“Cyclone Risk Management & COVID-19”

Date: 28 -29 September, 2021

Session 6

Impact of Climate Change on Cyclone Frequency & Intensity

By

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1) How one can define Cyclones and how they are structured?

2) How do they form in an Ocean basin?

3) Why they are considered as hazardous events?

4) Why and how the cyclones are named, how one can understand the severity of a cyclone?

5) What are the important scientific but generalized terminologies one should know to understand the tropical cyclone forecast?

6) Is there any difference in terms of frequency of occurrence, intensity and their respective distribution in different basins of North Indian Ocean?

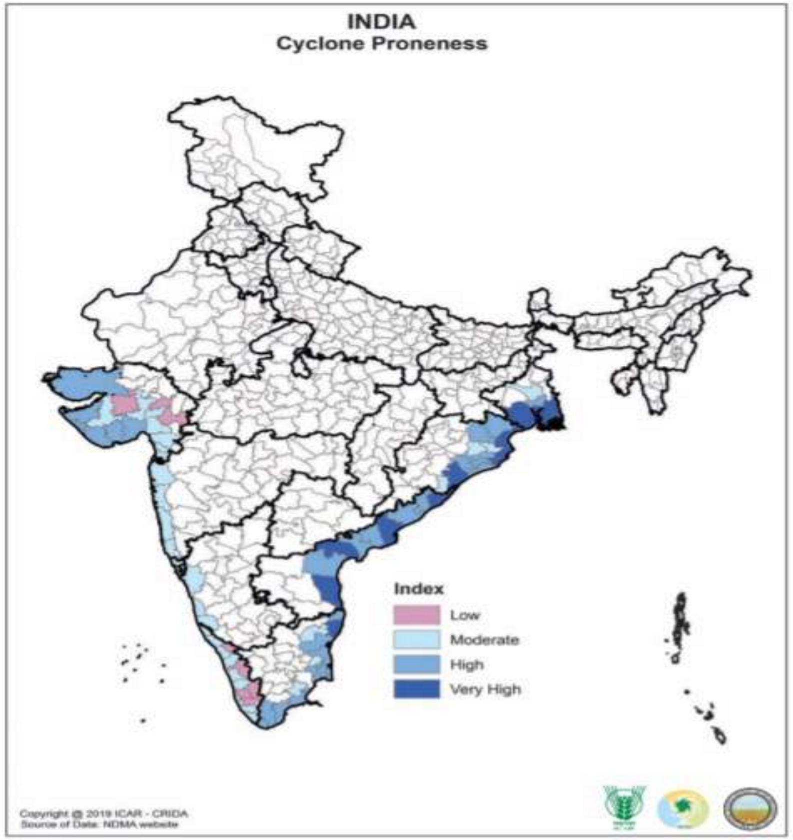
7) What is the usual seasons when the tropical cyclone occurs or which season is in general recognized as more prone to receive such events?

8) What is the usual frequency of occurrence of tropical cyclones in Arabian Sea and Bay of Bengal and their reported respective changes due to changing climate ?

9) What are the scientific attempts to understand the risk and improve the prediction skills for more accurate track and intensity forecast of a cyclone with their associated challenges and related statistics?

10) Whether these altering distribution of storm occurrence and their associated intensity is happening in Pacific and Atlantic Ocean basins as well or only to North Indian Ocean basins?

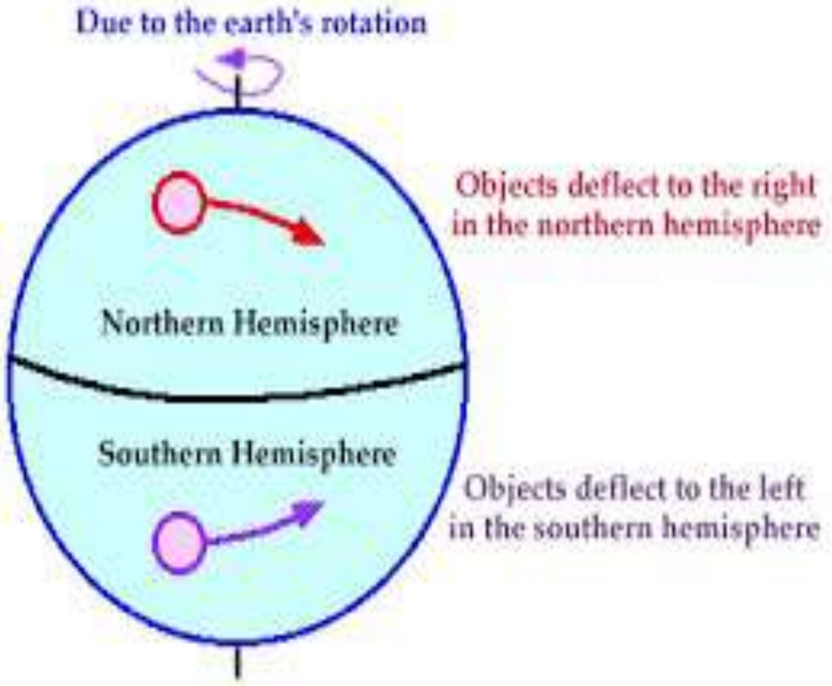
- India has a coastline of 7,516 km, of which 5,700 km are prone to cyclones of various degrees.
- About eight per cent of the Country’s area and one-third of it’s population live in 13 coastal states and UTs who are, thus vulnerable to cyclone related disasters.
- Loss of lives, damage to public and private property and severe damage to infrastructure are the resultant consequences, which can disrupt the process of development.
- A long coastline of flat coastal terrain, shallow continental shelf, high population density, geographical location and physiological features of its coastal areas makes India, in the North Indian Ocean (NIO) Basin, extremely vulnerable to cyclones and its associated hazards like storm tide (the combined effects of storm surge and astronomical tide), high velocity wind and heavy rains.



Cyclone proneness	Composite index constructed by combining number of cyclones crossing the district, number of severe cyclones crossing the district, probable maximum precipitation for a day, probable maximum winds in knot, probable maximum storm surge	Higher index of cyclone proneness means more frequent and intense incidence of cyclones and attendant problems and hence more hazard	Direct	NDMA web site http://ndma.gov.in

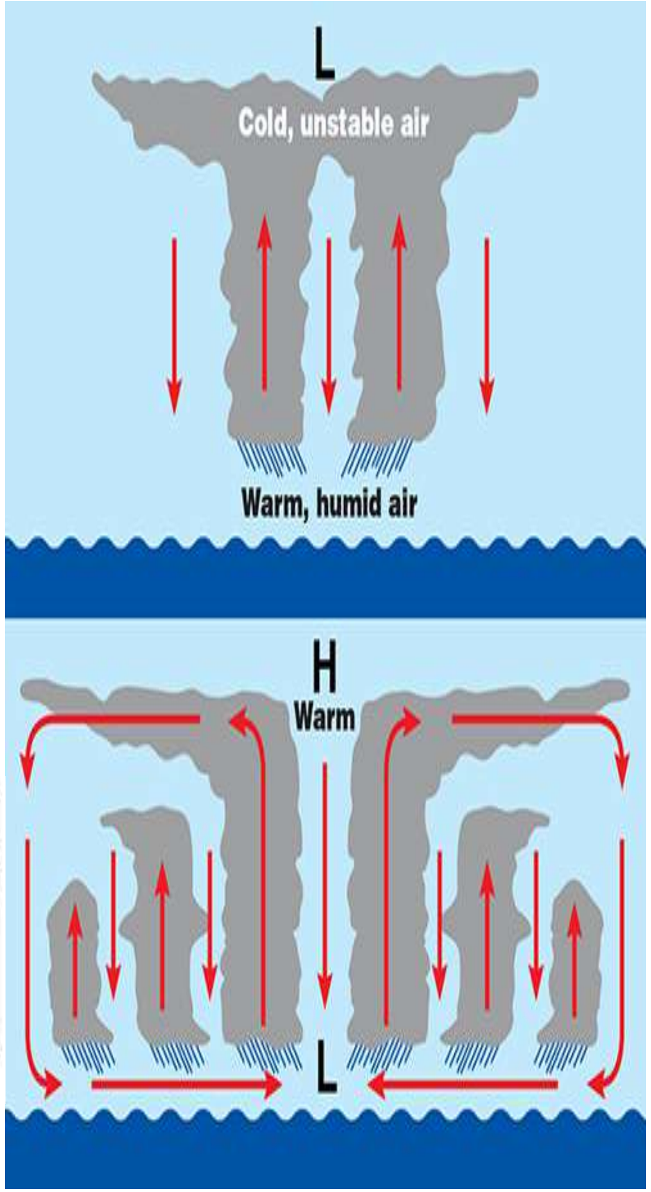
Derivation: The term 'Cyclone' is derived from the Greek word 'Cyclos' that means 'Coils of Snake'.

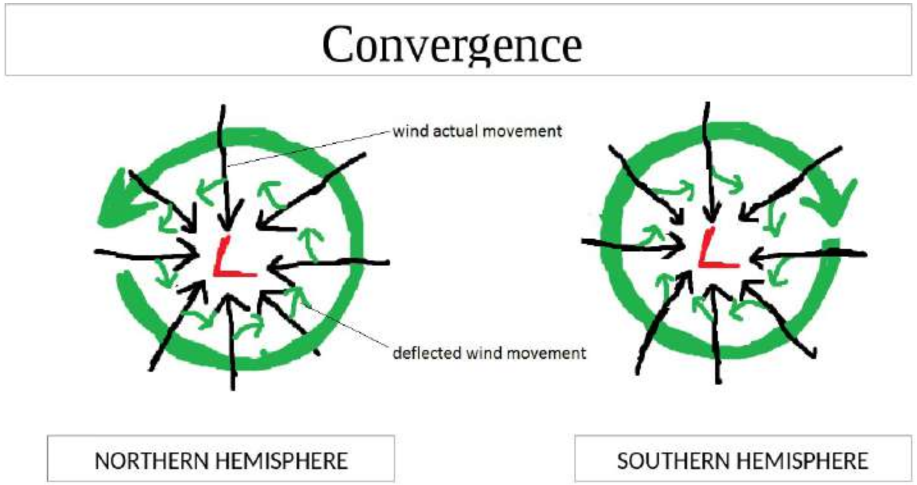
Definition: A cyclone is an intense whirl in the atmosphere with very strong winds circulating around it in an anti-clockwise and clockwise direction in the Northern and Southern Hemisphere respectively.

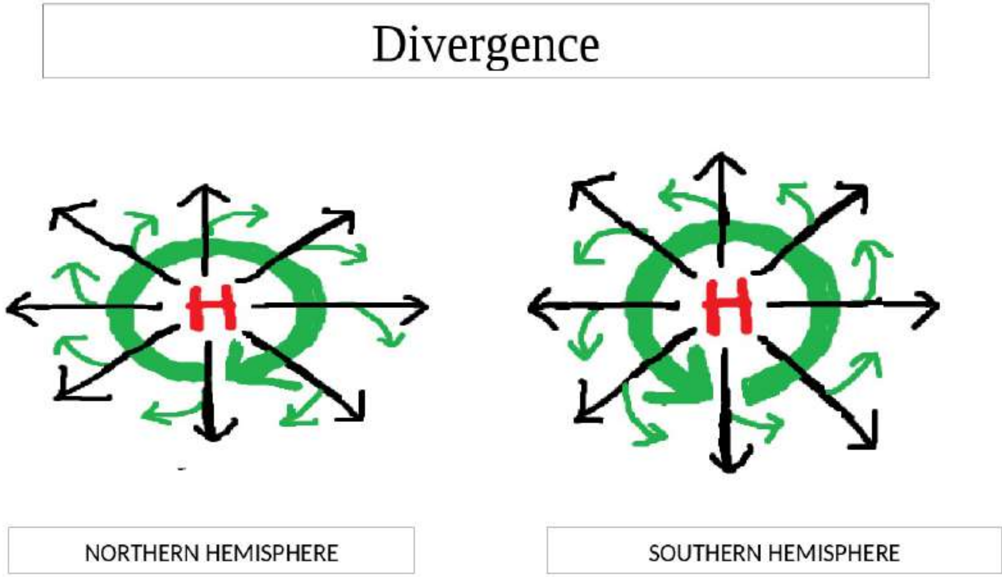


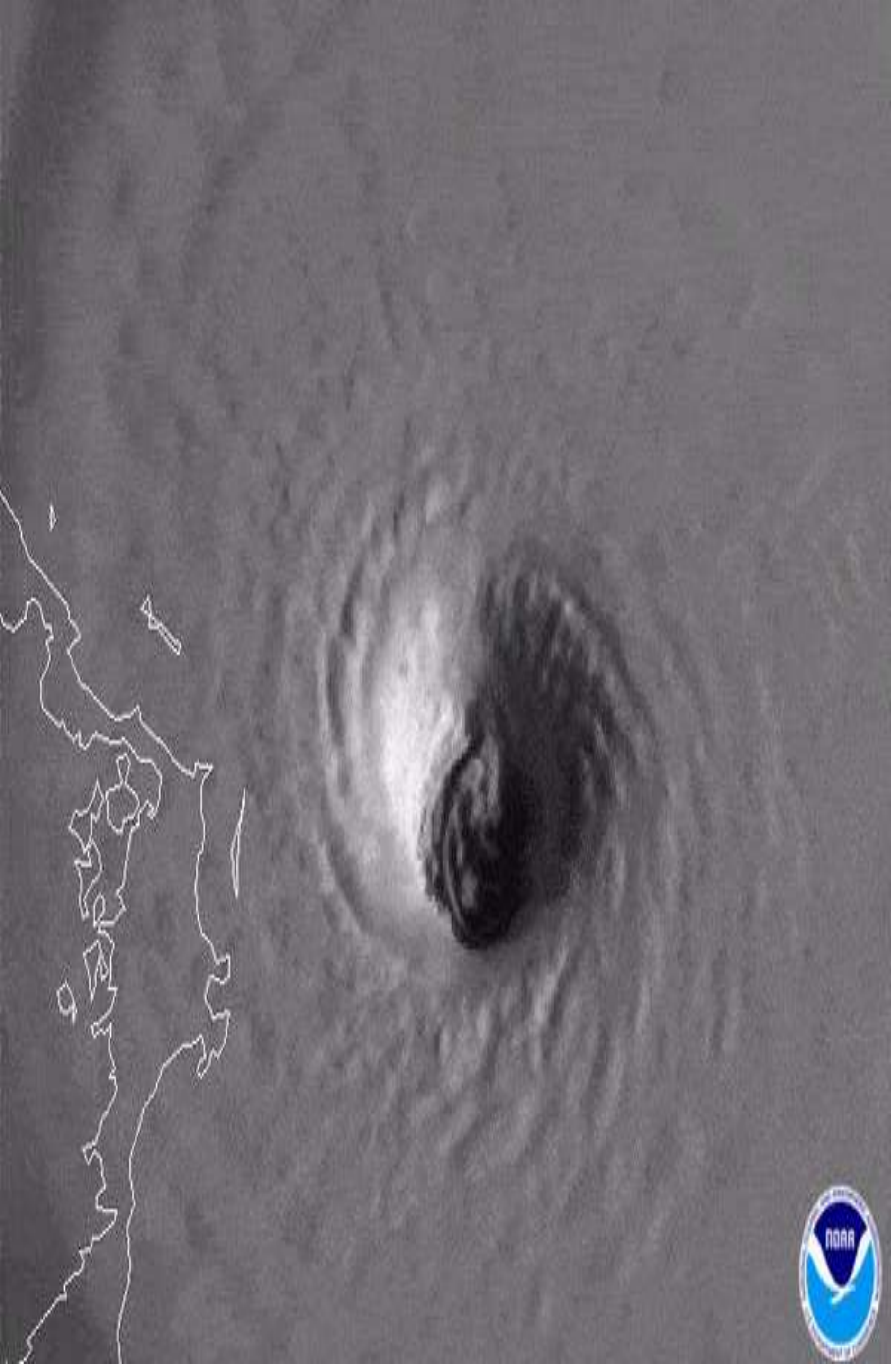
Pressure System	Pressure Condition at the Centre	Pattern of Wind Direction	
		Northern Hemisphere	Southern Hemisphere
Cyclone	Low	Anticlockwise	Clockwise
Anticyclone	High	Clockwise	Anticlockwise

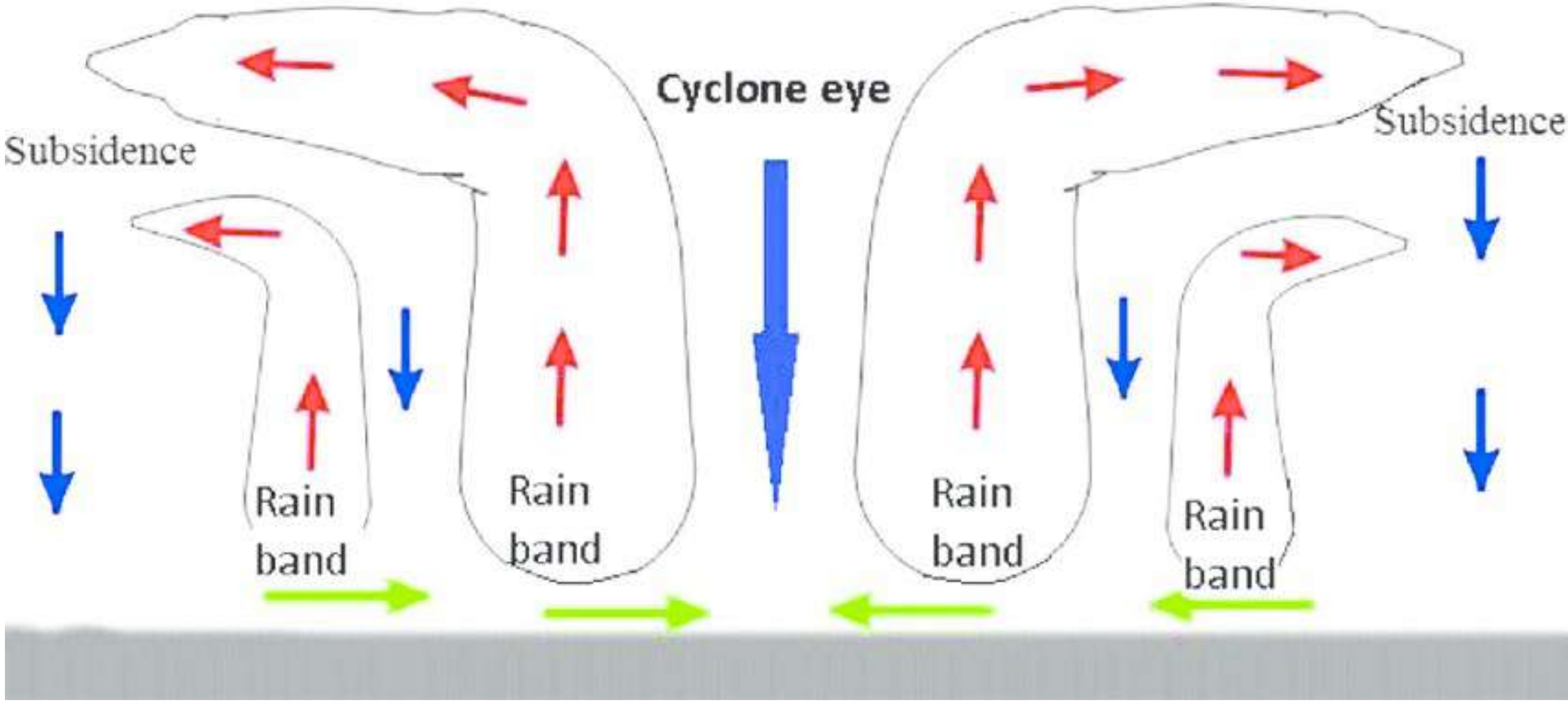
Table: Pattern of Wind Direction in Cyclones and Anticyclones

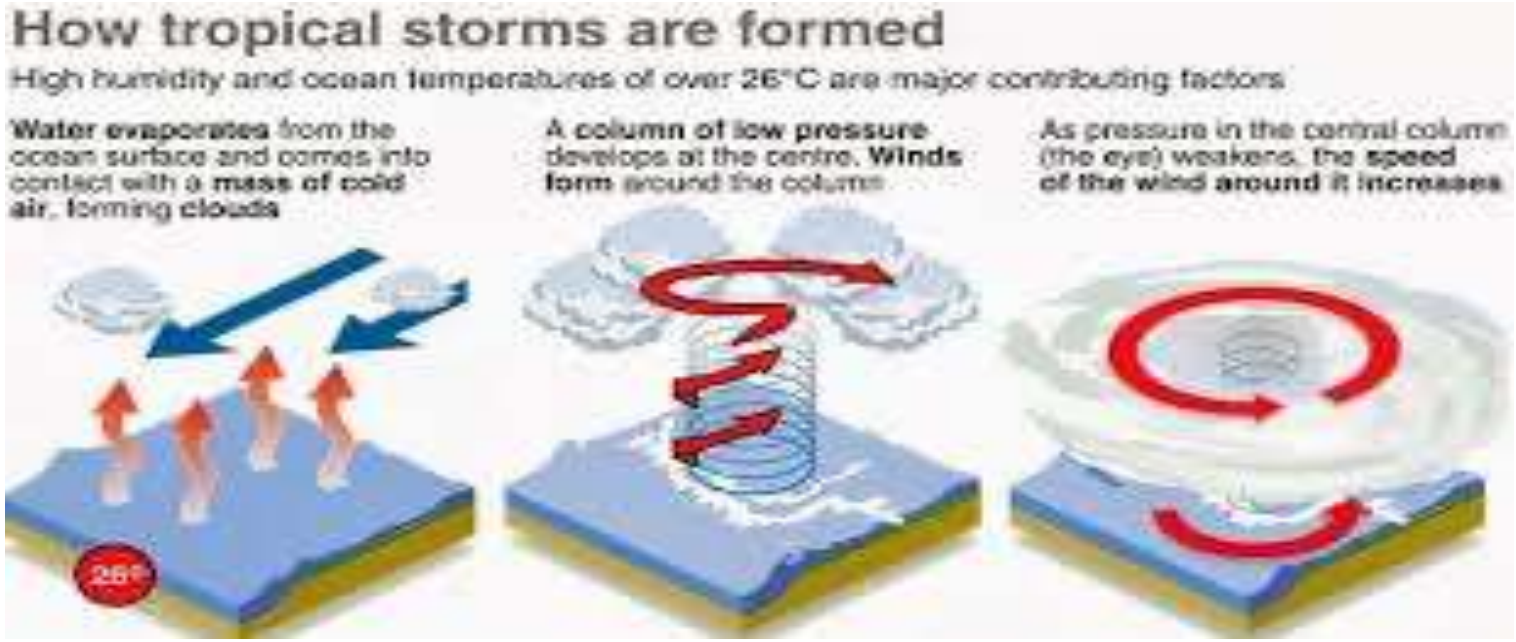









Cyclone eye
Subsidence
Subsidence
Rain band
Rain band
Rain band
Rain band


How tropical storms are formed
High humidity and ocean temperatures of over 26°C are major contributing factors
Water evaporates from the ocean surface and comes into contact with a mass of cold air, forming clouds
A column of low pressure develops at the centre. Winds form around the column
As pressure in the central column (the eye) weakens, the speed of the wind around it increases
26°

Gray has elucidated the necessary factors for genesis in Gray (1979),

tropical cyclogenesis to be a combination of dynamic and thermodynamic potentials:

1) **Cyclonic low-level vorticity (from a preexisting easterly wave, the monsoon trough, or an upper-level low/frontal boundary)**

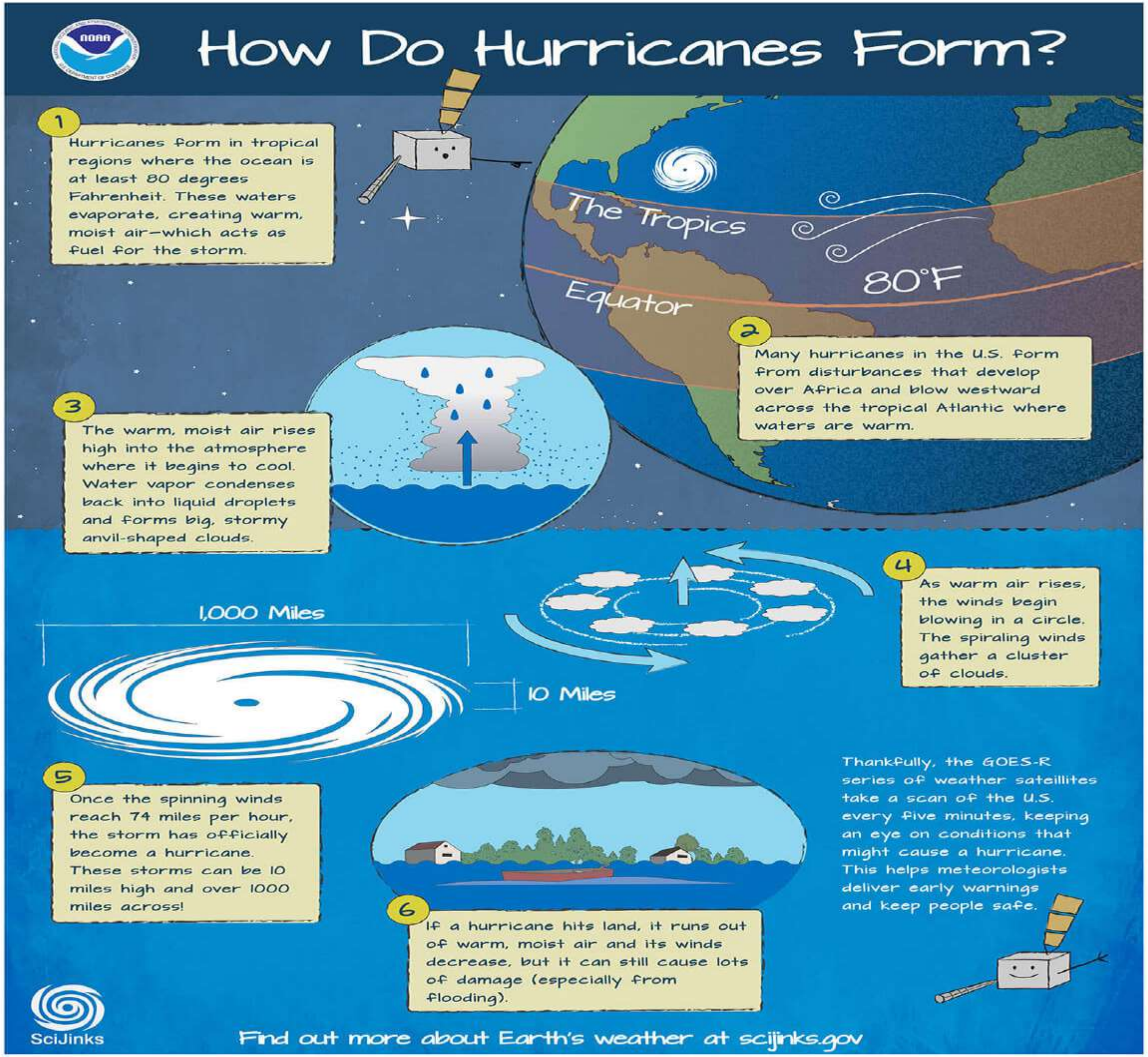
2) **Moist mid-troposphere**

3) **Conditional instability through a deep tropospheric layer**

4) **Warm (≥26.5 °C) and stratified Ocean (this maintains deep at least up to 60 m maintaining the Tropical Cyclone Heat Potential)**

5) **Weak tropospheric vertical shear of the horizontal wind, and**

6) **Location of disturbance a few degrees poleward of the equator (i.e., a significant value of Coriolis force).**



- WMO maintains rotating lists of names which are appropriate for each Tropical Cyclone basin.
- Tropical cyclones can last for a week or more; therefore there can be more than one cyclone at a time.
- Weather forecasters give each tropical cyclone a name to avoid confusion. In general, tropical cyclones are named according to the rules at regional level. In the Atlantic and in the Southern hemisphere (Indian ocean and South Pacific), tropical cyclones receive names in alphabetical order, and women and men's names are alternated.
- Nations in the Northern Indian ocean began using a new system for naming tropical cyclones in 2000; the names are listed alphabetically country wise, and are neutral gender wise.
- The common rule is that the name list is proposed by the National Meteorological and Hydrological Services (NMHSs) of WMO Members of a specific region, and approved by the respective tropical cyclone regional bodies at their annual/biennual sessions.

Importance for naming tropical cyclones:

- It helps to identify each individual tropical cyclone.
- It helps the public to become fully aware of its development.
- Local and international media become focused on the tropical cyclone.
- It does not confuse the public when there is more than one tropical cyclone in the same area.
- The name of the tropical cyclone is well remembered by millions of people as it is an unforgettable event and associated name will be remembered for a long time.
- Warnings reach a much wider audience very rapidly, if a name is associated with it

- The Panel member's names are listed alphabetically country wise.
- The name will be used sequentially column wise.
- The first name will start from the first row of column one and continue sequentially to the last row in column eight. Example, this will be as Onil, Hibaru, Pyarr, Baaz .... Amphan
- The names which have been already used from the list are highlighted.

The RSMC tropical cyclones, New Delhi gives a tropical cyclone an identification name from the given name list. The identification system covers both the Arabian Sea and the Bay of Bengal. These lists are used sequentially, and they

New list of tropical cyclone names adopted by WMO/ESCAP Panel Member Countries in April 2020 for naming of tropical cyclones over North Indian Ocean including Bay of Bengal and Arabian Sea

(To be used after the name 'Amphan' from the previous list is utilised)

WMO/ESCAP Panel Member countries	Column 1		Column 2		Column 3		Column 4	
	Name	Pron'	Name	Pron'	Name	Pron'	Name	Pron'
Bangladesh	Nisarga	Nisarga	Biparjoy	Biporjoy	Arnab	Ornab	Upakul	Upokul
India	Gati	Gati	Tej	Tej	Murasu	Murasu	Aag	Aag
Iran	Nivar	Nivar	Hamoon	Hamoon	Akvan	Akvan	Sepand	Sepand
Maldives	Burevi	Burevi	Midhili	Midhili	Kaani	Kaani	Odi	Odi
Myanmar	Tauktae	Tau'Te	Michaung	Migjaum	Ngamann	Ngaman	Kyarthit	Kjathi
Oman	Yaas	Yass	Remal	Re-Mal	Sail	Sail	Naseem	Naseem
Pakistan	Gulab	Gul-Aab	Asna	As-Na	Sahab	Sa-Hab	Afshan	Af-Shan
Qatar	Shaheen	Shaheen	Dana	Dana	Lulu	Lulu	Mouj	Mouj
Saudi Arabia	Jawad	Jowad	Fengal	Feinjal	Ghazeer	Razeer	Asif	Aasif
Sri Lanka	Asani	Asani	Shakhti	Shakhti	Gigum	Gigum	Gagana	Gagana
Thailand	Sitrang	Si-Trang	Montha	Mon-Tha	Thianyot	Thian-Yot	Bulan	Bu-Lan
United Arab Emirates	Mandous	Man-Dous	Senyar	Sen-Yaar	Afoor	Aa-Foor	Nahhaam	Nah-Haam
Yemen	Mocha	Mokha	Ditwah	Ditwah	Diksam	Diksam	Sira	Sira

WMO/ESCAP Panel Member countries	Column 5		Column 6		Column 7		Column 8	
	Name	Pron'	Name	Pron'	Name	Pron'	Name	Pron'
Bangladesh	Barshon	Borshon	Rajani	Rojoni	Nishith	Nishith	Urmi	Urmi
India	Vyom	Vyom	Jhar	Jhor	Probaho	Probaho	Neer	Neer
Iran	Booran	Booran	Anahita	Anahita	Azar	Azar	Pooyan	Pooyan
Maldives	Kenau	Kenau	Endheri	Endheri	Riyau	Riyau	Guruva	Guruva
Myanmar	Sapakyee	Zabagji	Wetwun	We'wum	Mwaihout	Mwei'hau	Kywe	Kjwe
Oman	Muzn	Muzn	Sadeem	Sadeem	Dima	Dima	Manjour	Manjour
Pakistan	Manahil	Ma-Na-Hil	Shujana	Shu-Ja-Na	Parwaz	Par-Waaz	Zannata	Zan Naa Ta
Qatar	Suhail	Es'hail	Sadaf	Sadaf	Reem	Reem	Rayhan	Rayhan
Saudi Arabia	Sidrah	Sadrah	Hareed	Haareed	Faid	Faid	Kaseer	Kusaer
Sri Lanka	Verambha	Ve-Ram-Bha	Garjana	Garjana	Neeba	Neeba	Ninnada	Nin-Na-Da
Thailand	Phutala	Phu-Ta-La	Aiyara	Ai-Ya-Ra	Saming	Sa-Ming	Kraison	Krai-Son
United Arab Emirates	Quffal	Quf-Faal	Daaman	Daa-Man	Deem	Deem	Gargoor	Gar-Goor
Yemen	Bakhur	Bakhoor	Ghwyzi	Ghwayzi	Hawf	Hawf	Balhaf	Balhaf

WMO/ESCAP Panel Member countries	Column 9		Column 10		Column 11		Column 12		Column 13	
	Name	Pron'	Name	Pron'	Name	Pron'	Name	Pron'	Name	Pron'
Bangladesh	Meghala	Meghla	Samiron	Somiron	Pratikul	Protikul	Sarobor	Sorobor	Mahanisha	Mohanisha
India	Prabhanjan	Prabhanjan	Ghurni	Ghurni	Ambud	Ambud	Jaladhi	Jaladhi	Vega	Vega
Iran	Arsham	Arsham	Hengame	Hengame	Savas	Savas	Tahamtan	Tahamtan	Toofan	Toofan
Maldives	Kurangi	Kurangi	Kuredhi	Kuredhi	Horangu	Horangu	Thundi	Thundi	Faana	Faana
Myanmar	Pinku	Pinnku	Yinkaung	Jin Gaun	Linyone	Lin Joun	Kyeekan	Kji Gan	Bautphat	Bau'hpa
Oman	Rukam	Roukaam	Watad	Wa Tad	Al-jarz	Al-Jarouz	Rabab	Ra Bab	Raad	Raad
Pakistan	Sarsar	Sar-Sar	Badban	Baad-Baan	Sarrab	Sarrab	Gulnar	Gul-Nar	Waseq	Waa-Seq
Qatar	Anbar	Anbar	Oud	Oud	Bahar	Bahar	Seef	Seef	Fanar	Fanaar
Saudi Arabia	Nakheel	Nakheel	Haboob	Haboob	Bareq	Bariq	Alreem	Areem	Wabil	Wobil
Sri Lanka	Viduli	Viduli	Ogha	Ogha	Salitha	Salitha	Rivi	Rivi	Rudu	Rudu
Thailand	Matcha	Mat-Cha	Mahingsa	Ma-Hing-Sa	Phraewa	Phrae-Wa	Asuri	A-Su-Ri	Thara	Tha-Ra
United Arab Emirates	Khubb	Khubb	Degl	Degl	Athmad	Ath-Md	Boom	Boom	Saffar	Saf-Faar
Yemen	Brom	Brom	Shuqra	Shuqrah	Fartak	Fartak	Darsah	Darsah	Samhah	Samhah

Stage	Description
Tropical wave	A trough of low pressure in the trade-wind easterlies
Tropical disturbance	A moving area of thunderstorms in the tropics that maintains its identity for 24 hours or more
Tropical depression	A tropical cyclone in which the maximum sustained surface wind is ≤38 miles/hour (≤61 km/hour; ≤33 knots†)
Tropical storm	A tropical cyclone in which the maximum sustained surface wind ranges from 39 miles/hour (62 km/hour; >33 knots) to 73 miles/hour (117 km/hour; <64 knots)
Hurricane/ typhoon/ cyclone	A tropical cyclone in which maximum sustained surface wind is ≥74 miles/hour (≥118 km/hour; ≥64 knots)

* Source: National Weather Service, National Oceanic and Atmospheric Administration (8).

† A knot is 1 nautical mile/hour; a nautical mile is approximately equal to 1.15 statute miles (1.84 km).

Type	Wind speed in km/h	Wind speed in knot (mps)	Number of closed isobars at interval of 2 hPa within 5° latitude/longitude square
Low pressure area (L)	Less than 31	Less than 17 (09)	1
Depression (D)	31–49	17–27 (9–14)	2
Deep depression (DD)	50–61	28–33 (15–17)	3
Cyclonic storm (CS)	62–88	34–47 (18–24)	4–7
Severe cyclonic storm (SCS)	89–118	48–63 (25–32)	8–10
Very severe cyclonic storm (VSCS)	119–165	64–89 (33–46)	11–25
Extremely severe cyclonic storm (ESCS)	166–220	90–119 (47–61)	26–39
Super cyclonic storm (SupCS)	221 or more	120 (62) or more	40 or more

Saffir–Simpson scale

Category	Wind speeds (for 1-minute maximum sustained winds)			
	m/s	knots (kn)	mph	km/h
Five	≥ 70 m/s	≥ 137 kn	≥ 157 mph	≥ 252 km/h
Four	58–70 m/s	113–136 kn	130–156 mph	209–251 km/h
Three	50–58 m/s	96–112 kn	111–129 mph	178–208 km/h
Two	43–49 m/s	83–95 kn	96–110 mph	154–177 km/h
One	33–42 m/s	64–82 kn	74–95 mph	119–153 km/h

Related classifications

(for 1-minute maximum sustained winds)

Tropical storm	18–32 m/s	34–63 kn	39–73 mph	63–118 km/h
Tropical depression	≤ 17 m/s	≤ 33 kn	≤ 38 mph	≤ 62 km/h

How to define Rapid Intensification, Maximum Sustained Wind Speed, Tropical Cyclone energy Potential

- Rapid Intensification (RI) is defined as the 24-h maximum sustained surface wind speed rate equal to 30 knots (15.4 ms^{-1}).
- The results suggest that the TCs formed over the NIO basin are both seasonal and basin sensitive. Since 2000, a significant trend is observed in RI TCs over the basin.
- At least one among three cyclones getting intensified is of RI category. More number of RI cases have been identified in the BoB basin than the AS.
- The post-monsoon season holds more RI and rapid decay cases, with 63% and 90% contribution.

(Nadimpalli, R., Mohanty, S., Pathak, N. *et al.* Understanding the characteristics of rapid intensity changes of Tropical Cyclones over North Indian Ocean. *SN Appl. Sci.* **3,** 68 (2021). https://doi.org/10.1007/s42452-020-03995-2)

- India Meteorological Department (IMD) uses a 3 minutes averaging for the sustained wind. The maximum sustained wind mentioned in the bulletins used by IMD is the highest 3 minutes surface wind occurring within the circulation of the system. These surface winds are observed (or, more often, estimated) at the standard meteorological height of 10 m (33 ft) in an unobstructed exposure (i.e., not blocked by buildings or trees). The National Hurricane Centre uses a 1 minute averaging time for reporting the sustained. Some countries also use 10 minutes averaging time for this purpose.

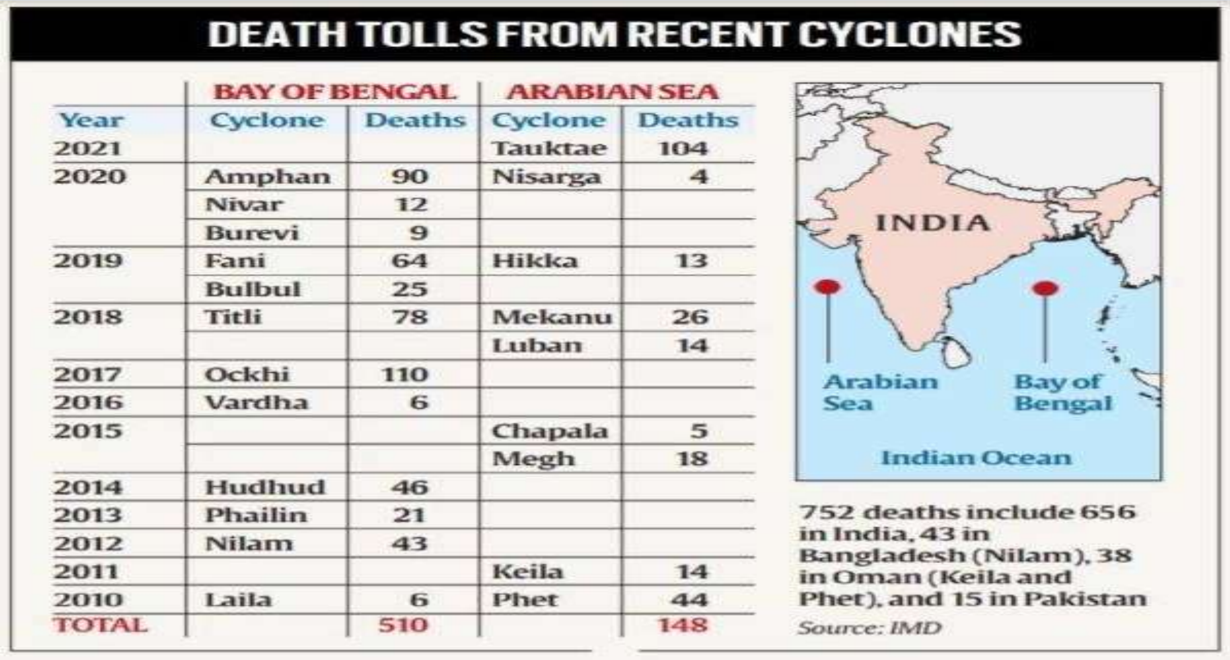
- Tropical Cyclone can be compared to a heat engine. The energy input is from warm water and humid air over tropical oceans. Release of heat is through condensation of water vapour to water droplets/rain. Only a small percentage (3%) of this released energy is converted into Kinetic energy to maintain cyclone circulation (windfield). A mature cyclone releases energy equivalent to that of 100 hydrogen bombs.

How to define Radius of Maximum Wind, its importance to assess impacts of cyclone , contrast b/w AS and BoB

- The radius of maximum wind (RMW) of a tropical cyclone is defined to be the distance between the center of the cyclone and its band of strongest winds. It is considered an important parameter in atmospheric dynamics and tropical cyclone forecasting.
- The distance between the coldest cloud top temperature and the warmest temperature within the eye, in infrared satellite imagery, is one method of determining RMW. The reason why this method has merit is that the strongest winds within tropical cyclone tend to be located under the deepest convection, which is seen on satellite imagery as the coldest cloud tops.
- The highest storm surge is normally coincident with the radius of maximum wind. Because the strongest winds within a tropical cyclone lie at the RMW, this is the region of a tropical cyclone which generates the dominant waves near the storm, and ultimately ocean swell away from the cyclone.
- size of a Tropical Cyclone over Indian seas varies from 50-100 km radius to 2000 km with an average of 300 –600 km.
- The average annual frequency of tropical cyclones in the north Indian Ocean (Bay of Bengal and Arabian Sea) is about 5 (about 5-6 % of the Global annual average) and in the globe is about 80. The frequency is more in the Bay of Bengal than in the Arabian Sea, the ratio being is 4:1.
- The Arabian Sea is relatively colder than Bay of Bengal and hence inhibits the formation and intensification of the system.
- The monthly frequency of tropical cyclones in the north Indian Ocean display a bi-modal characteristic with a primary peak in November and secondary peak in May. The months of May-June and October-November are known to produce cyclones of severe intensity. Tropical cyclones developing during the monsoon months (July to September) are generally not so intense.

Why Bay of Bengal is more prone to cyclones than Arabian Sea?

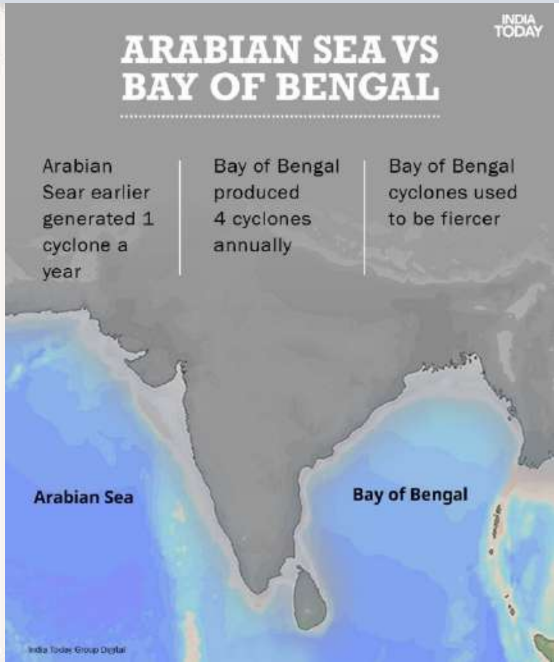
- The Bay of Bengal, located in the eastern part of the north Indian Ocean is a semi-enclosed tropical basin driven by seasonally reversing monsoons, that blow southwesterly in summer and northeasterly in winter.
- During the winter monsoon, a cyclonic gyre generally prevails in the bay, forming an equatorward western boundary current along the east coast of India.
- In spring, this is replaced by an anticyclonic gyre with a poleward western boundary current (Shetye et al., 1993; Somayajulu et al., 2003).
- In addition, during the summer monsoon, the Bay of Bengal receives a large quantity of fresh water from an excess of precipitation over evaporation and from river runoff, which makes the upper-layer waters less saline and highly stratified (Prasad, 1997; Han et al., 2001; Rao and Sivakumar, 2003).
- This strong stratification leads to the formation of a barrier layer that inhibits upper ocean mixing generated cooling of the ocean surface and provides a suitable conditions warm ocean floor (≥26.5 °C) for the generation of the tropical cyclones

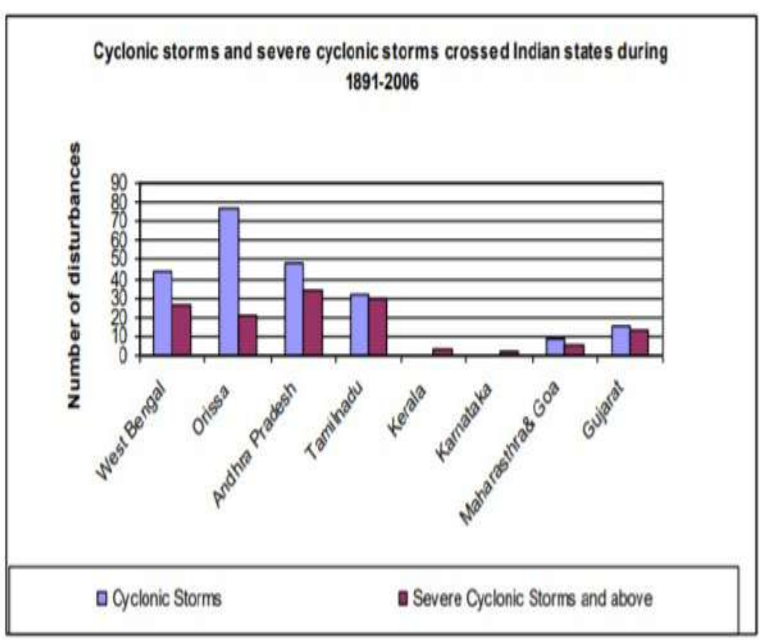

DEATH TOLLS FROM RECENT CYCLONES

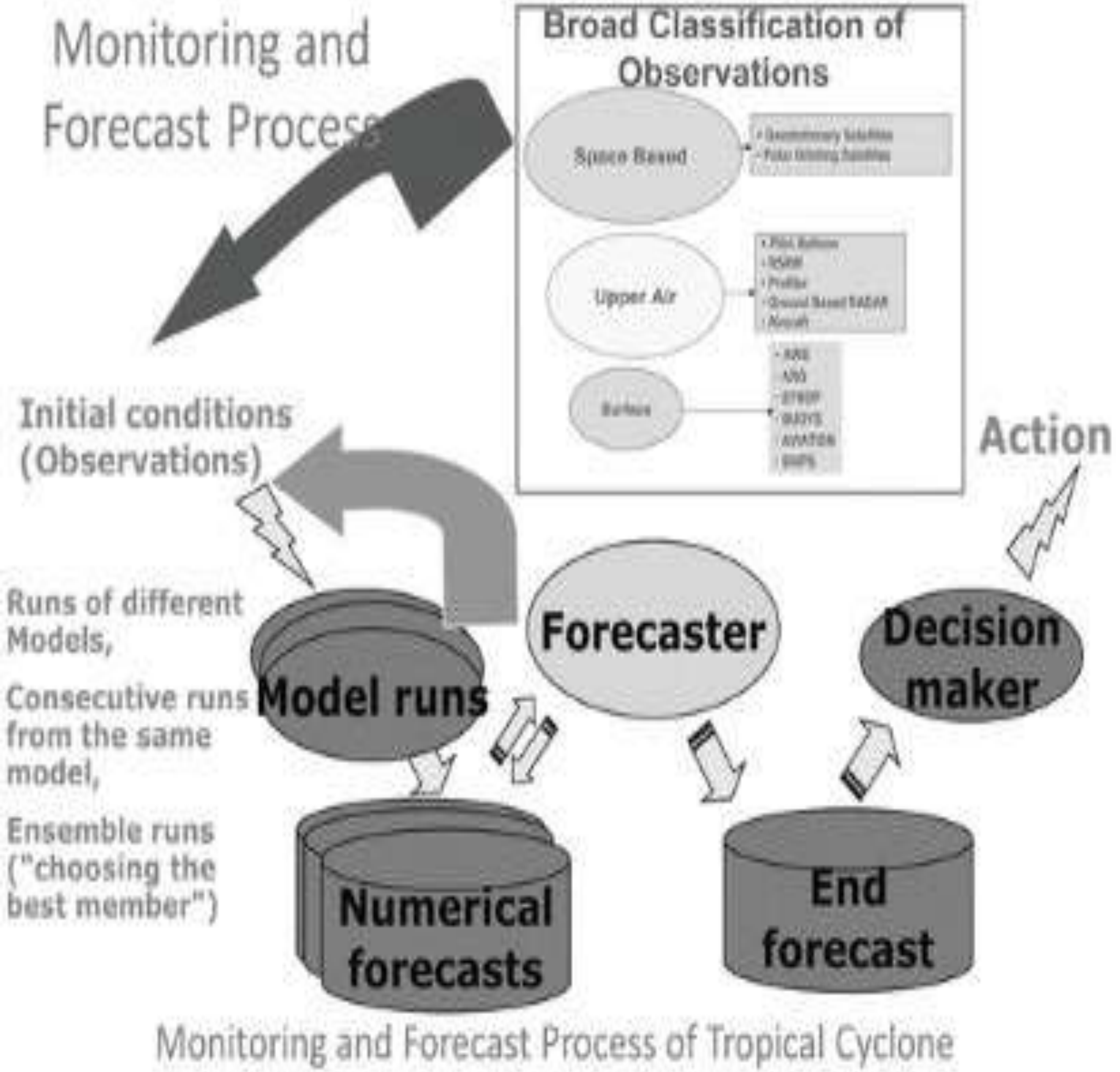
	BAY OF BENGAL		ARABIAN SEA	
Year	Cyclone	Deaths	Cyclone	Deaths
2021			Tauktae	104
2020	Amphan	90	Nisarga	4
	Nivar	12		
	Burevi	9		
2019	Fani	64	Hikka	13
	Bulbul	25		
2018	Titli	78	Mekanu	26
			Luban	14
2017	Ockhi	110		
2016	Vardha	6		
2015			Chapala	5
			Megh	18
2014	Hudhud	46		
2013	Phailin	21		
2012	Nilam	43		
2011			Keila	14
2010	Laila	6	Phet	44
TOTAL		510		148

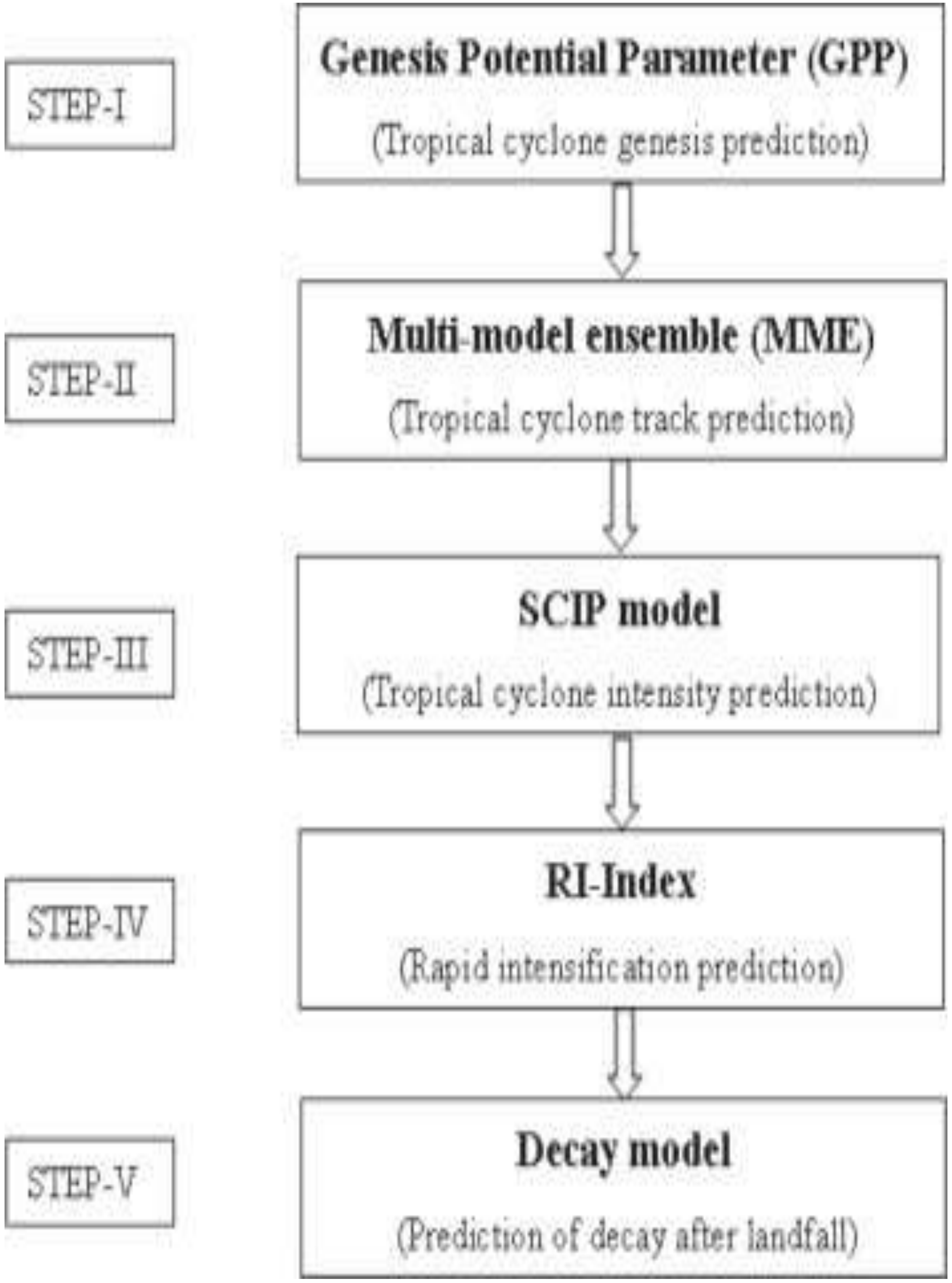
752 deaths include 656 in India, 43 in Bangladesh (Nilam), 38 in Oman (Keila and Phet), and 15 in Pakistan

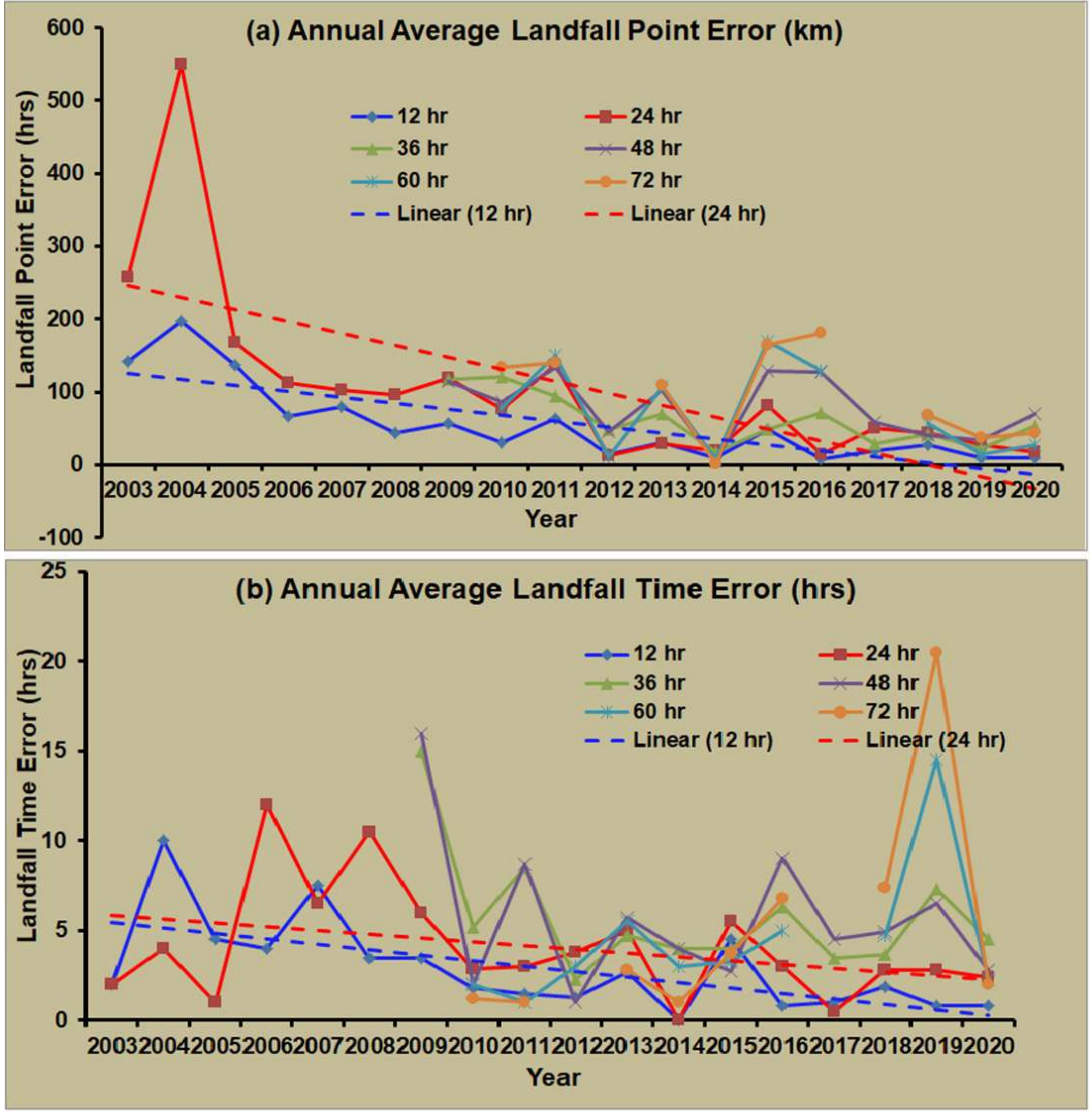
Source: IMD

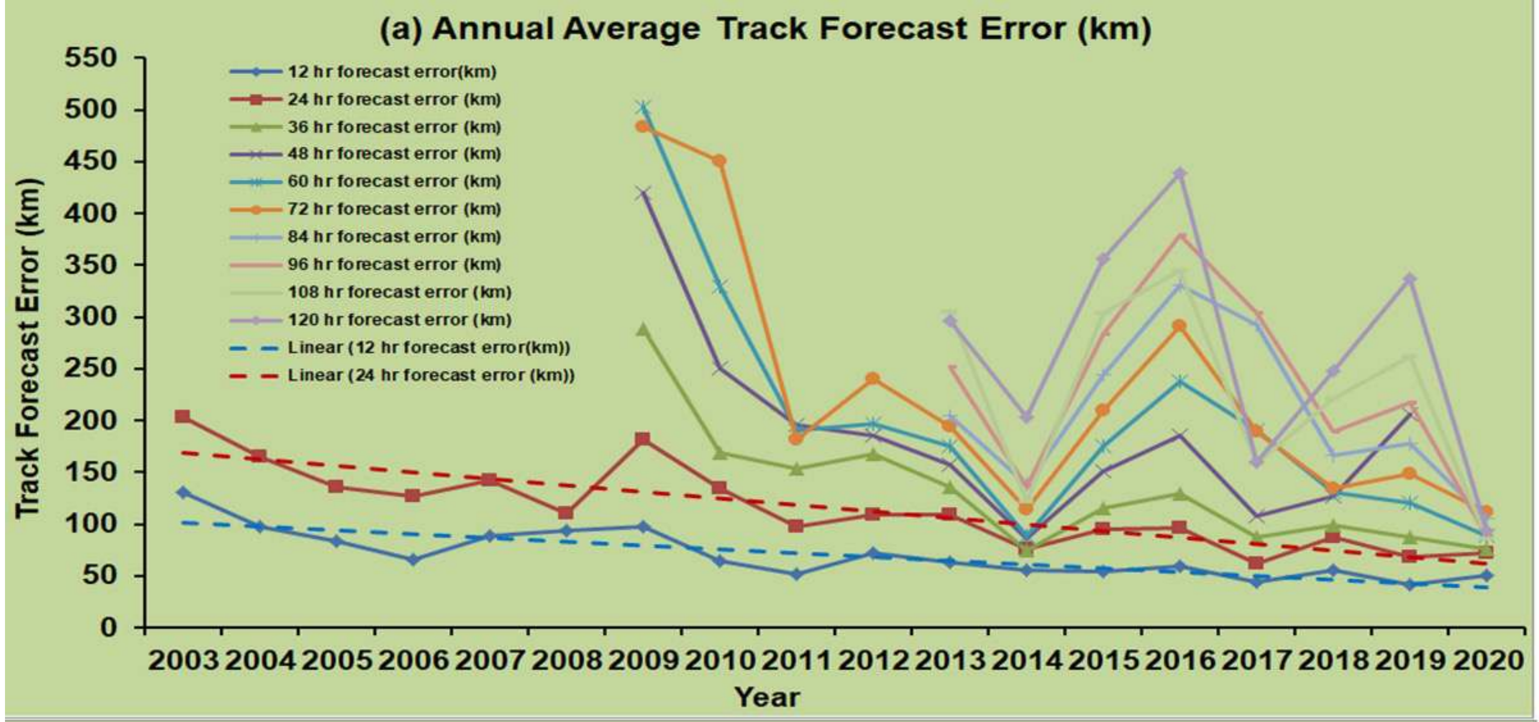


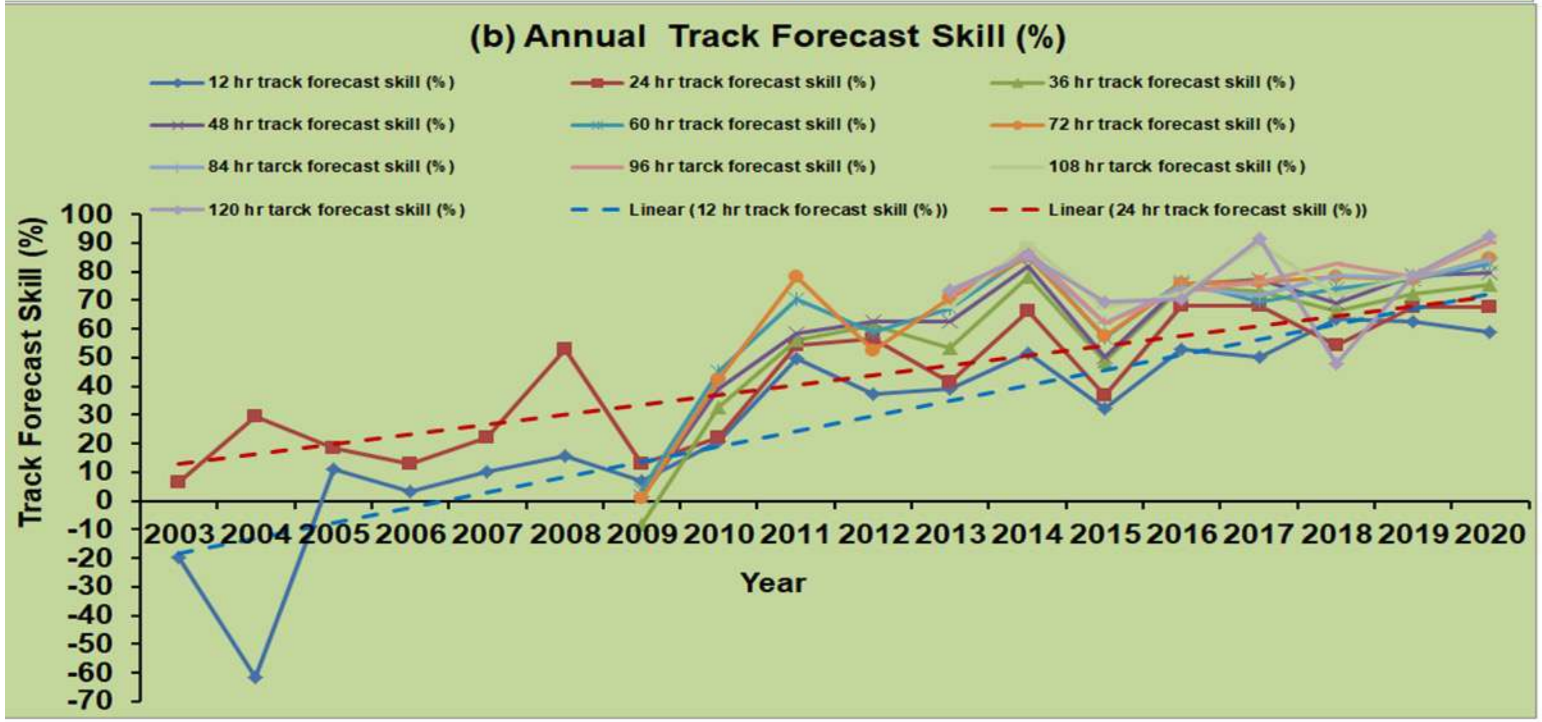


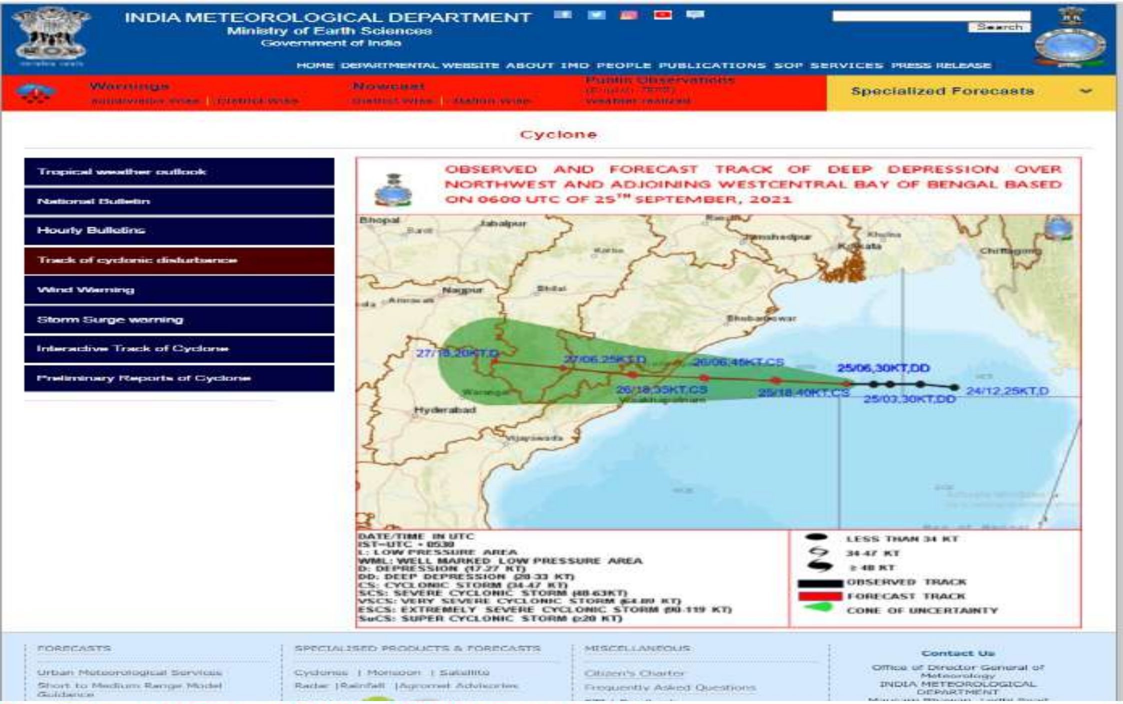

Monitoring and
Forecast Process
Broad Classification of
Observations
Space Based
Upper Air
Initial conditions
(Observations)
Action
Runs of different
Models,
Consecutive runs
from the same
model,
Ensemble runs
("choosing the
best member")
Model runs
Forecaster
Decision
maker
Numerical
forecasts
End
forecast
Monitoring and Forecast Process of Tropical Cyclone

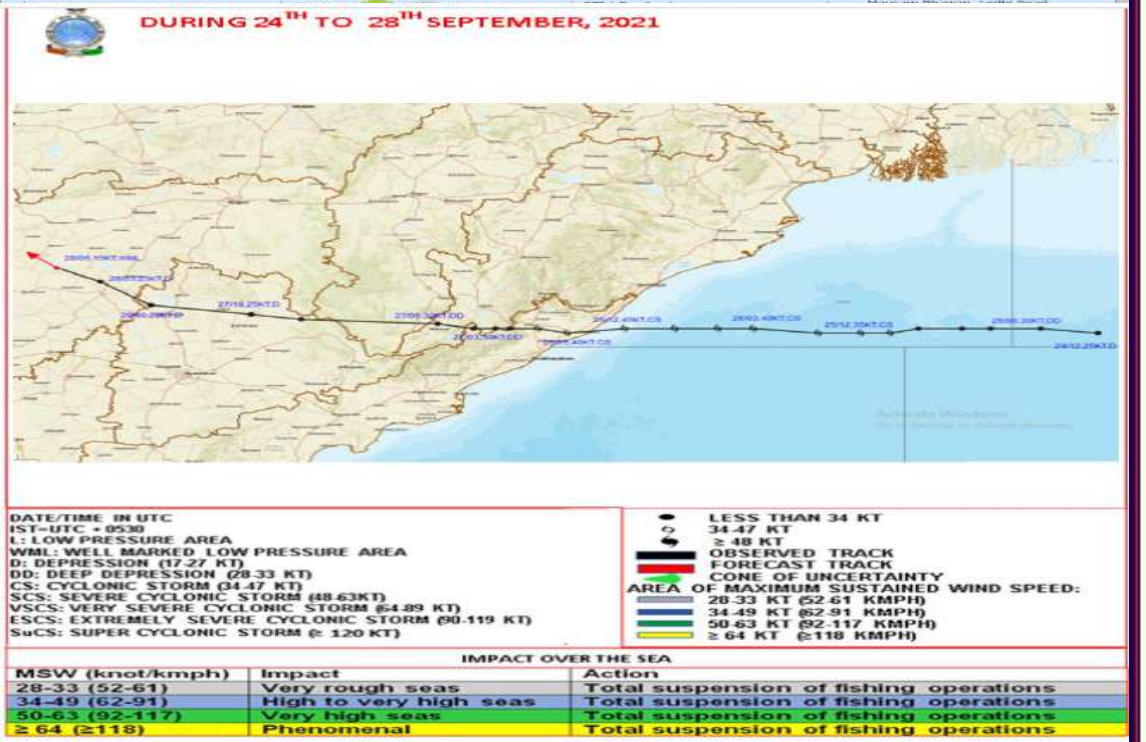

STEP-I
Genesis Potential Parameter (GPP)
(Tropical cyclone genesis prediction)
STEP-II
Multi-model ensemble (MME)
(Tropical cyclone track prediction)
STEP-III
SCIP model
(Tropical cyclone intensity prediction)
STEP-IV
RI-Index
(Rapid intensification prediction)
STEP-V
Decay model
(Prediction of decay after landfall)


(a) Annual Average Landfall Point Error (km)
Landfall Point Error (hrs)
600
500
400
300
200
100
0
-100
12 hr
24 hr
36 hr
48 hr
60 hr
72 hr
Linear (12 hr)
Linear (24 hr)
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year
(b) Annual Average Landfall Time Error (hrs)
Landfall Time Error (hrs)
25
20
15
10
5
0
12 hr
24 hr
36 hr
48 hr
60 hr
72 hr
Linear (12 hr)
Linear (24 hr)
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year


(a) Annual Average Track Forecast Error (km)
12 hr forecast error(km)
24 hr forecast error (km)
36 hr forecast error (km)
48 hr forecast error (km)
60 hr forecast error (km)
72 hr forecast error (km)
84 hr forecast error (km)
96 hr forecast error (km)
108 hr forecast error (km)
120 hr forecast error (km)
Linear (12 hr forecast error(km))
Linear (24 hr forecast error (km))
Track Forecast Error (km)
Year


(b) Annual Track Forecast Skill (%)
12 hr track forecast skill (%)
24 hr track forecast skill (%)
36 hr track forecast skill (%)
48 hr track forecast skill (%)
60 hr track forecast skill (%)
72 hr track forecast skill (%)
84 hr tarck forecast skill (%)
96 hr tarck forecast skill (%)
108 hr tarck forecast skill (%)
120 hr tarck forecast skill (%)
Linear (12 hr track forecast skill (%))
Linear (24 hr track forecast skill (%))
Track Forecast Skill (%)
Year





DATE/TIME IN UTC IST =UTC+0530

- **L:** LOW PRESSURE AREA
- **WML:** WELL MARKED LOW PRESSURE AREA
- **D:** DEPRESSION (17-27 KT / 32-51 kmph)
- **DD:** DEEP DEPRESSION (28-33 KT / 52-61 kmph)
- **CS:** CYCLONIC STORM (34-47 KT / 62-87 kmph)
- **SCS:** SEVERE CYCLONIC STORM (48-63KT / 88-117 kmph)
- **VSCS:** VERY SEVERE CYCLONIC STORM (64-89 KT / 118-165 kmph)
- **ESCS:** EXTREMELY SEVERE CYCLONIC STORM (90-119 KT / 166-221 kmph)
- **SUCS:** SUPER CYCLONIC STORM (≥ 120KT / ≥ 222 kmph)

OBSERVED TRACK
FORECAST TRACK
CONE OF UNCERTAINTY
LESS THAN 34 KT (D/DD)
34-47 KT (CS)
≥ 48 KT (SCS and above)

AREA OF MAXIMUM SUSTAINED WIND SPEED

28-33 KT (52-61 KMPH)
34-49 KT (62-91 KMPH)
50-63 KT (92-117 KMPH)
≥ 64 KT (≥118 KMPH)

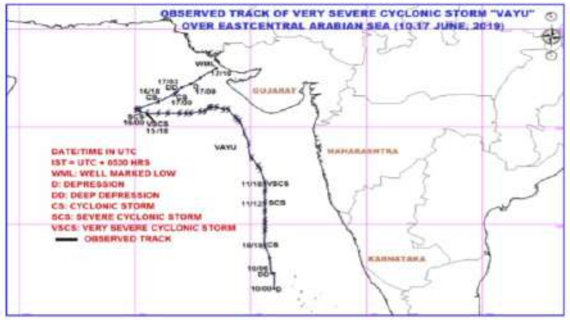
IMPACT OVER THE SEA

MSW (KNOT/KMPH)	IMPACT	ACTION
28-33 (52-61)	VERY ROUGH SEAS	TOTAL SUSPENSION OF FISHING OPERATIONS
34-49 (62-91)	HIGH TO VERY HIGH SEAS	TOTAL SUSPENSION OF FISHING OPERATIONS
50-63 (92-117)	VERY HIGH SEAS	TOTAL SUSPENSION OF FISHING OPERATIONS
≥ 64 (≥118)	PHENOMENAL	TOTAL SUSPENSION OF FISHING OPERATIONS

S.No.	From	To	Title
1	16-05-2020	21-05-2020	Super Cyclonic Storm Amphan over the southeast Bay of Bengal (May 16 - May 21)
2	29-05-2020	01-06-2020	Depression over the south coastal Oman and adjoining Yemen (May 29 - Jun 01)
3	01-06-2020	04-06-2020	Severe Cyclonic Storm, "NISARGA" over the Arabian Sea (01-04 June 2020)
4	11-10-2020	14-10-2020	Deep Depression over the Bay of Bengal (11-14 October, 2020)
5	17-10-2020	19-10-2020	Deep Depression over the Arabian Sea (17-19 October, 2020)
6	22-10-2020	24-10-2020	Depression over the Bay of Bengal (22-24 October, 2020)
7	21-11-2020	24-11-2020	Very Severe Cyclonic Storm, "GATI" over the Arabian Sea (21-24 November 2020)
8	22-11-2020	27-11-2020	Very Severe Cyclonic Storm, "NIVAR" over the Bay of Bengal (22nd -27th November 2020)
9	30-11-2020	05-12-2020	Cyclonic Storm, "BUREVI" over the Bay of Bengal (30th November - 05th December 2020)

S.No.	From	To	Title
1	04-01-2019	08-01-2019	Cyclonic Storm Pabuk over Andaman Sea (04-08 January).
2	26-04-2019	04-05-2019	Extremely Severe Cyclonic Storm, 'FANI' over the Bay of Bengal (26 April – 4 May 2019)
3	10-06-2019	17-06-2019	Very Severe Cyclonic Storm "VAYU" over southeast & adjoining eastcentral Arabian Sea and Lakshadweep (10 June – 17 June, 2019)
4	06-08-2019	09-08-2019	Deep Depression over the Bay of Bengal during 06-9 August
5	22-09-2019	25-09-2019	Very Severe Cyclonic Storm "HIKAA" over eastcentral and adjoining northeast Arabian Sea (22 – 25 September, 2019)
6	29-09-2019	01-10-2019	Depression over Gulf of Kutch & neighborhood during (29 September-01 October 2019)
7	24-10-2019	02-11-2019	Super Cyclonic Storm 'KYARR' over the Arabian Sea (24th October – 02 nd November 2019)
8	30-10-2019	07-11-2019	Extremely Severe Cyclonic Storm 'MAHA' over the Arabian Sea (30th October – 07 th November 2019)
9	05-11-2019	11-11-2019	Very Severe Cyclonic Storm "BUL BUL" over the Bay of Bengal (05th - 11th November 2019)
10	02-12-2019	07-12-2019	Cyclonic Storm 'PAWAN' over the southwest Arabian Sea and adjoining equatorial Indian Ocean (02nd - 07th December 2019)
11	03-12-2019	05-12-2019	Deep Depression over east central Arabian Sea during 03-05 December 2019
12	08-12-2019	10-12-2019	Deep Depression over southwest Arabian Sea (08-10 December,2019)

Source:- https://rsmcnewdelhi.imd.gov.in/



Observed track of VSCS VAYU (10-17 June, 2019) over Arabian Sea

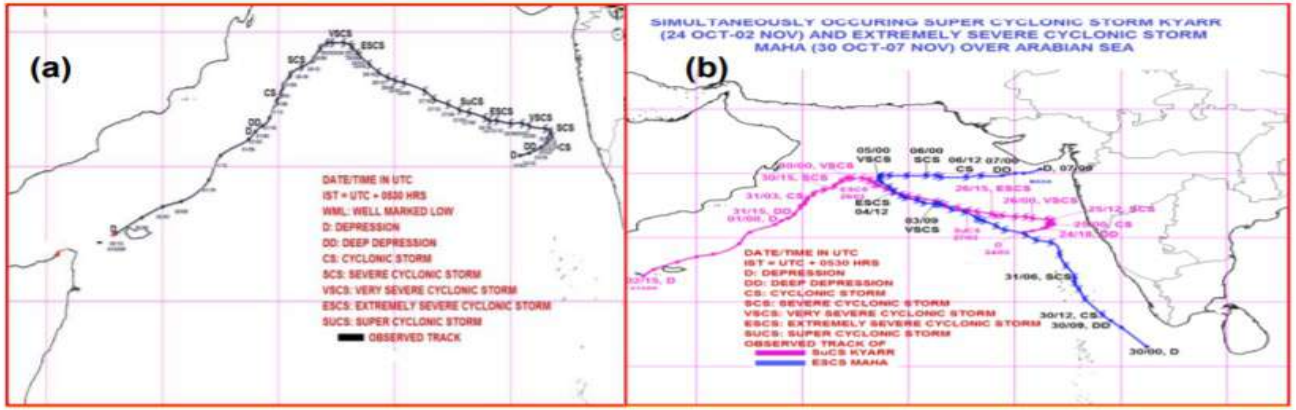
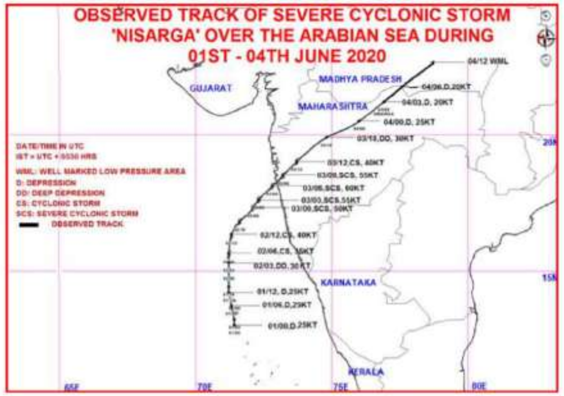


Fig.1: (a) Observed track of SuCS 'KYARR' over the Arabian Sea (24th October–02nd November, 2019) and (b) observed track of simultaneously occurring cyclones Kyarr and Maha



Observed track of SCS 'NISARGA' over the eastcentral and adjoining southeast Arabian Sea (1st-4th June, 2020)

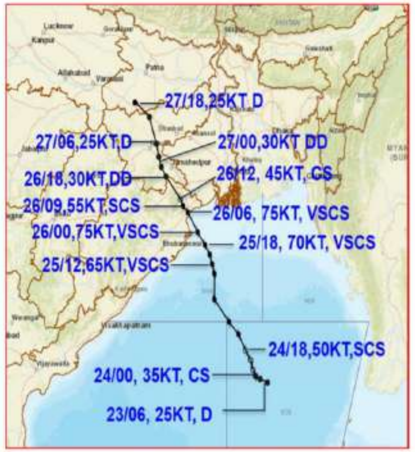


Fig.1: Observed track of VSCS YAAS during 23rd-28th May, 2021

Strongest Arabian Sea Tropical Cyclones (by 1-minute winds)

Rank	Storm	Year	Winds (mph)	Pressure	Landfall Location	Deaths	Damage (2021 USD)
1.	Gonu	Jun 2007	165	920 mb	Oman, Iran	88	$5.0 billion
2.	Kyarr	Oct 2019	155	922 mb	None	0	Minimal
3.	Chapala	Nov 2015	150	944 mb	Yemen	8	$0.2 billion
4.	Phet	Jun 2010	145	964 mb	Oman, Pakistan	39	$1.3 billion
5.	Tauktae	May 2021	140	950 mb	India	-	-
6.	Nilofar	Oct 2014	130	950 mb	None	4	Minimal
7.	Megh	Nov 2015	125	964 mb	Yemen	18	Unknown
7.	ARB 01	May 2001	125	932 mb	India	Unknown	Unknown
7.	02A/ARB 01	May 1999	125	946 mb	Pakistan	231	Unknown
7.	05B	Nov 1977	125	Unknown	India	Unknown	Unknown

Winds: Joint Typhoon Warning Center (JTWC)
Pressures: India Meteorology Department (IMD)
Deaths and Damages: EM-DAT

Cyclone Tauktae

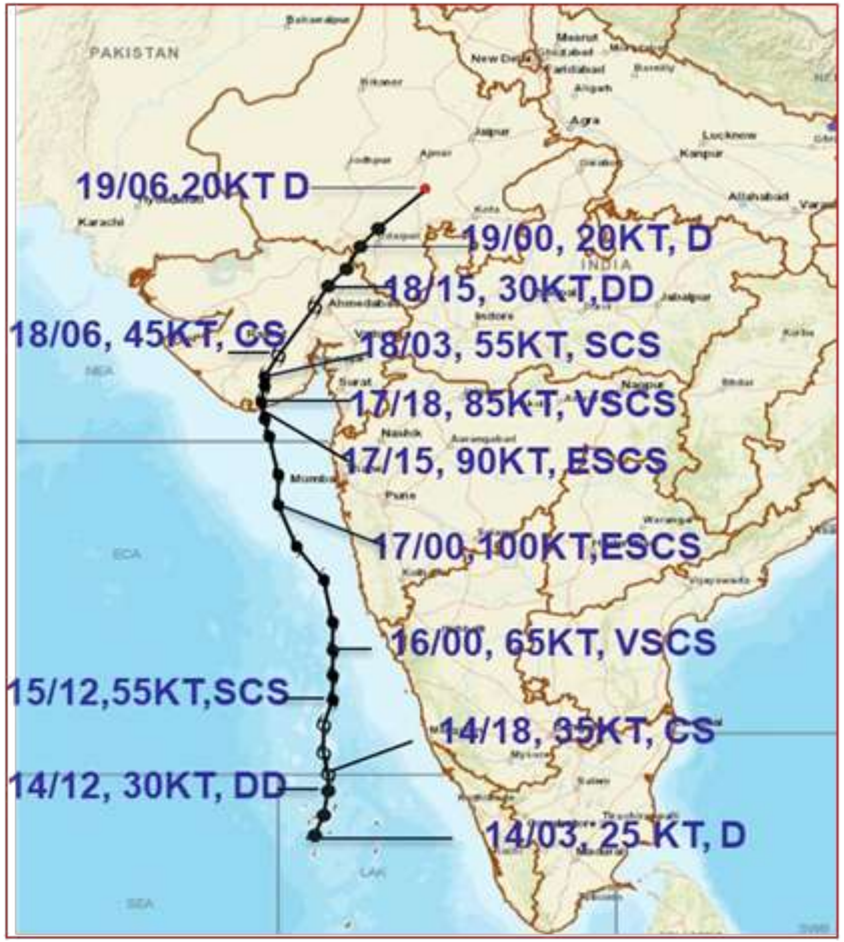
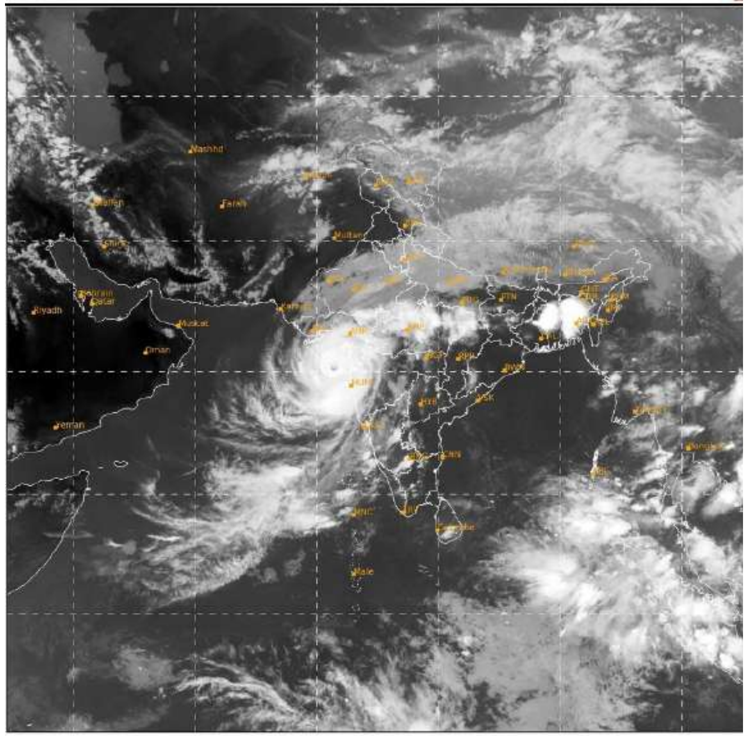


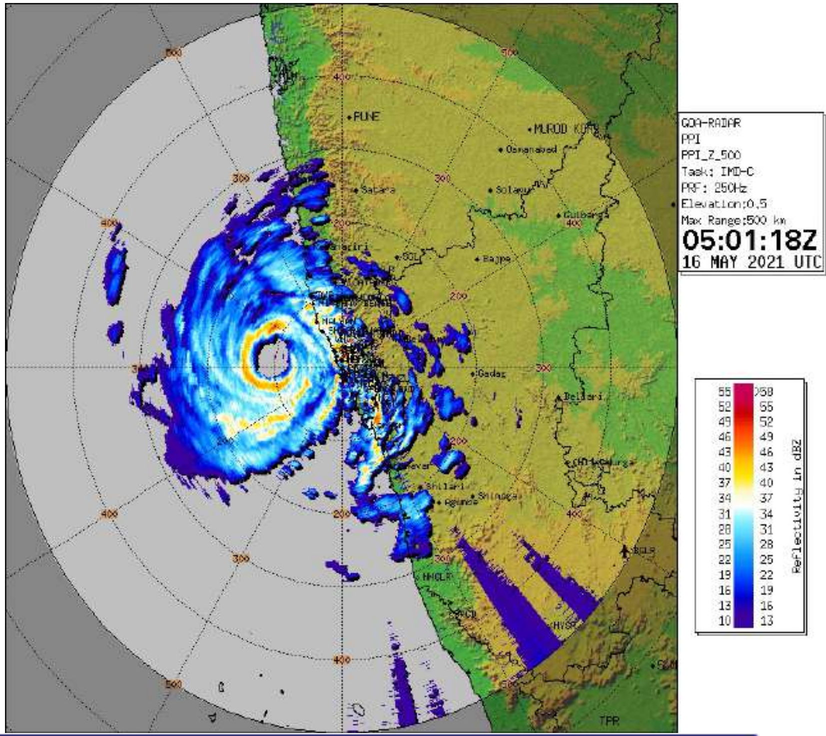
Fig. Observed track of extremely severe cyclone Tauktae during 14th-19th May, 2021

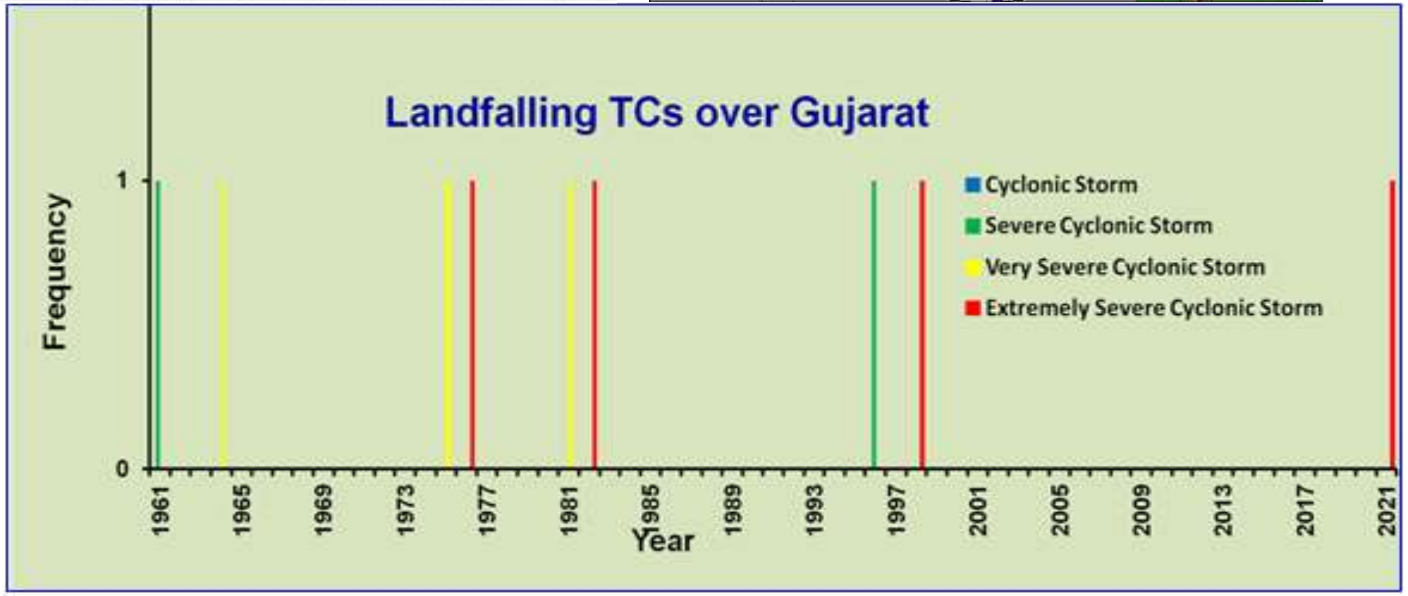
Credits: IMD

17 May 6:30 pm IST



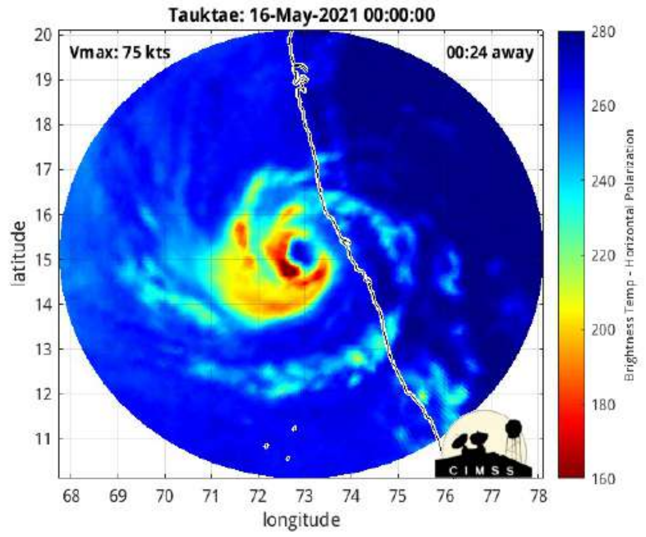
16 May 10:31 am IST

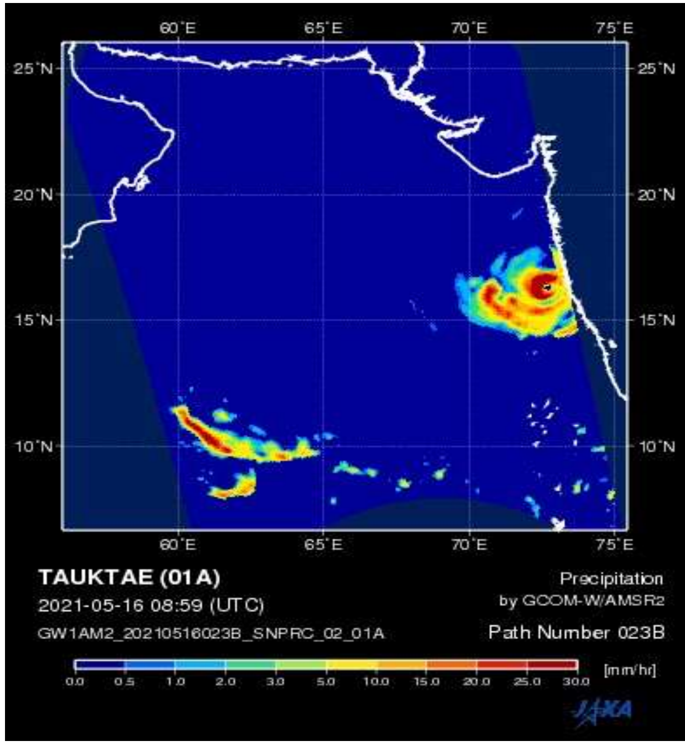




Cyclone Tauktae records

- For the first time in the last 40 years, 4 consecutive years (2018, 2019,2020 and 2021) see a pre-monsoon cyclone in the Arabian Sea.
- Cyclone Tauktae underwent rapid intensification and intensified by 45 knots in the 24 hrs (16 May 0530 IST to 17 May 0530 IST). This is the most rapid 24 hrs intensification by a cyclone in May month in the Arabian Sea after 1999.
- Cyclone Tauktae intensified from category 1 to category 4 cyclone in just 24 hrs.
- First time after 1976 and only the second time since 1900, a cyclone in May hit Gujarat coast with wind speed greater than 35 knots. Data from: IMD Cyclone e-Atlas
- Ratnagiri: 364 mm ending 17may in last 24 hrs. Highest 24hrs rain recorded there in may after 2006.
- Mumbai (Santacruz): 230 mm in 24 hrs ending 0830 IST of 18 May (highest 24 hrs rain recorded there in May month)
- Surat: 93 mm in 24 hrs ending 0830 IST of 18 May (highest 24 hrs rain recorded there in May month).





House damaged: 129297

Power supply affected: 9543 villages

Death (Gujarat): 67

Source: IMD, JTWC, RAL, JAXA

Cyclone Tauktae rainfall (cm)

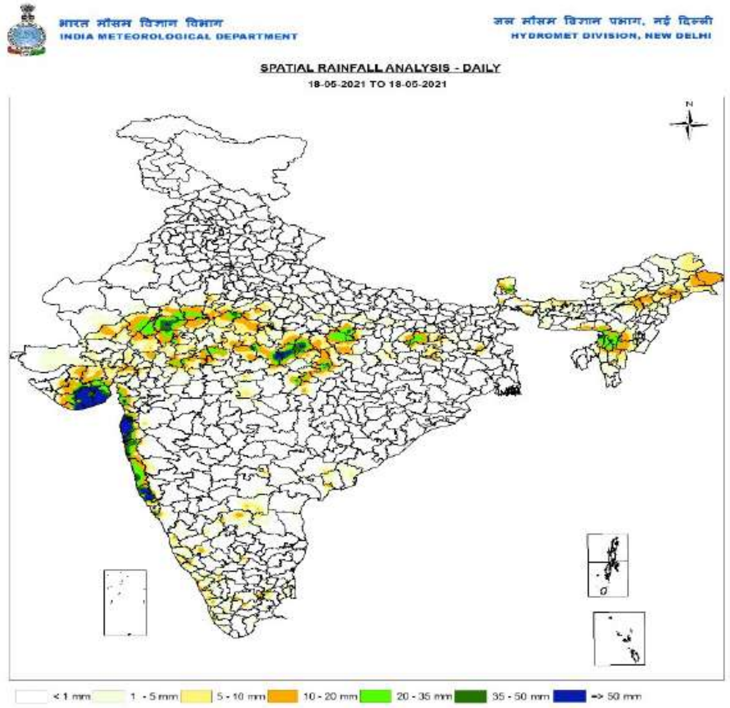
18 May 2021

SAURASHTRA & KUTCH: **Bagasra-21, Gir Gadhada-19**, Una-17, Savarkundla-17, Palitana- 16, Amreli-13, Mahuva-13, Rajula-13, Khambha-13, Babra-13, Gadhda-11, Visavadar-10

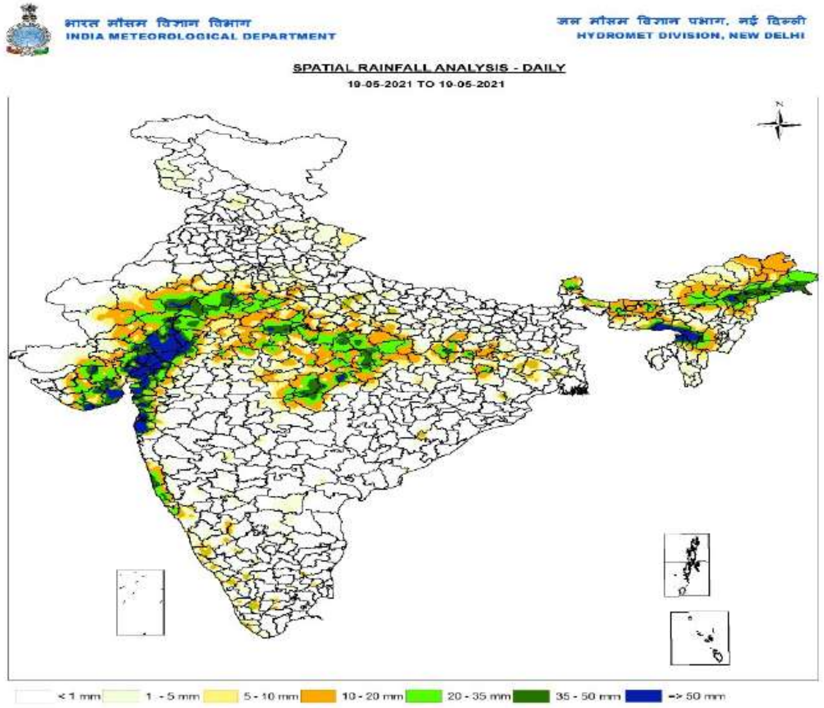
19 May 2021

GUJARAT REGION: **Nadiad-23, Mahudha-16, Anand-16**, Daman FMO-15, Umergam-15, Matar-15, Pardi-14, Daman-14, Khambhat-13, Kheda-13, Tarapur-13, Vaso-13, Olpad-12, Khergam-12, Mahemdavad-12, Dhansura-11, Ahmedabad City-11, Jalalpor-11, Sojitra-11, Kathalal-11, Prantij-10, Wanakbori-10, Borsad-10, Navsari-10, Kapadvanj-10, Virpur-10, Modasa-10.
SAURASHTRA & KUTCH: Gir Gadhada-19, Una-18, Bhavnagar-11, Rajula-10

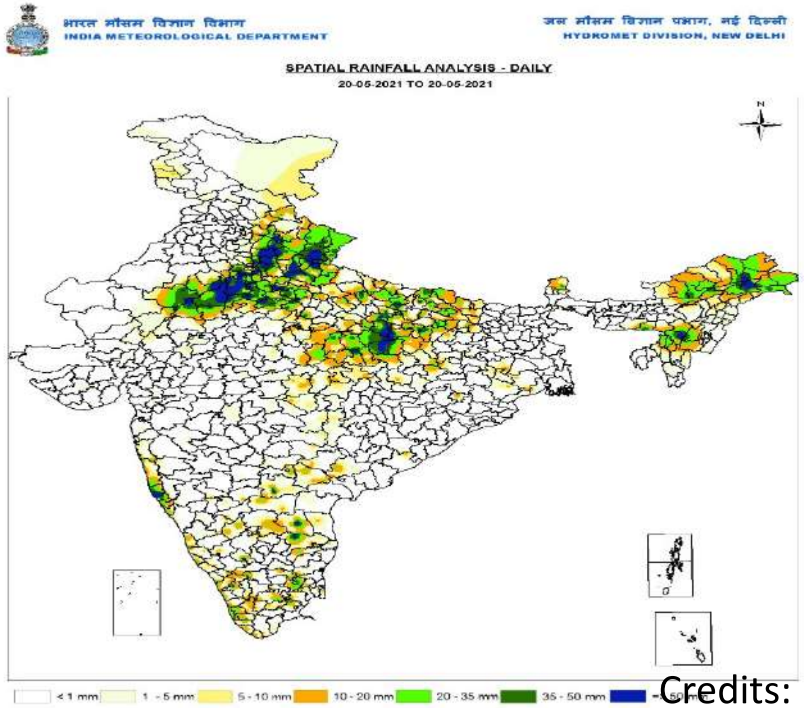
18 May 2021



19 May 2021



20 May 2021



Credits: IMD

Down To Earth

Cyclone Tauktae shows why north Indian Ocean is now whacky

These eddi
waters. The

20-May-2021

Times of India

Cyclones over Arabian Sea more frequent: IMD study

The frequen
are higher by

01-Jun-2021

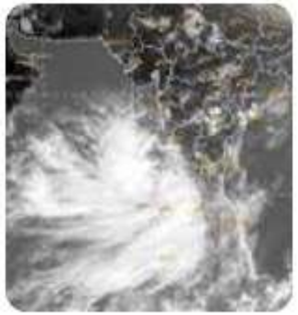
Business Line

India's coastal cities need to brace up for super cyclones

The frequen
was the first

06-Jun-2021

Mint Lounge



Why Arabian Sea cyclones have increased by 52% in twenty years

A new study by Indian climate scientists finds an alarming rise in the frequency, intensity and duration of cyclones in the last 20 years.

23-Jul-2021

Hindustan Times

Intensity of severe cyclonic storms increased in past 4 decades, say scientists

Intensity of severe cyclonic storms in the North Indian Ocean region ... like the increase in frequency and intensity of tropical cyclones...

29-Jul-2021

India Today

Intensity of severe cyclonic storms increasing in North Indian Ocean region: Study

Earlier this month, another study said the frequency of cyclones in the Arabian Sea increased by 52 per cent and the number of very severe...

30-Jul-2021

Why frequency of extreme weather events is growing and putting India's coasts at risk

Intense cyclones such as Tauktae, heavy rains and sea level rise are overlapping as climate warms. The country should conduct coastal risk assessments

June 21, 2021 by Dr *Roxy Mathew Koll*

- An unprecedented set of extreme weather events have shaken up India's western coast.
- During the last three years, cyclones came very close to the west coast, with Cyclone Nisarga in 2020 and recently, Cyclone Tauktae skirting extremely close to the city of Mumbai.
- It is not just cyclones; Kerala experienced widespread floods in 2018 and 2019, and regional floods in 2020.
- Floods in Mumbai have become an annual event since the tragic event of 2005, giving a misguided sense of resilience to the city. There have been 285 reported flooding events in India between 1950 and 2017, affecting about 850 million people, leaving 19 million homeless and killing about 71,000 people.
- The total damage during this period comes to about $60 billion.
- The **loss per year** has been increasing — and **during the last decade** the damage due to floods has been about **$3 billion per year**.
- A recent study from the Ministry of Earth Sciences points out that altogether, floods, cyclones, heat and cold waves, and lightning took about 1.4 lakh lives during the past five decades.

Global distribution of tropical cyclones

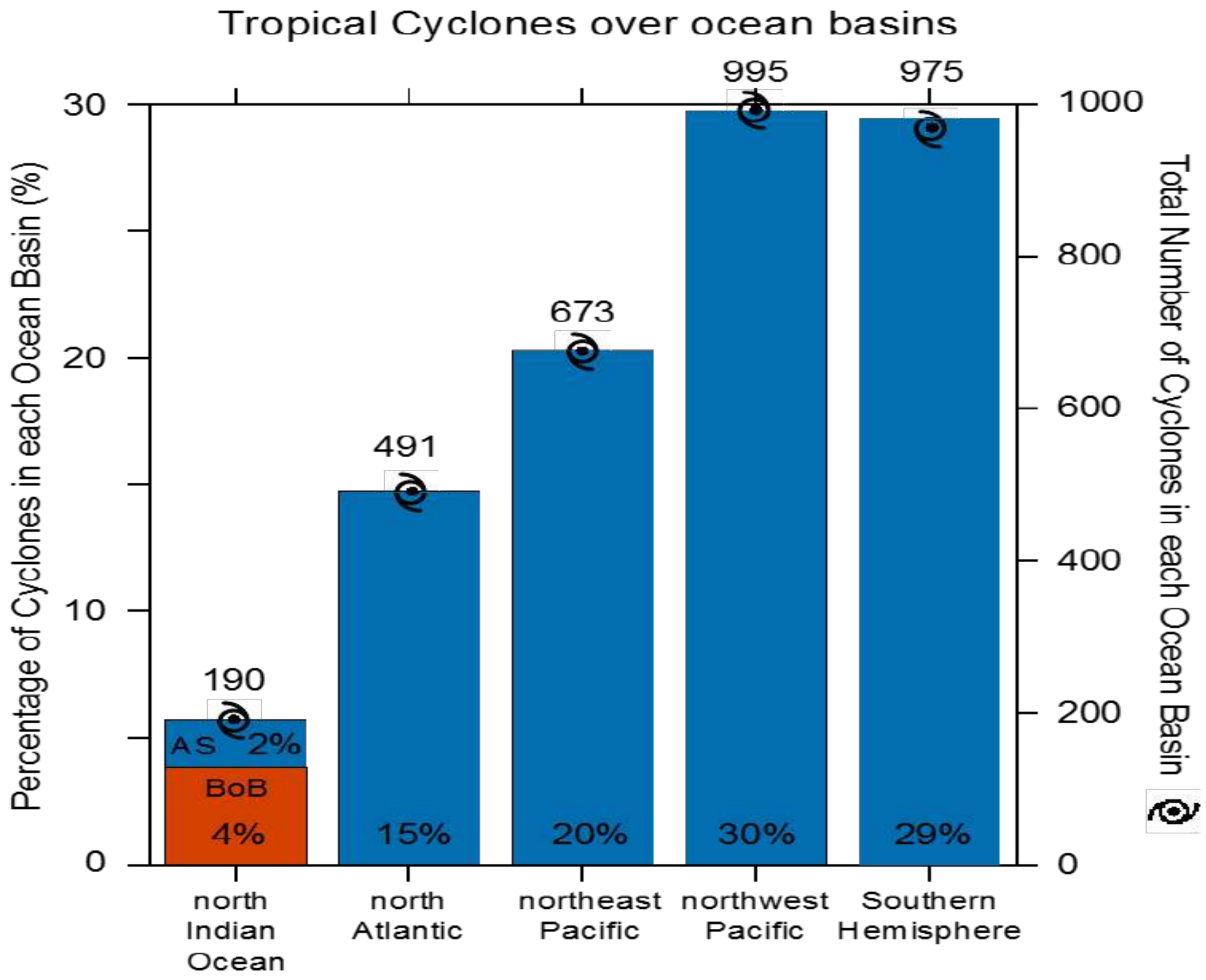


Fig. Percentage and the total number of cyclones in each ocean basins, during the period 1980-2019. Singh et al. (2021)

4% of total cyclones occur in the Bay of Bengal and ~ 2% occur in the Arabian Sea.

Cyclones hitting Gujarat coast

(a) Pre-monsoon (10 cyclones)

(b) Post-monsoon (6 cyclones)

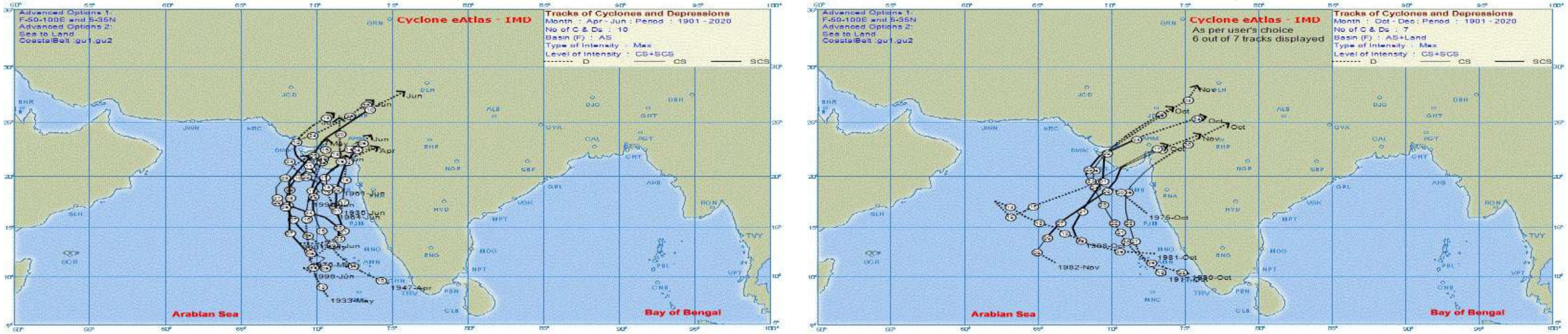


Fig. Cyclones hitting Gujarat coast during the period 1901-2020 in (a) Pre-monsoon season (April-June) (b) Post-monsoon season (October-December). Source: IMD

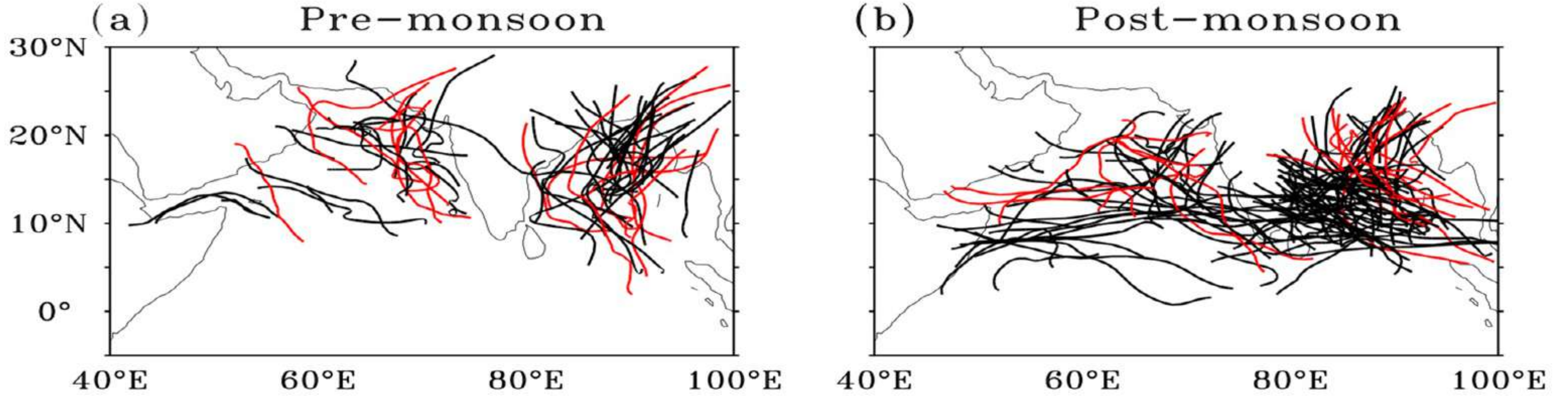
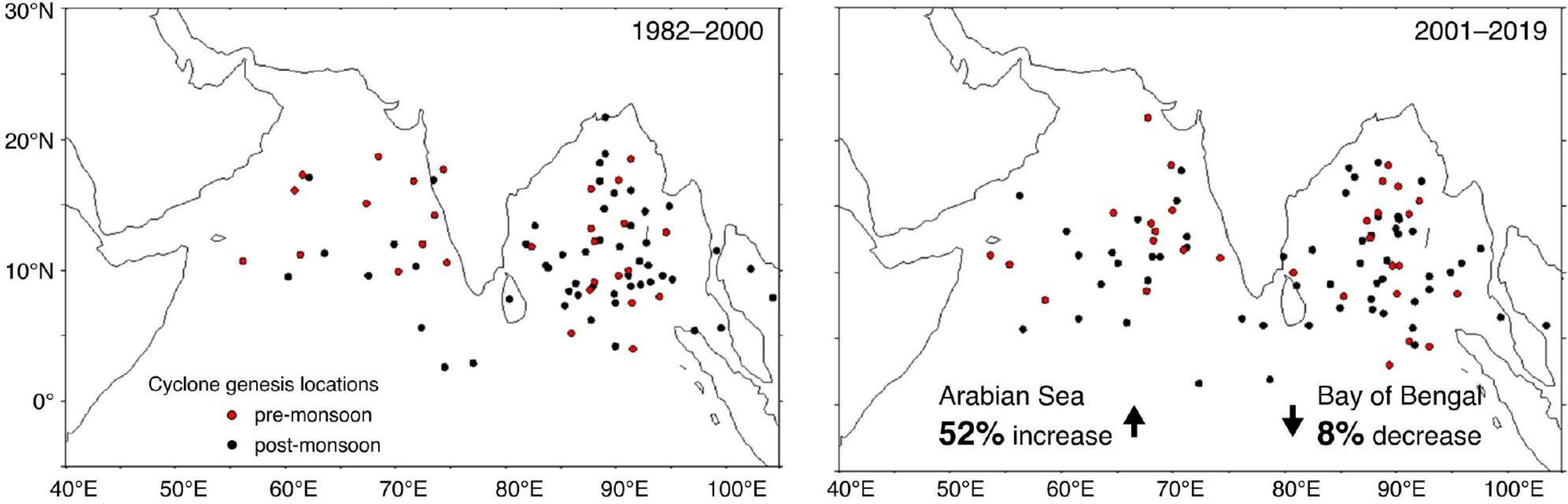


Fig. Cyclones hitting Gujarat coast in the satellite era (1980-2019). Red color track denote cyclones having wind speed ≥ 100 knots. Singh et al. (2021)

Changes in cyclone frequency

Deshpande et al. Changing status of tropical cyclones over the north Indian Ocean, *Climate Dynamics*, 2021



Arabian Sea: **52% increase** in the cyclone frequency and **150% increase** in the frequency of very severe cyclones (wind speed at least 65 knots).

Changes in cyclone intensity, duration and rapid intensification

Intensity of cyclone

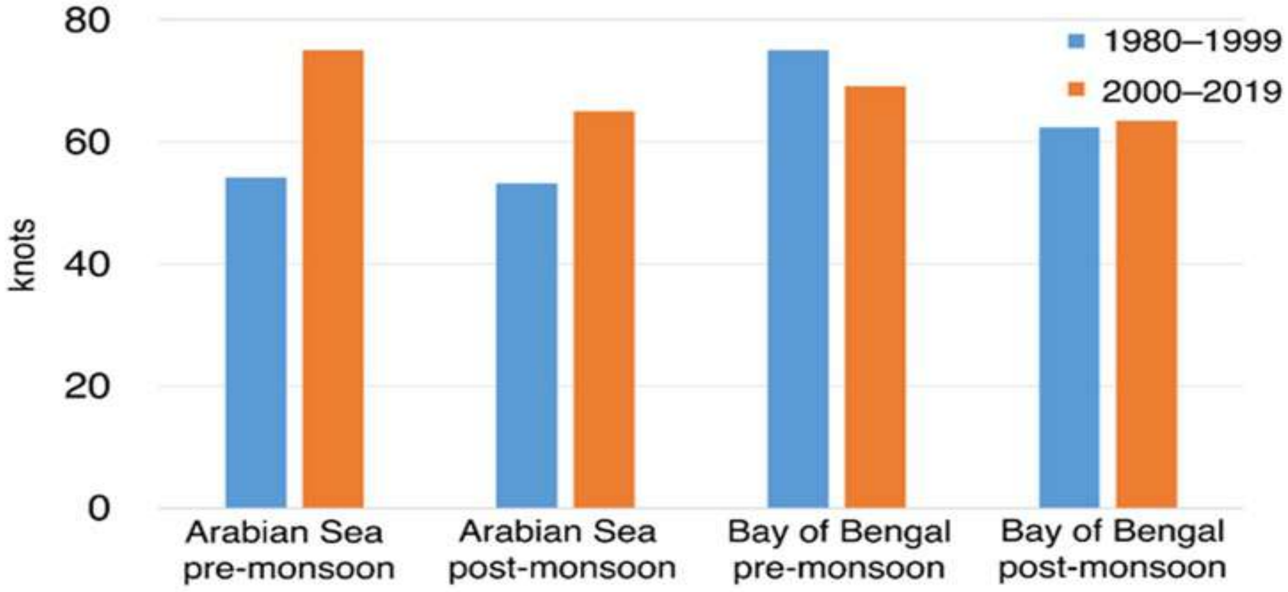
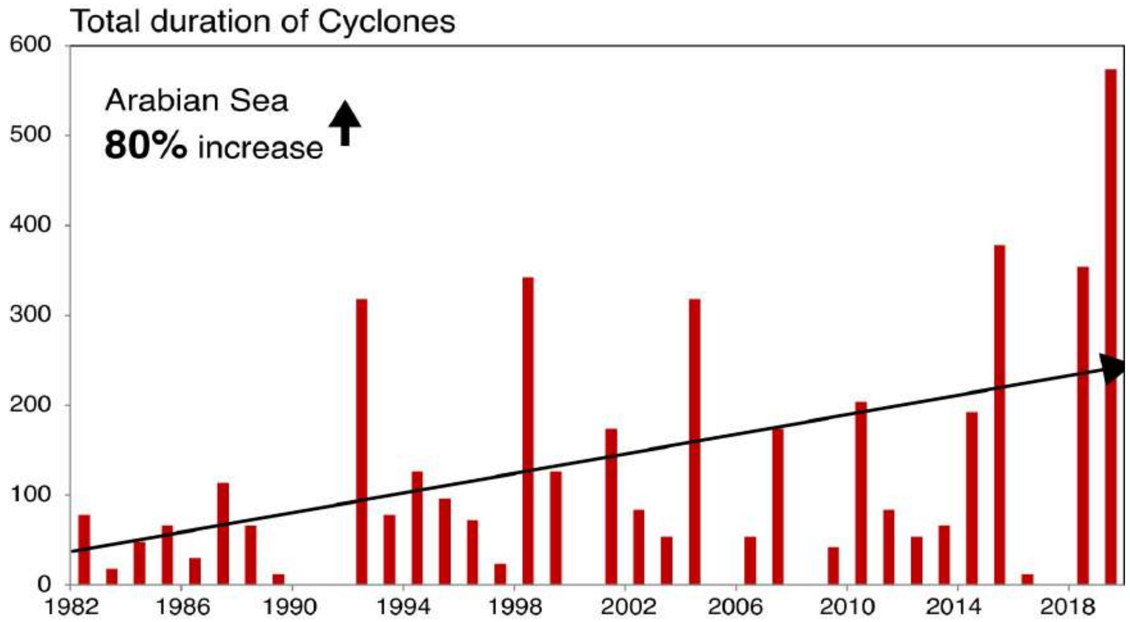


Fig. Average maximum intensity of the cyclones (knots) during the period 1980-1999 (blue bars) and 2000-2019 (orange bars).



Deshpande et al. Changing status of tropical cyclones over the north Indian Ocean *Climate Dynamics*, 2021

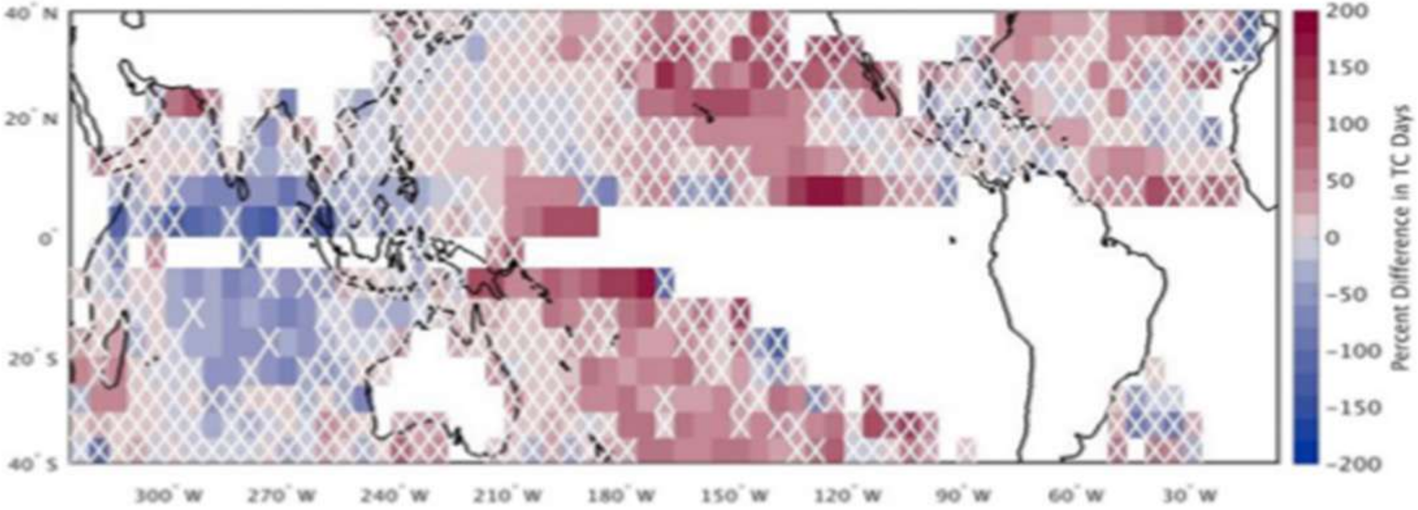
Changes in the rapid intensification rate of cyclones in the Arabian Sea

1980-1999: Every **eight cyclone** intensify rapidly (12.25% of total cyclones)
2000-2019: Every **third cyclone** intensifying rapidly (33.3% of total cyclones)

This rate of rapid intensification of cyclones in the Arabian Sea in the recent period is even higher than the most cyclone prone basin that is northwest Pacific Ocean. (Vinodhkumar et al. (2021))

Projected changes in cyclone characteristics under global warming scenario

(a) Changes in cyclone days



(b) Changes in cyclone rapid intensification

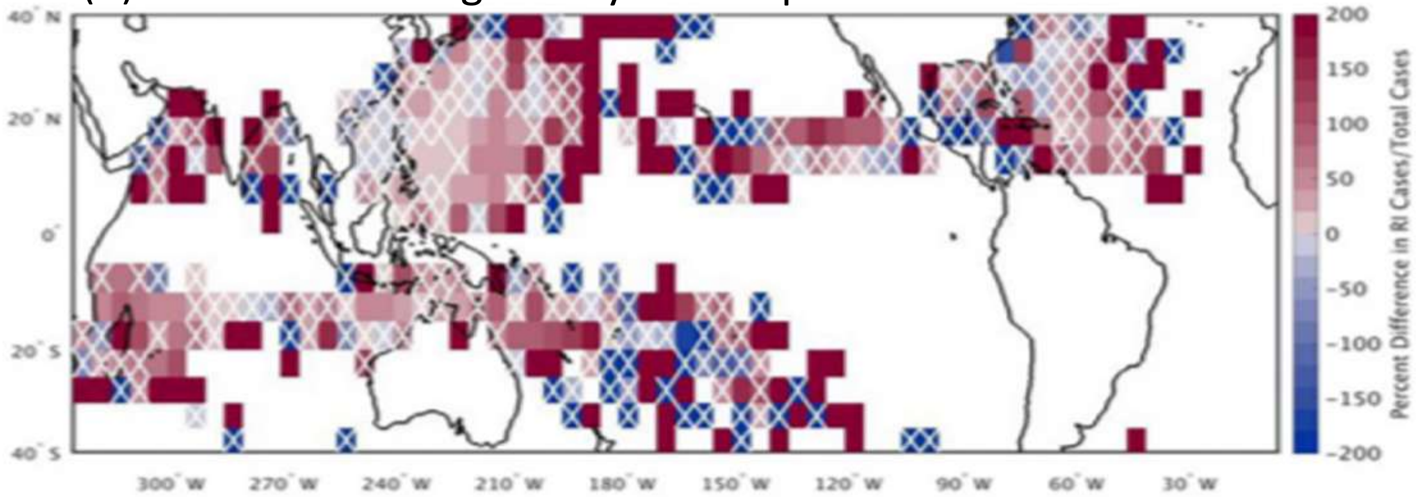


Fig. Changes in (a) cyclones days (b) percentage change in rapidly intensifying cyclones during the period 2018-2100 as compared to the period 1986-2005 using HiFLOR model. Bhatia et al. (2018)

RCP 8.5 - Historical

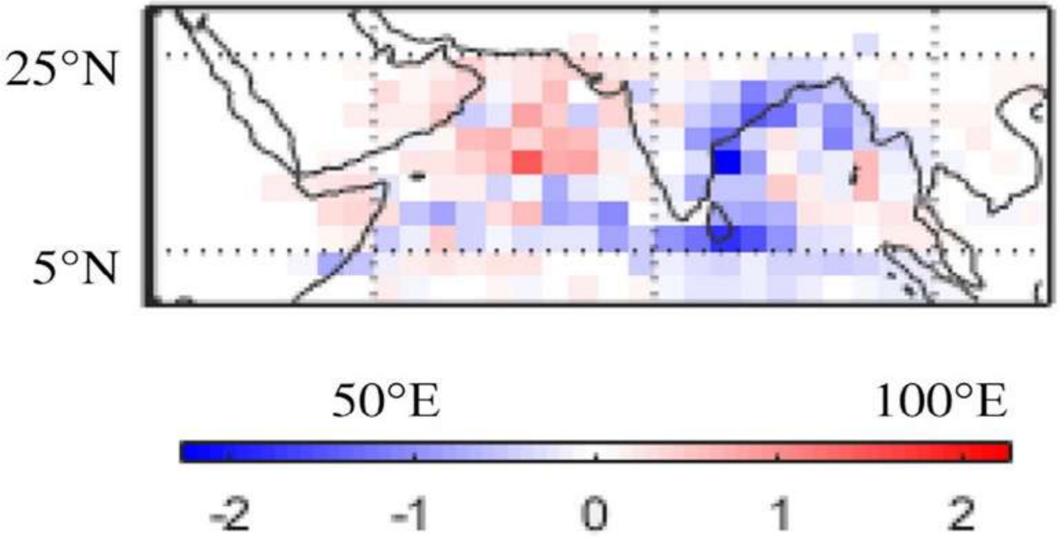
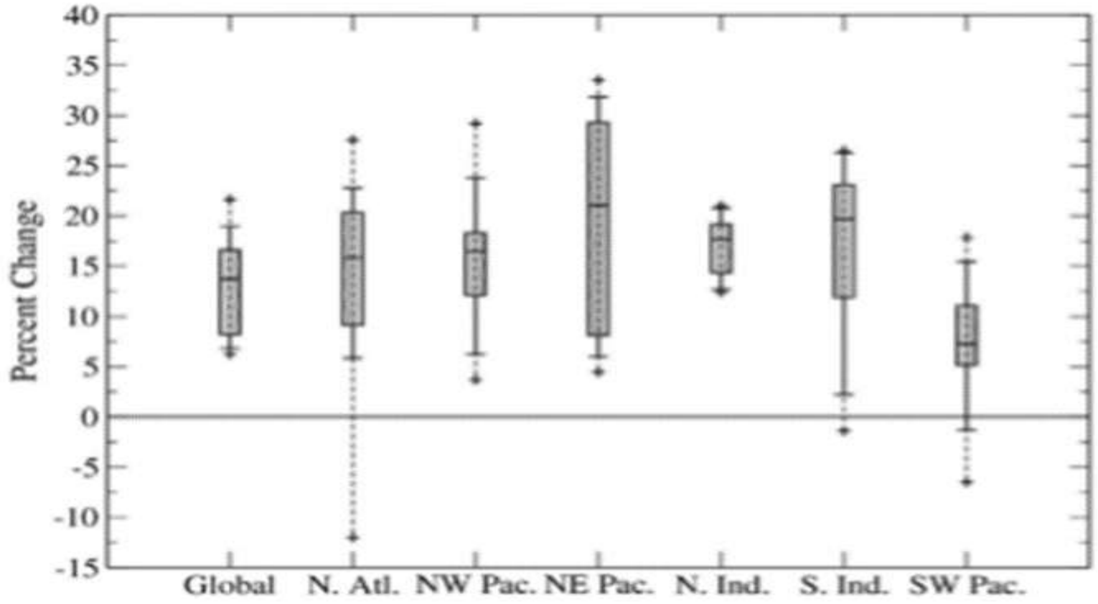


Fig. Projected change in cyclone track density (per decade) between RCP 8.5 and historical CMIP5 simulations. Bell et al. (2020)

Arabian sea: Increase in the cyclone frequency, cyclone days and increase in rapid intensification of cyclones is projected by climate models.

Projected changes in cyclone characteristics under global warming scenario

(a) **Changes in cyclone rainfall**



(b) **Changes in cyclone intensity**

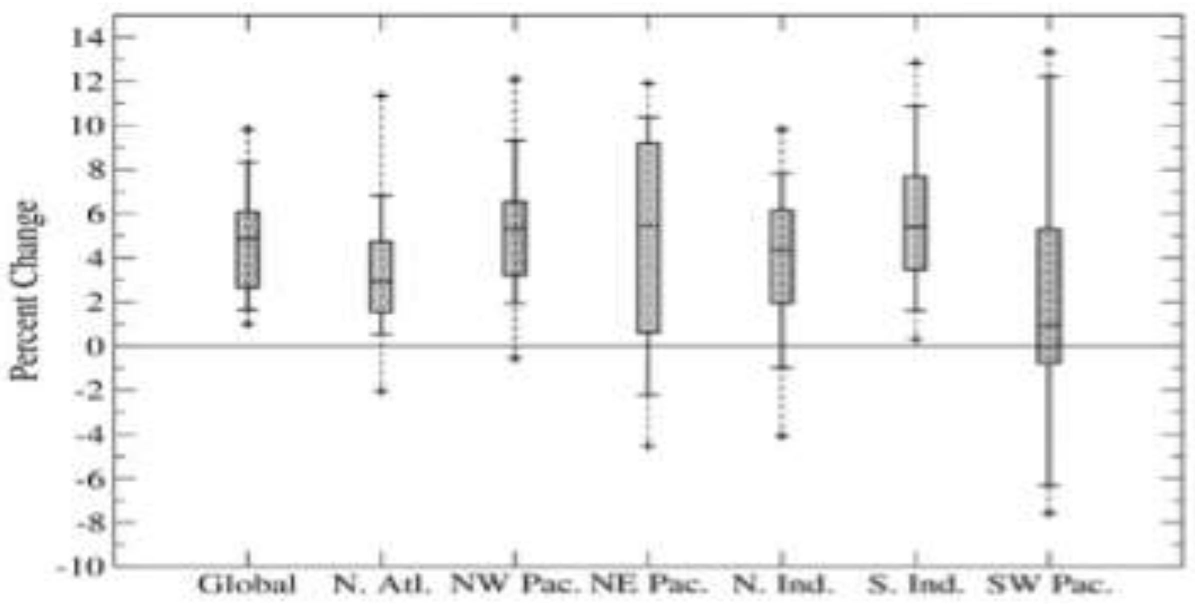


Fig. Projected changes in (a) cyclone rainfall rate (b) intensity of cyclone in a global warming scenario. Knutson et. al 2020

In the north Indian Ocean, cyclone rainfall is projected to increase by ~18% and intensity of the cyclone is projected to increase by ~5%.

Vulnerability of Indian coasts to cyclones

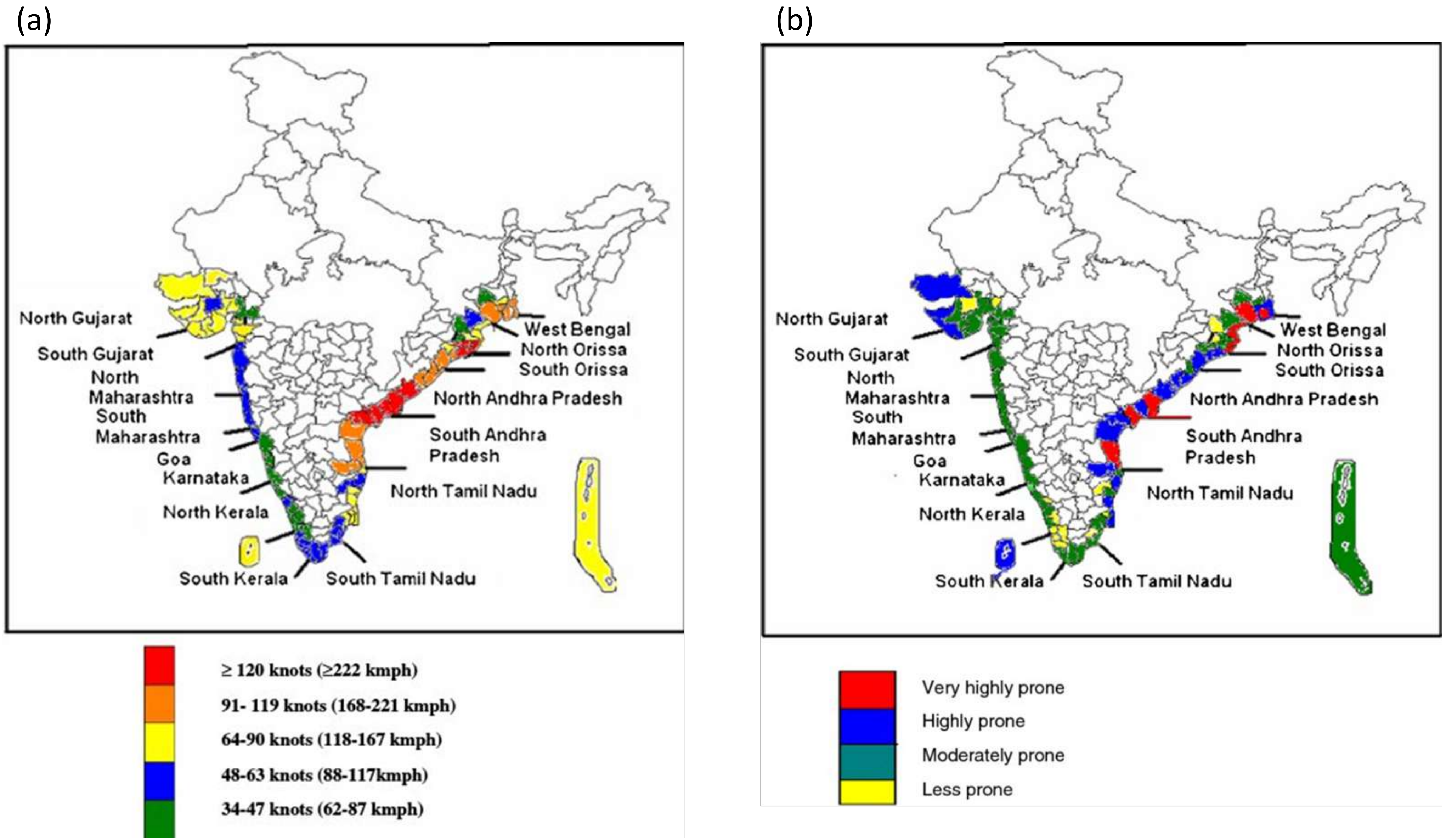


Fig. (a) Maximum wind strength over districts of India based on actual/estimated maximum wind speed. (b) Cyclone hazard prone districts based on frequency and intensity of cyclones. Mohapatra et al. (2015)

THANKS
for Attention & welcome to questions

For any Query you can message to any of these below mentioned emails

tanuja@nio.org
vineetsingh@tropmet.res.in

The Intergovernmental Panel on Climate Change (IPCC)

- IPCC is active socially and Created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the objective of the IPCC is to provide governments at all levels with scientific information that they can use to develop climate policies.
- IPCC reports are also a key input into international climate change negotiations.
- The IPCC is an organization of governments that are members of the United Nations or WMO. The IPCC currently has 195 members. Thousands of people from all over the world contribute to the work of the IPCC.
- For the assessment reports, IPCC scientists volunteer their time to assess the thousands of scientific papers published each year to provide a comprehensive summary of what is known about the drivers of climate change, its impacts and future risks, and how adaptation and mitigation can reduce those risks.
- **The IPCC is divided into three Working Groups and a Task Force.**
- Working Group I deals with The Physical Science Basis of Climate Change,
- Working Group II with Climate Change Impacts, Adaptation and Vulnerability and
- Working Group III with Mitigation of Climate Change.
- The main objective of the Task Force on National Greenhouse Gas Inventories is to develop and refine a methodology for the calculation and reporting of national greenhouse gas emissions and removals.

Faster warming

- The report provides new estimates of the chances of crossing the global warming level of 1.5°C in the next decades, and finds that unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to close to 1.5°C or even 2°C will be beyond reach.

- The report shows that emissions of greenhouse gases from human activities are responsible for approximately 1.1°C of warming since 1850-1900, and finds that averaged over the next 20 years, global temperature is expected to reach or exceed 1.5°C of warming.
- This assessment is based on improved observational datasets to assess historical warming, as well progress in scientific understanding of the response of the climate system to human-caused greenhouse gas emissions.

- "This report is a reality check," said IPCC Working Group I Co-Chair Valérie Masson-Delmotte. **"We now have a much clearer picture of the past, present and future climate, which is essential for understanding where we are headed, what can be done, and how we can prepare."**

- **Climate change is bringing multiple different changes in different regions – which will all increase with further warming.**
  - ✓ Climate change is intensifying the water cycle. This brings more intense rainfall and associated flooding, as well as more intense drought in many regions.
  - ✓ Climate change is affecting rainfall patterns. In high latitudes, precipitation is likely to increase, while it is projected to decrease over large parts of the subtropics. Changes to monsoon precipitation are expected, which will vary by region.
  - ✓ Coastal areas will see continued sea level rise throughout the 21st century, contributing to more frequent and severe coastal flooding in low-lying areas and coastal erosion. Extreme sea level events that previously occurred once in 100 years could happen every year by the end of this century.
  - ✓ Further warming will amplify permafrost thawing, and the loss of seasonal snow cover, melting of glaciers and ice sheets, and loss of summer Arctic sea ice.
  - ✓ Changes to the ocean, including warming, more frequent marine heatwaves, ocean acidification, and reduced oxygen levels have been clearly linked to human influence. These changes affect both ocean ecosystems and the people that rely on them, and they will continue throughout at least the rest of this century.
  - ✓ For cities, some aspects of climate change may be amplified, including heat (since urban areas are usually warmer than their surroundings), flooding from heavy precipitation events and sea level rise in coastal cities.

Montreal and Kyoto Protocol

- Aware of the negative impact of the depletion of the stratospheric ozone layer and the climatic changes on the development of large regions of the Earth, the international community has lately enforced a series of measures for the protection of the atmosphere.

- The Montreal Protocol enforced in 1987 initiated a global strategy for the protection of the ozone layer by forbidding the industrialized countries and from 2004 the developing countries as well to produce and consume those substances that are assumed to be responsible for the destruction of stratospheric ozone.

- Through the 1997 Kyoto Protocol, the industrialized countries (responsible for over 70% of the global emissions of "greenhouse gases") have committed themselves (not yet in a binding way) to reduce their emissions by 5.2% compared to those of 1990 by 2008-2012.

- It is a particularly demanding task, also in financial terms, since it requires a change in the energy systems and in other sectors in each country (less consumption of fossil fuels, higher use of renewable or less polluting energy sources, such as natural gas), with huge investments in the development of new high-efficiency and low environmental-impact technologies.

- There is no doubt that, in order to reduce or eliminate the risk that human activities may cause the climate to change, the international community must soon agree on the definition and acceptance of effective measures.

- Scientists agree that, even if the emissions of "greenhouse gases" should disappear today, it would still take many years before the concentrations of these gases could be brought back to the levels of before the industrial development, because of the long time spent in the atmosphere by this type of emissions.