di:83-100 E and 5-35 N
Cyclone eAtlas - IMD
Tracks of Cyclones and Depressions
Month : Oct - Dec ; Period : 1891 - 2020
No of C & Ds : 222
Basin (F) : BOB+Land
Type of Intensity : Max
Level of Intensity : D+CS+SCS
D
CS
SCS
Arabian Sea
Bay of Bengal


Advanced Options 1:
F-68-78E and 5-35N
Di:56-100 E and 5-35 N
Cyclone eAtlas - IMD
Tracks of Cyclones and Depressions
Month : Oct - Dec ; Period : 1891 - 2020
No of C & Ds : 58
Basin (F) : AS
Type of Intensity : Max
Level of Intensity : D+CS+SCS
D
CS
SCS
Arabian Sea
Bay of Bengal


Advanced Options 1:
F-67-78E and 5-35N
Di:65-100 E and 5-35 N
Cyclone eAtlas - IMD
Tracks of Cyclones and Depressions
Month : Oct - Dec ; Period : 1891 - 2020
No of C & Ds : 41
Basin (F) : AS
Type of Intensity : Max
Level of Intensity : D+CS+SCS
D
CS
SCS
Arabian Sea
Bay of Bengal

Landfall of Cyclones

- Land fall → most crucial event associated with the life cycle of a TC

- Damage due to gale force winds / storm surge occur in association with TCs of intensity SCS and above

- TCs of intensity CS can cause heavy rainfall

Seasonal frequencies of CS+SCS, SCS crossing coast from BOB (1961 – 2014) (Intensity at time of crossing)

	TN	AP	ORS	WB	BD	ARAKAN	SLE
MAM	2,1	4,3	2,2	2,2	17,11	9,8	0,0
JJAS	0,0	4,1	12,2	4,3	4,1	0,0	0,0
OND	20,16	27,17	11,8	5,4	18,13	2,2	8,3
ANN	22,17	35,21	25,12	11,9	39,25	11,10	8,3

Seasonal frequencies of CS+SCS, SCS crossing coast from AS (1961 – 2014) (Intensity at the time of crossing)

	KER	CK	KG	GUJ
MAM	0,0	0,0	1,1	1,1
JJAS	0,0	0,0	0,0	4,4
OND	0,0	0,0	1,0	4,3
ANN	0,0	0,0	2,1	9,8

Dissipation of Cyclonic Disturbances

Frequency of CDs dissipated over BOB, AS and Land during pre-monsoon, monsoon and post-monsoon seasons and the year as a whole

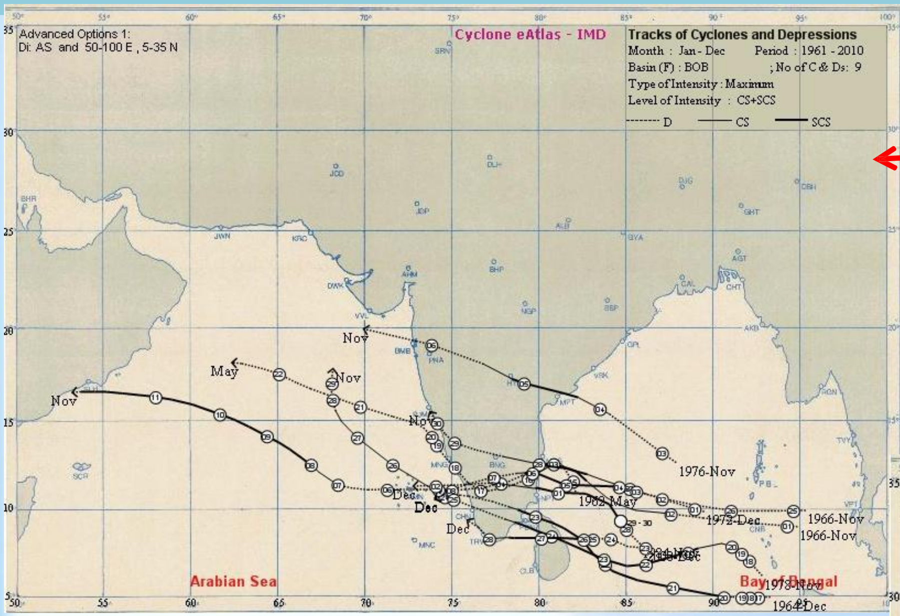
Formed over	Dissipated over											
	BOB				AS				Land			
	MAM	JJAS	OND	ANN	MAM	JJAS	OND	ANN	MAM	JJAS	OND	ANN
BOB	6	2	51	**68**	1	2	9	**13**	47	184	136	**368**
AS	0	0	0	**0**	7	27	38	**72**	9	15	11	**35**
Land	0	1	0	**1**	0	5	0	**5**	1	46	4	**51**

Looping & Binary TCs

- **Looping of a TC is a rare occurrence**

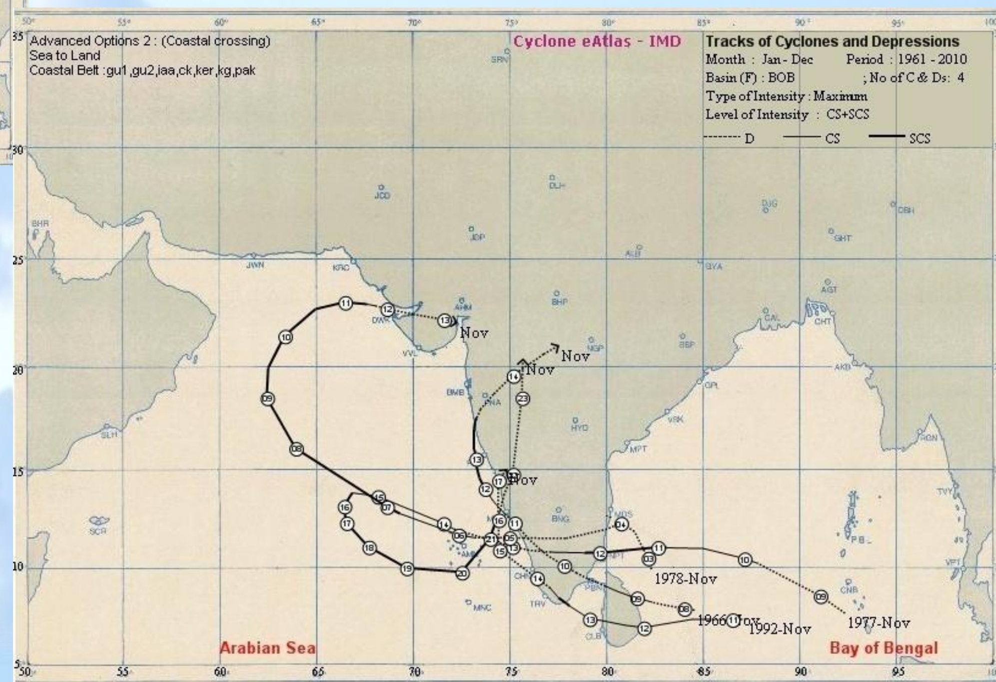
- **Binary TCs→ 2 TCs simultaneously present in BOB & AS**

Tracks of TCs that formed in BOB and affected AS, 1961-2010

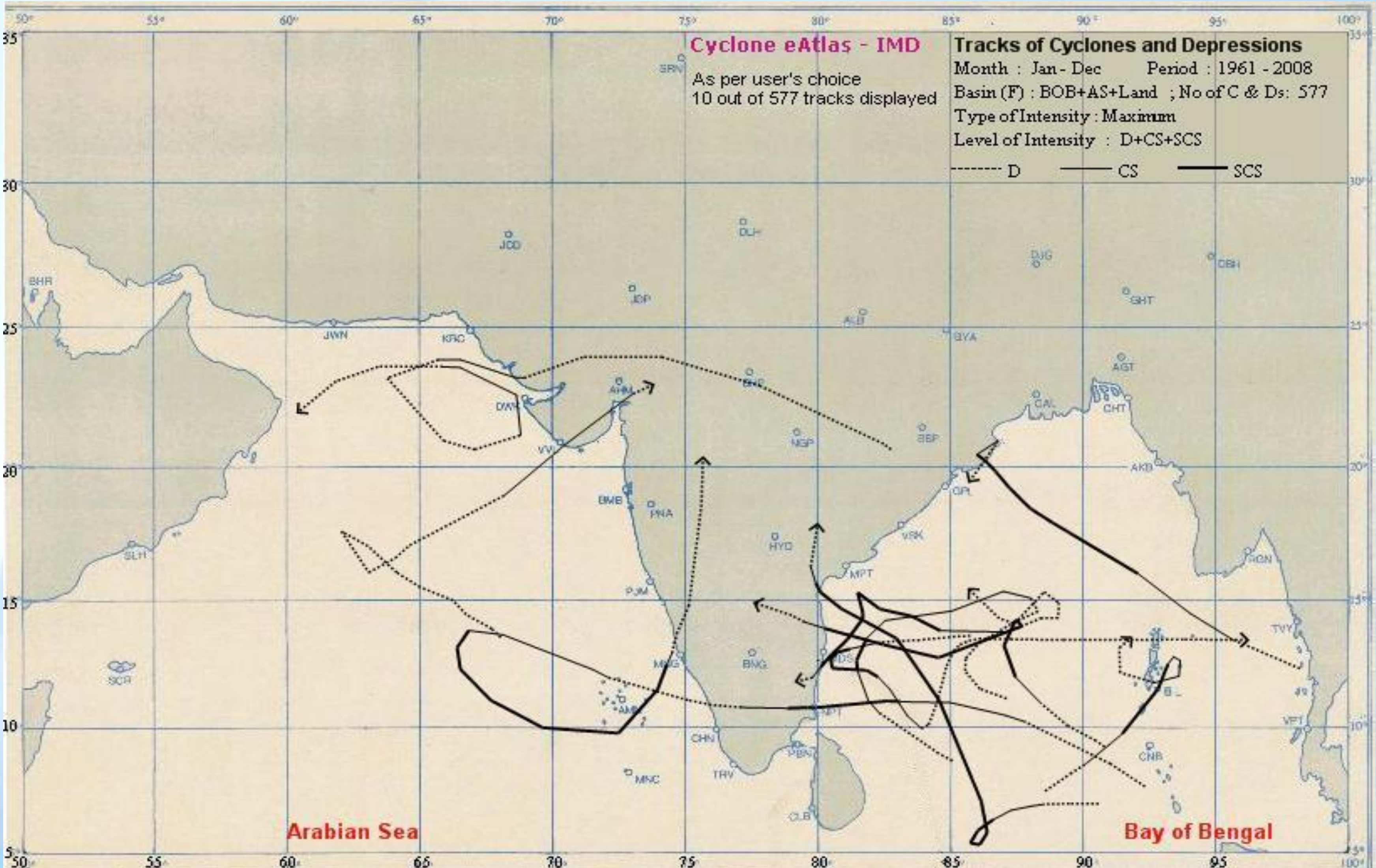


Moved westward / dissipated in AS

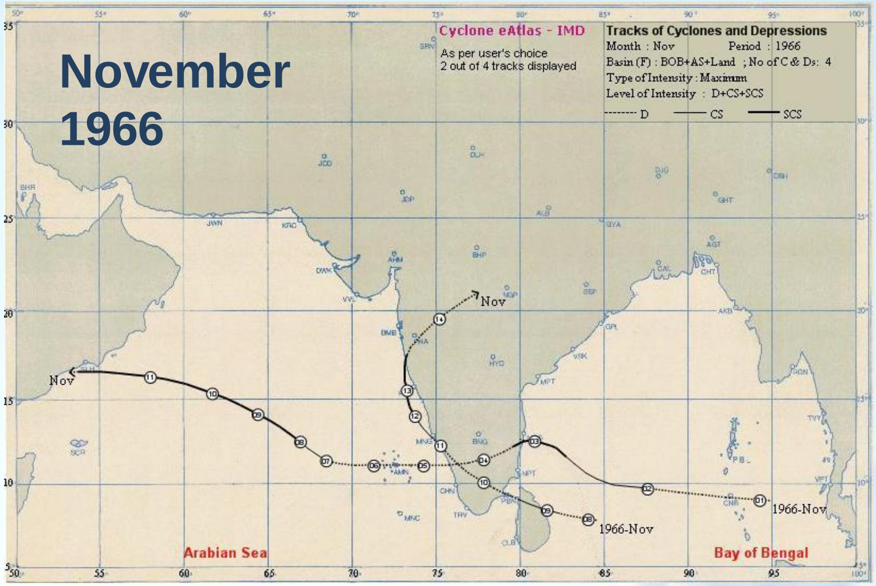
Made landfall after remerging into AS

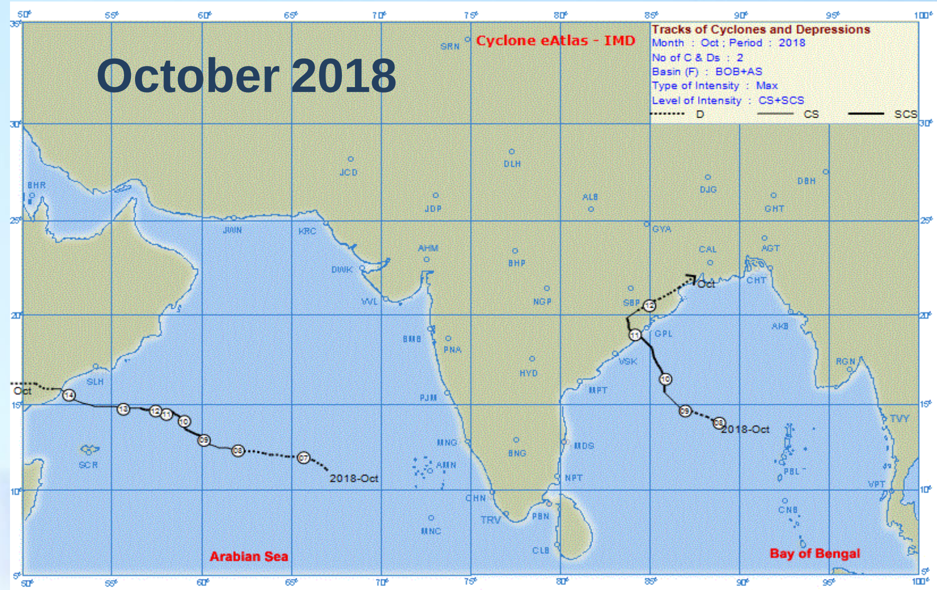


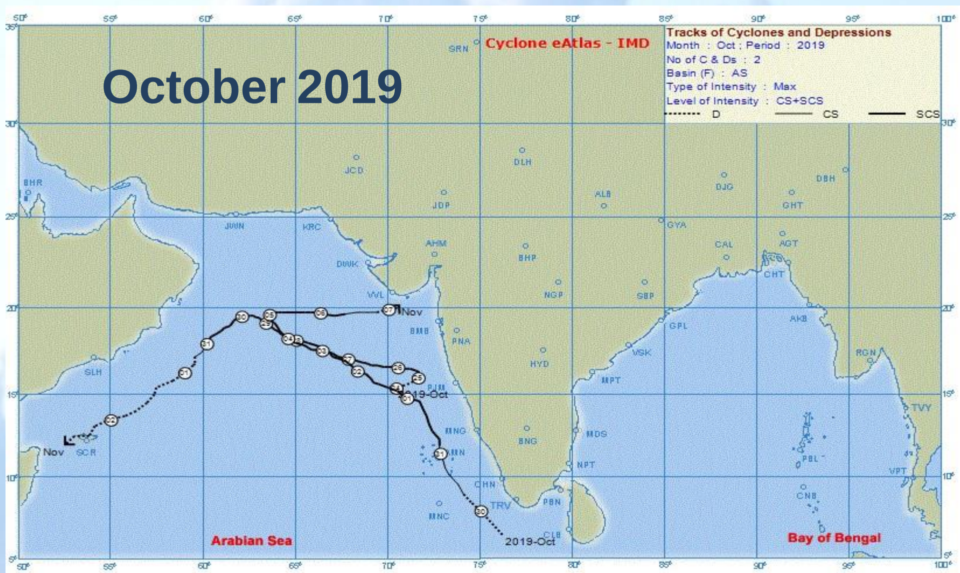
Tracks of 10 tropical cyclones which executed loop over North Indian Ocean during 1961-2014.



Tracks of a few binary tropical cyclones over Arabian Sea

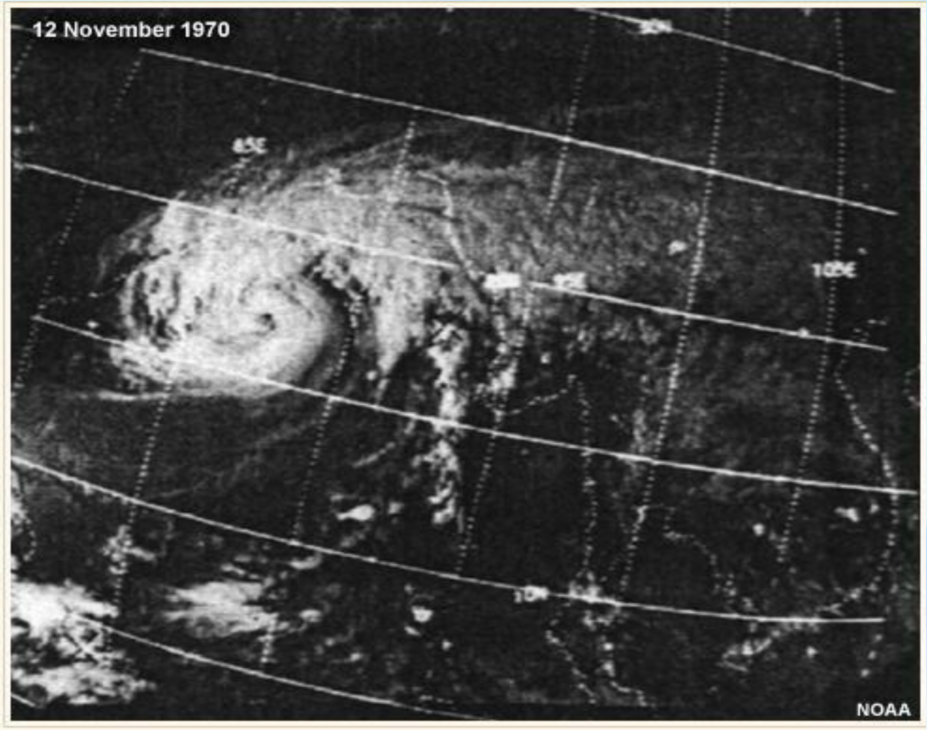


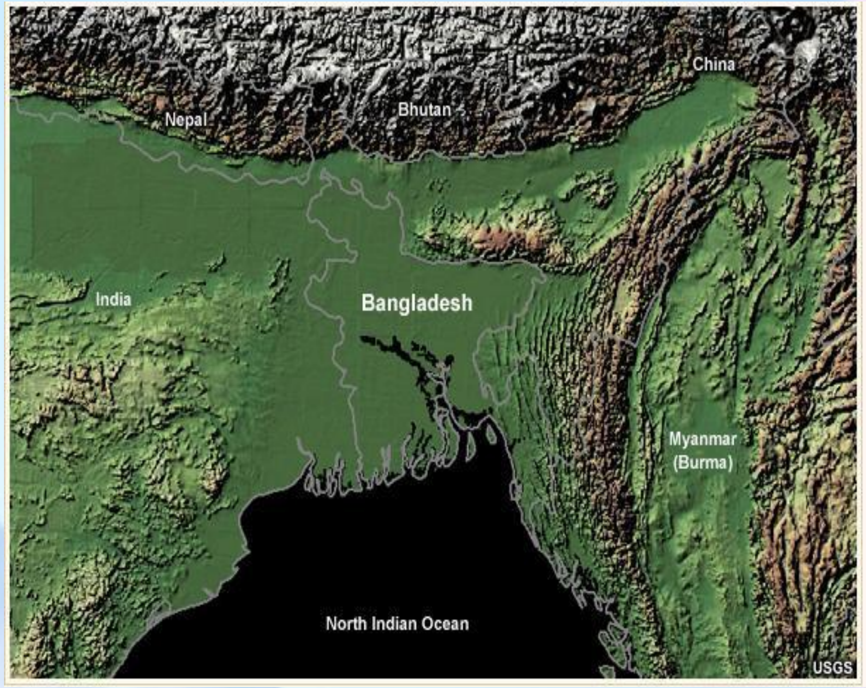




A few deadliest Cyclones over North Indian Ocean

1. Bhola Cyclone (12th November 1970)



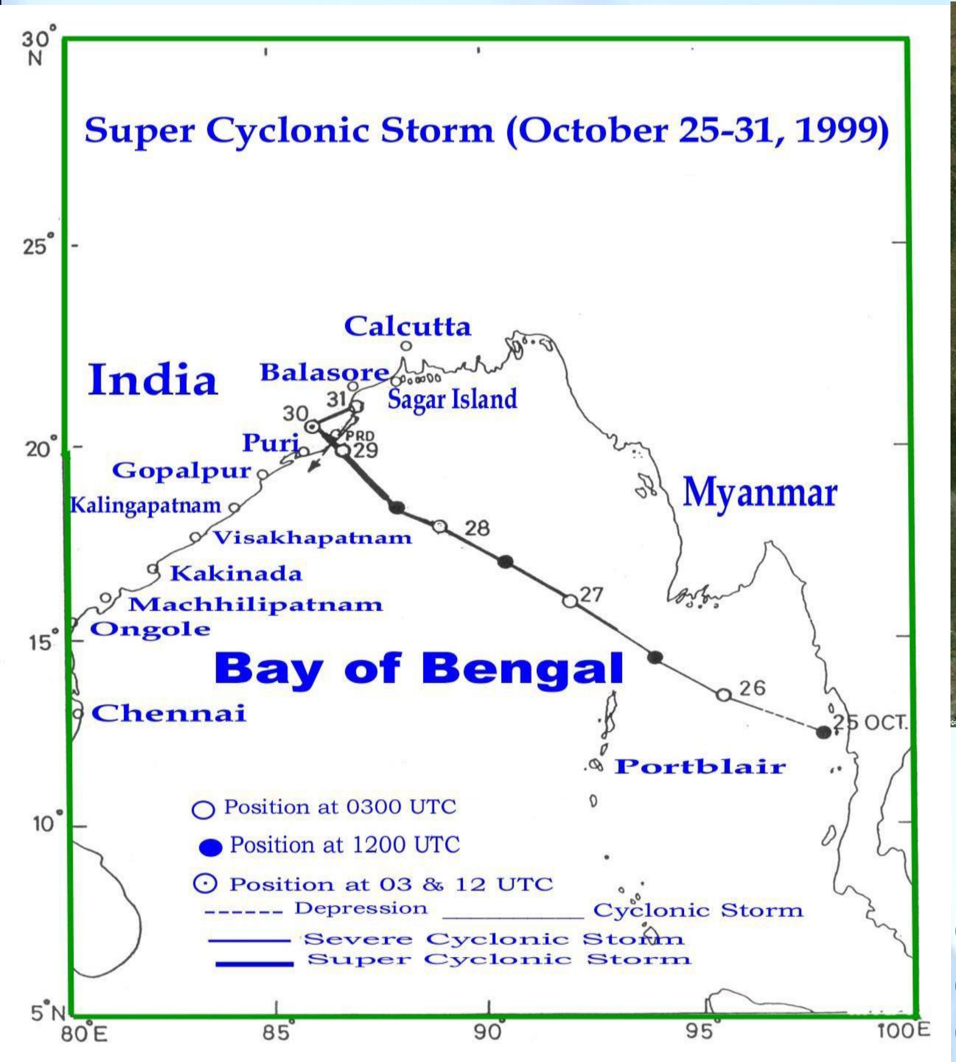


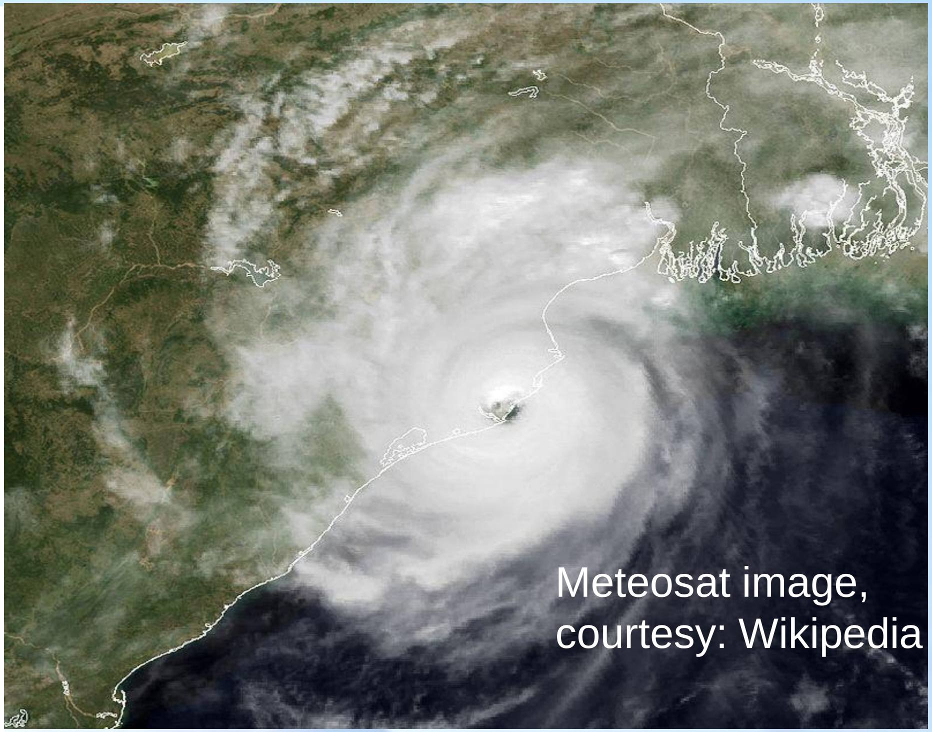
Many of offshore Islands were devastated by storm surge . The city of Tazumuddin (in the Bhola district of Bangladesh) was the most severely affected, with over 45% of the population of 167,000 killed by the storm. Topographic enhancement of rainfall by the mountains and storm surge make a devastating and deadly combination in the low–lying areas in the northern reaches of the Bay of Bengal

2. Chittagong Cyclone (29^{th} April 1991)

The coastal region was devastated by peak 1–minute averaged surface winds more than 260 km h^{-1}, 898 hPa minimum pressure and a 6.1 meter storm surge. Evacuations of 2–3 million coastal residents were effective in reducing the fatalities, although the storm was still the largest natural disaster globally in 1991. The value of evacuation and shelter was demonstrated even more dramatically when powerful Category 4 Cyclone Sidr made landfall on 15 November 2007. The death toll was estimated at just over 3000 persons compared with the hundreds of thousands from the past cyclones. Although the damage was still costly and the destruction affected approximately 8.9 million people, better planning reduced fatalities by two orders of magnitude.

3. Odisha Super Cyclone (29th October 1999)



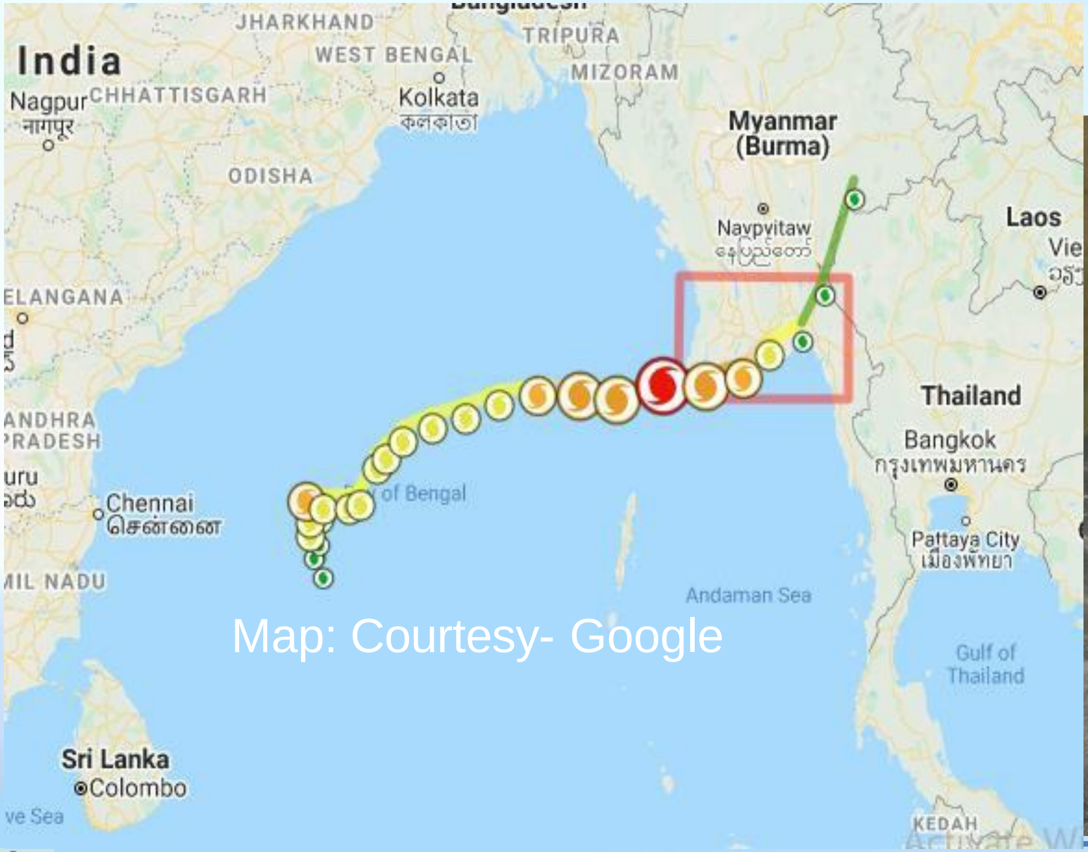


Highest winds: 260 kmph
Lowest Pressure: 912 hPa.
More than 9,885 deaths & Rs. 6,170 Crores of damage are reported to have occurred in the October 1999 Super Cyclone.

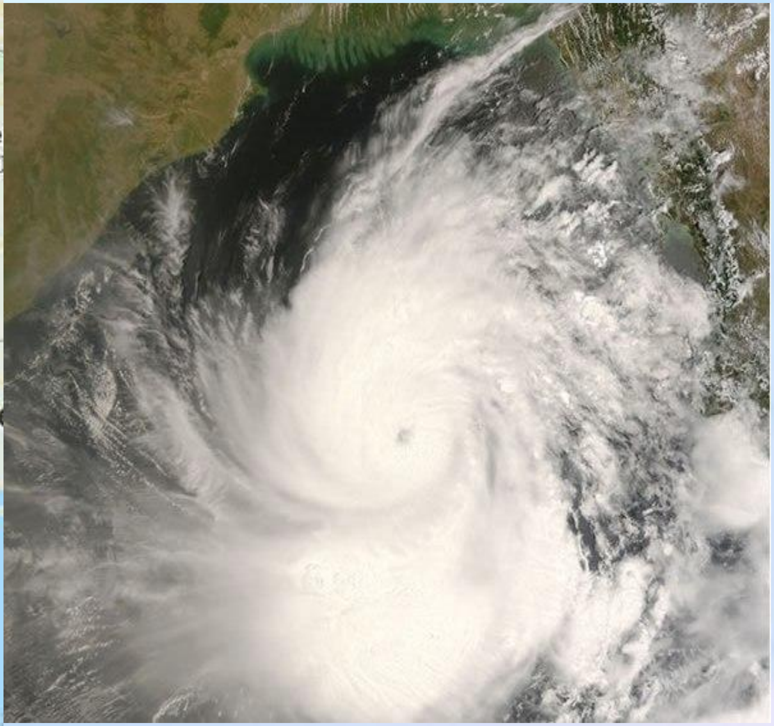
4. Cyclone 'Nargis' (…. May 2008)

Relative success in Bangladesh stands in contrast to tremendous loss of life in Burma (Myanmar) due to storm surge and flooding from Cyclone Nargis, May 2008. The official death toll stood at 84,530; unofficial estimates were considerably higher.

Highest winds: 165 kmph
Lowest Pressure: 962 hPa

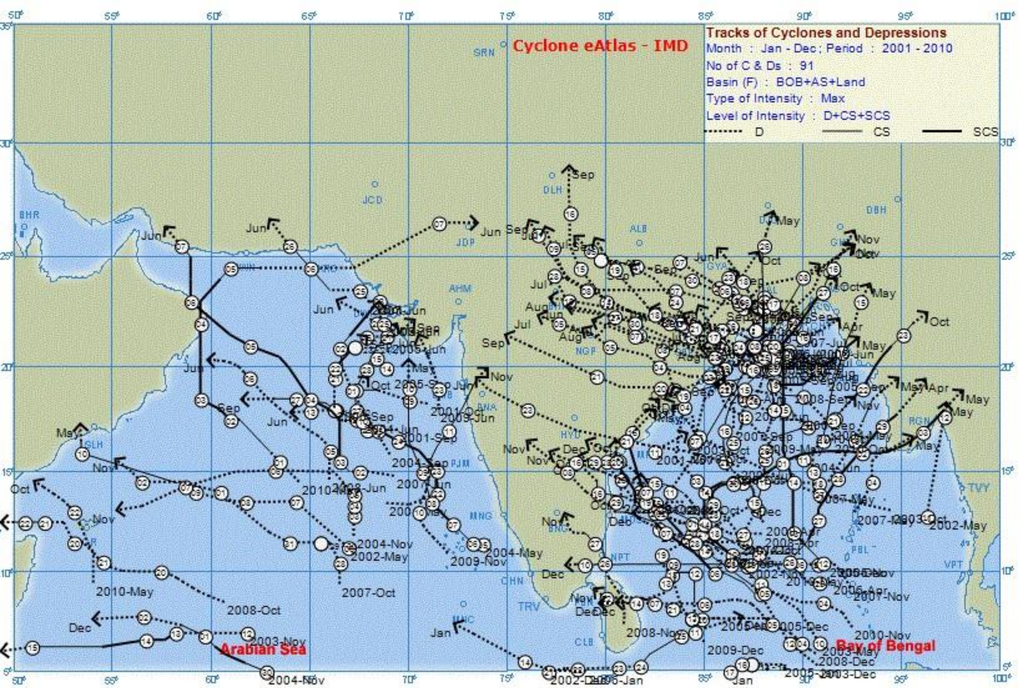


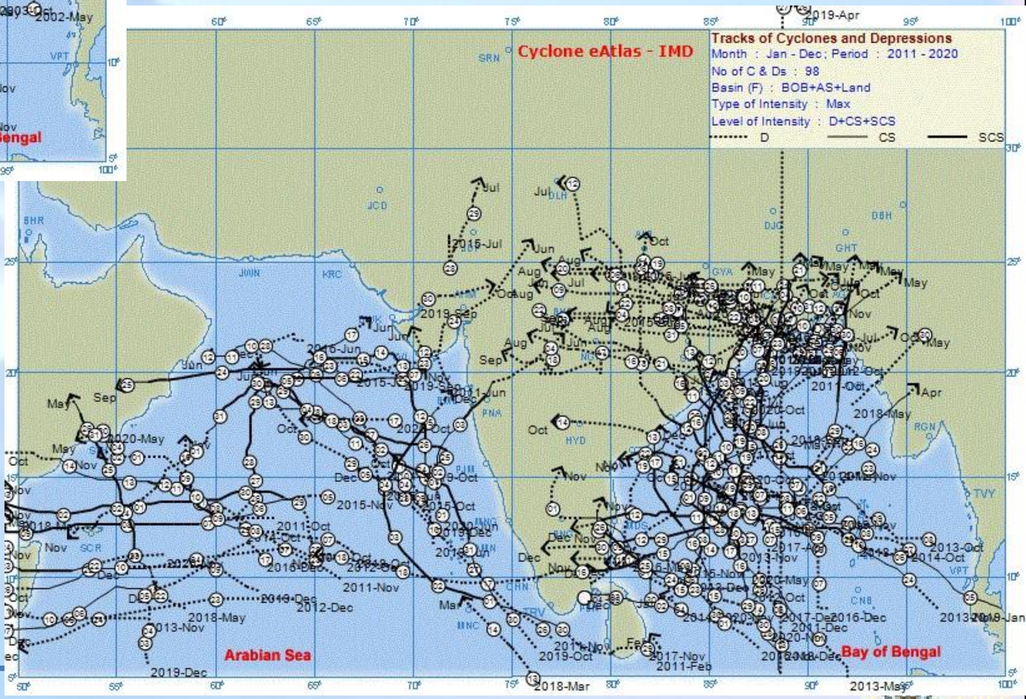
Map: Courtesy- Google



Cyclone eAtlas-IMD: Login page

Formation & movement of Tropical Cyclones over the Bay of Bengal & Arabian Sea (2001-2010) vs. (2011-2020)





Summary

- **Tropical cyclone frequency over NIO shows a bimodal character, with post-monsoon season of October-December being the major cyclone season and pre-monsoon season of March-May being the secondary cyclone season.**
- **The cyclone e-Atlas of IMD is useful in getting information about the climatological tracks of cyclonic disturbances over North Indian Ocean.**

- **The frequency of Super Cyclonic Storms has increased during the recent years since 1990 both over the BoB and AS and hence over the NIO.**

- **During the period 1990-2020, there have been 4 and 2 SuCS over the BOB and AS respectively against 2 and 0 over the BOB and AS during 1965-1989.**
- **There have been 7 ESCS over AS during 1990-2020 against 3 during 1965-1989. There is a rising trend in frequency of ESCS and above intensity storms over the AS since 1990.**


Thank you