Cyclone Prediction System (CPS) for the North Indian Ocean

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Operational NWP Models at IMD

- GFS T1534L64 (12 km)
- WRF (3DVAR -9 km, 3 km)
- HWRF (18 km, 6 km, 2 km)
- GEFS (T1534)
- GPP (Genesis Potential)
- SCIP (for cyclone intensity prediction)
- MME (for cyclone track)
- RI-Index (Rapid Intensification)
- Decay after landfall (Decay model)

NWP Model product from Other Centres

- ECMWF
- JMA
- NCEP GFS
- UKMO
- NCMRWF, IITM

Model configuration

HWRF:

- **v3.7 with GFS T1534 initial and boundary condition**
- **Triple Nested (18 Km, 6 Km, 2 Km) - Vertical level 61**
- **Run time 00, 06, 12, 18 UTC**

WRF:

- **V3.6 with RADAR data assimilation using 3DVAR**
- **Horizontal resolution 9km & 3km**
- **Run time 00, 06, 12, 18 UTC**

GFS:

- **T1534L64 (12 Km)**
- **Run time 00, 06, 12, 18 UTC**

GEFS

- **Run time 00, 12 UTC**

Dynamical models are providing very useful guidance to operational forecasters:

- Limitation of models.
- Variation of forecasts among NWP models.
- Requirements are also different for different forecast services.
- Need to generate more skillful, consensus, and requirement based products.

NWP BASED OBJECTIVE CYCLONE FORECAST SYSTEM

Kotal, S.D., Bhattacharya S.K. and Roy Bhowmik S.K. 2014. Development of NWP based objective Cyclone Prediction System (CPS) for North Indian Ocean Tropical Cyclones – Evaluation of performance. ***Tropical Cyclone Research and Review, 3(3), 162-177*** **.**

STEP-I : CYCLOGENESIS

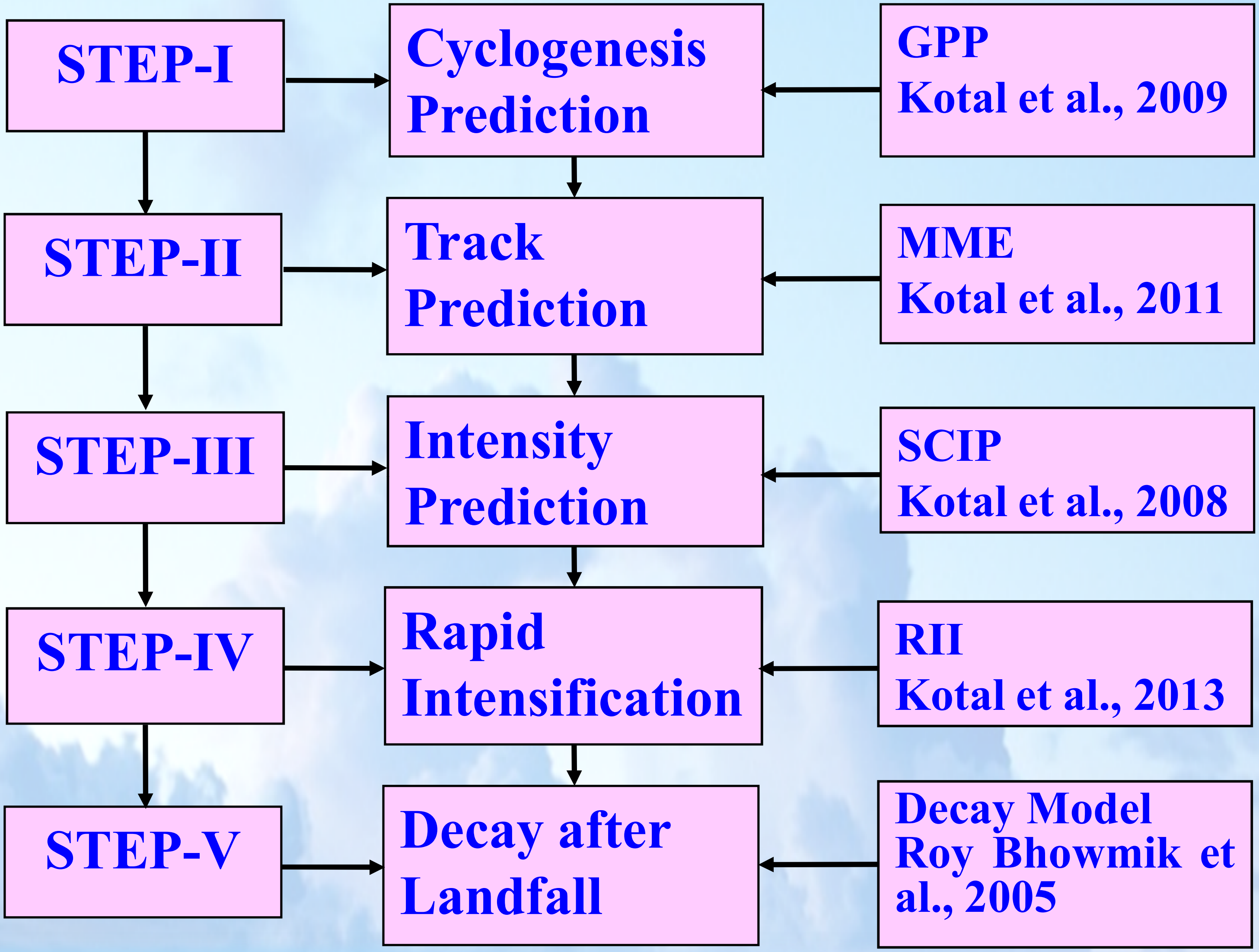
STEP-II : TRACK

STEP-III : INTENSITY

STEP-IV : RAPID INTENSIFICATION

STEP-V : DECAY AFTER LANDFALL

Cyclone Prediction System



GENESIS POTENTIAL PARAMETER (GPP)

STEP- I : Tropical Cyclogenesis

[Kotal S.D., Kundu P.K. and Roy Bhowmik S.K., 2009. Analysis of Cyclogenesis parameter for developing and non-developing low pressure systems over the Indian Sea. Natural hazards (Springer) 50:389-402.
Kotal, S.D. and Bhattacharya S.K. 2013. Tropical Cyclone Genesis Potential Parameter (GPP) and its application over the North Indian Sea. Mausam, 64(1):149-170]

Objective:

To understand the potential zone of cyclogenesis and potential for intensification of a system at early stages of development

Formulation of the Genesis potential parameter (GPP):

Two Dynamic variables :

(i) Low level relative vorticity (ζ_{850})

(ii)Vertical wind shear (S)

Two Thermo-dynamical variables:

(i) Middle troposphere relative humidity (M)

(ii) Middle-trpospheric instability (I)

The GPP is defined as:

(Natural Hazards, 2009, 50,389-402)

$$GPP = \frac{\xi_{850} x M x I}{S} \quad \textit{if} \;\; \zeta_{850} > 0, \;\; M > 0 \text{ and } I > 0$$

$$= 0 \quad \textit{if} \;\; \zeta_{850} \le 0, \;\; M \le 0 \text{ and } I \le 0$$

Where , ζ_{850} = Low level relative vorticity (at 850 hPa) in 10^{-5} s^{-1}

S = Vertical wind shear between 200 and 850 hPa (ms^{-1})

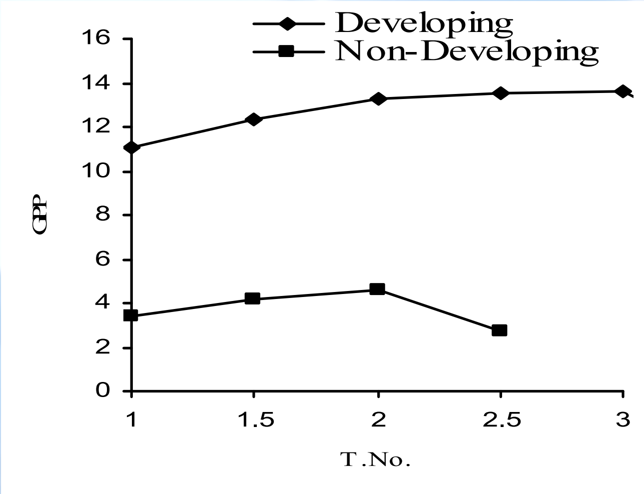
$M = \frac{[RH - 40]}{30}$ *= Middle troposphere relative humidity*

Where RH is the mean relative humidity between 700 and 500 hPa

I = (T_{850} – T_{500}) °C = Middle-trpospheric instability (Temperature difference between 850 hPa and 500 hPa)

Genesis potential parameter for developing versus non- developing systems:

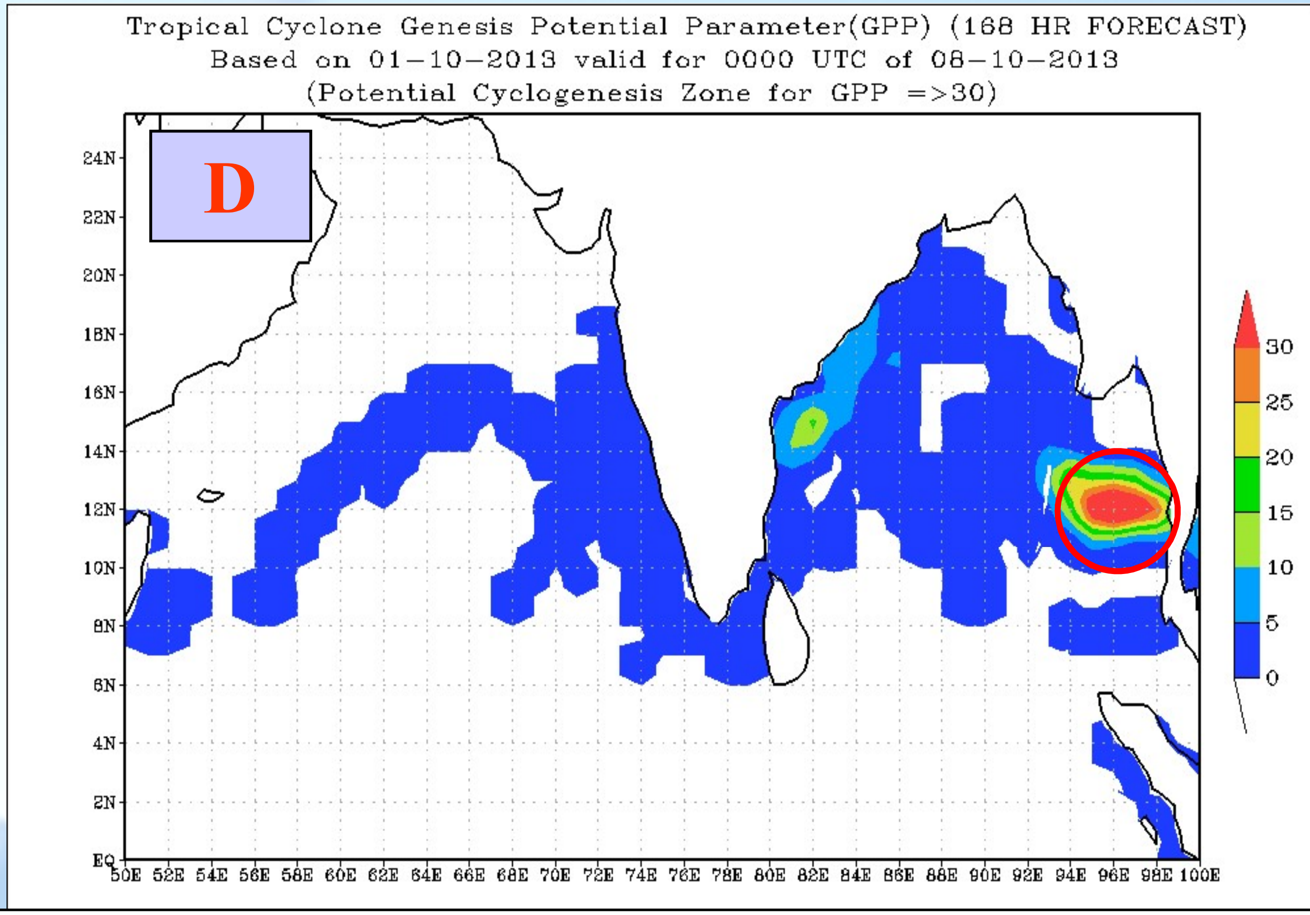
GPP(x10^{-5}) →					
T.No. →	1.0	1.5	2.0	2.5	3.0
Developing	11.1	12.3	13.3	13.5	13.6
Non-Developing	3.4	4.2	4.6	2.7	-



Threshold value of GPP => 8.0

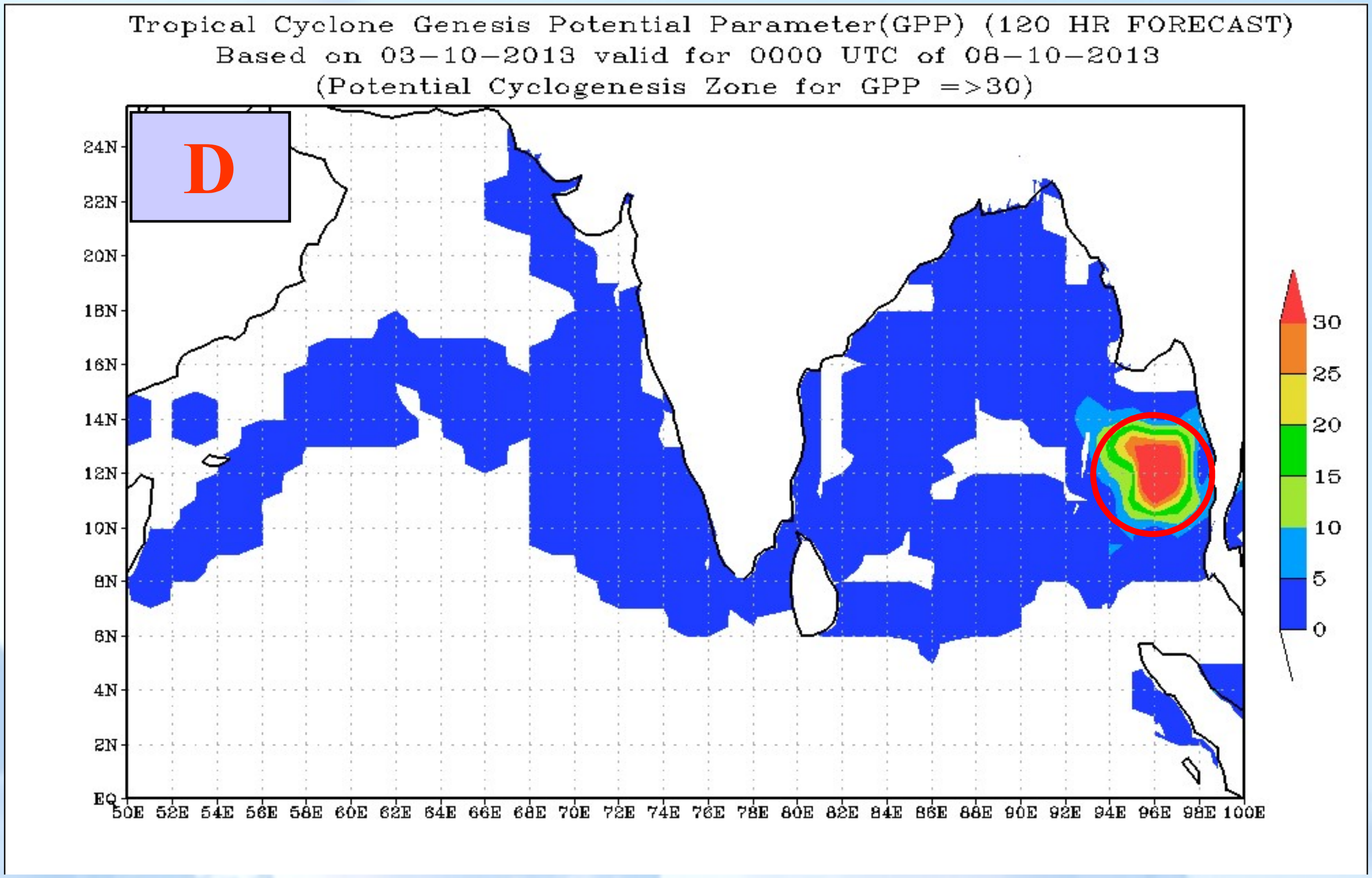
PHAILIN
(Bay of Bengal October 2013)

Grid Point Analysis of Genesis Potential Parameter (GPP)



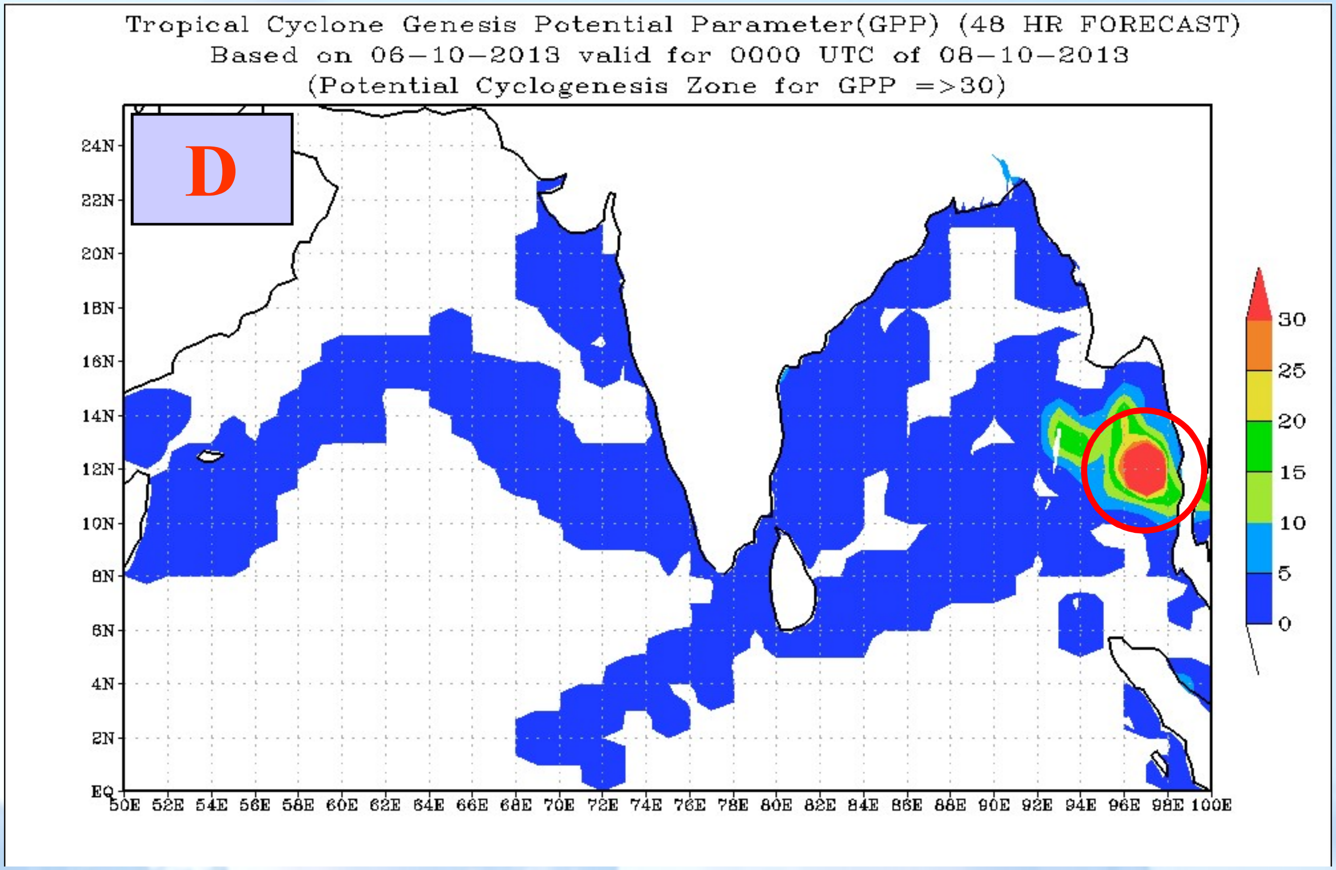
On 1 Oct. 2013: 168 hour forecast (7 days in advance) of GPP valid for 00 UTC 08 October 2013 correctly indicated the location of potential cyclogenesis zone, where Depression formed on that day.

Grid Point Analysis of Genesis Potential Parameter (GPP)



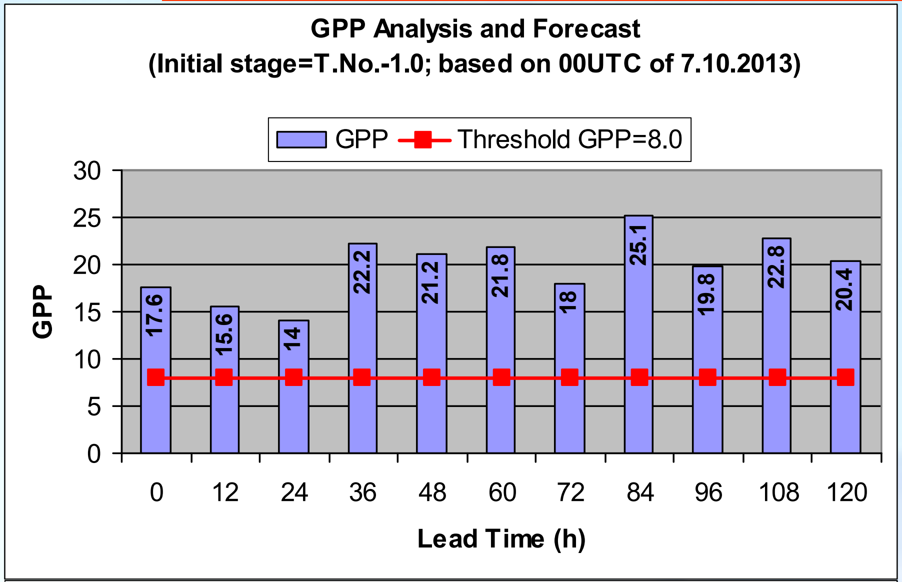
On 3 Oct. 2013: 120 hour forecast (5 days in advance) of GPP valid for 00 UTC 08 October 2013 correctly indicated the location of potential cyclogenesis zone, where Depression formed on that day.

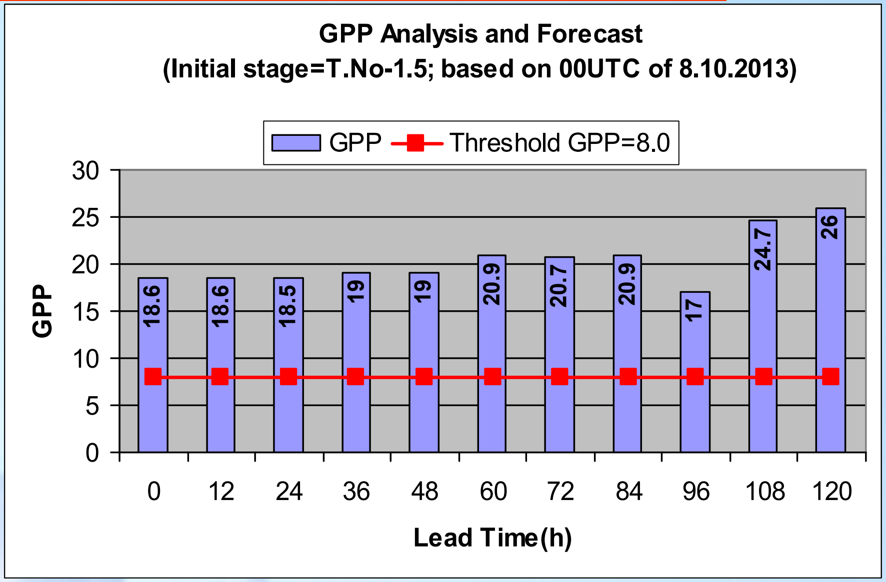
Grid Point Analysis of Genesis Potential Parameter (GPP)

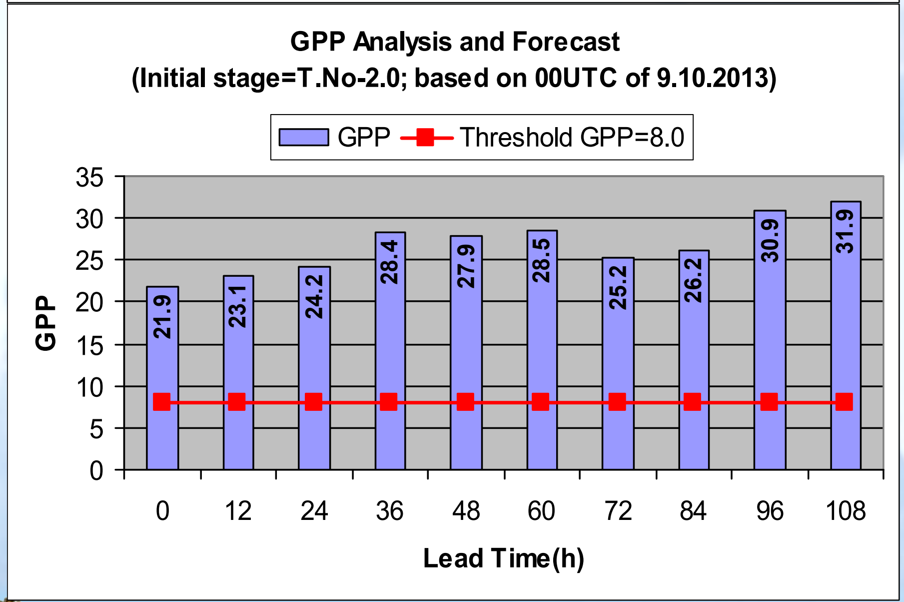


On 6 Oct. 2013: 48 hour forecast (2 days in advance) of GPP valid for 00 UTC 08 October 2013 correctly indicated the location of potential cyclogenesis zone, where Depression formed on that day.

Area average Genesis potential parameter (GPP)



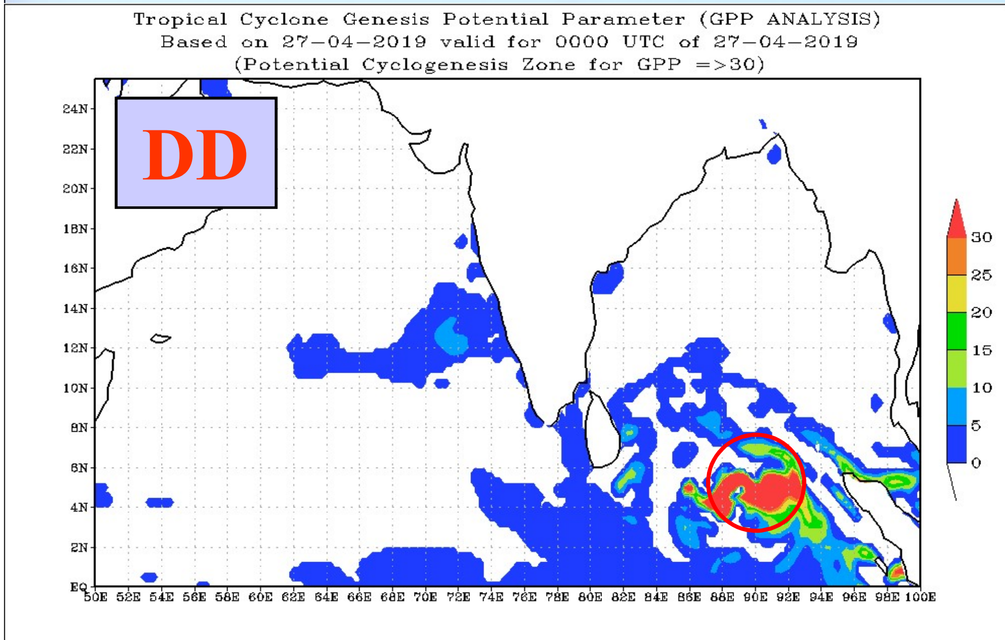


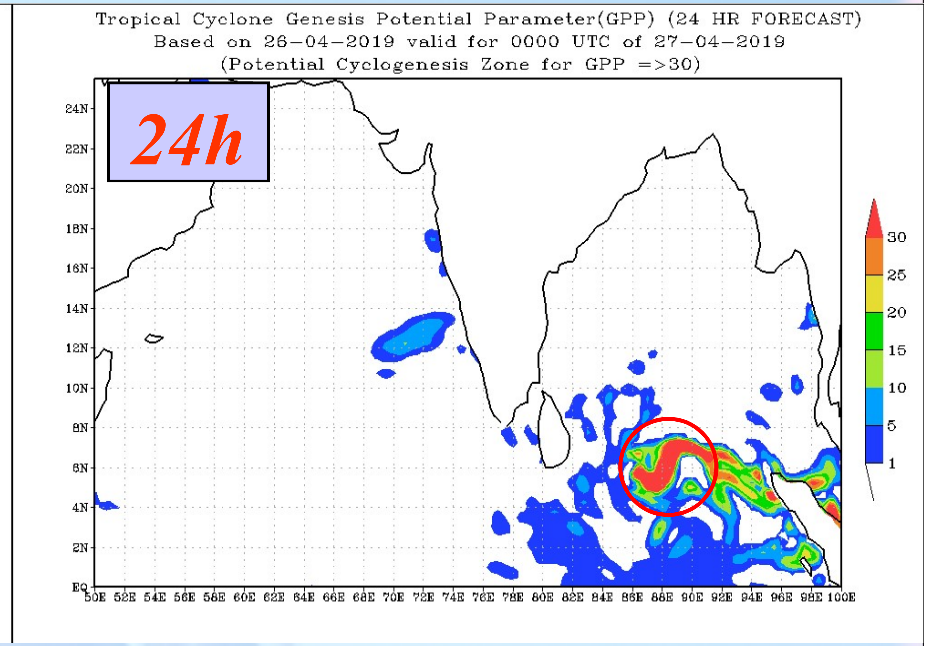


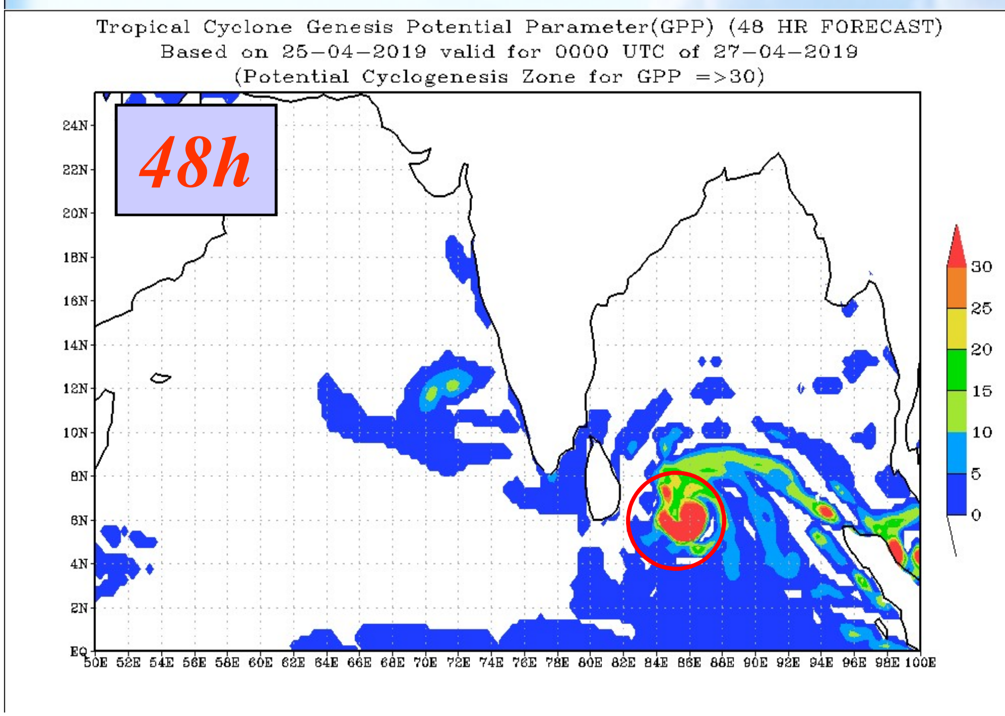
Inference: Analysis and forecasts of GPP show that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potentential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).

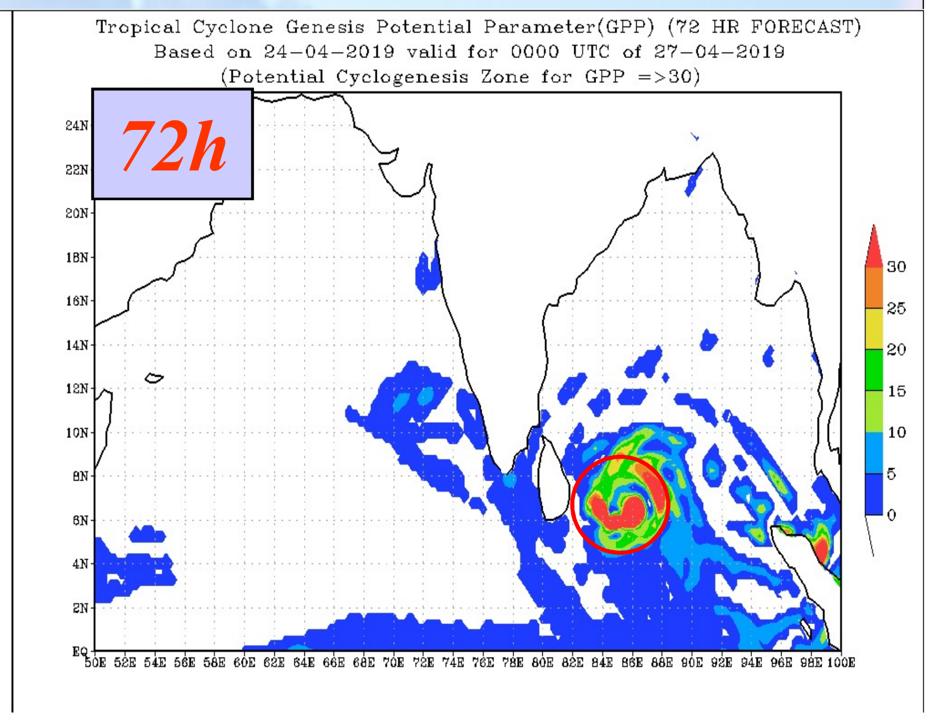
ESCS FANI: 26April-04 May 2019

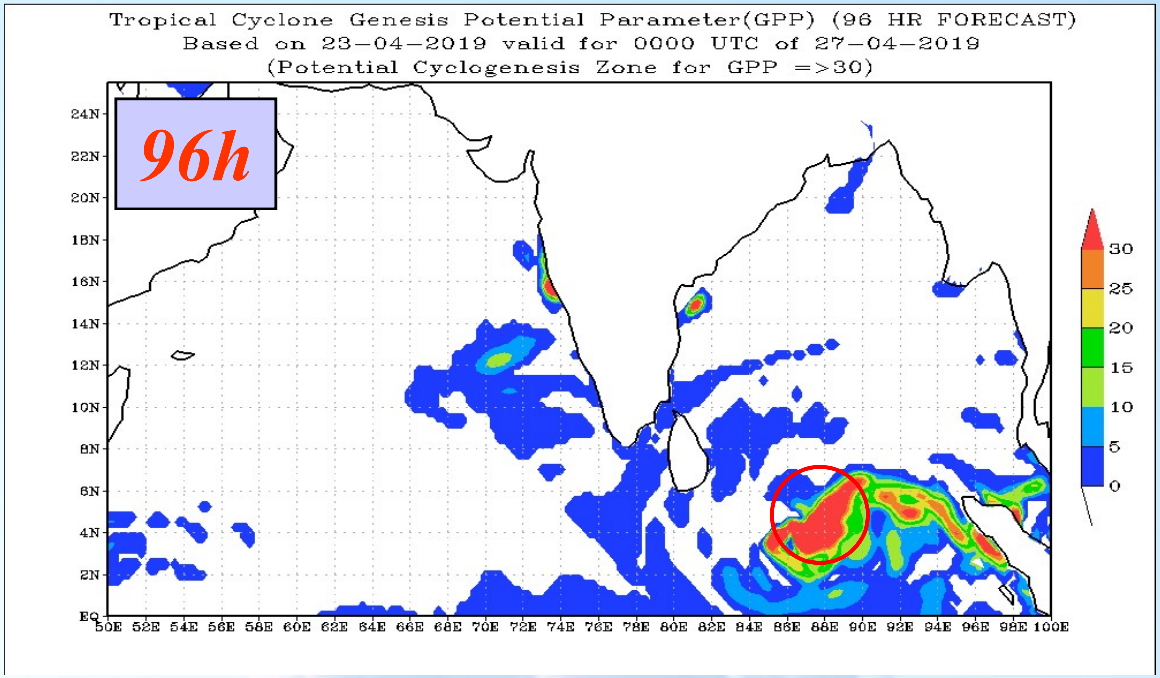
Genesis forecasts by GPP FANI

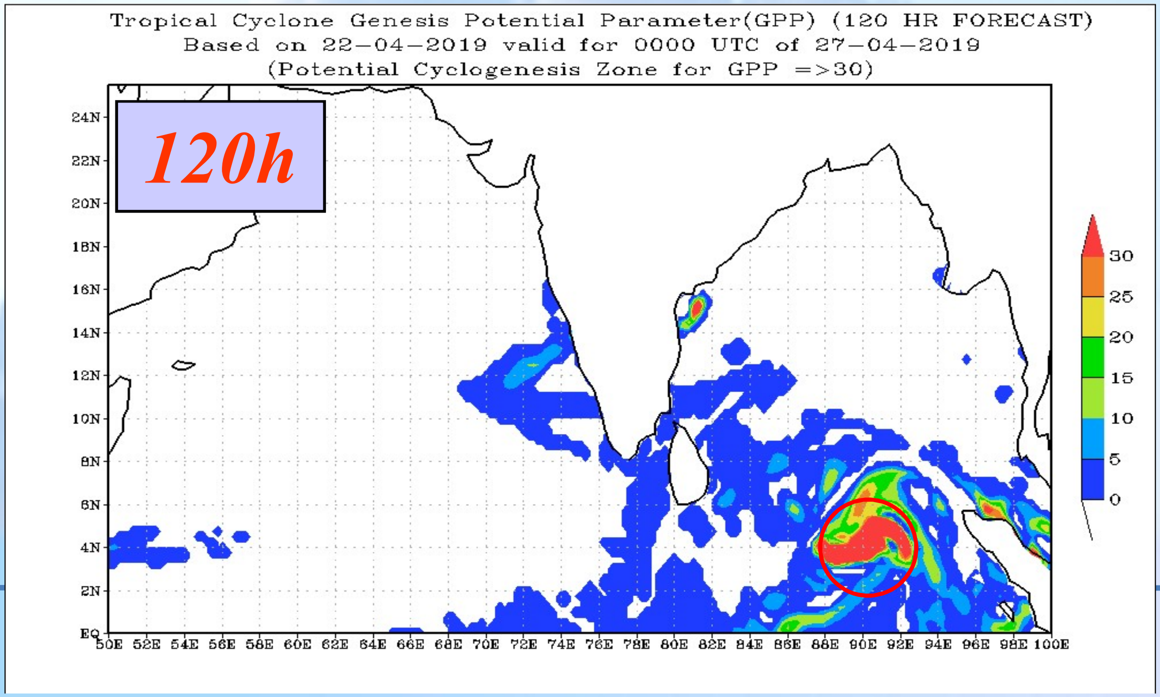




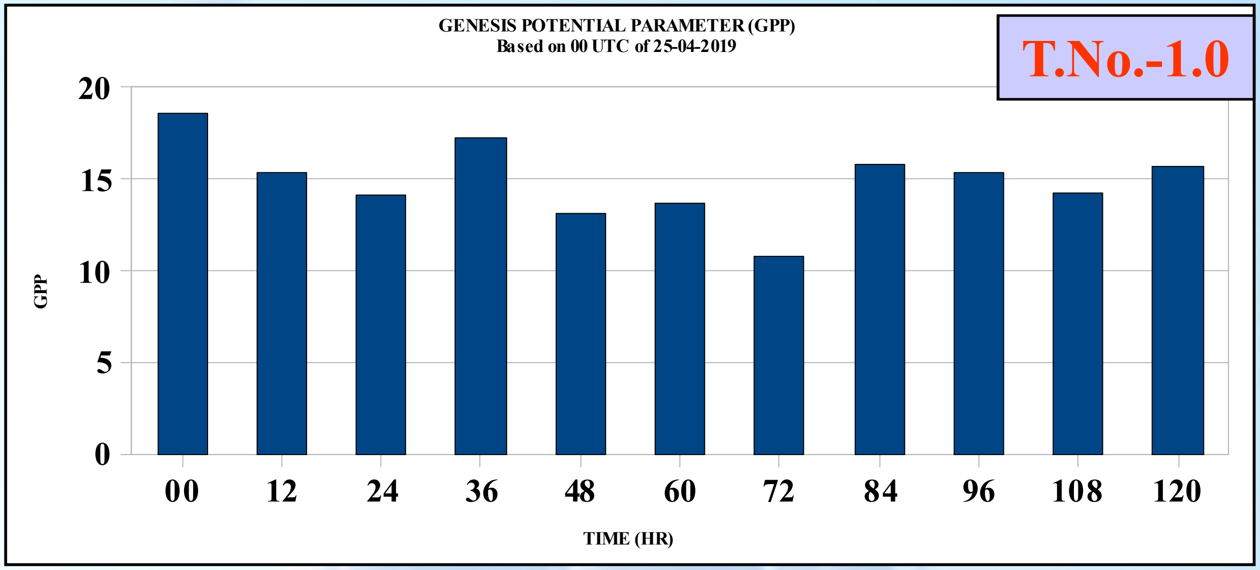




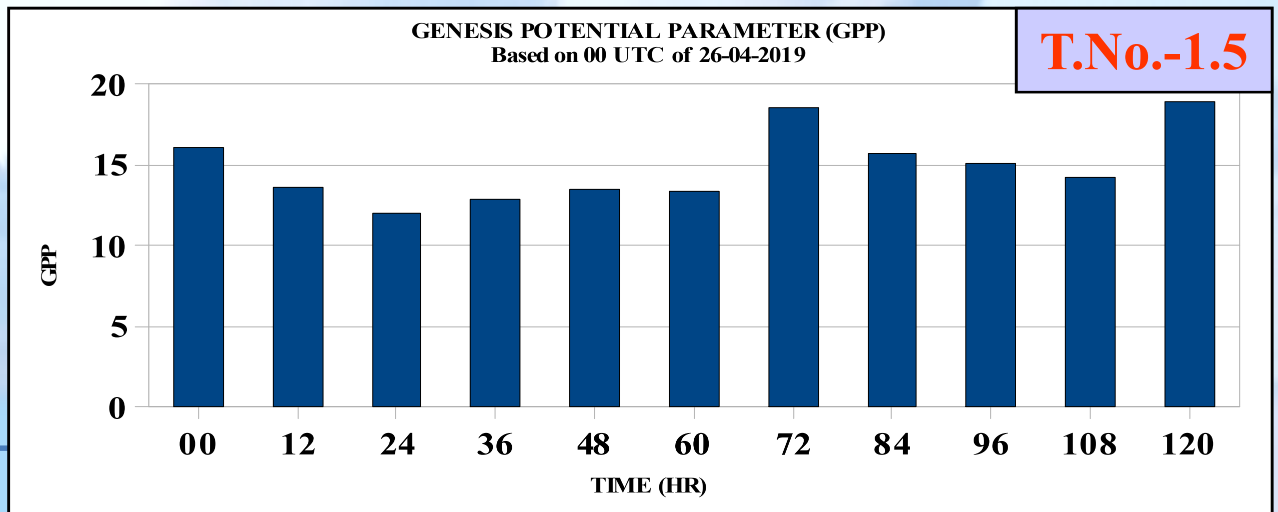

Tropical Cyclone Genesis Potential Parameter(GPP) (96 HR FORECAST)
Based on 23-04-2019 valid for 0000 UTC of 27-04-2019
(Potential Cyclogenesis Zone for GPP =>30)
96h


Tropical Cyclone Genesis Potential Parameter(GPP) (120 HR FORECAST)
Based on 22-04-2019 valid for 0000 UTC of 27-04-2019
(Potential Cyclogenesis Zone for GPP =>30)
120h

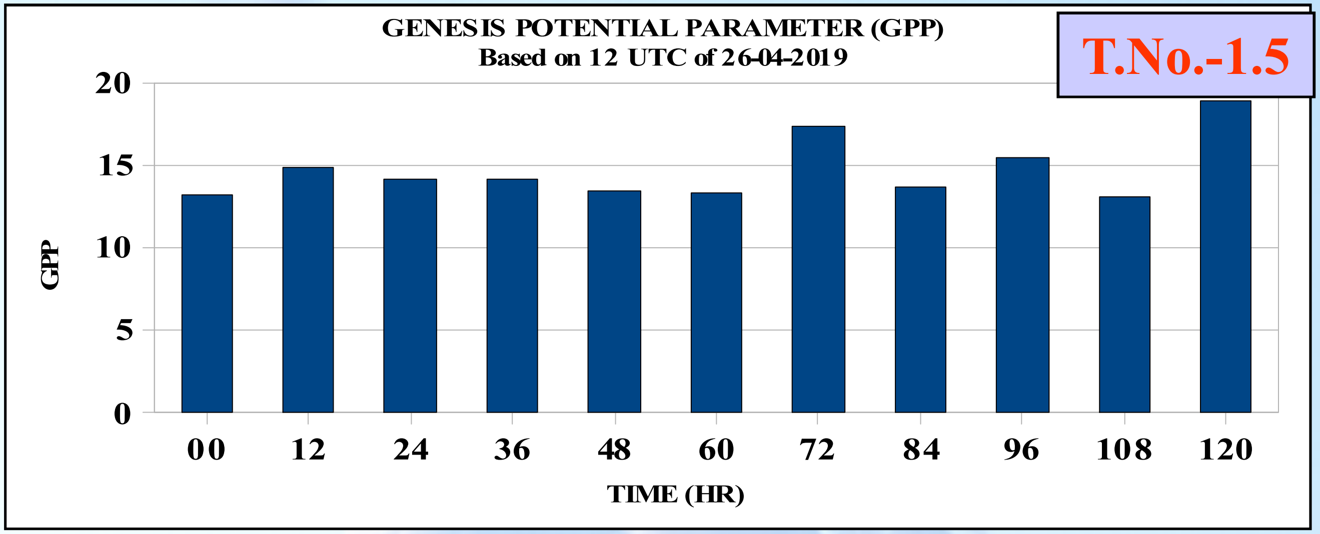
Mean GPP forecasts forecasts based on 00 UTC of 25.04.2019 (FANI)



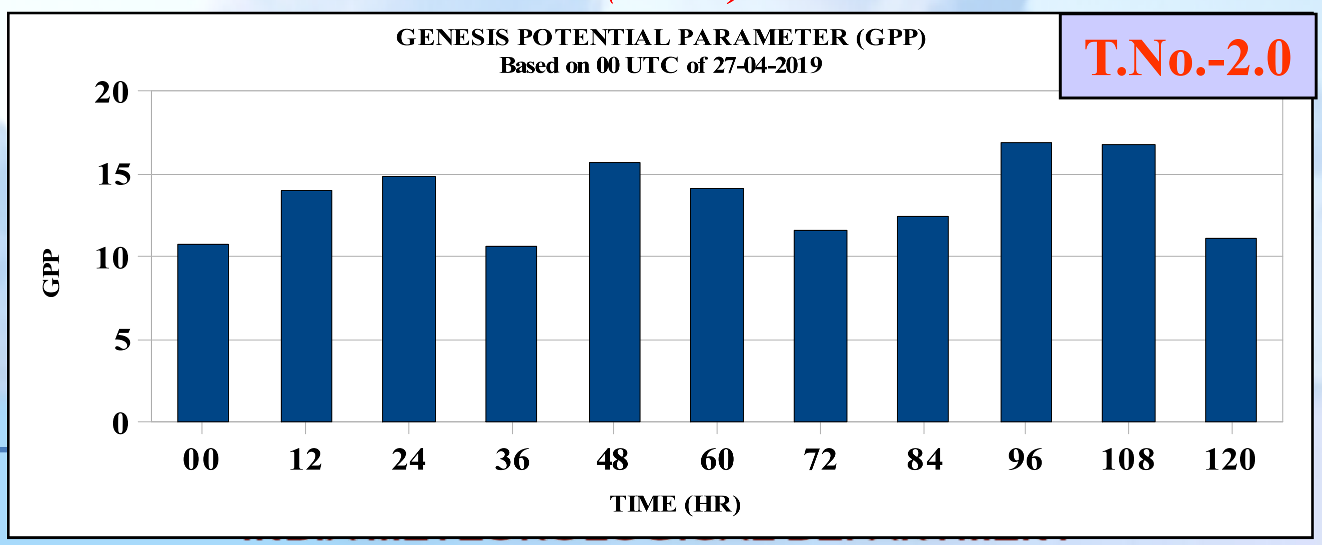
Mean GPP forecasts forecasts based on 00 UTC of 26.04.2019 (FANI)



Mean GPP forecasts forecasts based on 1200 UTC of 26.04.2019 (FANI)



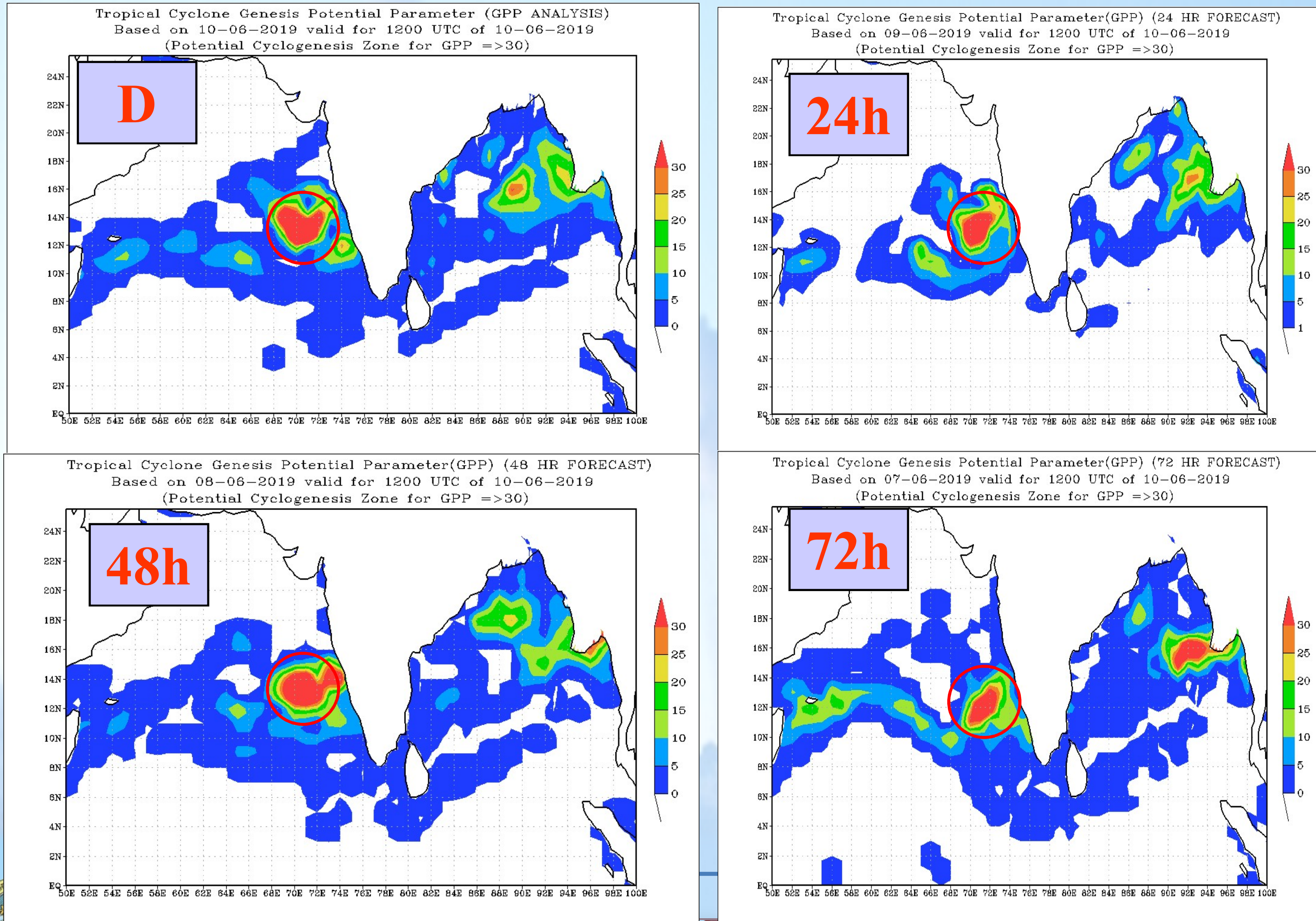
Mean GPP forecasts forecasts based on 0000 UTC of 27.04.2019 (FANI)

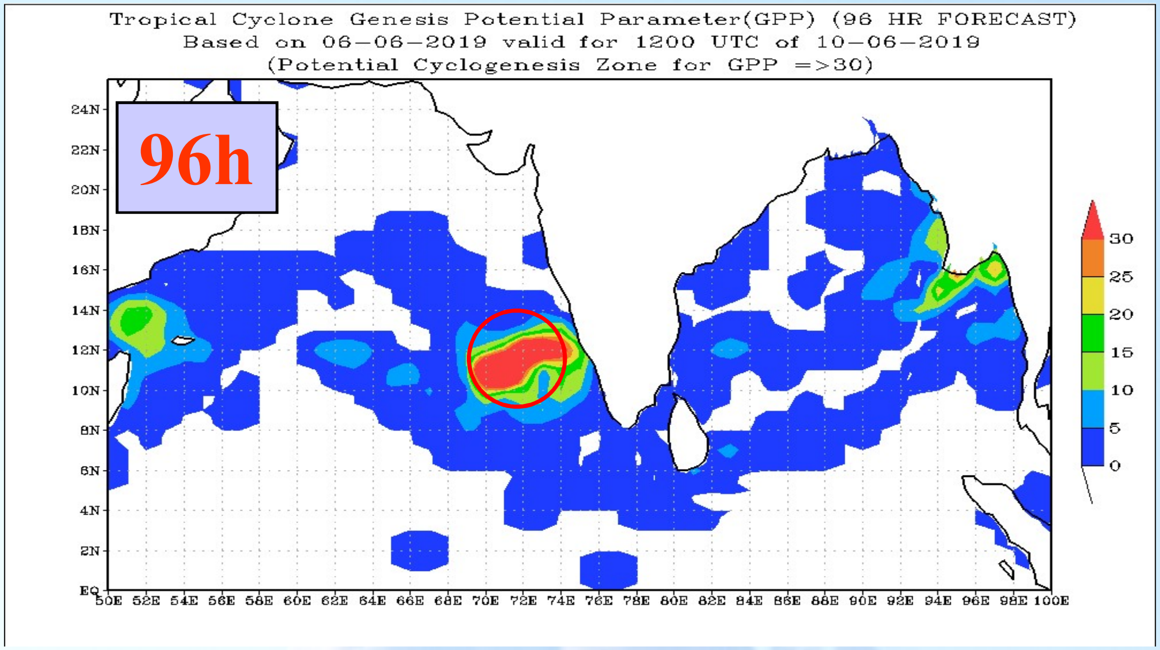


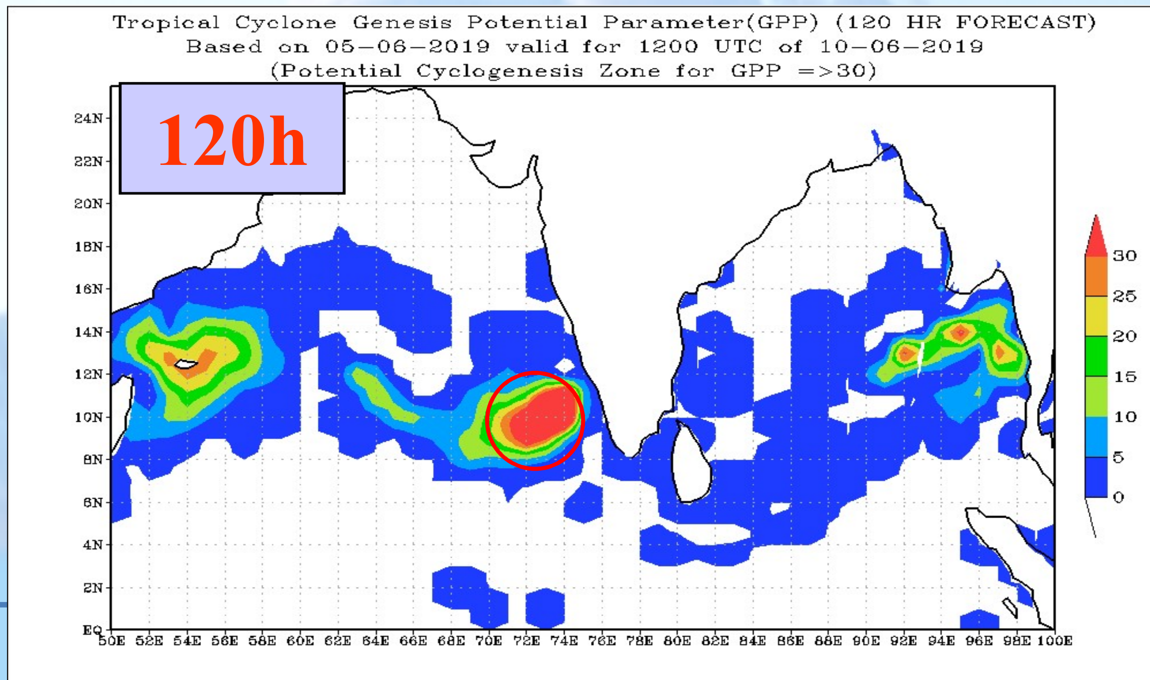
Very Severe Cyclonic Storm ‘VAYU’

Arabian Sea during (10-17) June 2019

Genesis potential parameter (VAYU)

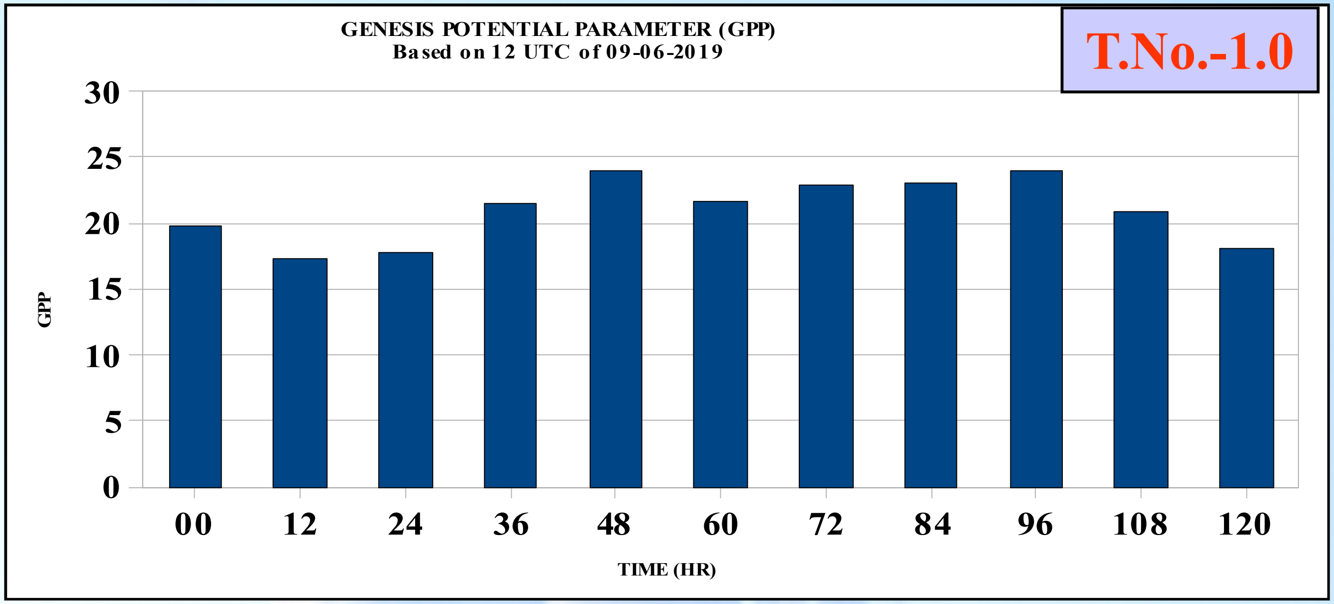


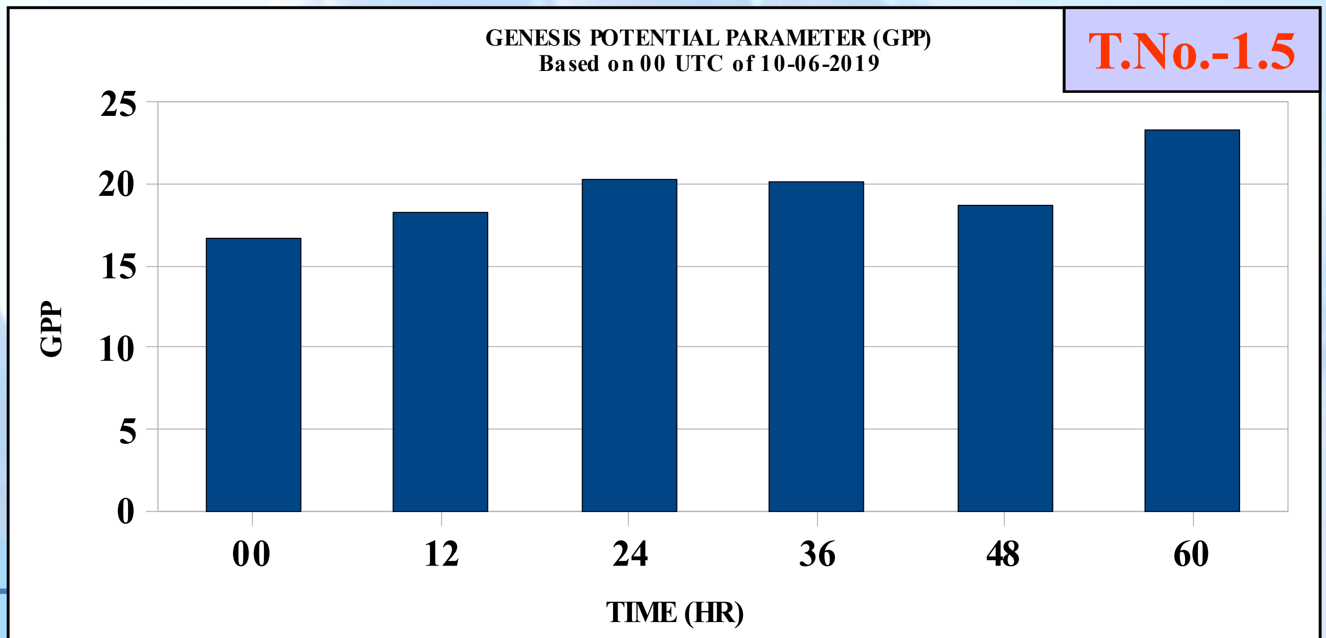


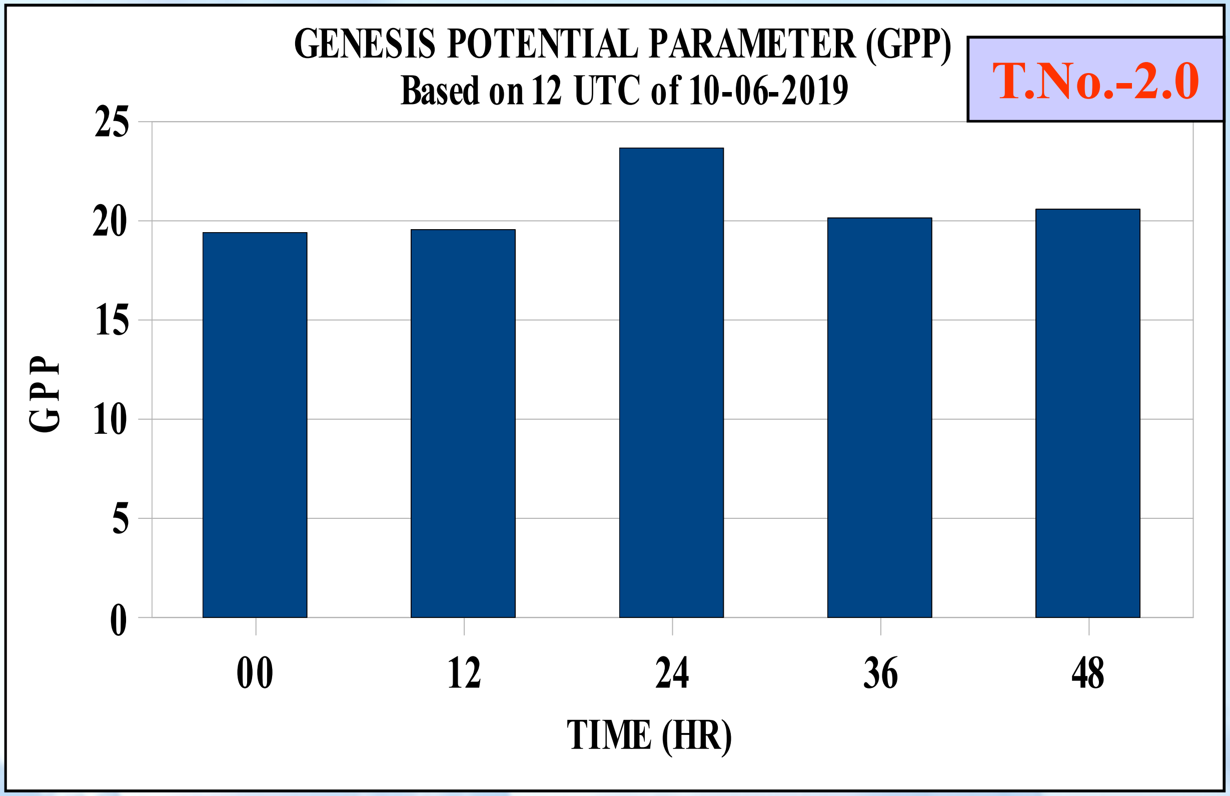


INDIA METEOROLOGICAL DEPARTMENT

Area average Genesis potential parameter (GPP)

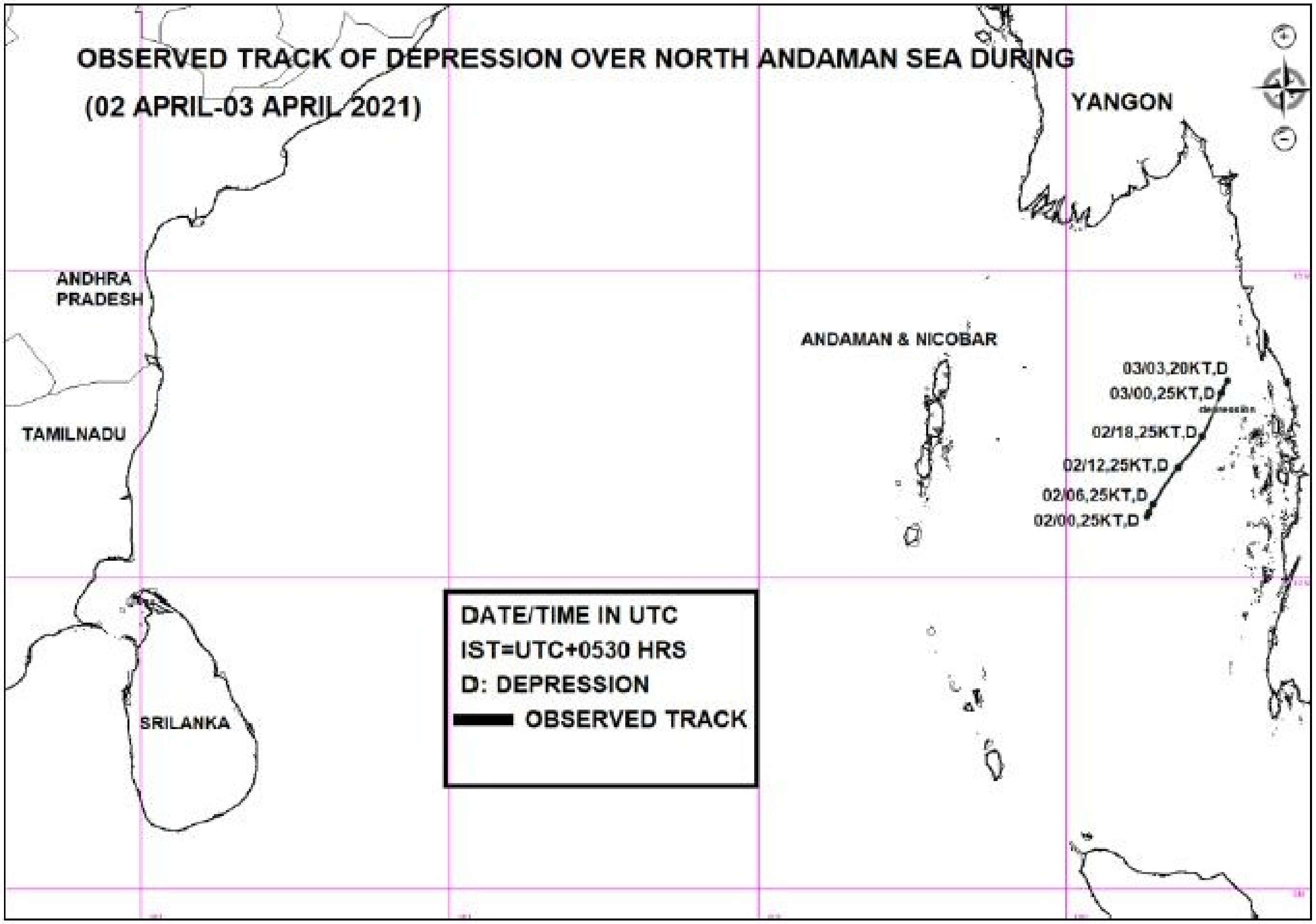




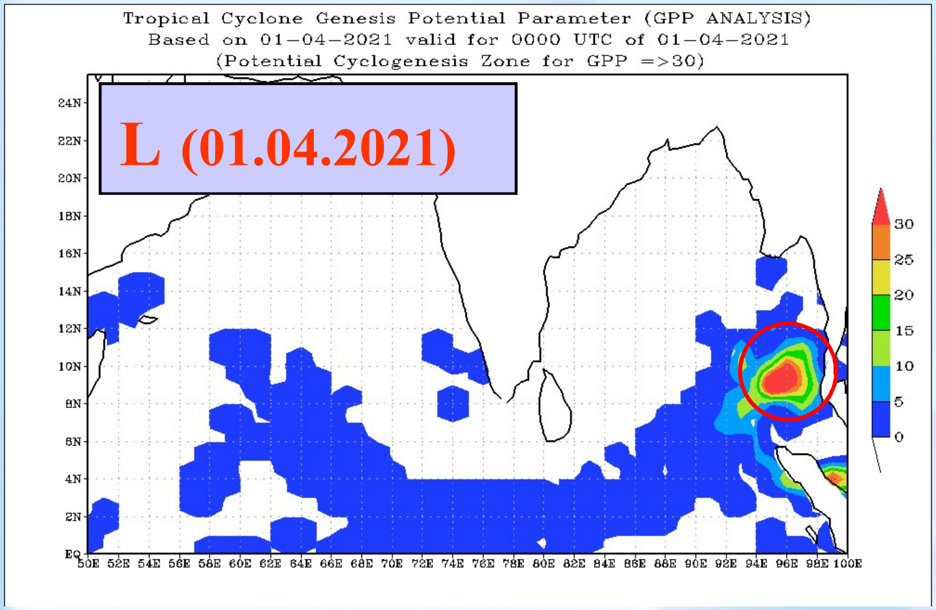

GENESIS POTENTIAL PARAMETER (GPP)
Based on 12 UTC of 10-06-2019
T.No.-2.0
25
20
15
10
5
0
GPP
00
12
24
36
48
TIME (HR)

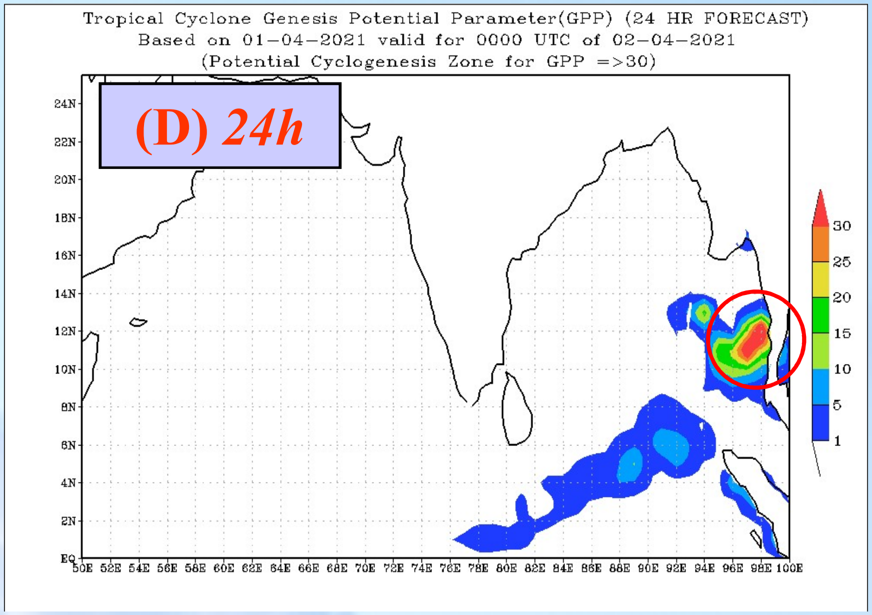
DEPRESSION over the Bay of Bengal during 2-3 April 2021

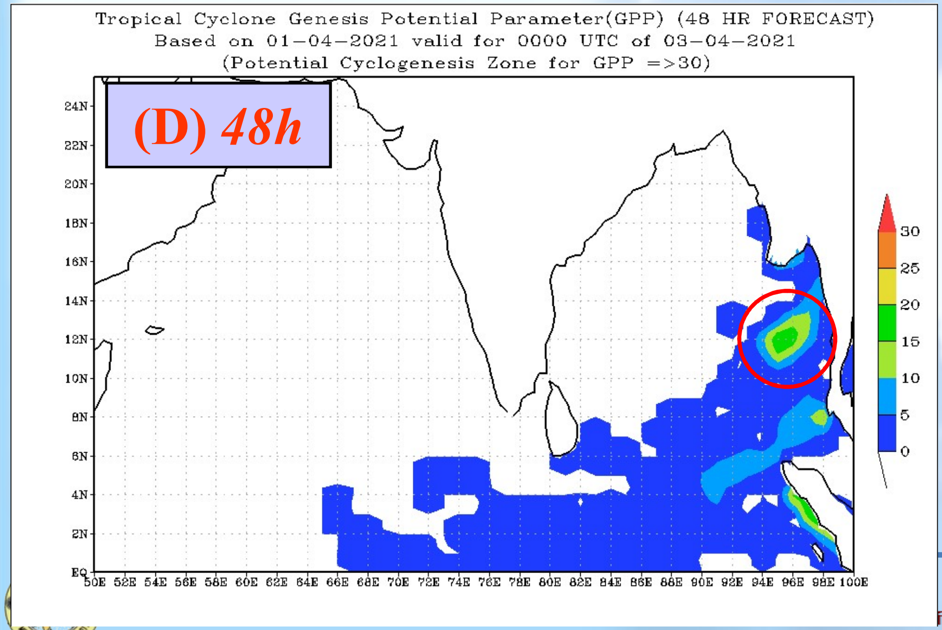
DEPRESSION over the Bay of Bengal during 2-3 April 2021

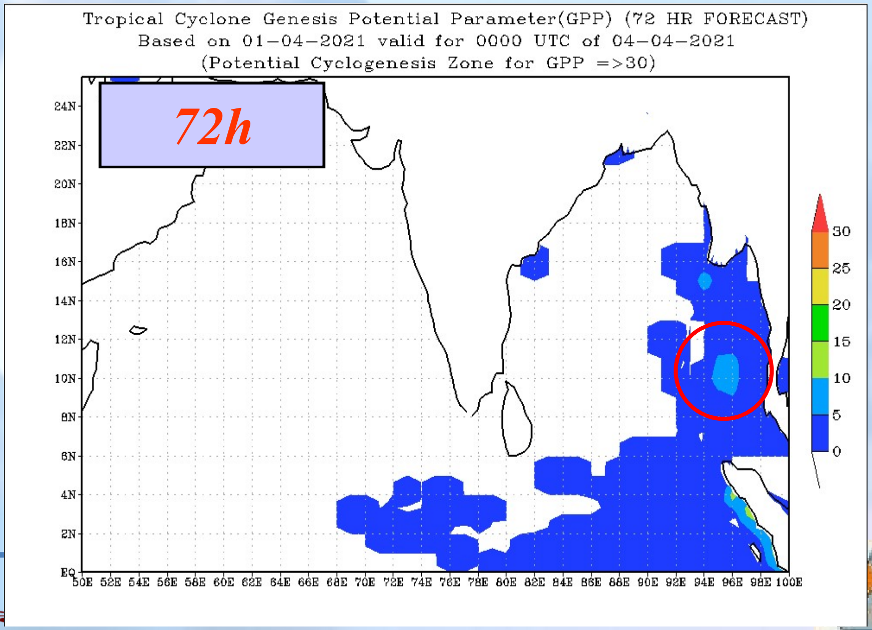


Genesis forecasts by GPP (DEPRESSION)





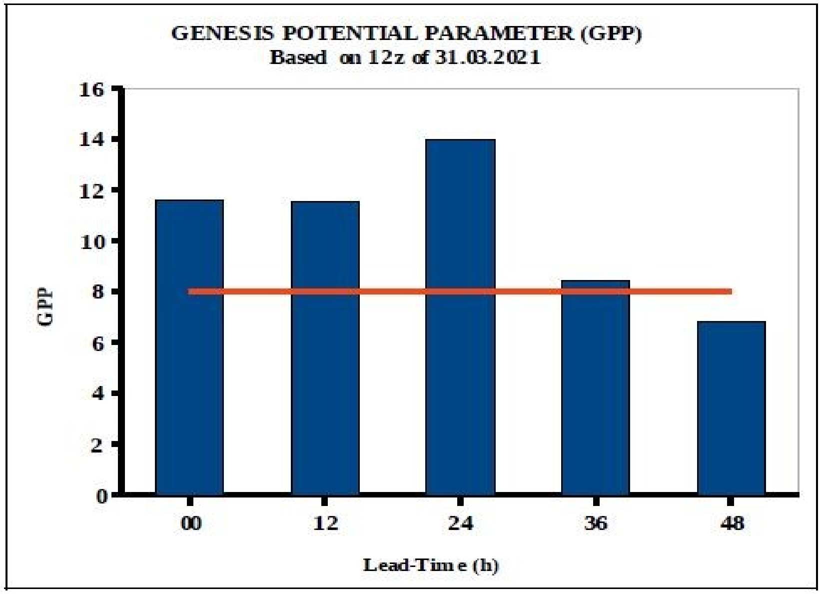


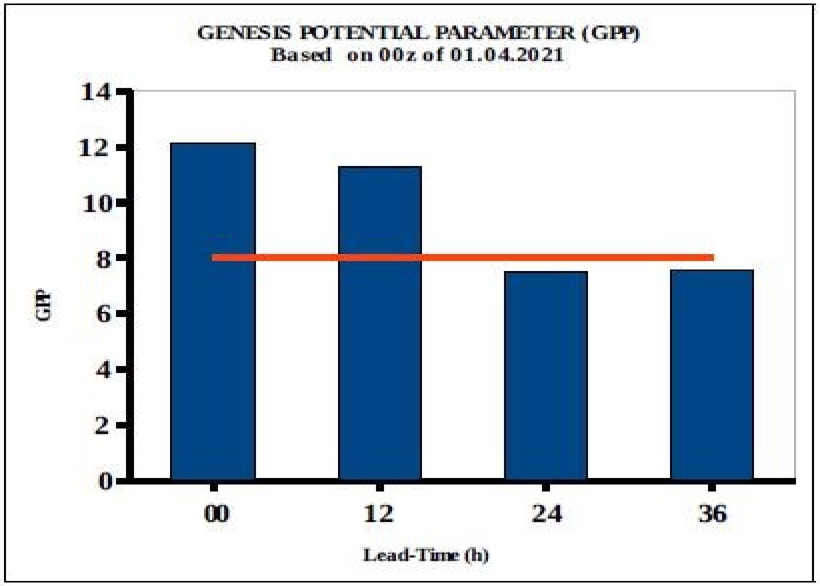


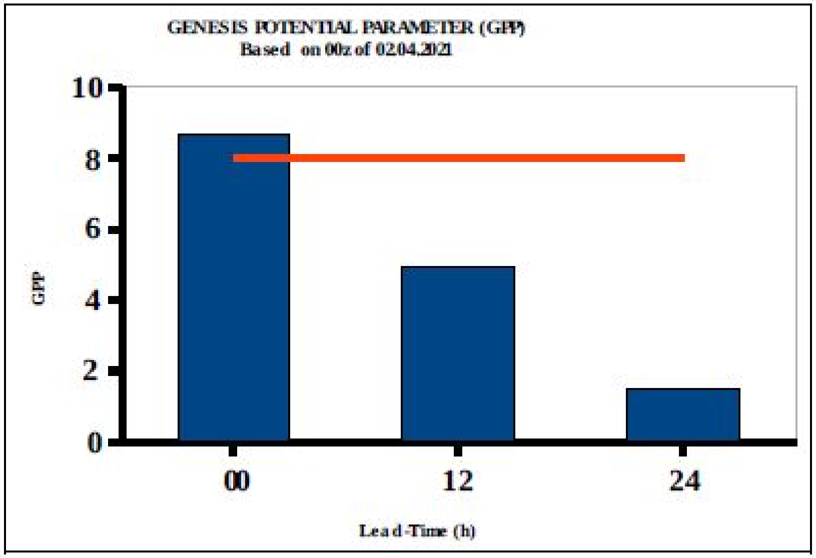
L(31.03.2021/12 UTC)

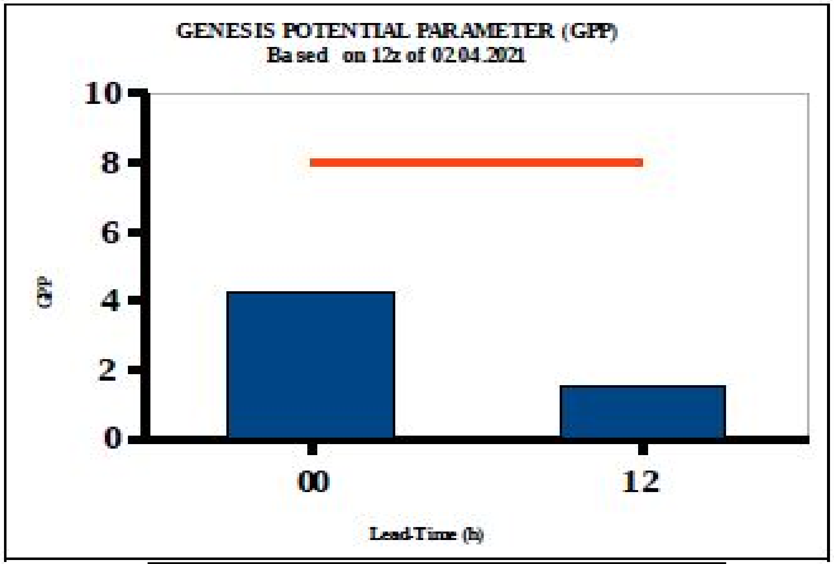
Genesis forecasts by GPP

L(01.04.2021/00 UTC)







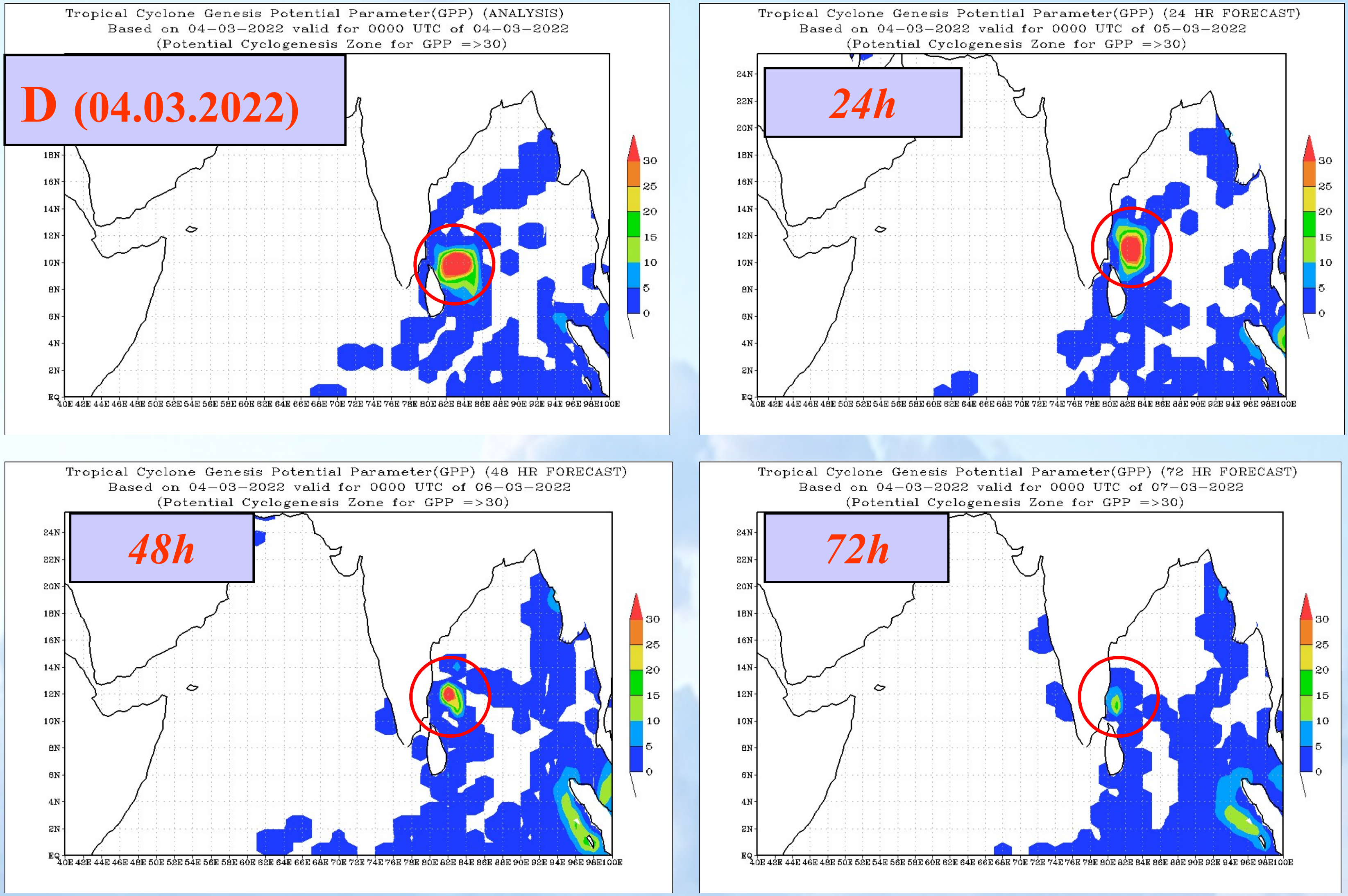


D(02.04.2021/00 UTC)

D(01.04.2021/12 UTC)

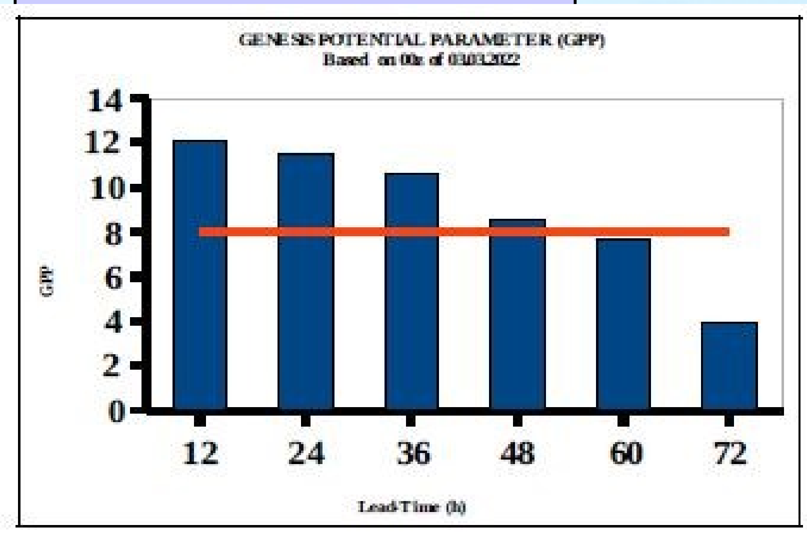
DEPRESSION over the Bay of Bengal during (4-6) March 2022

Genesis forecasts by GPP (DEPRESSION)

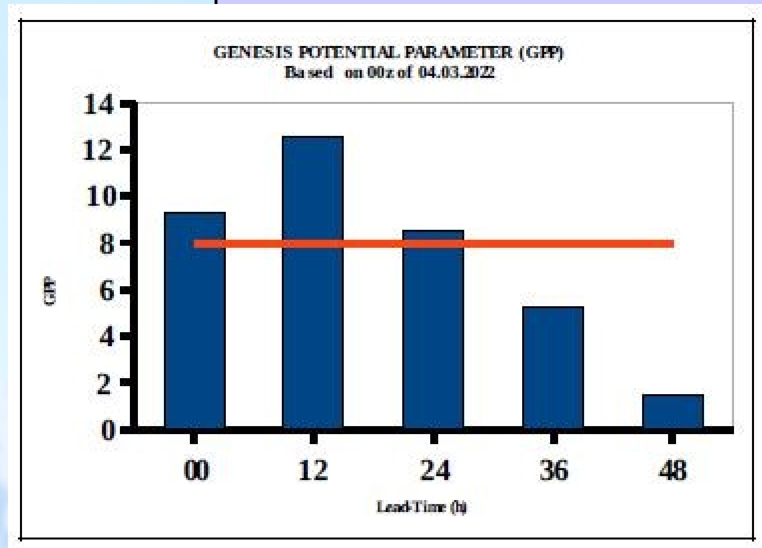


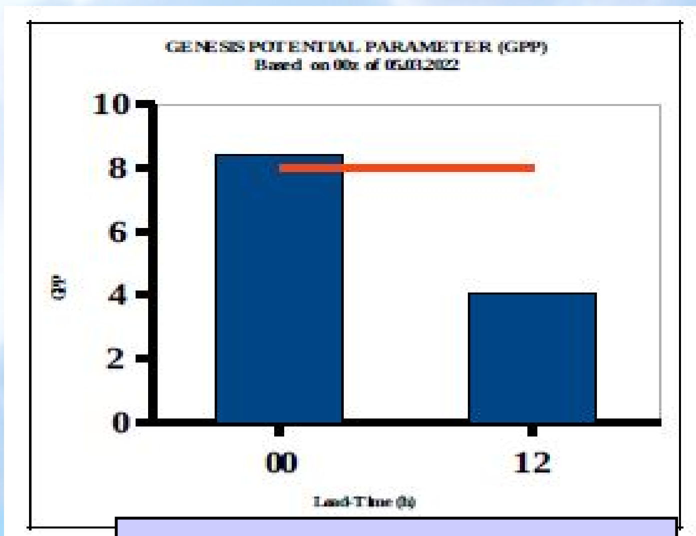
Genesis forecasts by GPP

L(03.03.2022/00 UTC)



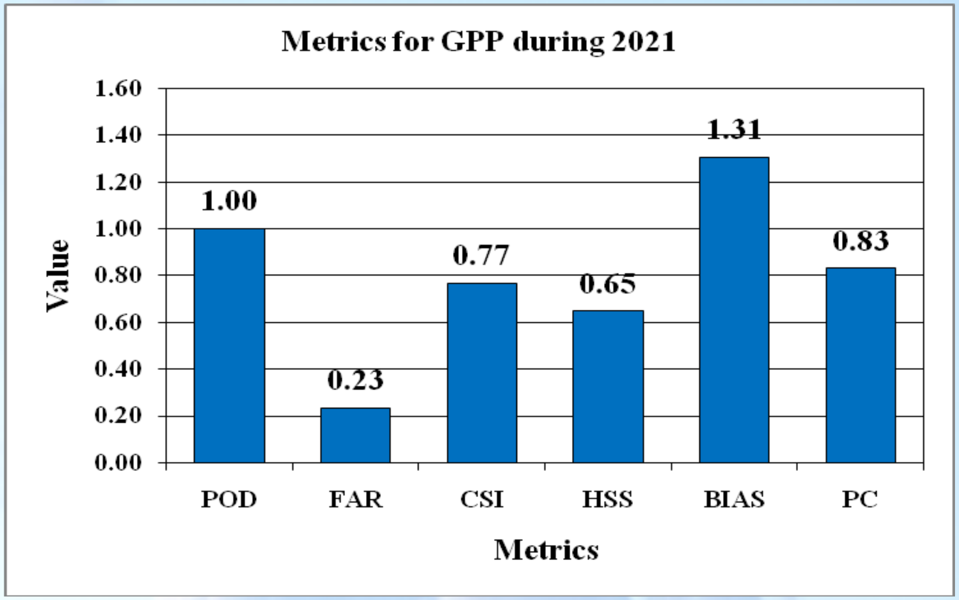
D(04.03.2022/00UTC



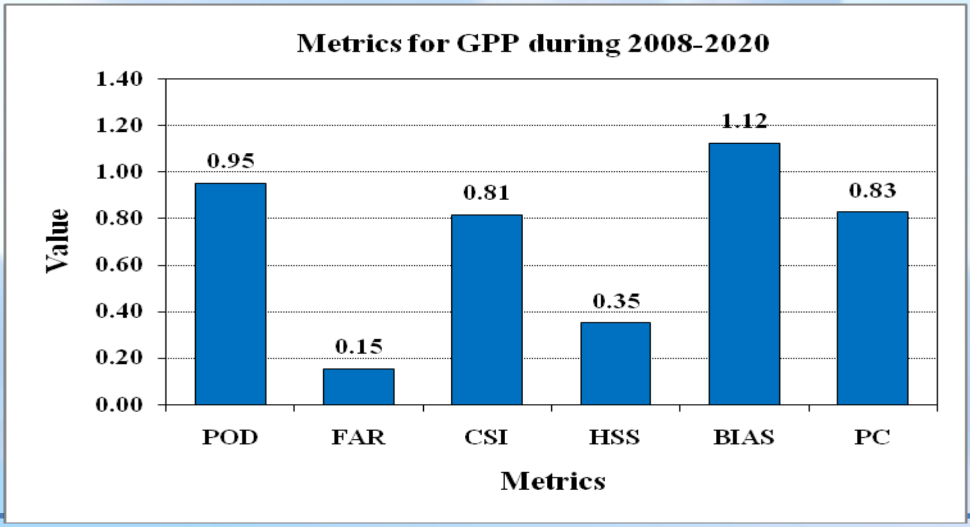


D(05.03.2022/00UTC UTC)

Forecast Skill of Genesis potential parameter (GPP) during 2021



Forecast Skill of Genesis potential parameter (GPP) during 2008-2020

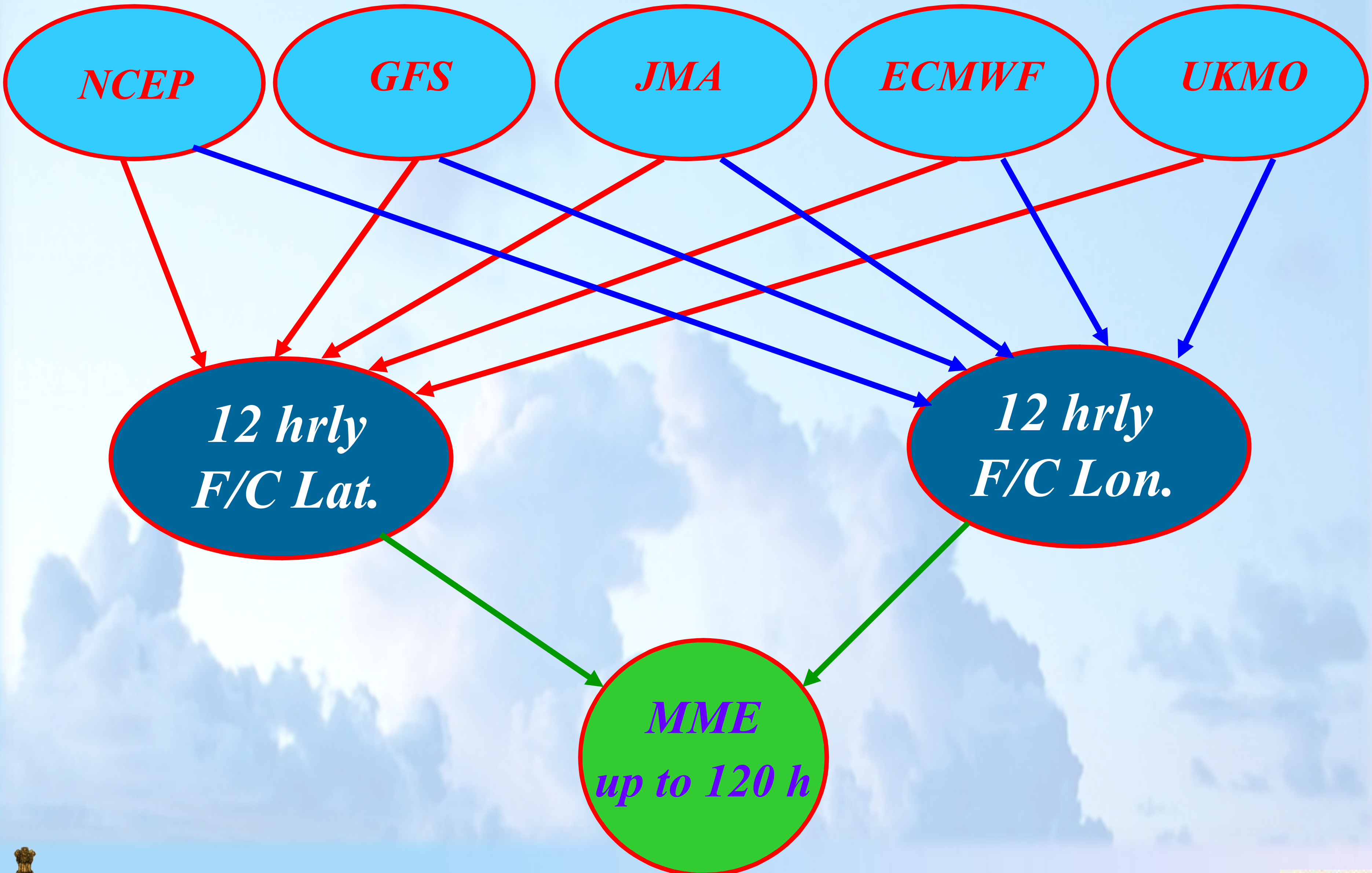


STEP-II: TRACK PREDICTION BY MME

[Kotal, S.D. and Roy Bhowmik S.K. 2011. A Multimodel Ensemble (MME) Technique for Cyclone Track Prediction over the North Indian Sea. *Geofizika*, 28(2): 275-291]

Objective: To generate a consensus track forecast of NWP models by collective bias correction

TRACK PREDICTION BY NWP MODELS AND MME



MME Cyclone Track Prediction

12-hourly forecast latitude (LAT^f) and longitude (LON^f) positions at time t is defined as:

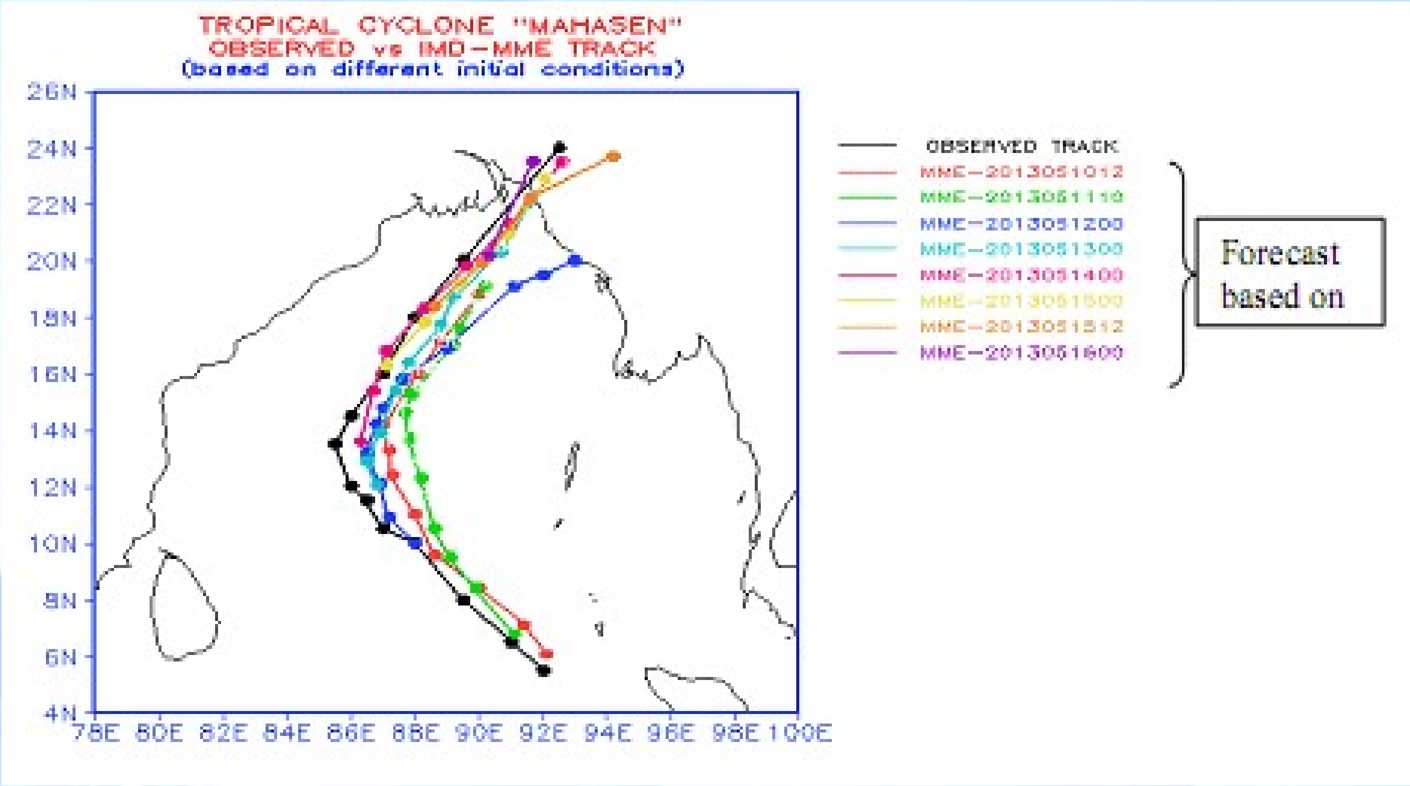
$$LAT^f_t = a_o + a_1 NCEP_t^{lat} + a_2 GFS_t^{lat} + a_3 JMA_t^{lat} + a_4 ECMWF_t^{lat} + a_5 UKMO_t^{lat}$$

$$LON^f_t = a'_o + a'_1 NCEP_t^{lon} + a'_2 GFS_t^{lon} + a'_3 JMA_t^{lon} + a'_4 ECMWF_t^{lon} + a'_5 UKMO_t^{lon}$$

for t = forecast hour 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 h

VIYARU
(Bay of Bengal May 2012)

MME track forecasts based on different initial conditions

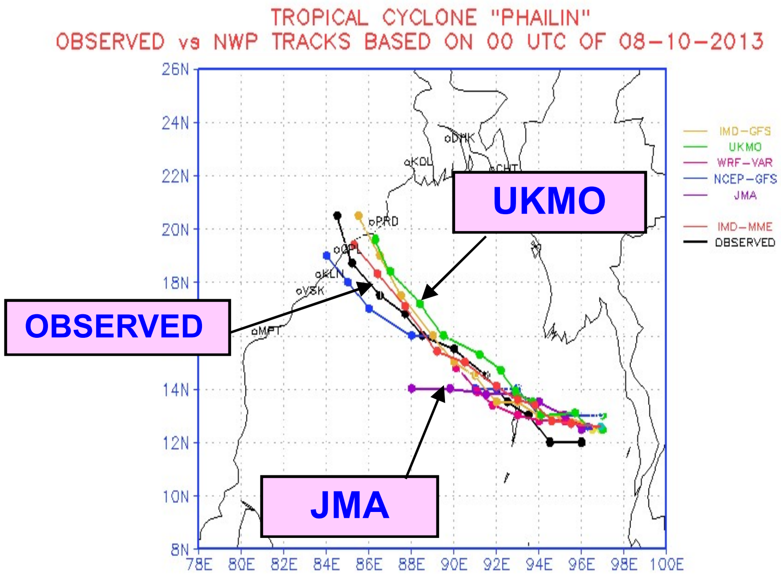


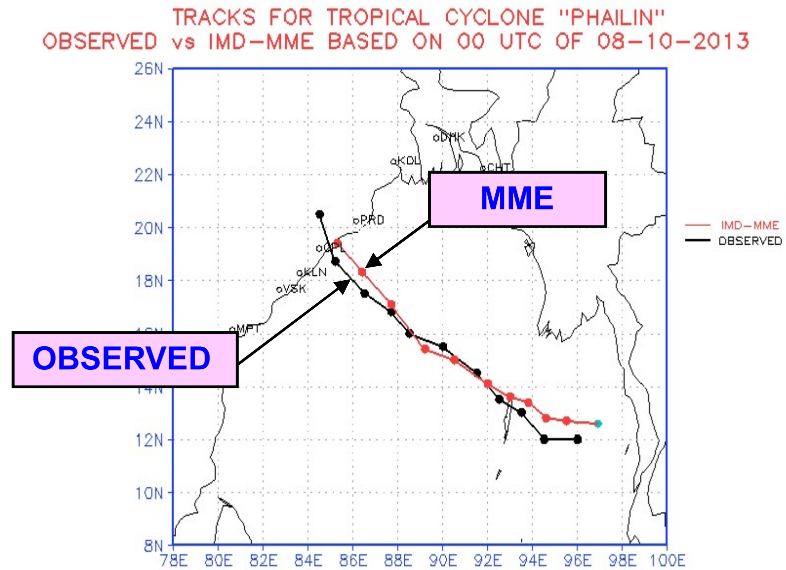
Landfall point error (km)- VIYARU

Model	FC based on 00 UTC/14.05.2013	FC based on 00 UTC/15.05.2013	FC based on 12 UTC/15.05.2013	FC based on 00 UTC/16.05.2013
	Lead time: 56 h	Lead time: 32 h	Lead time: 20 h	Lead time: 8 h
IMD-GFS	NO LF	NO LF	136	-
IMD-WRF	NO LF	147	49	45
IMD-QLM	NO LF	63	137	243
JMA	137	63	98	49
NCEP-GFS	289	169	136	136
ECMWF	259	274	127	15
IMD-MME	63	63	63	25
IMD-HWRF	84	174	121	-

PHAILIN
(Bay of Bengal October 2013)

NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 00 UTC of 08.10.2013 for cyclone PHAILIN

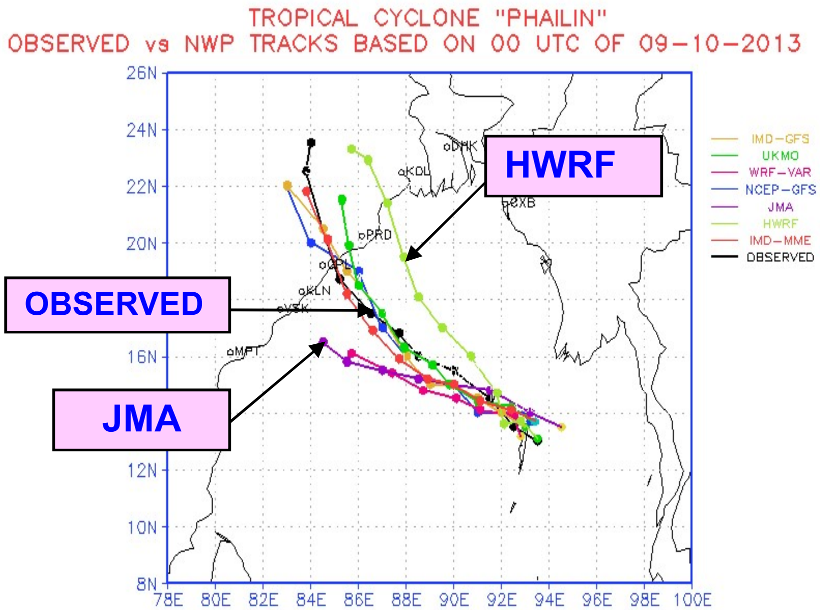


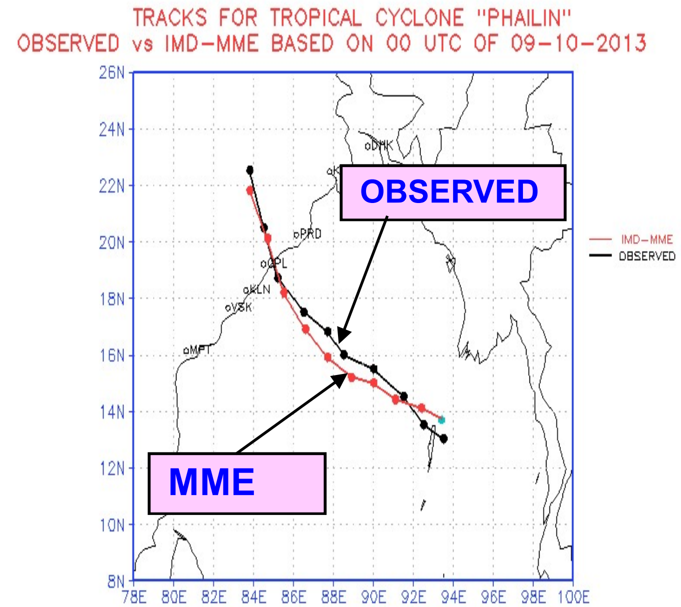


All model landfall point forecasts varied from north AP to Paradip(Odisha)

Consensus track forecast correctly predicted landfall at GOPALPUR(Odisha)

NWP model and Multi-model ensemble track forecasts based on 00 UTC of 09.10.2013

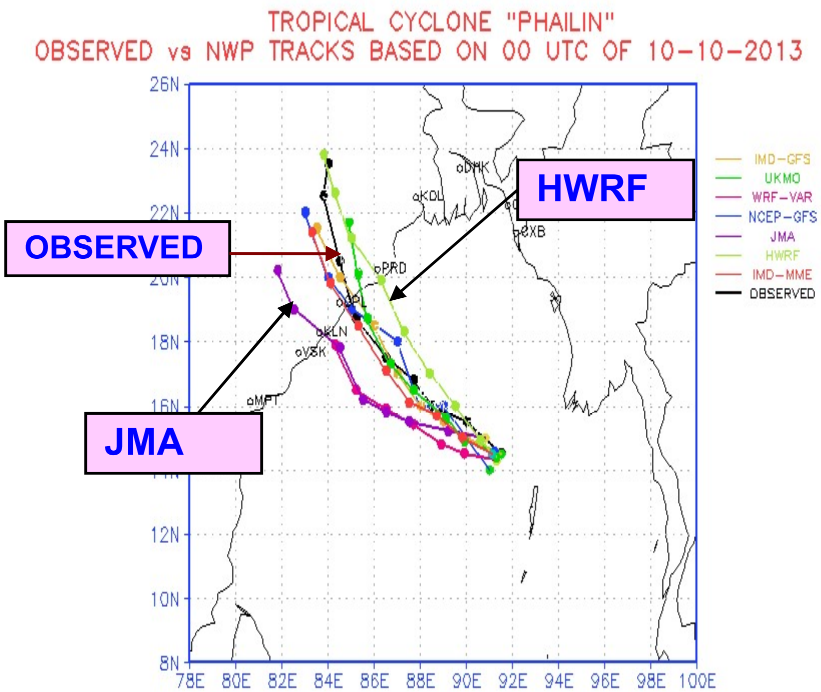


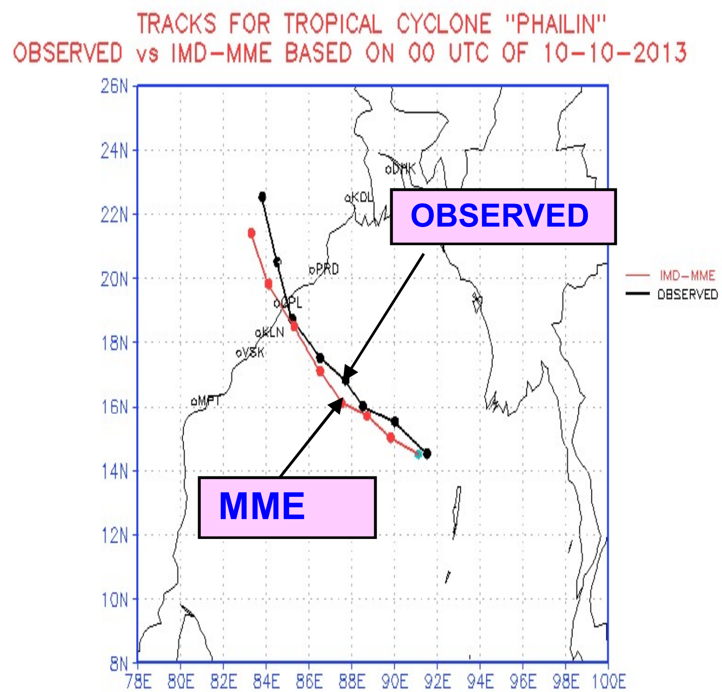


All model landfall point forecasts varied from North AP to Sagar Island(west Bengal)

Consensus track forecast correctly predicted landfall at GOPALPUR

NWP model and Multi-model ensemble track forecasts based on 00 UTC of 10.10.2013

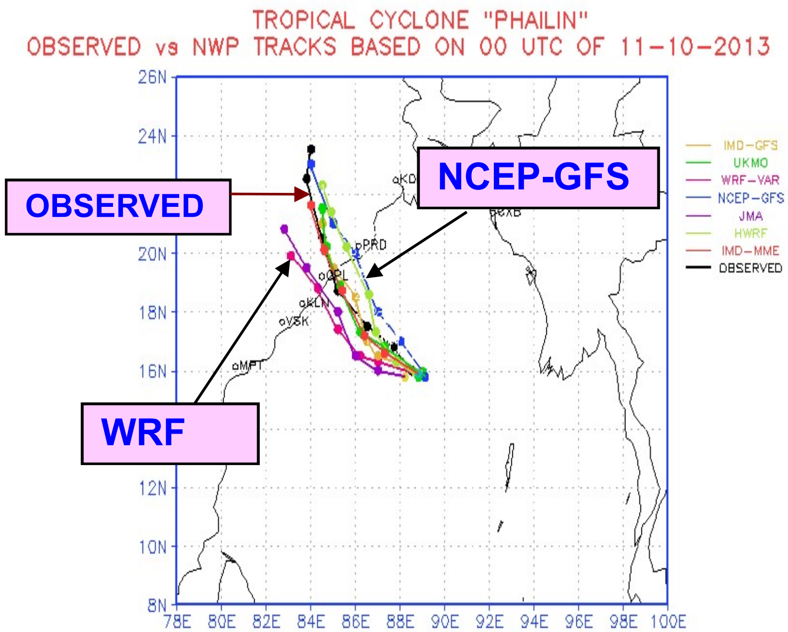


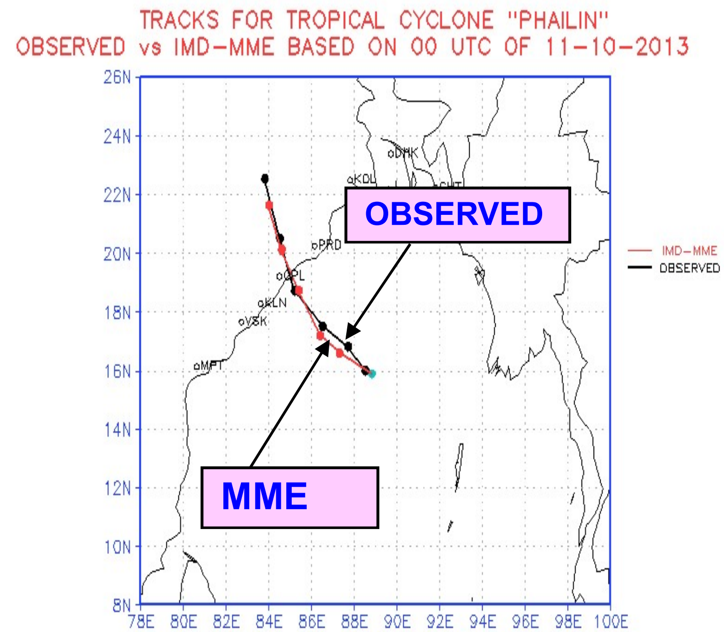


All model landfall point forecasts varied from Kalingapattanam(North AP) to Paradip(Odisha)

Consensus track forecast correctly predicted landfall at GOPALPUR

NWP model and Multi-model ensemble track forecasts based on 00 UTC of 11.10.2013

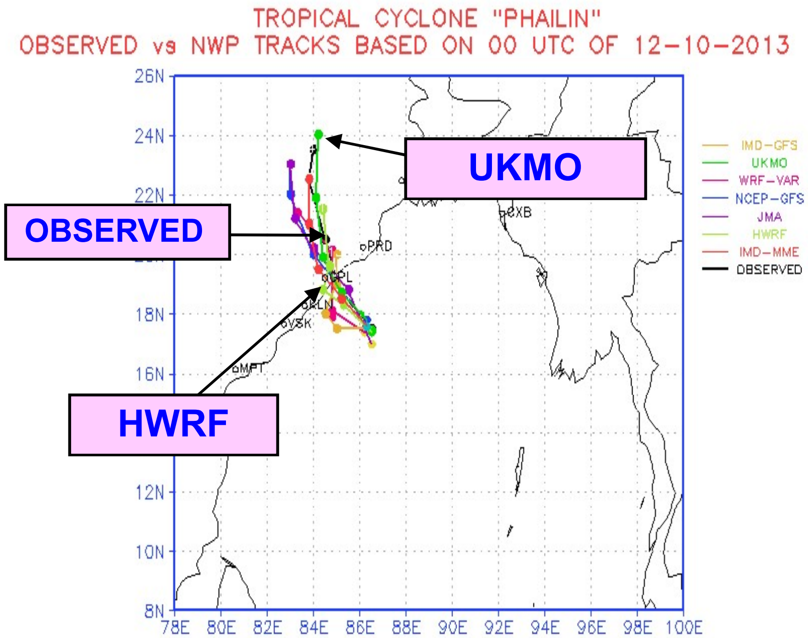


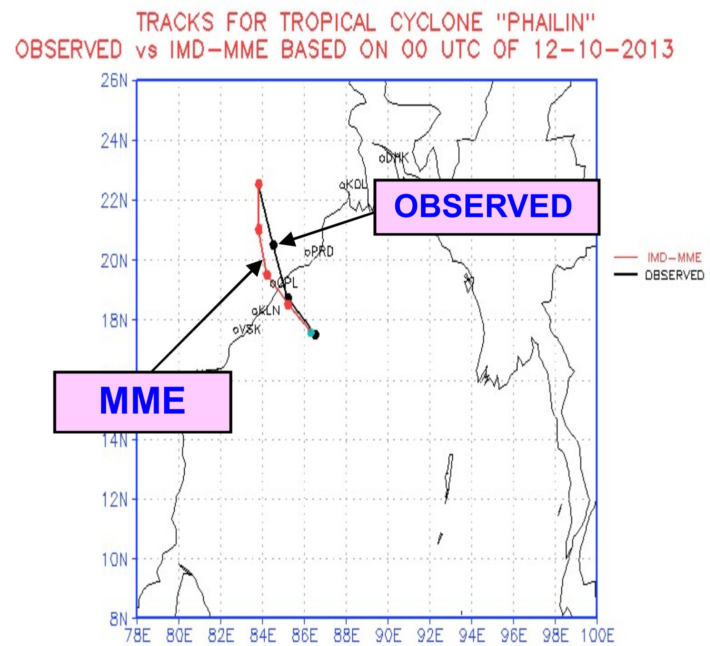


All model landfall point forecasts varied from Kalingapattanam(North AP) to Paradip(Odisha)

Consensus track forecast correctly predicted landfall at GOPALPUR

NWP model and Multi-model ensemble track forecasts based on 00 UTC of 12.10.2013

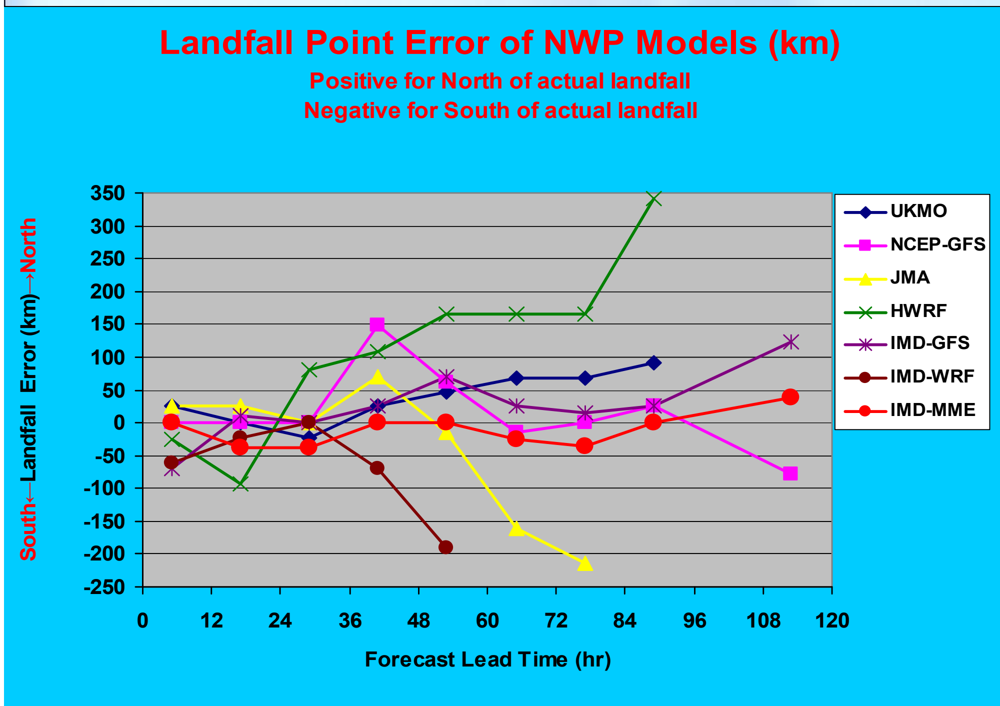


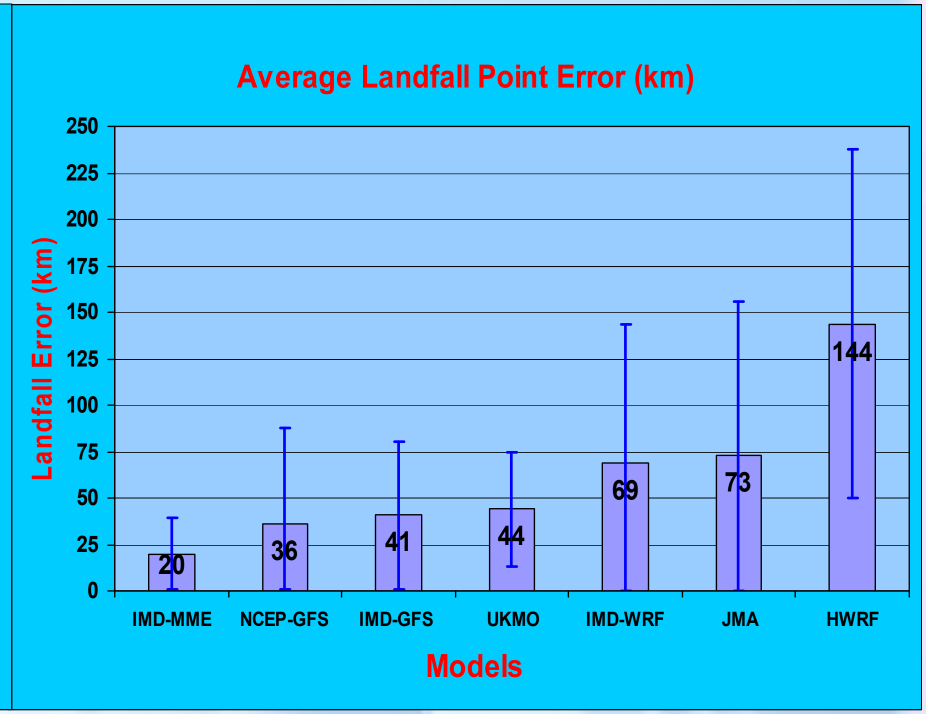


All model landfall point forecasts varied from Kalingapattanam(North AP) to Gopalpur(Odisha)

Consensus track forecast correctly predicted landfall at GOPALPUR

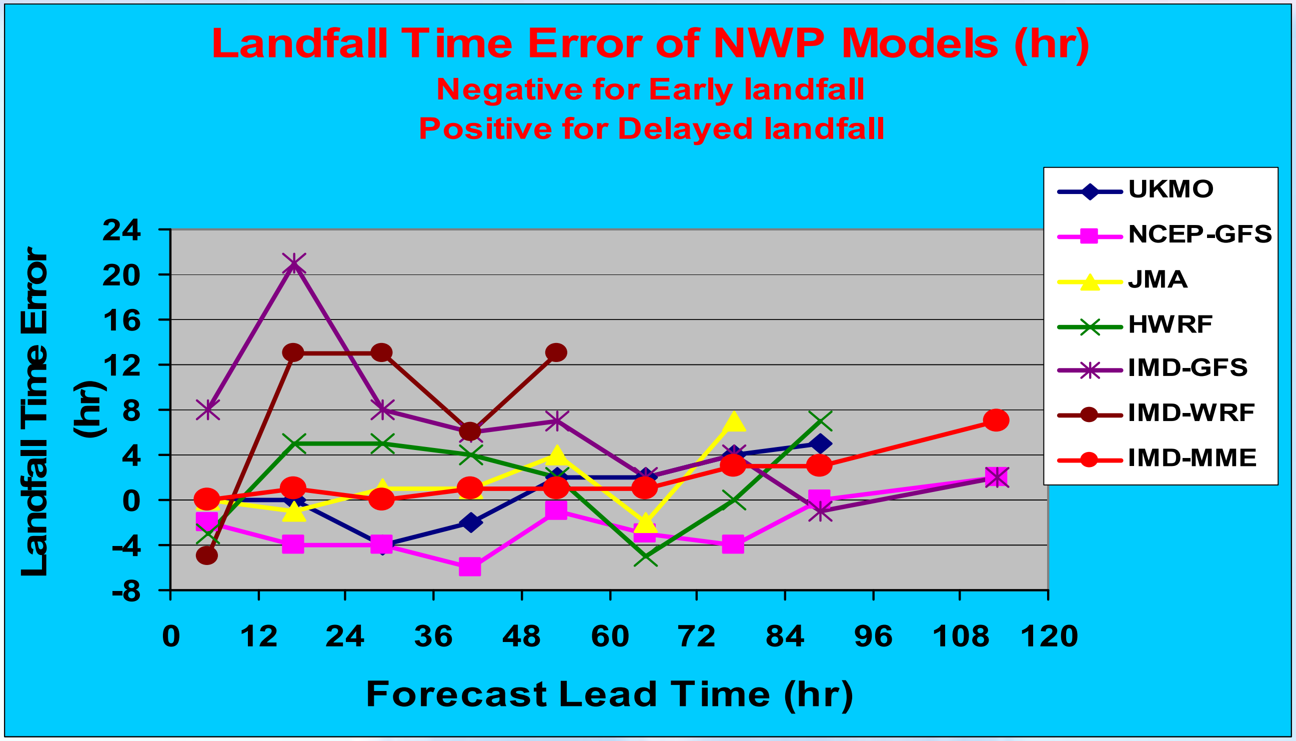
Landfall Point Error (km) of NWP Models

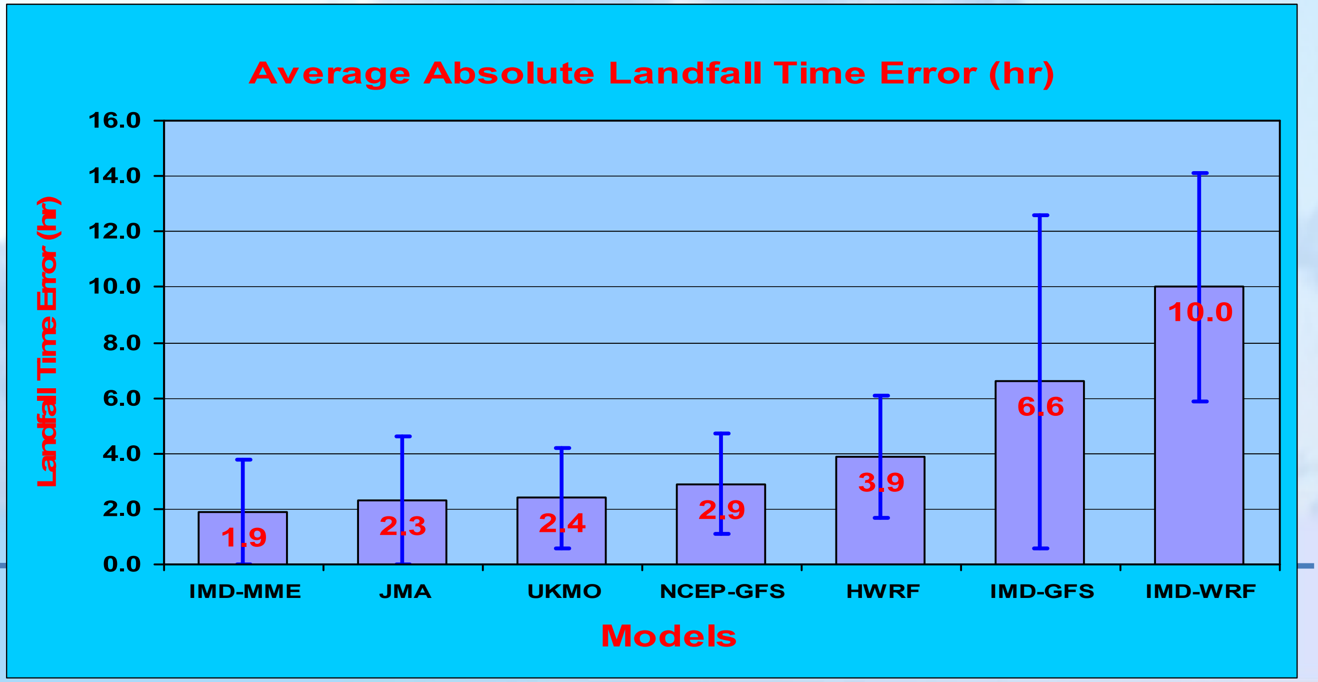




MME landfall forecast errors were consistently low at all lead time

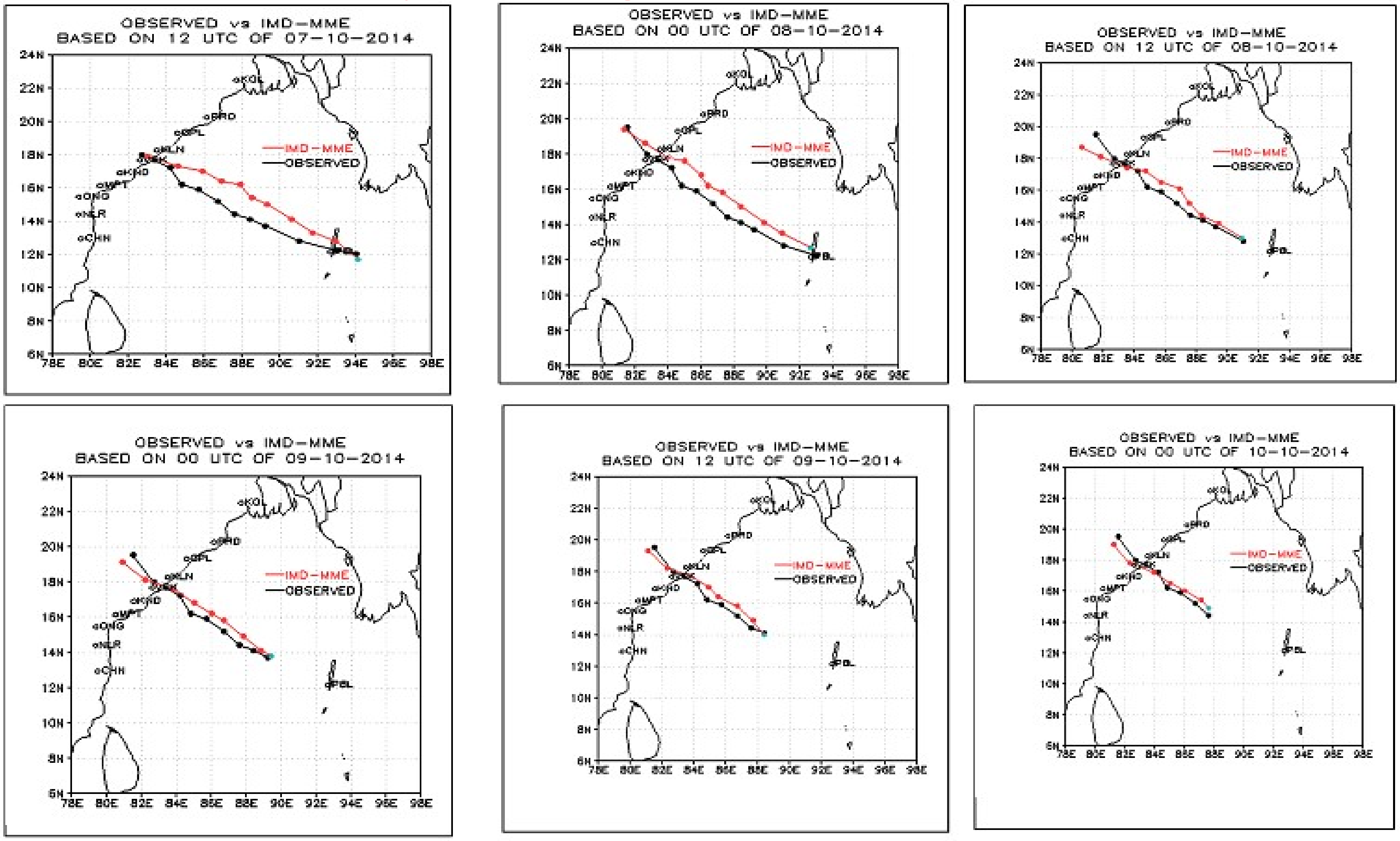
Average landfall forecast error was lowest for MME


Landfall Time Error of NWP Models (hr)
Negative for Early landfall
Positive for Delayed landfall
UKMO
NCEP-GFS
JMA
HWRF
IMD-GFS
IMD-WRF
IMD-MME
Landfall Time Error (hr)
Forecast Lead Time (hr)

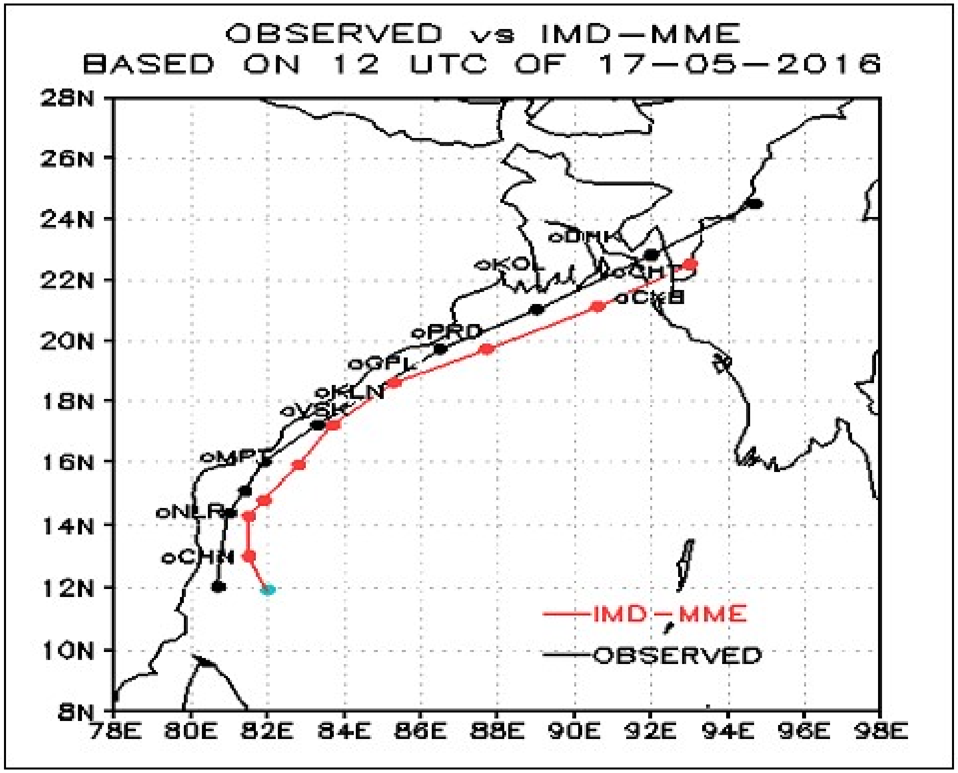

Average Absolute Landfall Time Error (hr)
Landfall Time Error (hr)
1.9
2.3
2.4
2.9
3.9
6.6
10.0
IMD-MME
JMA
UKMO
NCEP-GFS
HWRF
IMD-GFS
IMD-WRF
Models

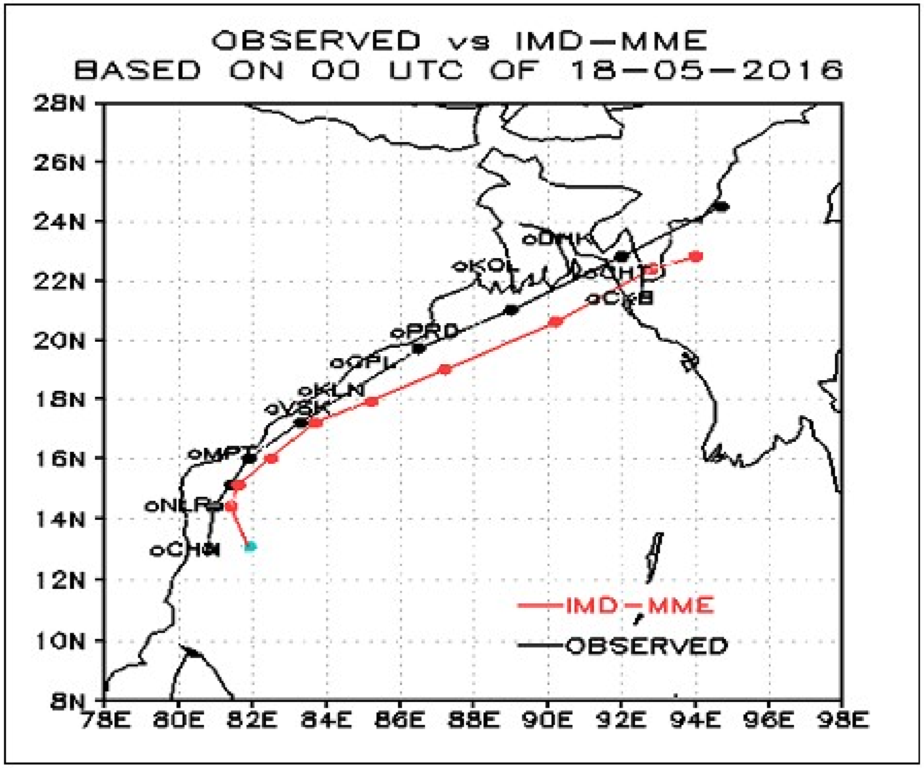
MME forecasts track for cyclone HUDHUD

(Bay of Bengal October 2014)



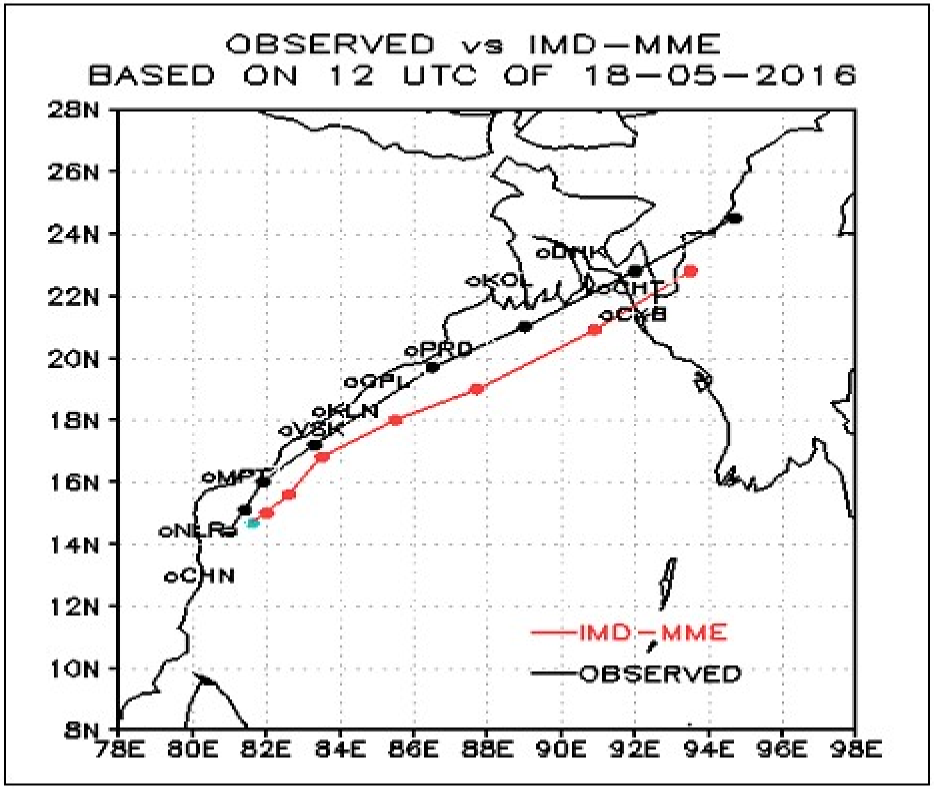
NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 12 UTC of 17.05.2016 and 00 UTC of 18.05.2016 for cyclone ROANU (Landfall Time-10 UTC 21.5.2016)



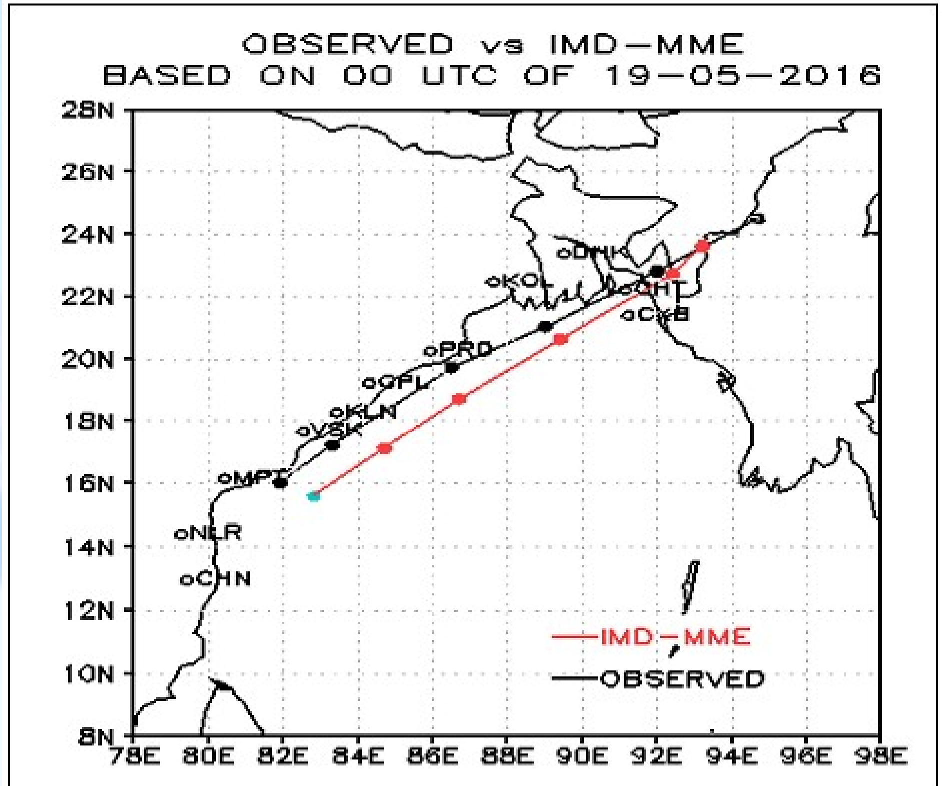


Landfall forecast Lead Time -94 h	***Landfall forecast Lead Time -82 h***

NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 12 UTC of 18.05.2016 and 00 UTC of 19.05.2016 for cyclone ROANU

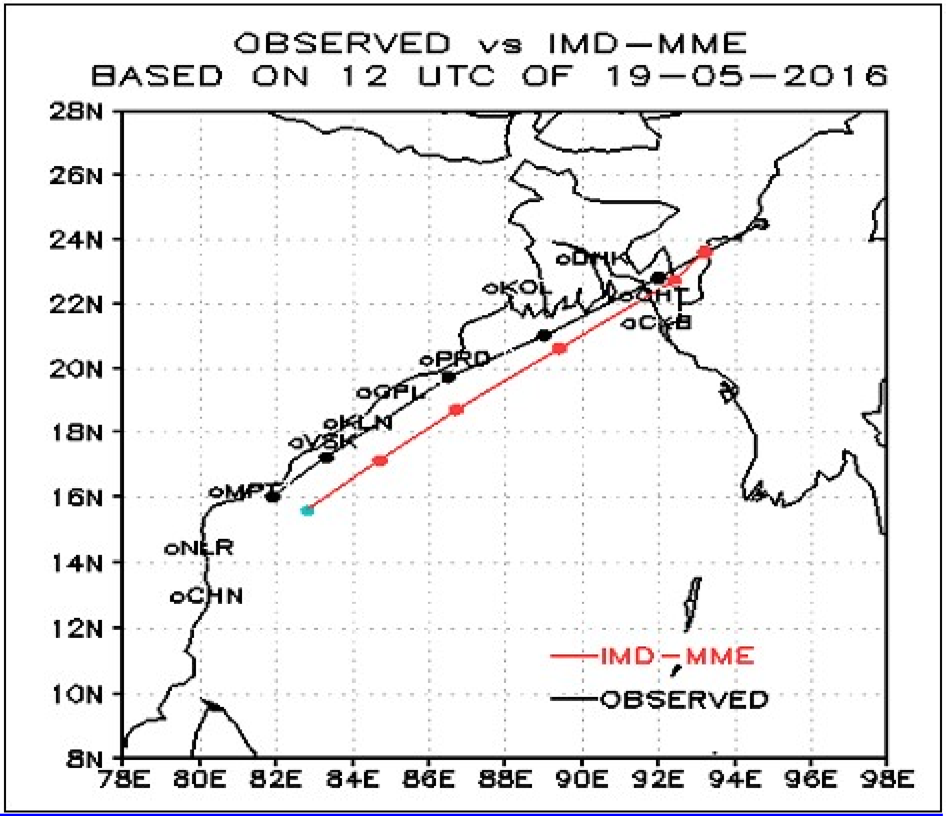


Landfall forecast Lead Time -70 h

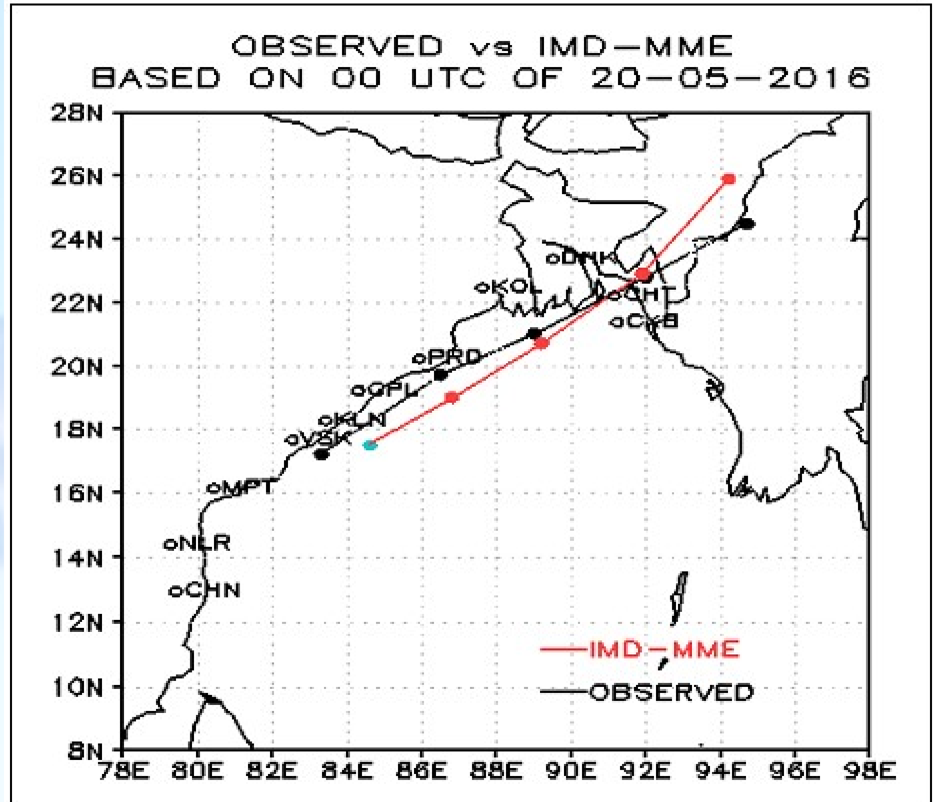


Landfall forecast Lead Time -58 h

NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 12 UTC of 19.05.2016 and 00 UTC of 20.05.2016 for cyclone ROANU

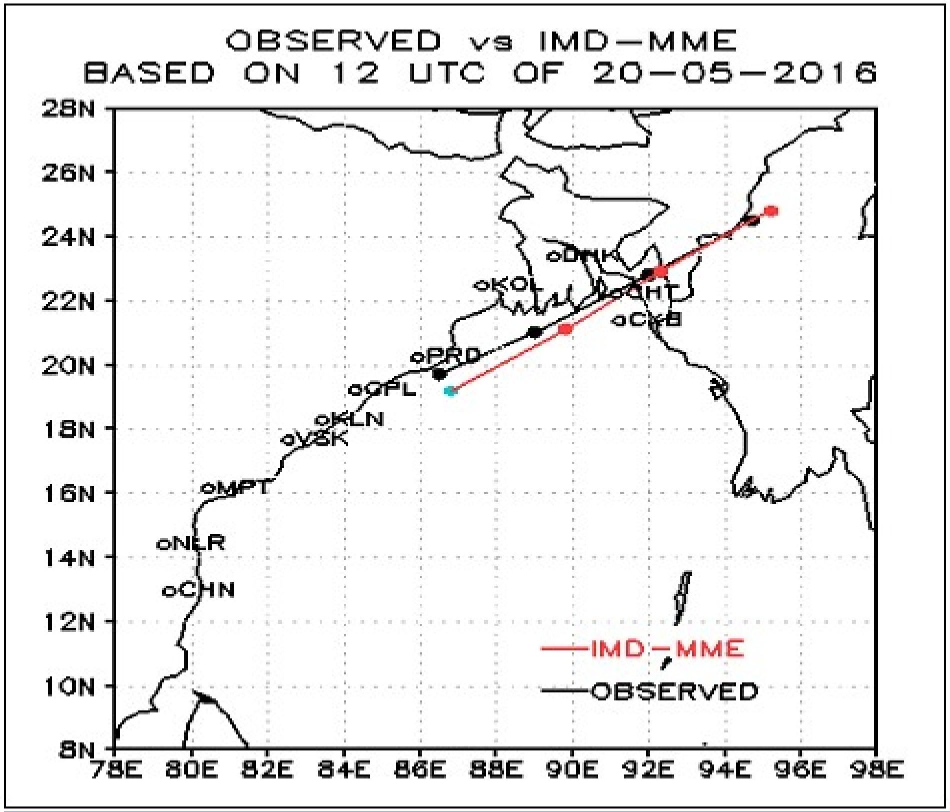


Landfall forecast Lead Time -46 h

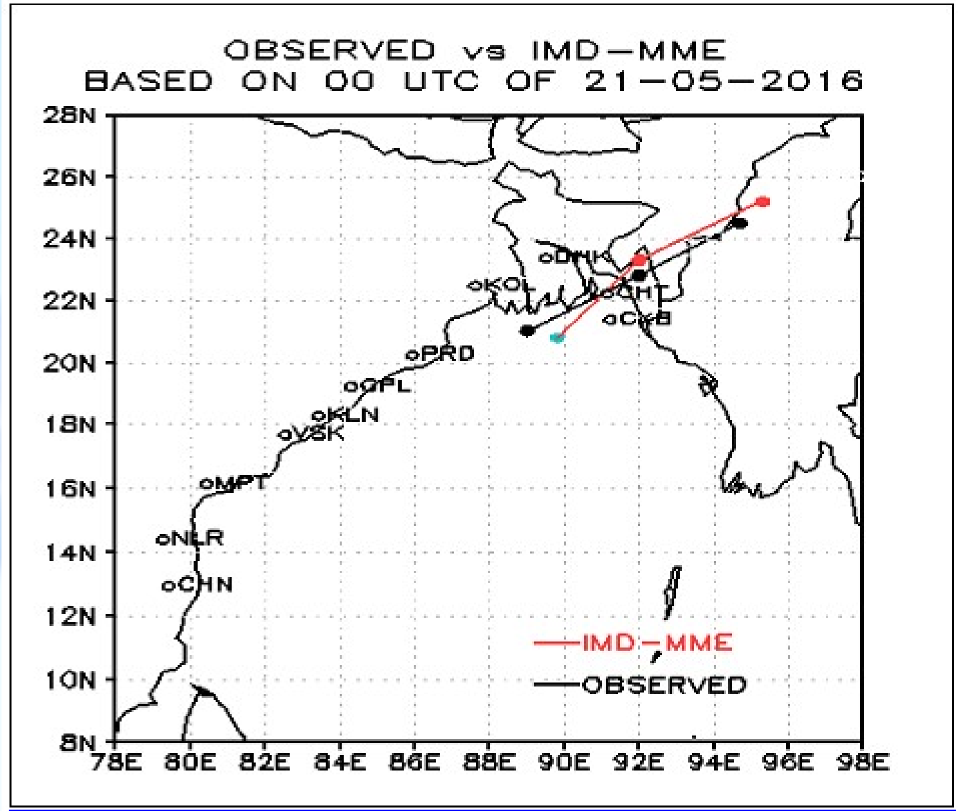


Landfall forecast Lead Time -34 h

NWP model and consensus NWP (Multi-model ensemble) track forecasts based on 12 UTC of 20.05.2016 and 00 TUC 21.05.2016 for cyclone ROANU



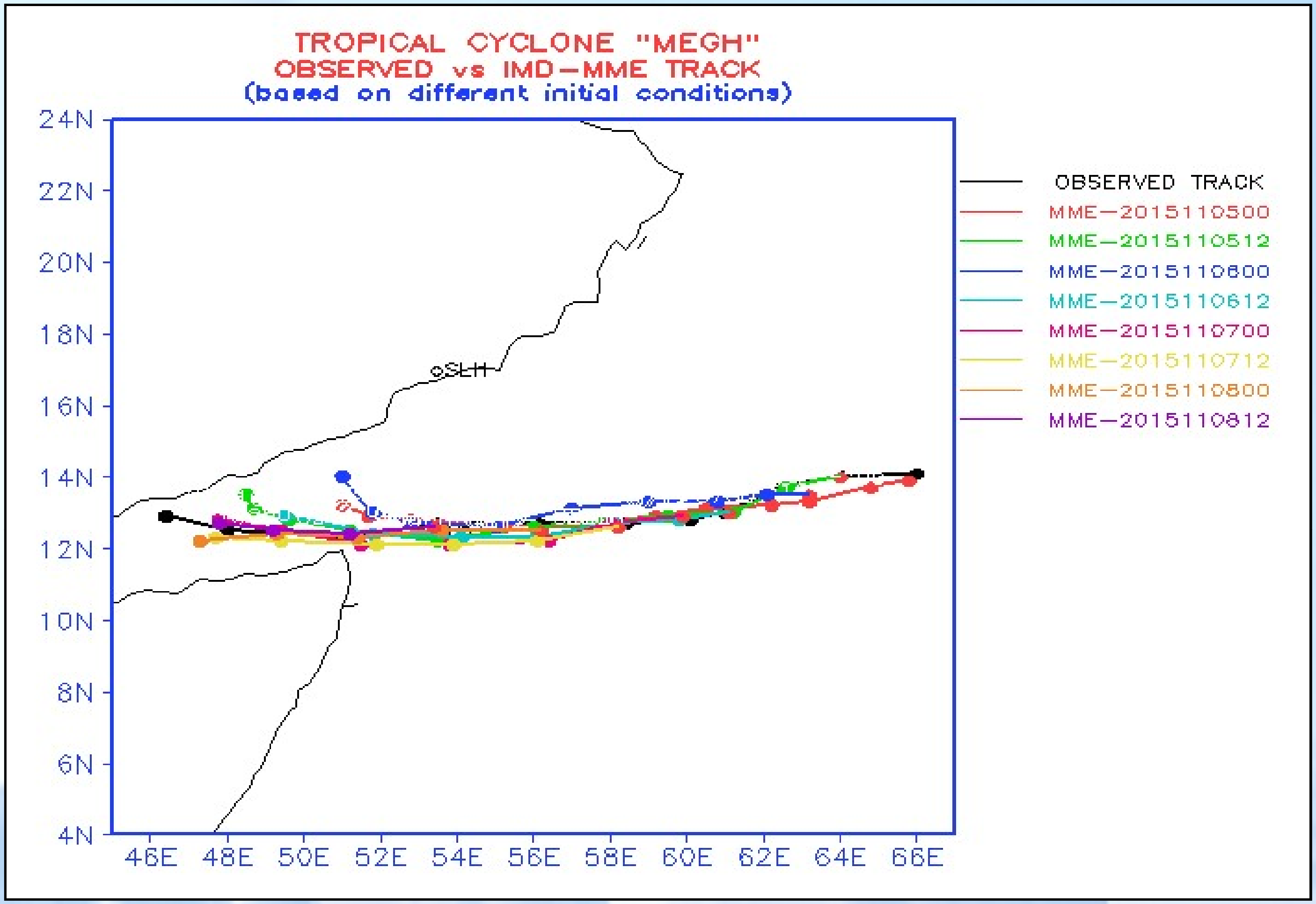
Landfall forecast Lead Time -22 h



Landfall forecast Lead Time -10 h

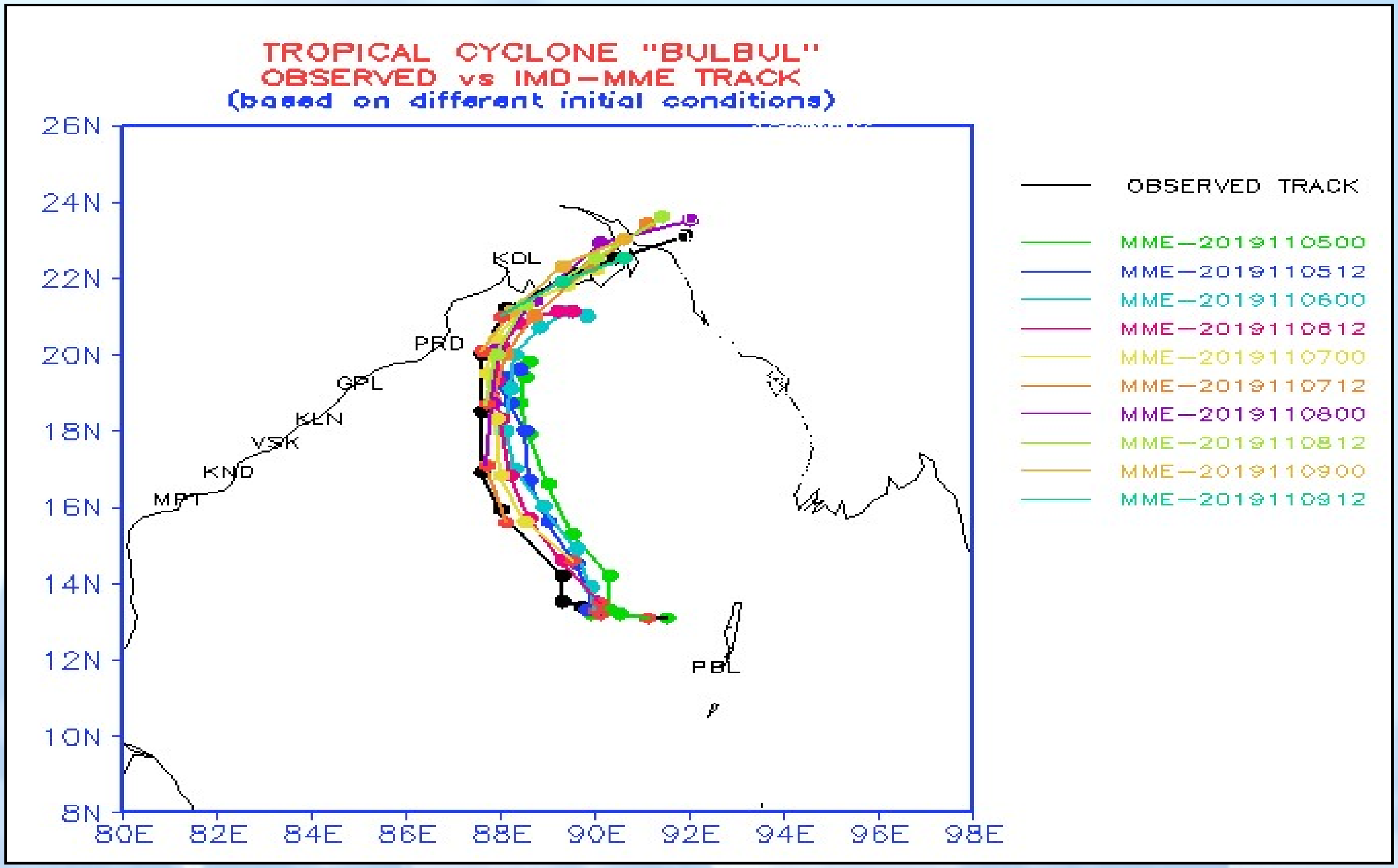
ESCS MEGH: 05-10 November 2015

(Arabian Sea)


TROPICAL CYCLONE "MEGH"
OBSERVED vs IMD-MME TRACK
(based on different initial conditions)
24N
22N
20N
18N
16N
14N
12N
10N
8N
6N
4N
46E
48E
50E
52E
54E
56E
58E
60E
62E
64E
66E
SLH
OBSERVED TRACK
MME-2015110500
MME-2015110512
MME-2015110600
MME-2015110612
MME-2015110700
MME-2015110712
MME-2015110800
MME-2015110812

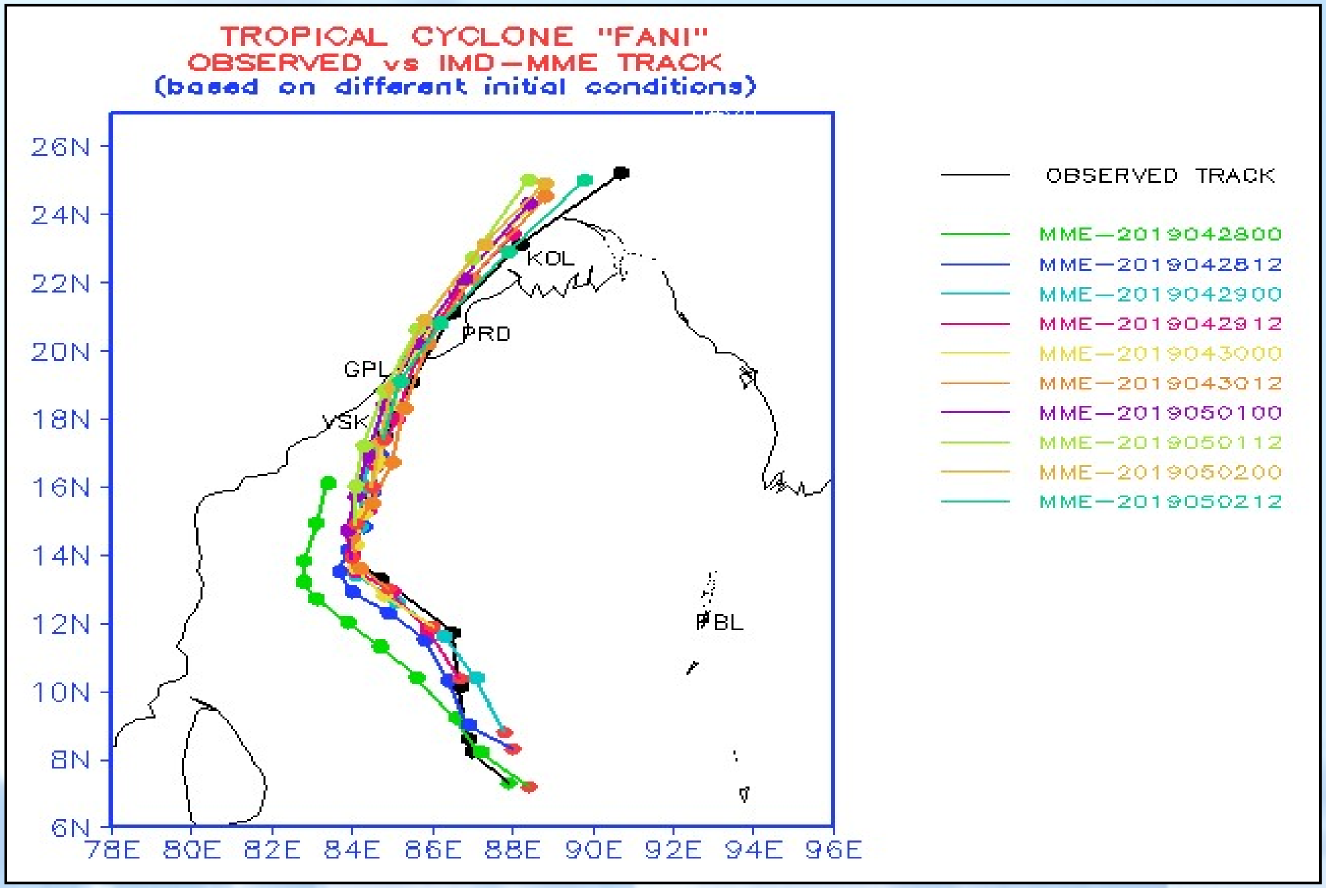
All Track forecasts by MME vs Observed Track (BULBUL)

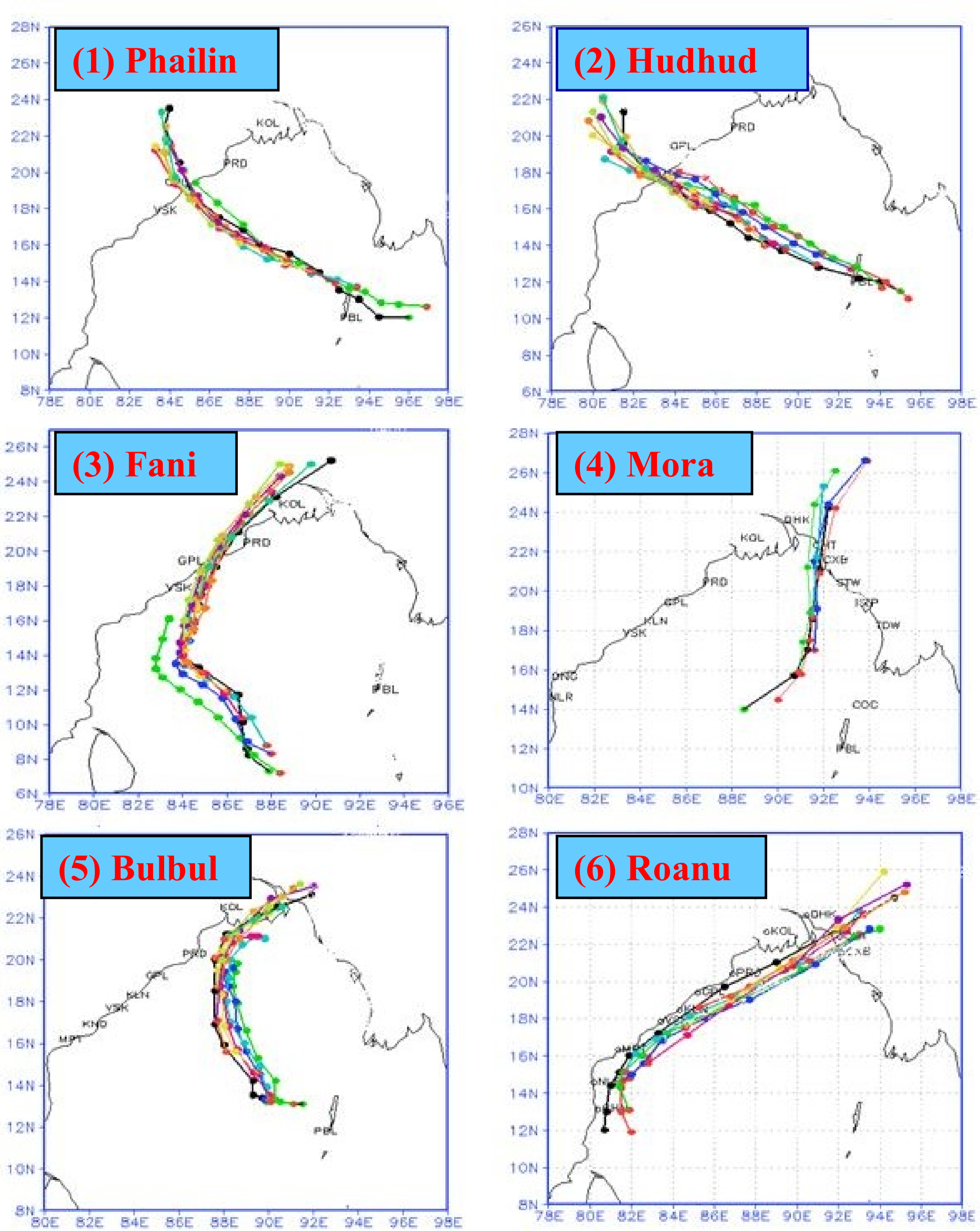
(Bay of Bengal November 2019)

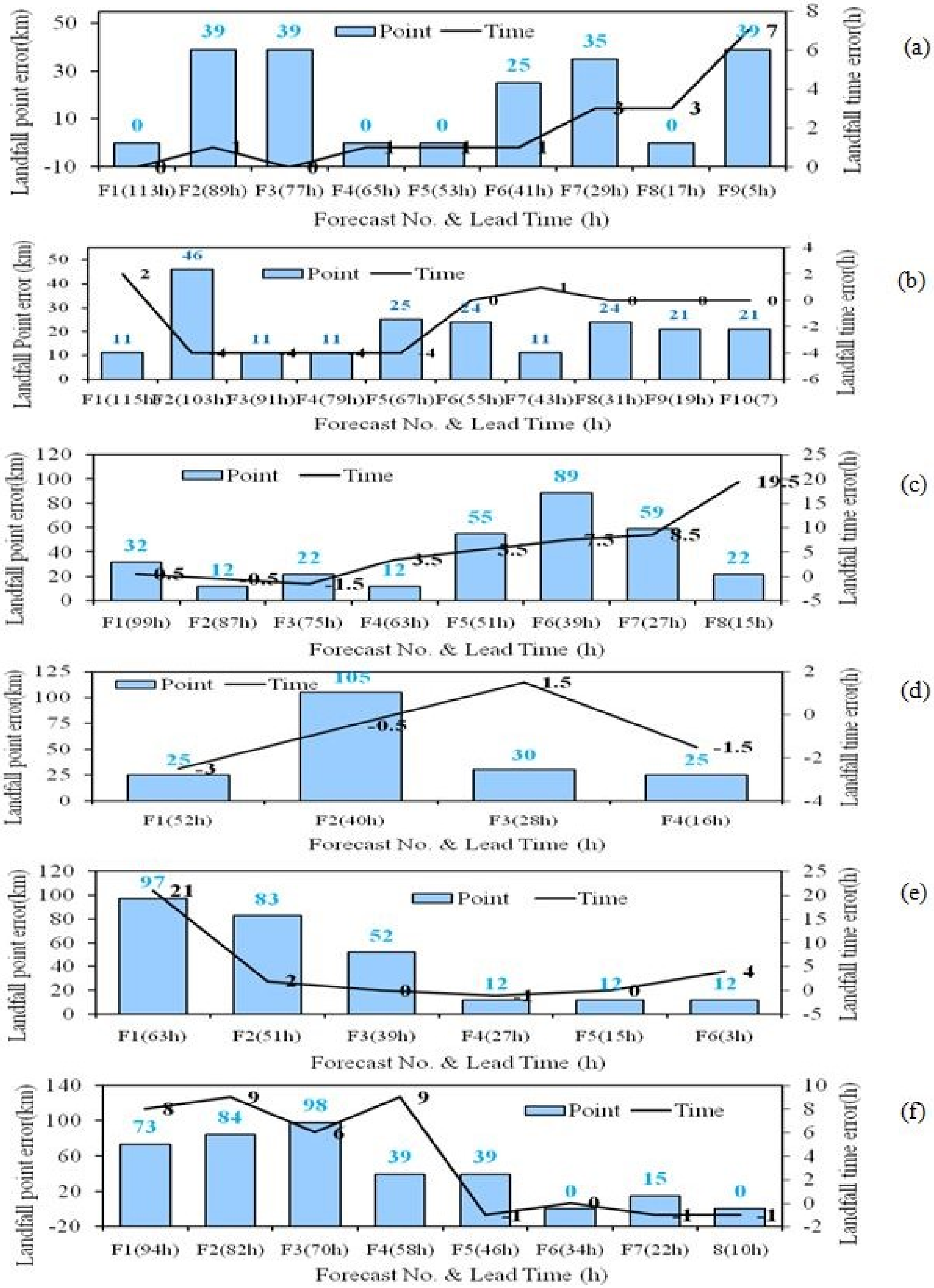


All Track forecasts by MME vs Observed Track (FANI)

(Bay of Bengal April 2019)

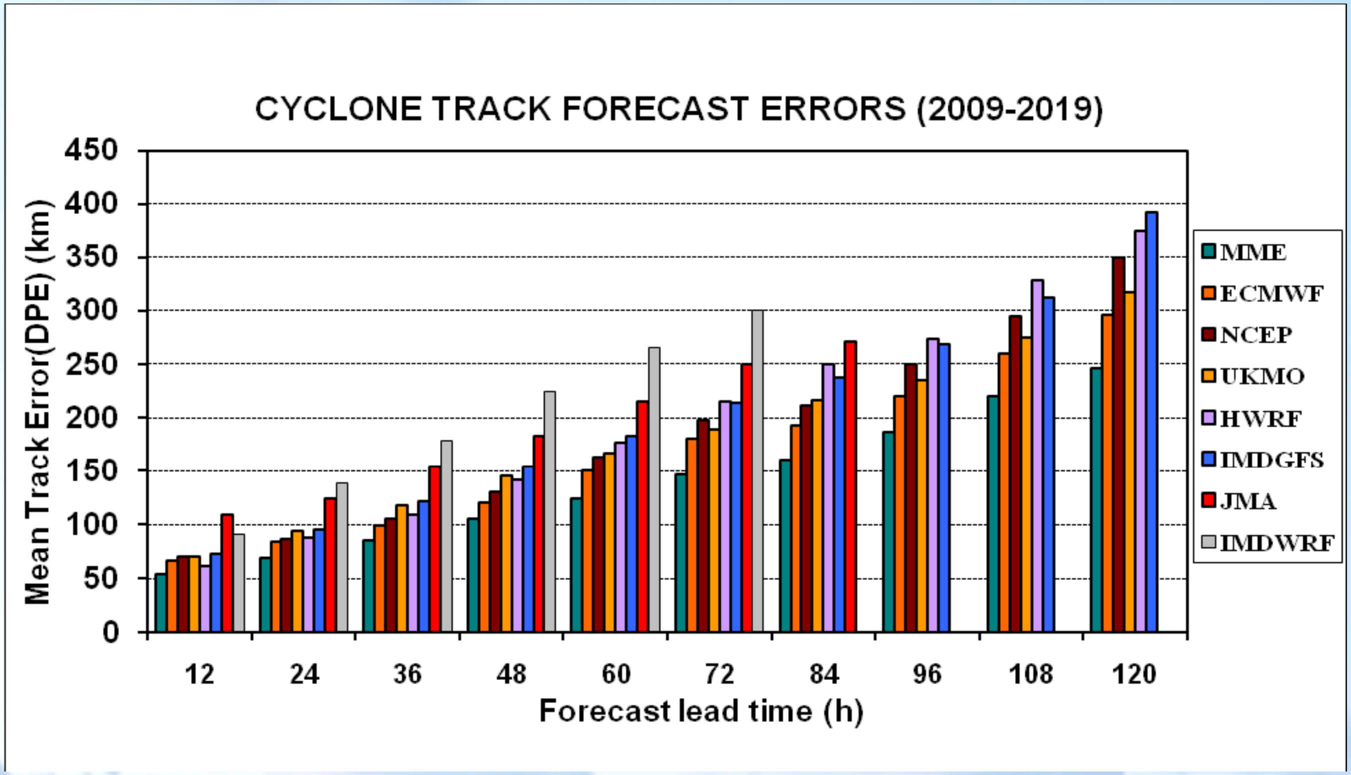



(1) Phailin
KOL
PRD
VSK
PBL
(2) Hudhud
PRD
GPL
PBL
(3) Fani
KOL
PRD
GPL
VSK
PBL
(4) Mora
DHK
KOL
PRD
GPL
KLN
VSK
CXB
STW
KKP
TDW
COC
PBL
(5) Bulbul
KOL
PRD
GPL
KLN
VSK
KND
MPT
PBL
(6) Roanu
DHK
KOL
CXB
PRD

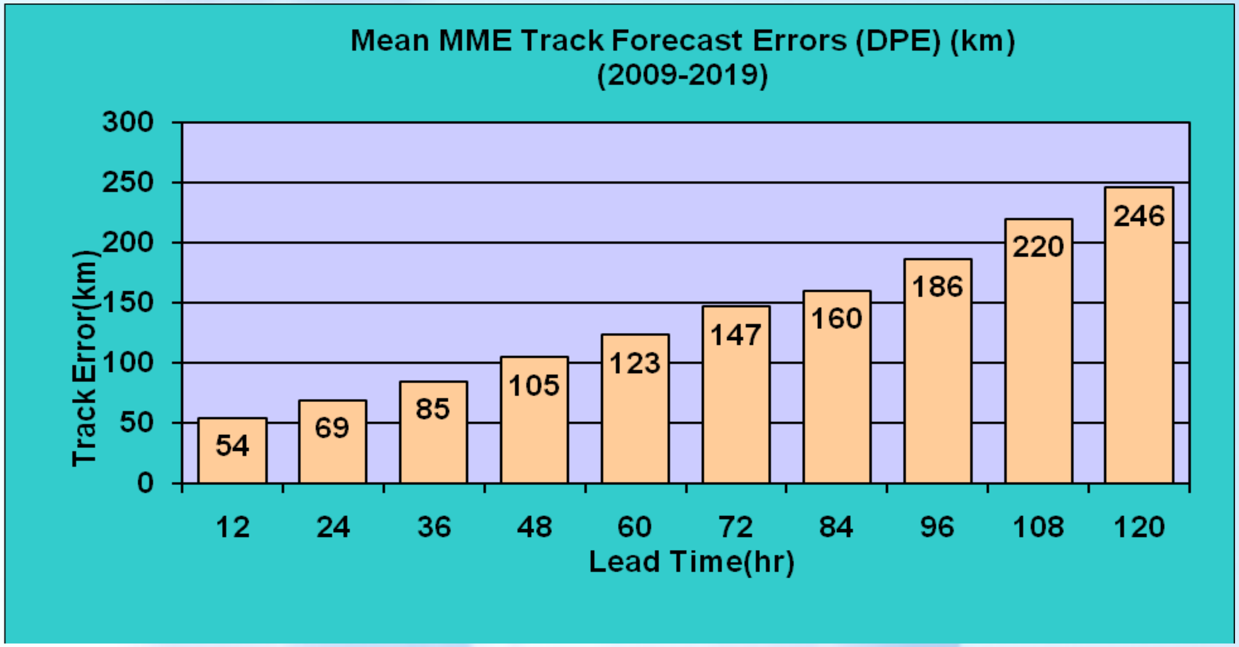


TCs (a) Phailin, (b) Hudhud, (c) Fani, (d) Mora, (e) Bulbul, and (f) Roanu.

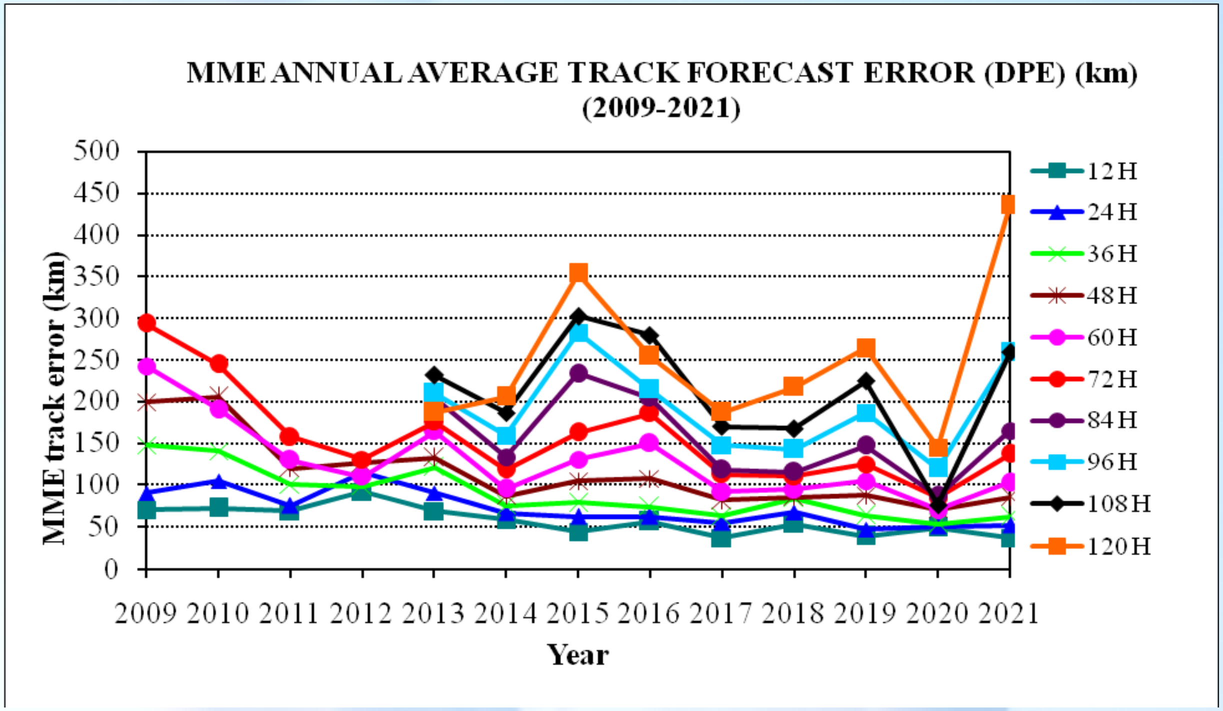
Mean track forecast error (km) – 2009-2019



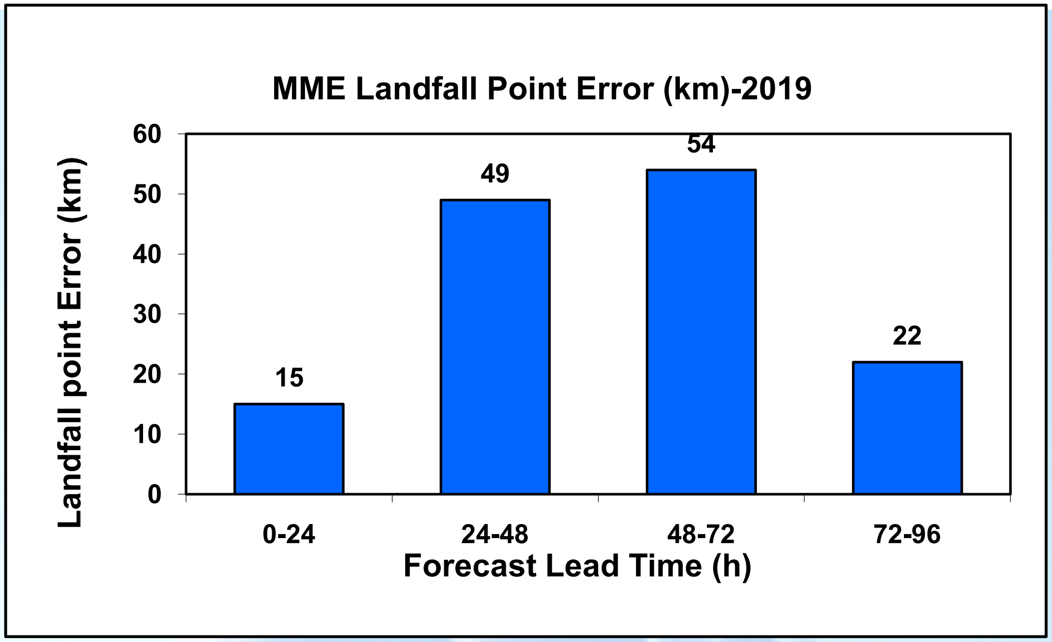
Mean MME track forecast error (km)

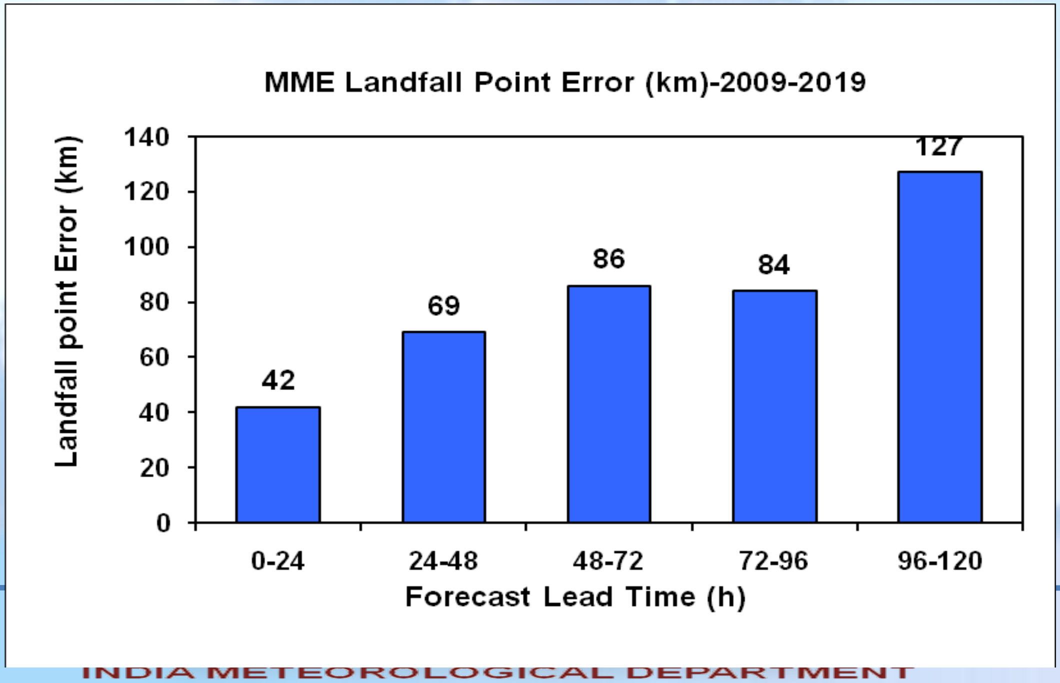


Year wise MME track forecast error (km)

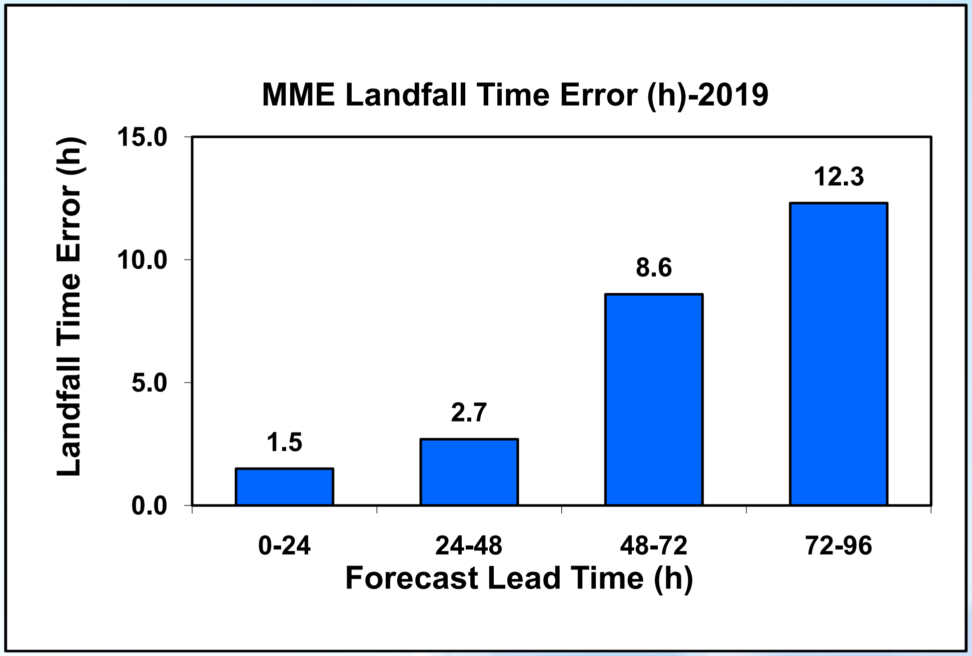


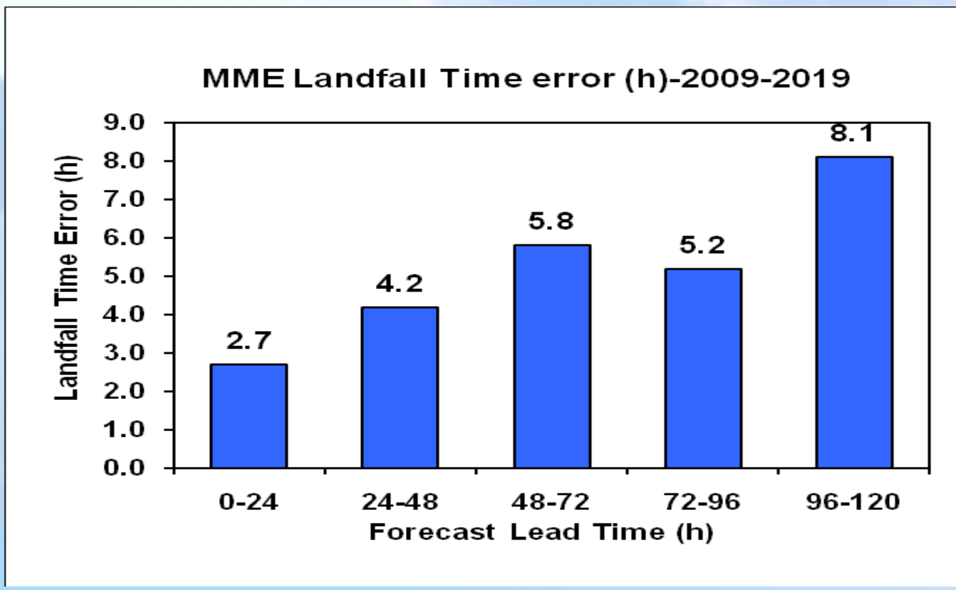
Landfall Point error (km)





Landfall Time error (h)





Kotal, S.D., and Bhattacharya S.K., 2021. "Evolution of Tropical Cyclone Forecasts of Dynamical-statistical Cyclone Prediction System (CPS) over the North Indian Ocean during the decade (2010-2019)". ***MAUSAM, 72(1):87-106. January 2021 (17 April 2021).***

STEP-III: Tropical Cyclone Intensity Prediction by SCIP model

[Kotal, S.D., Roy Bhowmik, S.K., Kundu, P.K. and Das, A.K., 2008. A Statistical Cyclone Intensity Prediction (SCIP) Model for Bay of Bengal. *Journal of Earth System Science (Springer) 117:157-168.*]

Objective:

Intensity prediction at 12-hr interval up to 72 hours

Statistical Cyclone Intensity Prediction (SCIP) Model

Data sample: 62 Tropical Cyclones during the period 1981 to 2000

The predictors:

S.No	Predictors	Symbol of Predictors	Unit
1.	Intensity change during last 12 hours	IC12	Knots
2.	Vorticity at 850 hPa	V850	$x\ 10^5\ s^{-1}$
3.	Storm motion speed	SMS	ms^{-1}
4.	Divergence at 200 hPa	D200	$x\ 10^5\ s^{-1}$
5.	Initial Storm intensity	ISI	Knots
6.	Initial Storm latitude position	ISL	°N
7.	Sea surface temperature	SST	°C
8.	Vertical wind shear	VWS	Knots

Formulation of the model:

The model is developed using multiple linear regression technique

$y = a_o + a_1 x_1 + a_2 x_2 + \ldots\ldots\ldots + a_n x_n$

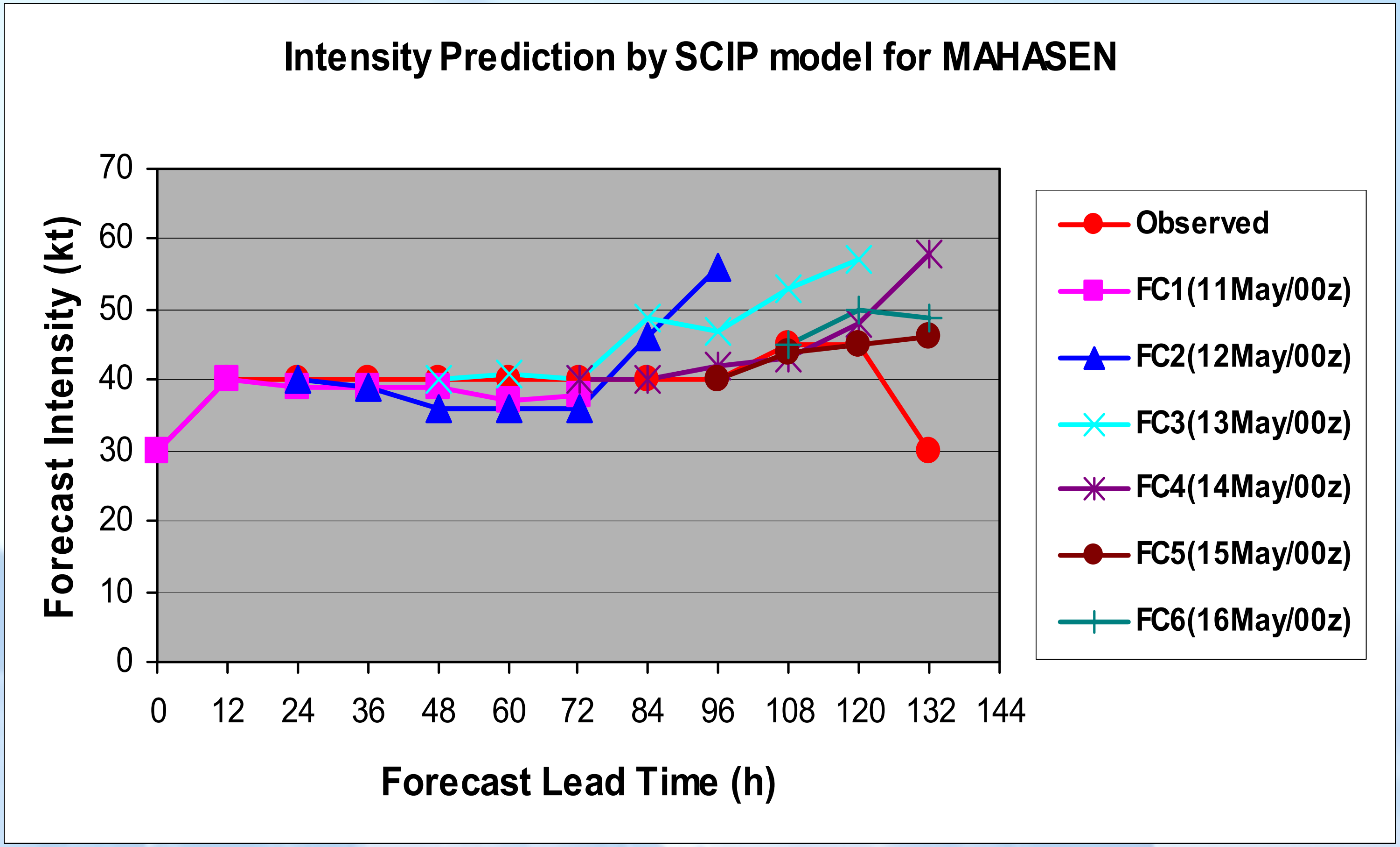
The SCIP model estimates changes of intensity at 12, 24, 36, 48, 60 and 72 hours. Six separate regression analyses are carried out for forecast interval 12, 24, 36, 48, 60 and 72 hour.

12 hours intensity change by multiple linear regression technique is defined as:

$$dv_t = a_o + a_1\, IC12 + a_2\, SMS + a_3\, VWS + a_4\, D200 + a_5 V850 + a_6\, ISL + a_7\, SST + a_8\, ISI$$

for t = forecast hour 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120h

CS VIYARU: May 10-16



Intensity Prediction by SCIP model for MAHASEN
Forecast Intensity (kt)
70
60
50
40
30
20
10
0
0
12
24
36
48
60
72
84
96
108
120
132
144
Forecast Lead Time (h)
Observed
FC1(11May/00z)
FC2(12May/00z)
FC3(13May/00z)
FC4(14May/00z)
FC5(15May/00z)
FC6(16May/00z)

Intensity forecast error (kt)- VIYARU

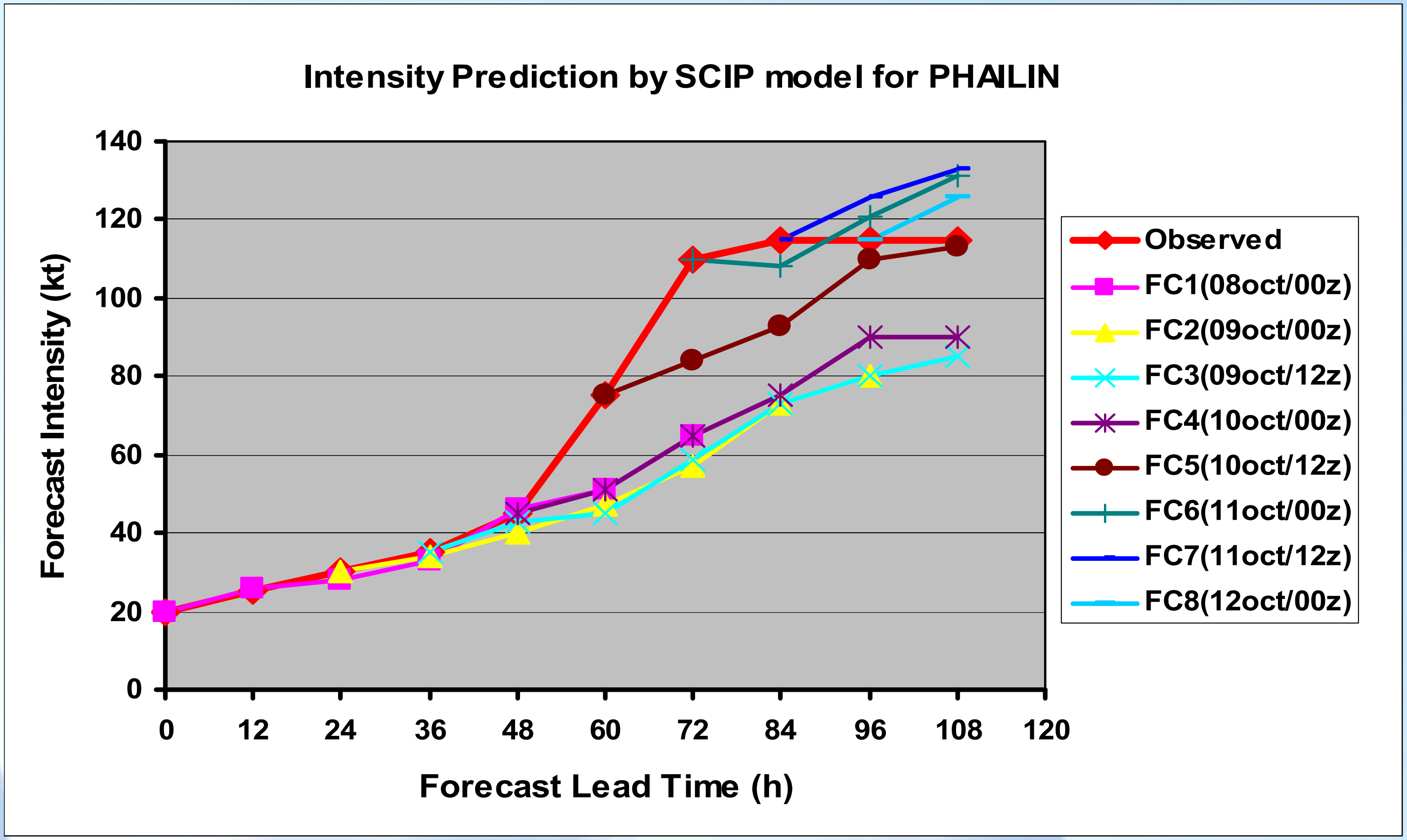
Average absolute errors (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	1.3 (6)	4.3 (6)	6.4 (5)	3.8 (4)	11.3 (4)	10.0 (3)	-	-	-	-
IMD-HWRF	27.2(10)	21.3(9)	8.6(8)	10.9(7)	19.2(6)	23.0(5)	29.5(4)	14.0(3)	22.0(2)	29.0(1)
OFFICIAL	3.6 (24)	6.8(22)	8.7(20)	10.0(18)	13.0(16)	15.0(14)	14(10)	13(8)	17(6)	14(4)

Root Mean Square (RMSE) errors (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	2.2 (6)	8.0 (6)	8.5 (5)	4.3 (4)	14.9 (4)	11.6 (3)	-	-	-	-
IMD-HWRF	30.0(10)	24.3(9)	12.2(8)	12.8(7)	22.8(6)	28.0(5)	31.5(4)	14.3(3)	22.4(2)	29.0(1)
OFFICIAL	4.6 (24)	8.9(22)	10.8(20)	12.5(18)	16.1(16)	17.8(14)	16.1(10)	15.7(8)	17.5(6)	16.4(4)

VSCS PHAILIN: October 8-14



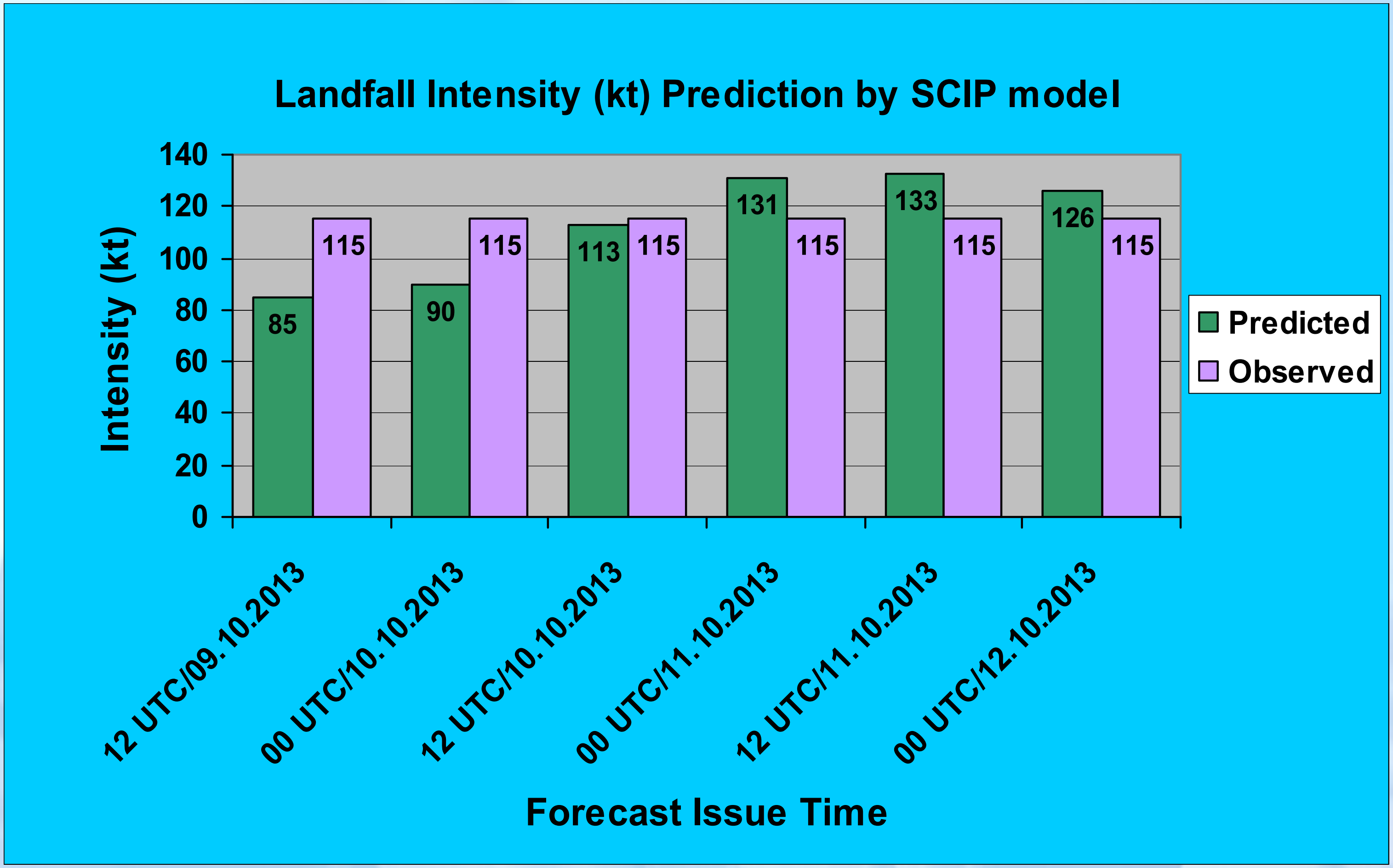
Intensity Prediction by SCIP model for PHAILIN
140
120
100
80
60
40
20
0
0
12
24
36
48
60
72
84
96
108
120
Forecast Intensity (kt)
Forecast Lead Time (h)
Observed
FC1(08oct/00z)
FC2(09oct/00z)
FC3(09oct/12z)
FC4(10oct/00z)
FC5(10oct/12z)
FC6(11oct/00z)
FC7(11oct/12z)
FC8(12oct/00z)

Average absolute errors (PHAILIN)
(Number of forecasts verified is given in t he parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-SCIP	10.4(8)	18.3(7)	23.7(6)	24.6(5)	31.5(4)	36.7(3)	-
IMD-HWRF	17.0(6)	21.0(5)	27.8(5)	30.5(4)	28.3(3)	19.5(2)	11.0(1)

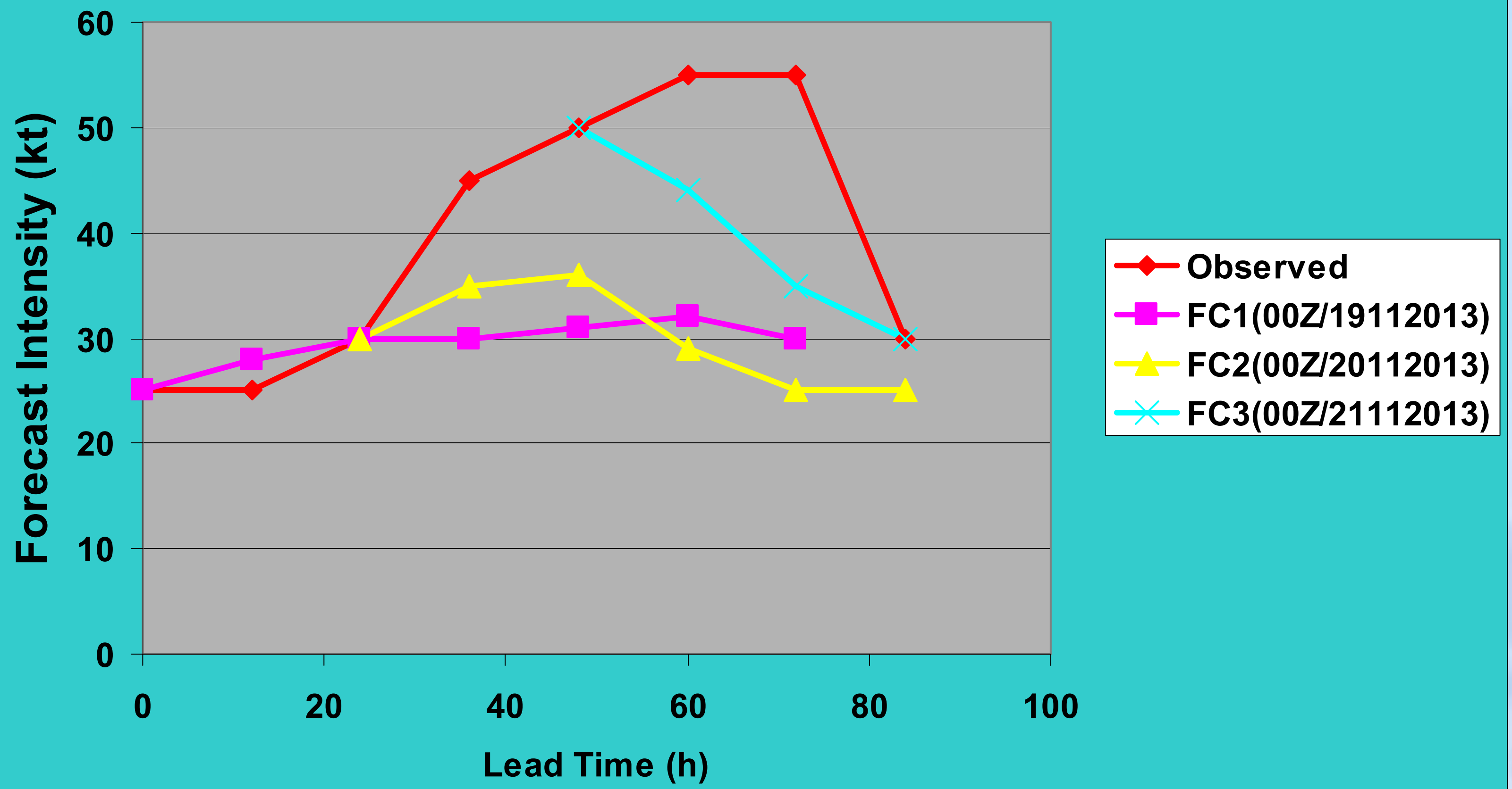
Root Mean Square (RMSE) errors
(Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-SCIP	13.9(8)	23.3(7)	29.6(6)	32.3(5)	32.4(4)	37.2(3)	-
IMD-HWRF	19.0(6)	24.2(5)	31.7(5)	31.2(4)	28.6(3)	20.0(2)	14.9(1)


Landfall Intensity (kt) Prediction by SCIP model
Intensity (kt)
140
120
100
80
60
40
20
0
85
115
90
115
113
115
131
115
133
115
126
115
12 UTC/09.10.2013
00 UTC/10.10.2013
12 UTC/10.10.2013
00 UTC/11.10.2013
12 UTC/11.10.2013
00 UTC/12.10.2013
Forecast Issue Time
Predicted
Observed

SCS HELEN: Nov 19-23

Intensity Prediction by SCIP model for HELEN



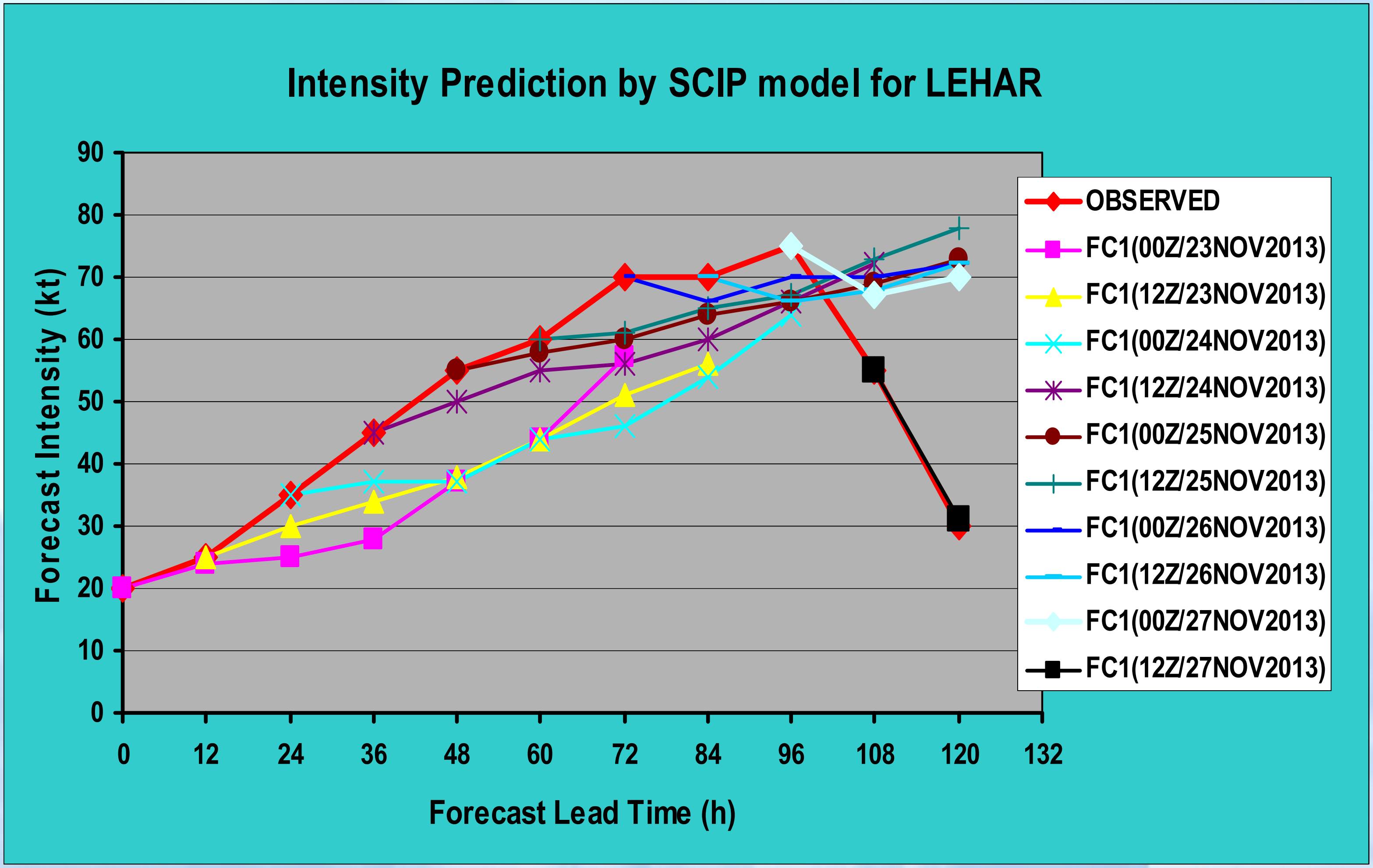
Average absolute errors (HELEN)
(Number of forecasts verified is given in t he parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-SCIP	8.0(3)	11.3(3)	20.5(2)	24.5(2)	14.0(2)	25.0(1)	-
IMD-HWRF	5.3(4)	11.0(4)	7.0(3)	6.0(2)	-	-	-

Root Mean Square (RMSE) errors
(Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-SCIP	8.8(3)	14.1(3)	21.2(2)	25.1(2)	16.6(2)	25.0(1)	-
IMD-HWRF	7.9(4)	11.6(4)	8.2(3)	6.7(3)	-	-	-

VSCS LEHAR: Nov 23-28



Intensity Prediction by SCIP model for LEHAR
Forecast Intensity (kt)
Forecast Lead Time (h)
0
10
20
30
40
50
60
70
80
90
0
12
24
36
48
60
72
84
96
108
120
132
OBSERVED
FC1(00Z/23NOV2013)
FC1(12Z/23NOV2013)
FC1(00Z/24NOV2013)
FC1(12Z/24NOV2013)
FC1(00Z/25NOV2013)
FC1(12Z/25NOV2013)
FC1(00Z/26NOV2013)
FC1(12Z/26NOV2013)
FC1(00Z/27NOV2013)
FC1(12Z/27NOV2013)

Average absolute errors (LEHAR)
(Number of forecasts verified is given in the parentheses)

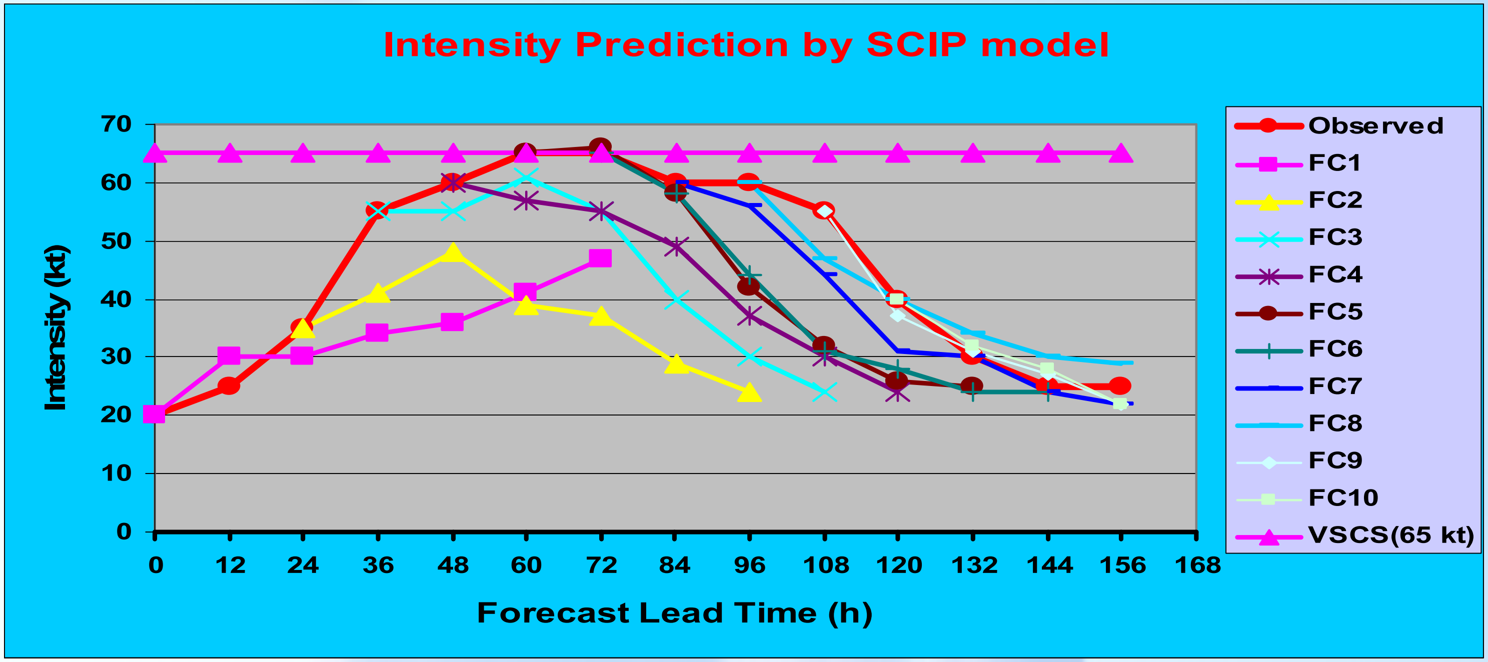
Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	5.6 (10)	13.0 (9)	16.9 (8)	19.6 (7)	20.3 (6)	19.6 (5)	-	-	-	-
IMD-HWRF	23.4(9)	12.9(8)	12.4(7)	12.7(7)	7.3(6)	13.6(5)	21.3(4)	22.7(3)	30.5(2)	57(1)

Root Mean Square (RMSE) errors
(Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	6.6 (10)	16.6 (9)	19.7 (8)	22.1 (7)	24.0 (6)	22.9 (5)	-	-	-	-
IMD-HWRF	25.7(9)	17.1(8)	15.5(7)	13.6(7)	9.7(6)	19.2(5)	28.3(4)	29.5(3)	31.2(2)	57(1)

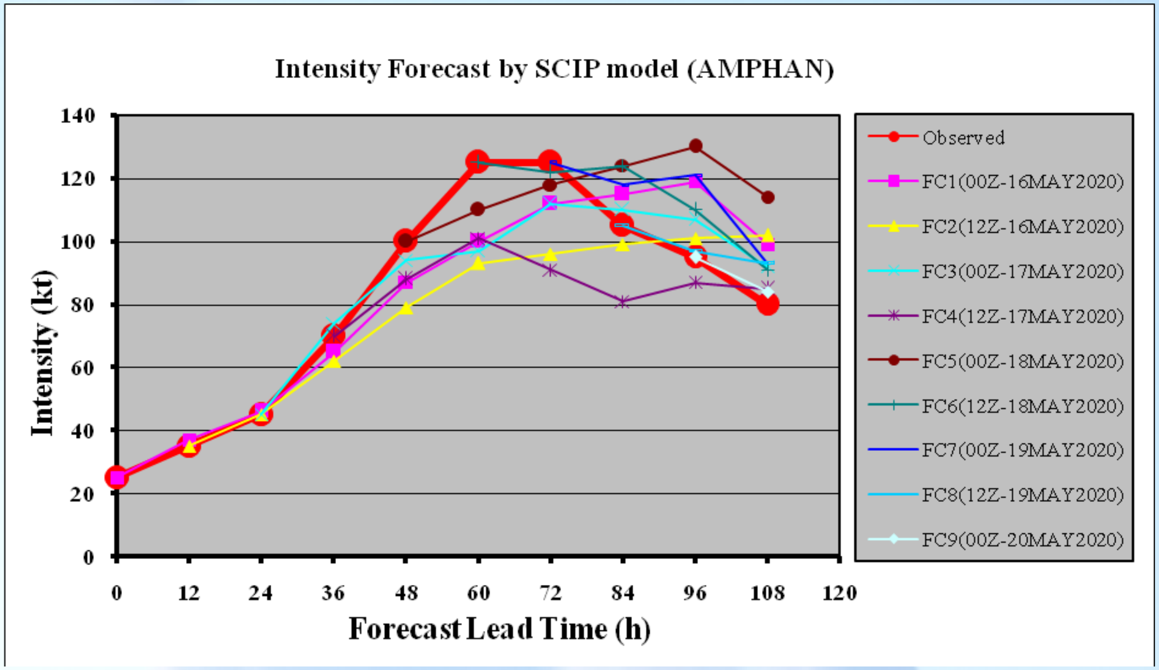
VSCS MADI: Dec 6-13

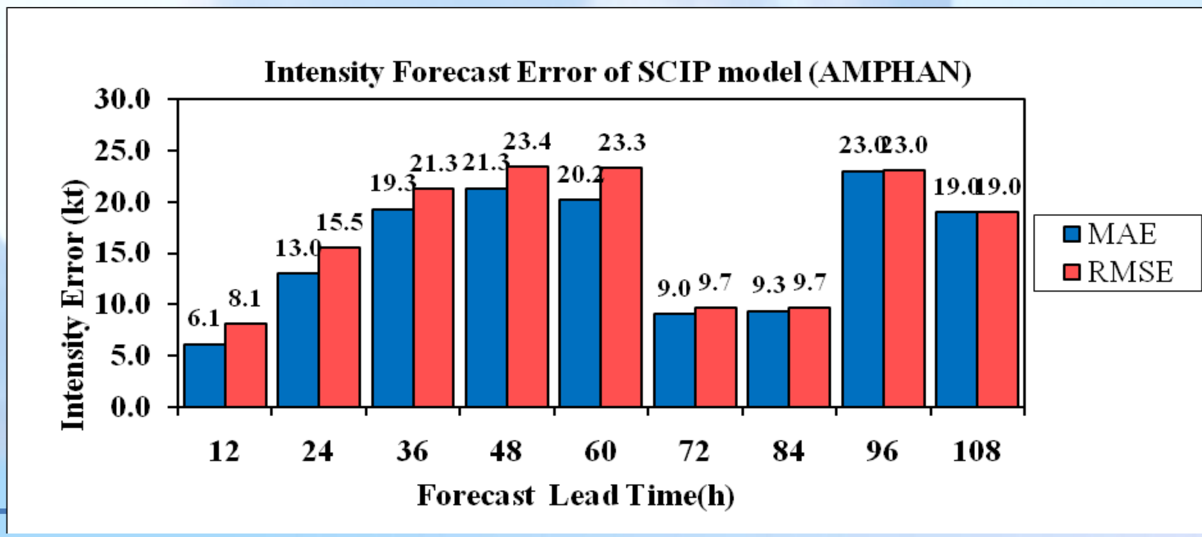
INTENSITY FORECASTS BY SCIP (MADI)



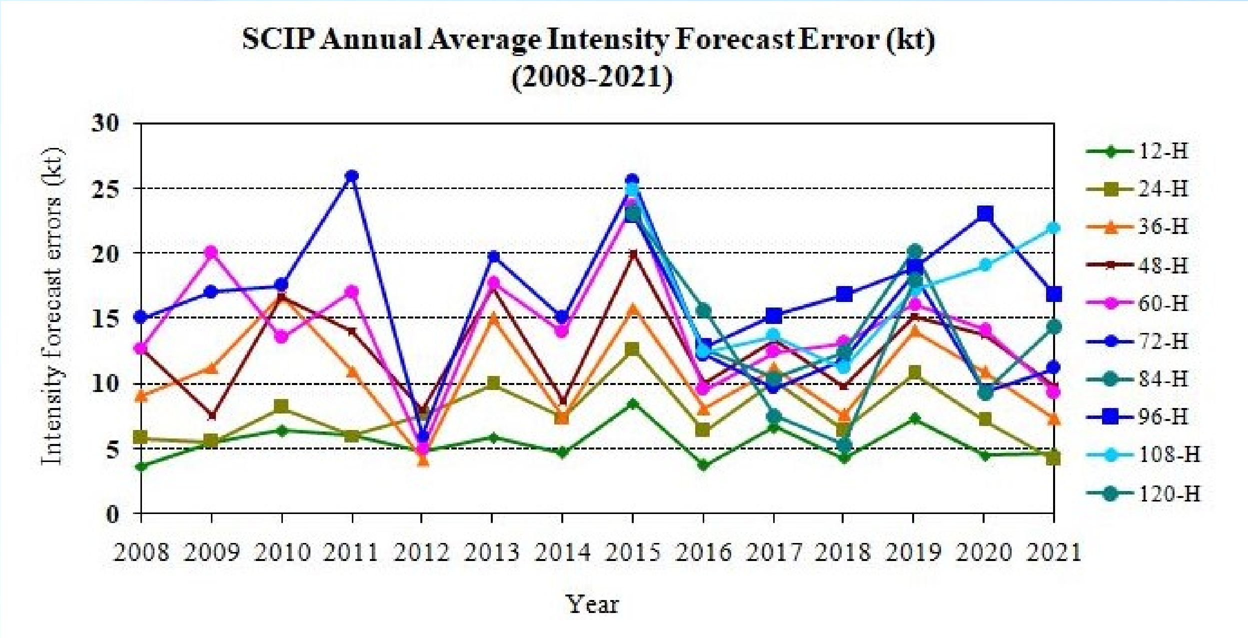
Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
AAE	5.2 (10)	6.4 (10)	12.8(10)	15.3 (9)	16.9 (8)	15.7 (7)
RMSE	6.4 (10)	8.2 (10)	15.3(10)	18.2 (9)	20.3 (8)	20.3 (7)

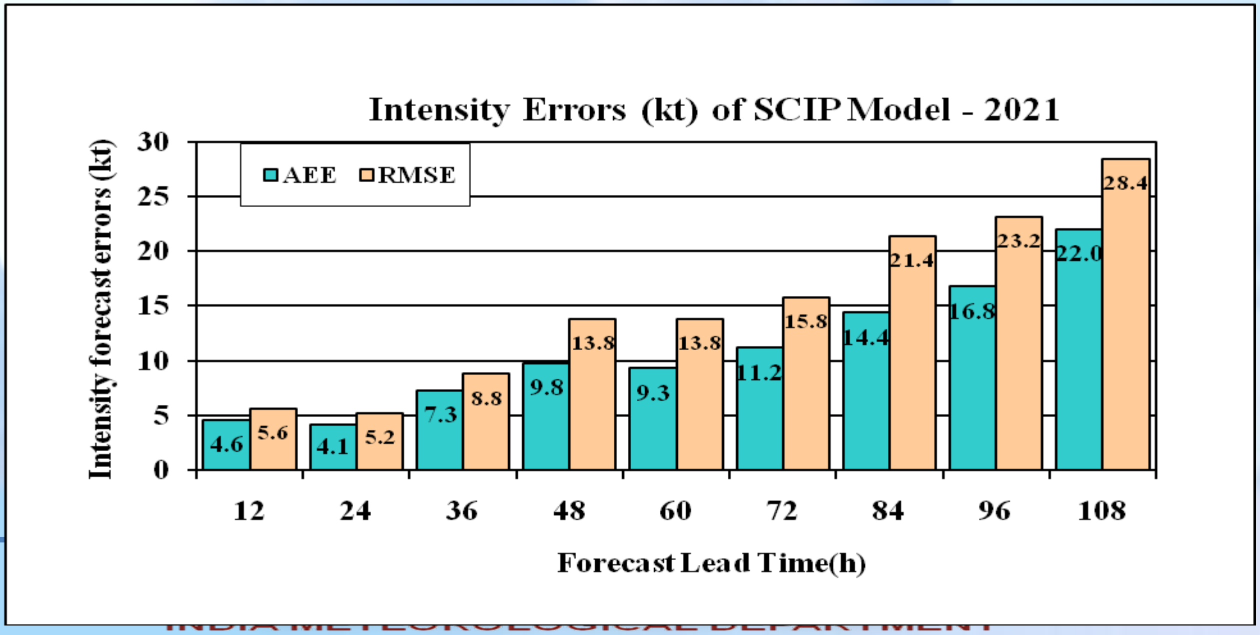
INTENSITY FORECASTS BY SCIP (AMPHAN)



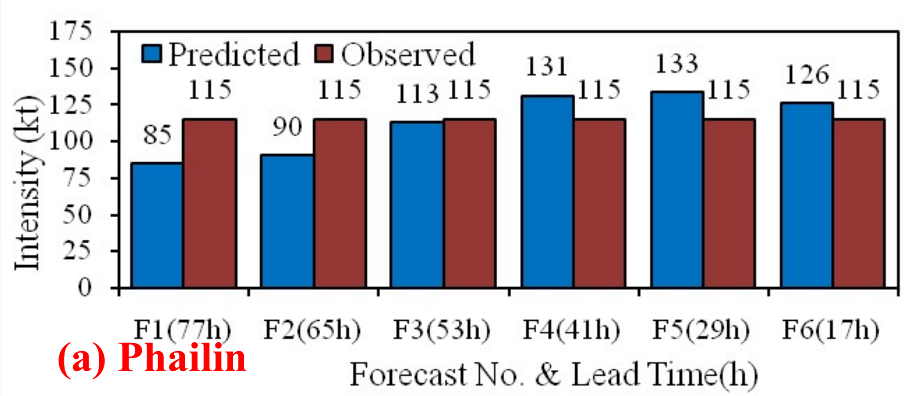


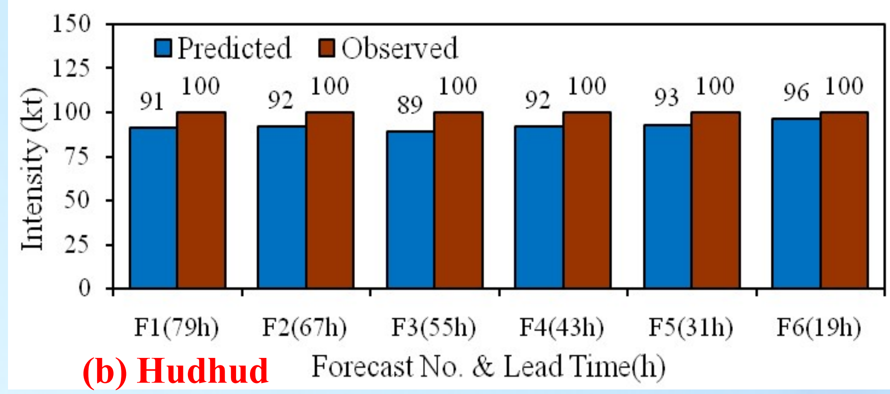
MEAN FORECAST ERRORS : 2008-2021

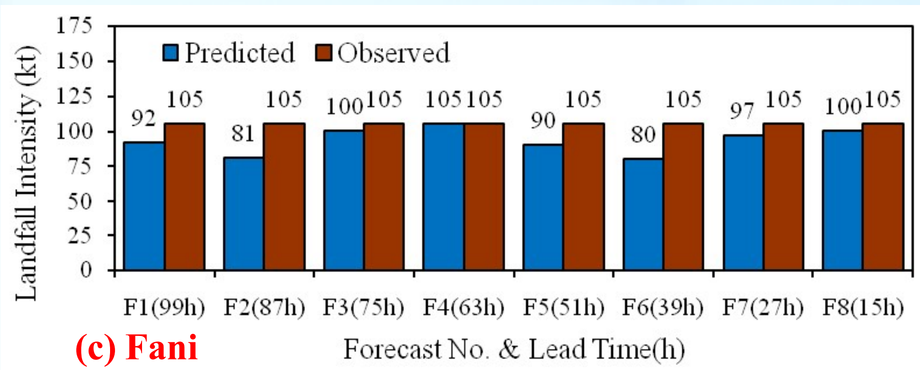


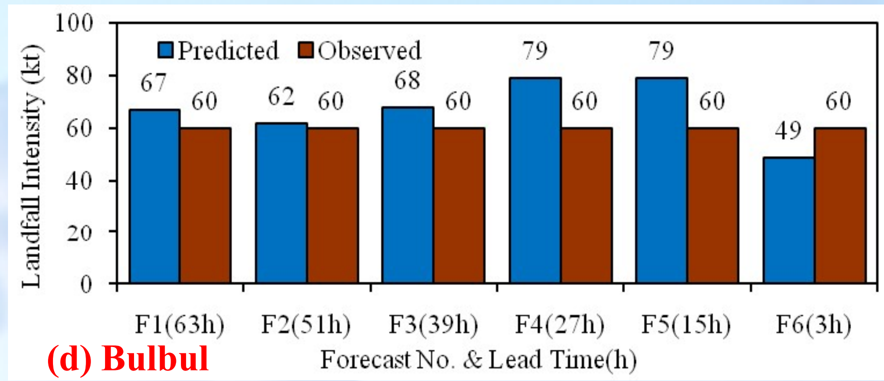


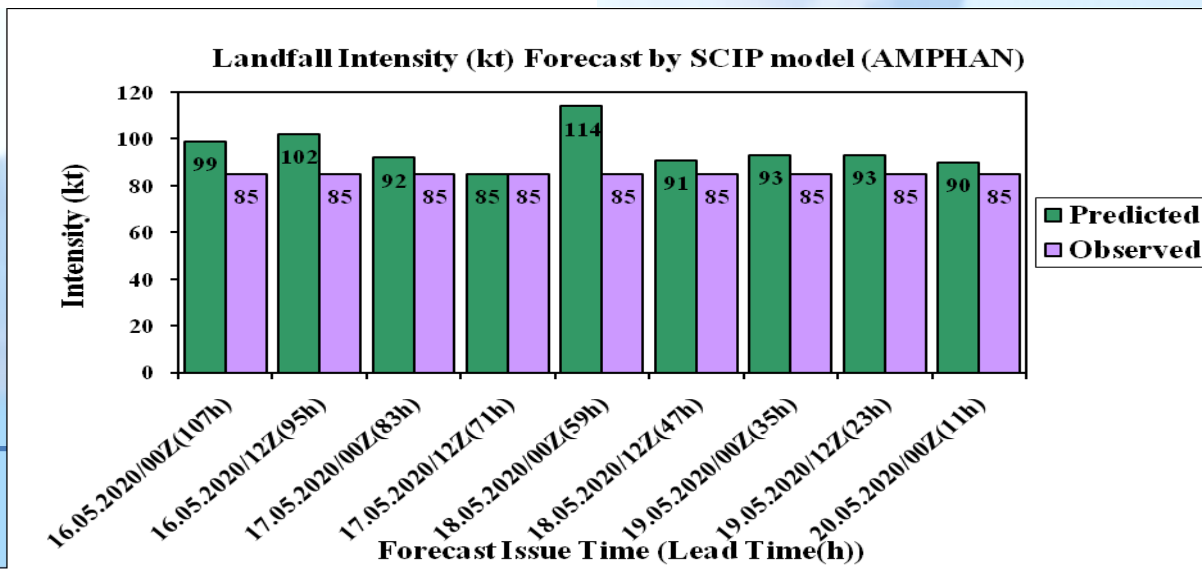
LANDFALL INTENSITY FORECASTS BY SCIP

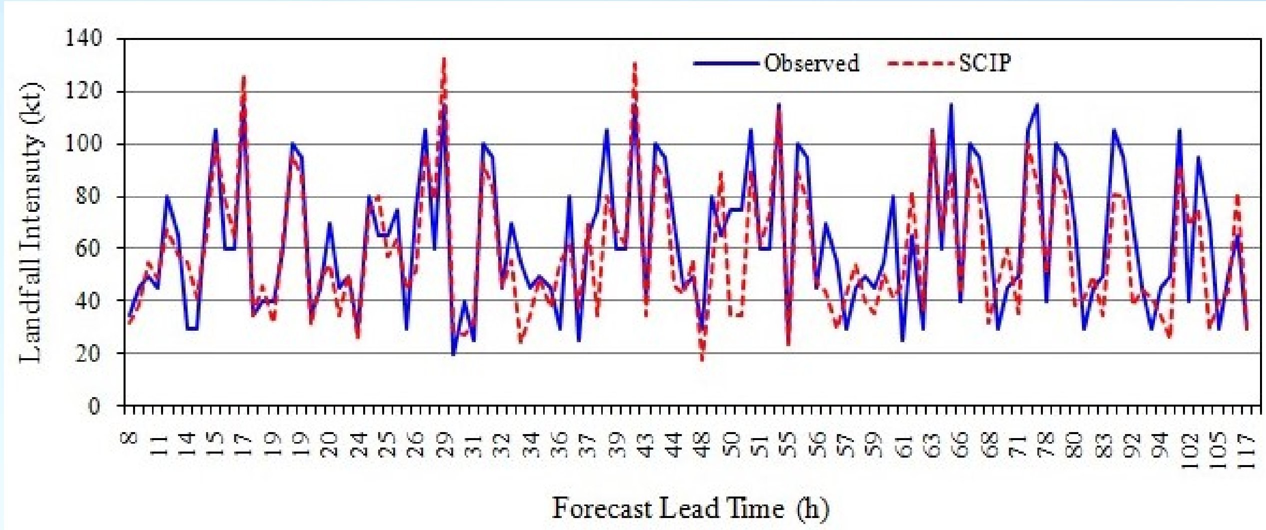




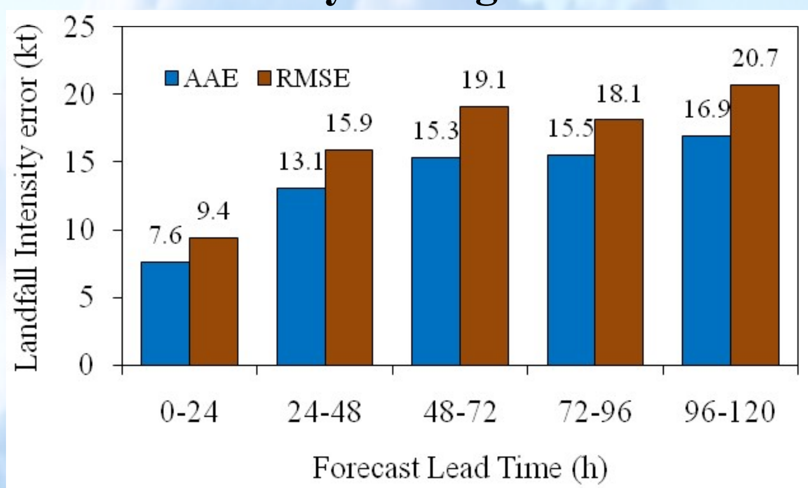








Landfall intensity forecast by SCIP versus Observed intensity during 2010-2019



Mean landfall intensity error(h) of SCIP model during 2010-2019

STEP-IV: Rapid Intensification(RI)

[<u>Kotal, S.D</u>. and Roy Bhowmik S.K. 2013. Large-Scale Characteristics of Rapidly Intensifying Tropical Cyclones over the Bay of Bengal and a Rapid Intensification (RI) Index. *Mausam,* 64(1):13-24.]

<u>Objective:</u> Probability forecast of Rapid Intensification

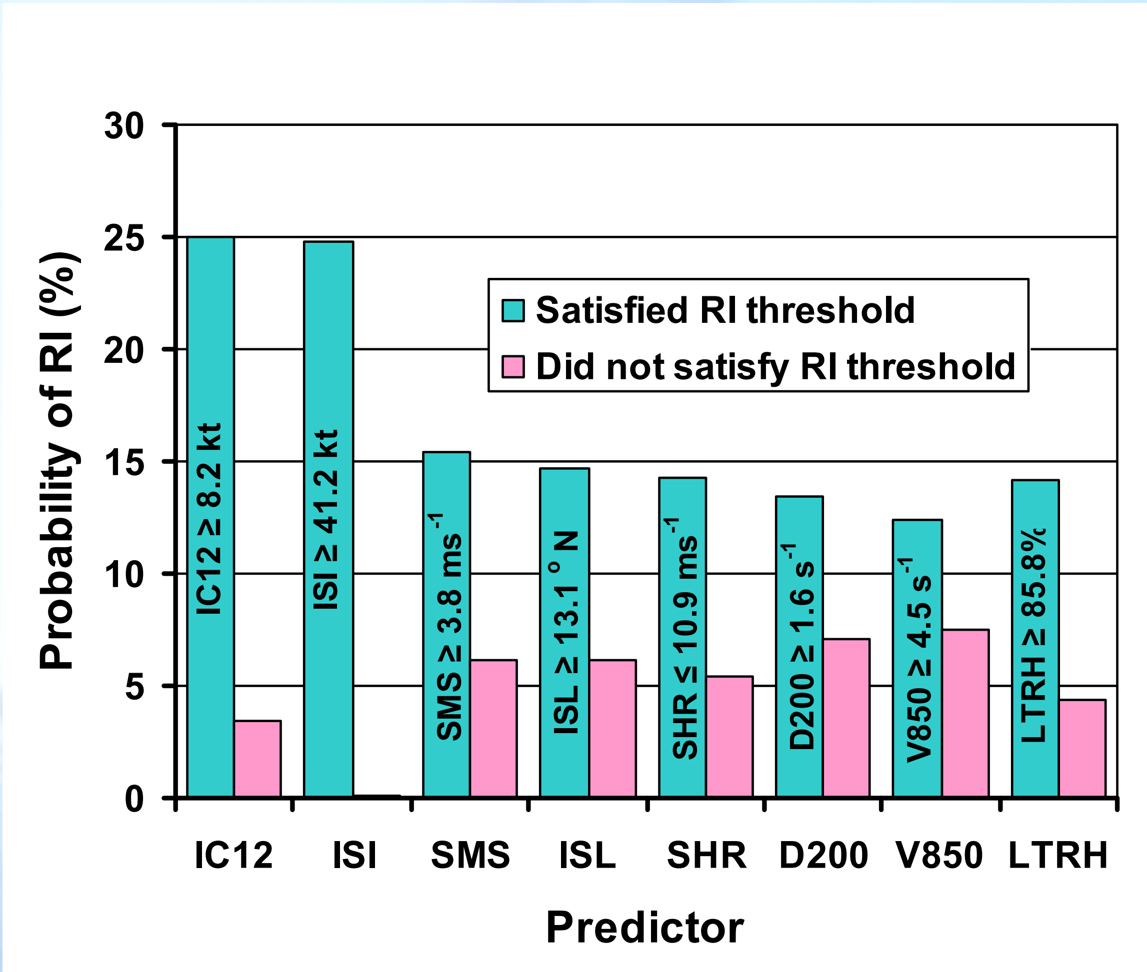
<u>Rapid Intensification</u>: Increase of intensity by 30 kt during 24 h

<u>Data sample:</u> 88 Tropical Cyclones during the period 1981 to 2010

Rapid Intensification

S.No.	Variables	Symbol of Variables	Unit
1.	Previous 12-h intensity change	IC12	kt
2.	Vorticity at 850 hPa	V850	10^{-5} s^{-1}
3.	Storm motion speed	SMS	ms^{-1}
4.	Divergence at 200 hPa	D200	10^{-5} s^{-1}
5.	Initial Storm intensity	ISI	kt
6.	Initial Storm latitude position	ISL	°N
7.	850-700 hPa average relative humidity	LTRH	%
8.	850-200 hPa vertical wind shear	SHR	ms^{-1}
9.	Sea Surface Temperature	SST	°C

Rapid Intensification Index (RII)



- Data Period - 1981-2010
- No. of TC - 88
- No. of data sample - 483
- No. of parameter - 8

Composite probability of Rapid Intensification

The composite probability of RI (P_n) is defined as:

$$P_n = \left(\frac{n_1}{(n_1 + n_2)} \right) \times 100\%$$

Where,

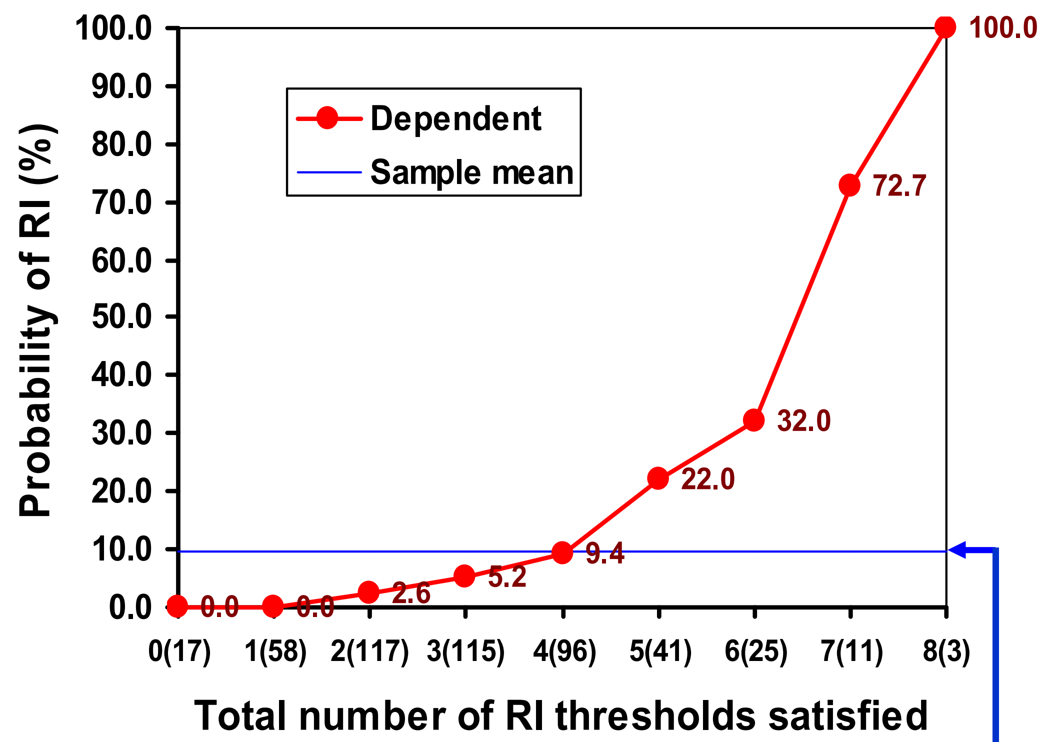
P_n = RI probability for n number of variables that satisfied their respective thresholds

n_1 = Number of RI cases that satisfied the n number thresholds

n_2 = Number of non-RI cases that satisfied the n number thresholds

n = 0, 1, 2, 3, 4, 5, 6, 7, 8 (number of variables)

Composite probability of Rapid Intensification



No. of RI- Indices satisfied	Probability(%) of RI	Chances of occurrence
0	0	NIL
1	0	NIL
2	2.6	VERY LOW
3	5.2	VERY LOW
4	9.4	VERY LOW
5	22.0	LOW
6	32.0	MODERATE
7	72.7	HIGH
8	100	VERY HIGH

Climatological Probability of RI=9.5%

Probability of Rapid intensification (by RI-Index)

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Occurrence
00 UTC/11.05.2013	9.4 %	VERY LOW	NO
00 UTC/12.05.2013	5.2 %	VERY LOW	NO
00 UTC/13.05.2013	2.6 %	VERY LOW	NO
00 UTC/14.05.2013	5.2 %	VERY LOW	NO
00 UTC/15.05.2013	9.4 %	VERY LOW	NO
12 UTC/15.05.2013	22.0 %	LOW	NO

Inference: RI-Index could able to predict non-occurrence of Rapid Intensification of cyclone VIYARU during its lifetime.

Probability of Rapid intensification (by RI-Index)-PHAILIN

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/08.10.2013	9.4 %	VERY LOW	5	NO
00 UTC/09.10.2013	9.4 %	VERY LOW	15	NO
12 UTC/09.10.2013	9.4 %	VERY LOW	40	YES
00 UTC/10.10.2013	72.7 %	HIGH	65	YES
12 UTC/10.10.2013	72.7 %	HIGH	40	YES
00 UTC/11.10.2013	72.7 %	HIGH	5	NO
12 UTC/11.10.2013	32.0 %	MODERATE	0	NO

Inference: RI-Index could able to predict OCCURENCE as well as NON-OCCURENCE of Rapid Intensification of cyclone PHAILIN during its lifetime except forecast for 12 UTC of 09.10.2013 and 00 UTC of 11.10.2013.

Probability of Rapid intensification (by RI-Index)-HELEN

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/19.12.2013	**5.2 %**	**VERY LOW**	**5**	**NO**
00 UTC/20.12.2013	**9.4 %**	**VERY LOW**	**20**	**NO**
00 UTC/21.10.2013	**9.4 %**	**VERY LOW**	5	NO

Inference: RI-Index was able to predict NON-OCCURENCE of Rapid Intensification of cyclone HELEN during its lifetime.

Probability of Rapid intensification (by RI-Index)-LEHAR

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/23.11.2013	5.2 %	VERY LOW	5	NO
12 UTC/23.11.2013	5.2 %	VERY LOW	20	NO
00 UTC/24.11.2013	22.0 %	LOW	20	NO
12 UTC/24.11.2013	22.0 %	LOW	15	NO
00UTC/25.11.2013	32.0 %	MODERATE	15	NO
12 UTC/25.11.2013	9.4 %	VERY LOW	10	NO
00 UTC/26.11.2013	9.4%	VERY LOW	5	NO
12 UTC/26.11.2013	5.2%	VERY LOW	-15	NO
00 UTC/27.11.2013	9.4%	VERY LOW	-45	NO
12 UTC/27.11.2013	0.0%	NIL	-30	NO

Inference: RI-Index was able to predict NON-OCCURENCE of Rapid Intensification of cyclone LEHAR during its lifetime.

Rapid Intensification and Rapid Decay of TC CHAPALA over Arabian Sea

(28 October - 4 November 2015)

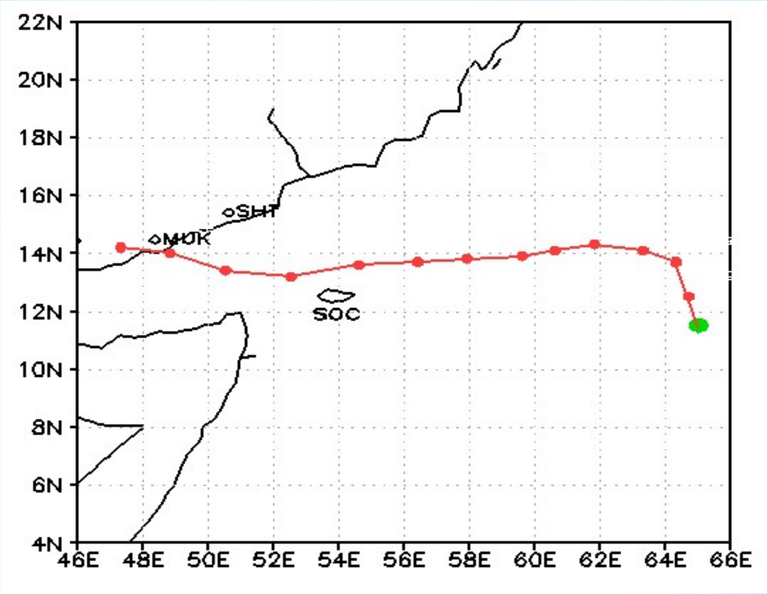
[Kotal, S.D. and Bhattacharya, S.K. 2017. Evolution of thermodynamic structures during rapid growth and decay of extremely severe cyclonic storm CHAPALA (2015). ***Tropical Cyclone Research and Review, 6, 3-4 : 67-80***.]

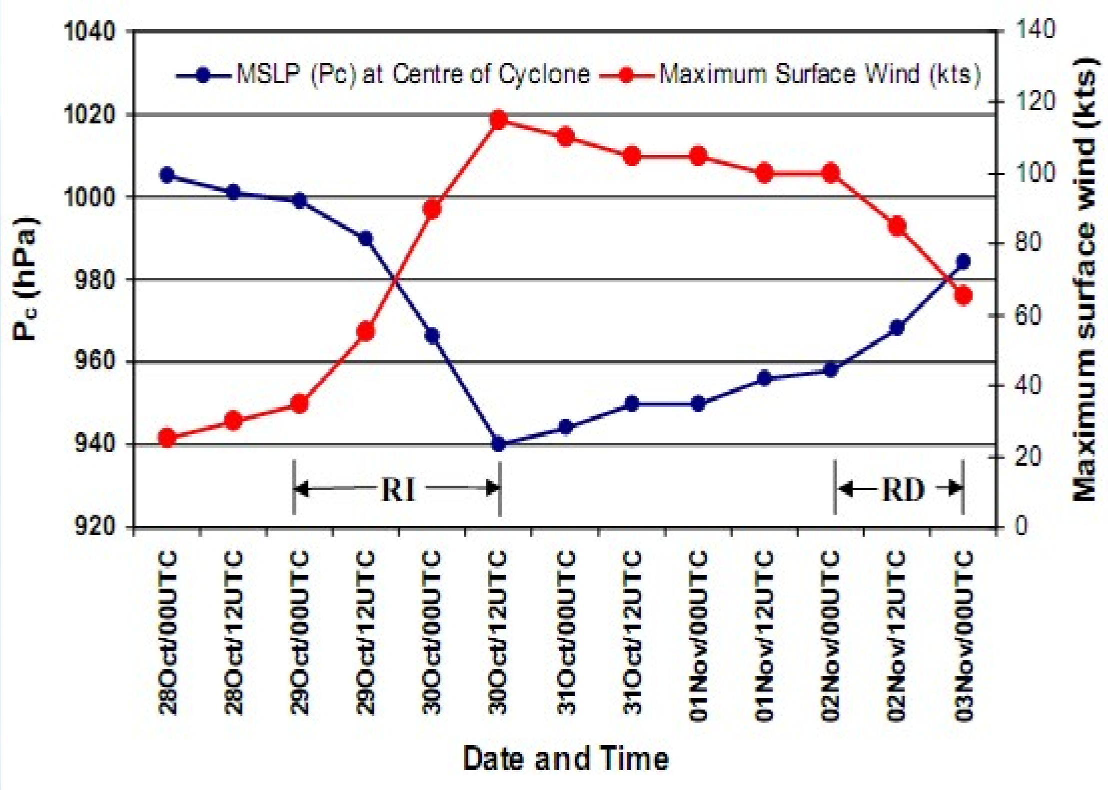
Kotal, S.D., Bhattacharya S.K., Roy Bhowmik S.K. and Kundu P.K. 2014. Growth of cyclone VIYARU and PHAILIN – a comparative study. ***Journal of Earth System Science, 123(7):1619-1635.***

Kotal, S.D., Bhattacharya S.K., Roy Bhowmik S.K. and Kundu P.K. 2013. The Rapid Growth and Decay of Severe Cyclone JAL (2010) over the Bay of Bengal. ***Meteorology and Atmospheric Physics, 121:161-179.***

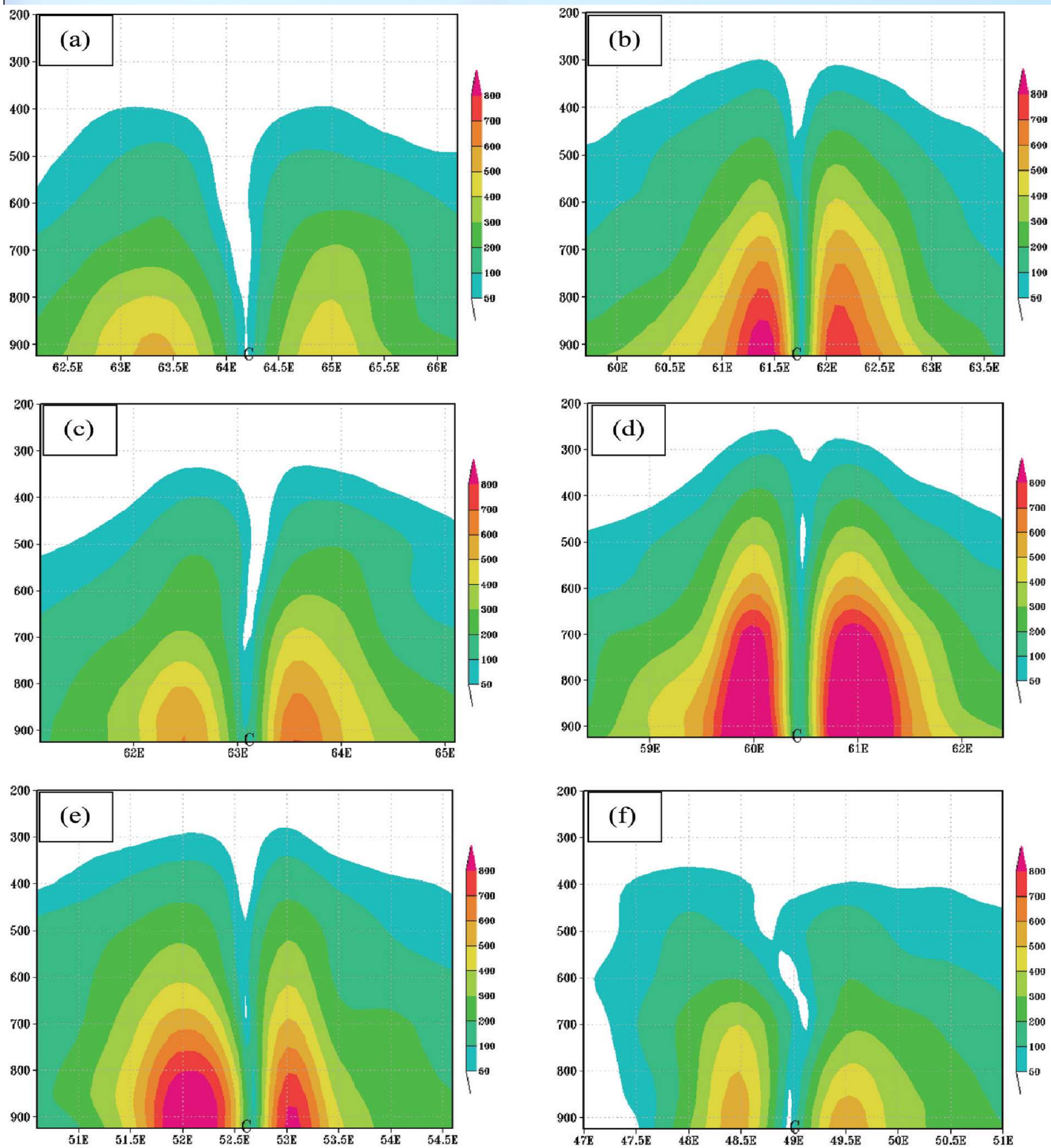
Kotal, S.D., Ajit Tyagi and Roy Bhowmik S.K. 2012. Potential Vorticity Diagnosis of Rapid Intensification of Very Severe Cyclone GIRI (2010) over the Bay of Bengal. ***Natural hazards (Springer), 60:461-484.***

CHAPALA: Track & Intensity





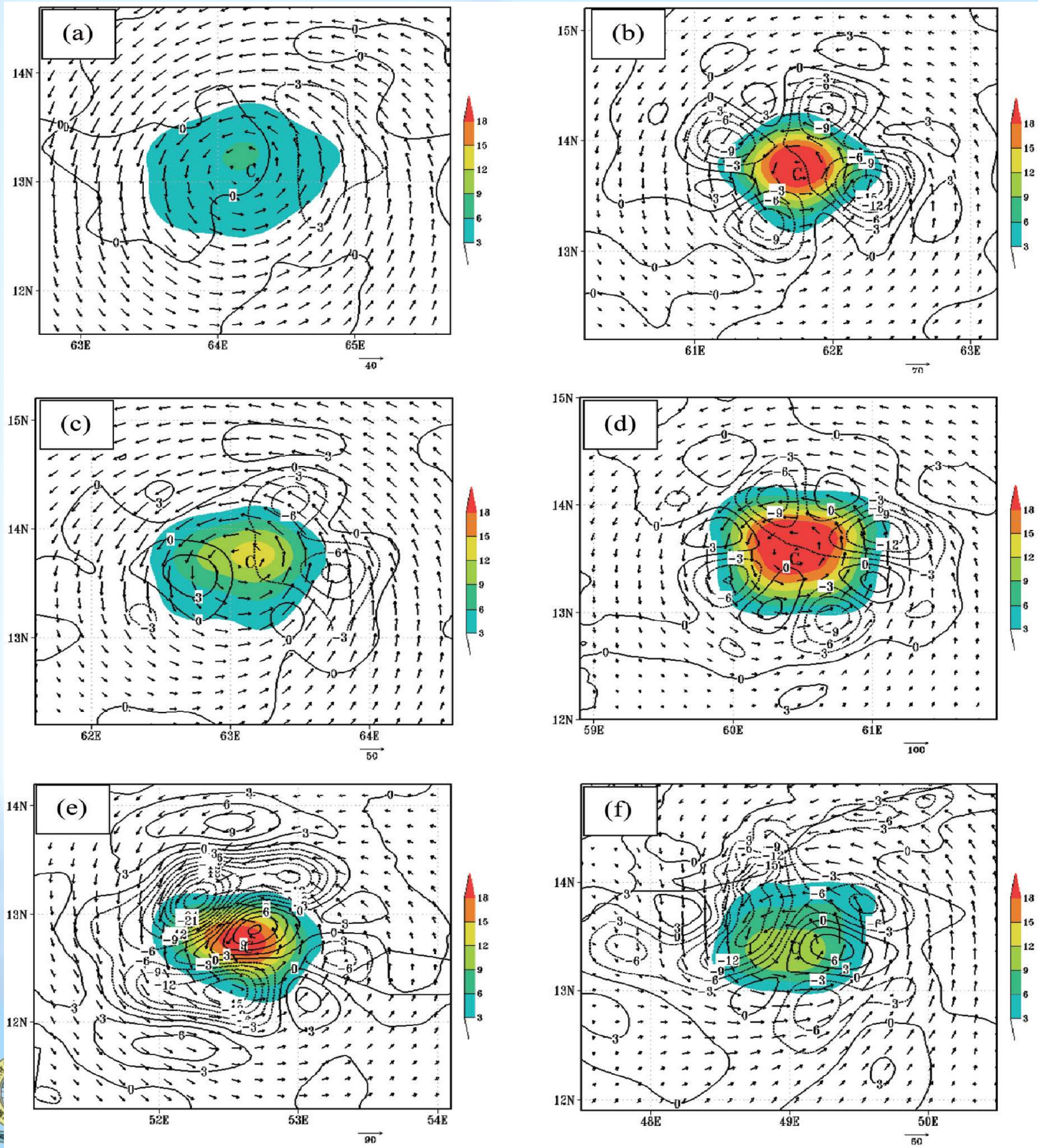
Vertical cross section plots of axisymmetric specific humidity flux



Vertical cross section plots of axisymmetric specific humidity flux (shaded in g m^{-2} s^{-1}) at

(a) 0000 UTC 29 October 2015,
(b) 0000 UTC 30 October 2015,
(c) 1200 UTC 29 October 2015,
(d) 1200 UTC 30 October 2015,
(e) 0000 UTC 2 November 2015,
(f) 0000 UTC 3 November 2015.

Potential vorticity (shaded in PVU) at 850 hPa



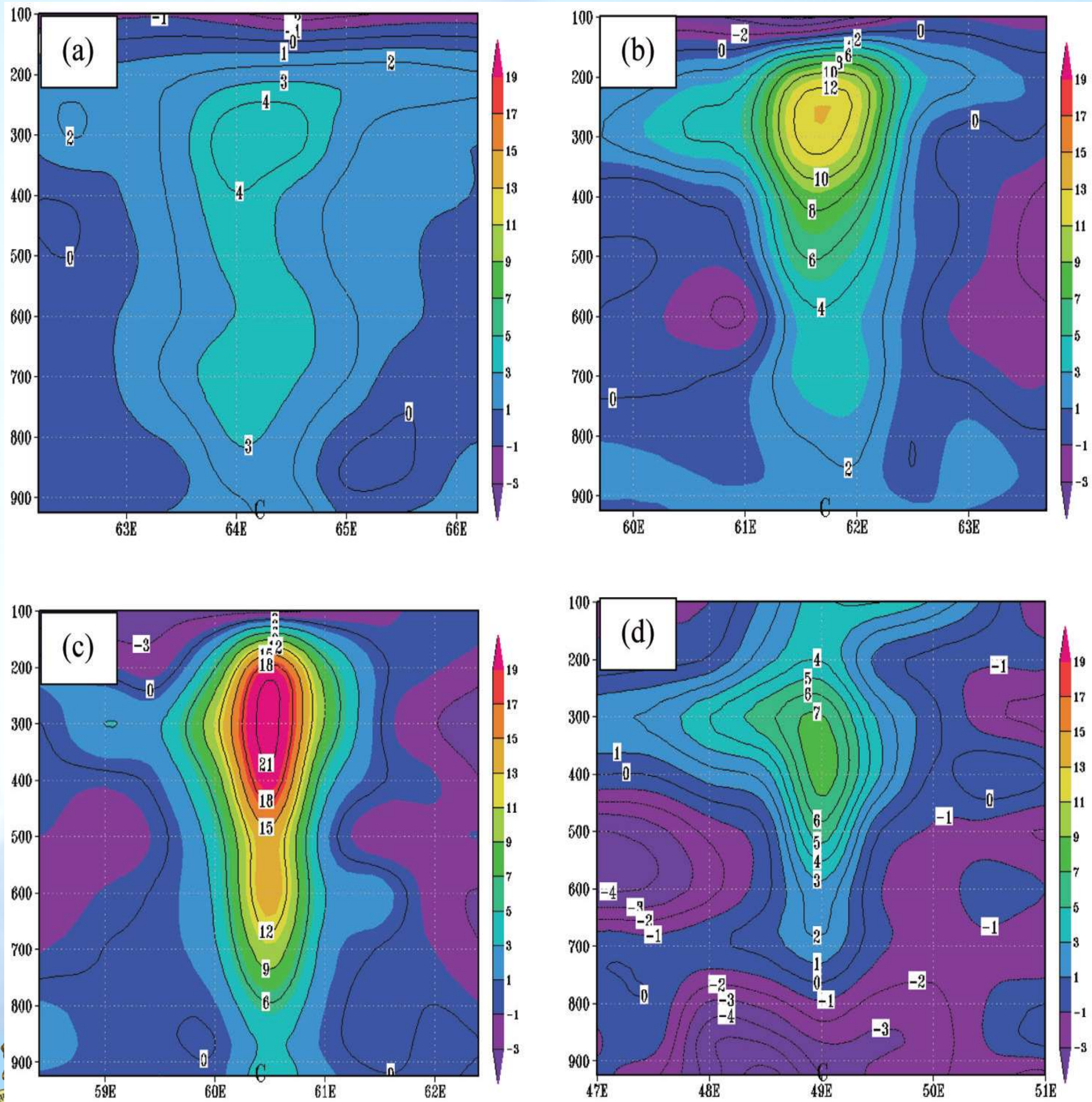
(a) Potential vorticity (shaded in PVU) at 850 hPa, vertical velocity averaged in the Surface-850 hPa layer (contours in Pa s^{-1}), and 850-hPa winds (vectors in ms^{-1}) at (a) 0000 UTC 29 October 2015, (b) 0000 UTC 30 October 2015, (c) 1200 UTC 29 October 2015, (d) 1200 UTC 30 October 2015, (e) 0000 UTC 2 November 2015, (f) 0000 UTC 3 November 2015.

Mathematically, Ertel's (1942) form of potential vorticity (PV) is given by the equation:

$$PV = \frac{1}{\rho}\zeta^{a} \cdot \nabla\theta$$

PV is a measure of the intrinsic cyclonicity of an air parcel. It can be shown through a combination of the first law of thermodynamics and momentum conservation that the potential vorticity can only be changed by diabatic heating (such as latent heat released from condensation) or frictional processes.

Vertical cross section plots of diabatic heating



Vertical cross section plots of diabatic heating (shaded in ^{o}C)

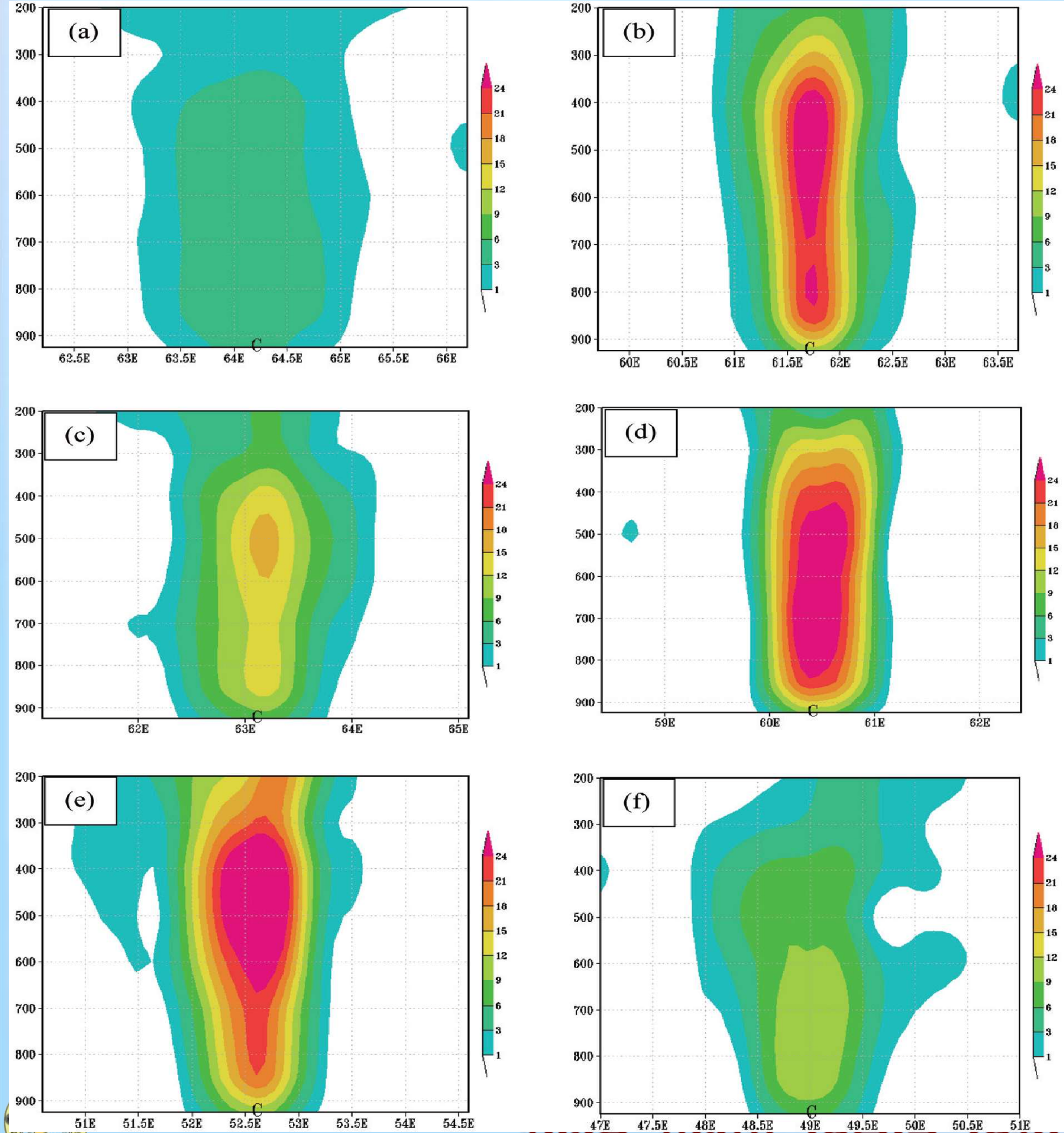
(a) from 0000 UTC 28 October 2015 to 0000 UTC 29 November 2015,

(b) from 0000 UTC 29 October 2015 to 0000 UTC 30 November 2015,

(c) from 1200 UTC 29 October 2015 to 1200 UTC 30 October 2015,

(d) from 0000 UTC 2 November 2015 to 3 November 2015.

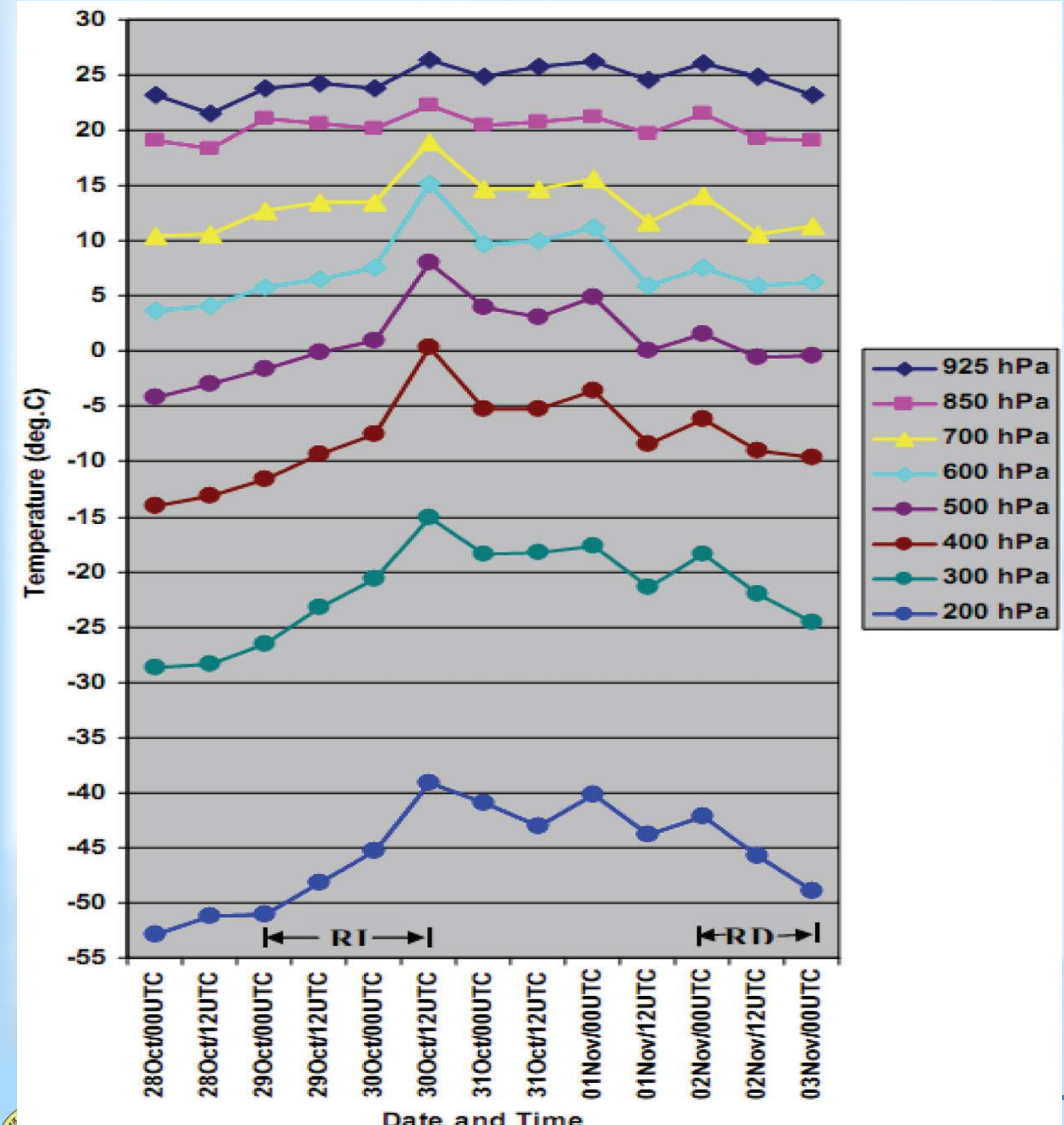
Vertical cross section plots of potential vorticity (shaded in PVU)



Vertical cross section plots of potential vorticity (shaded in PVU) at

(a) 0000 UTC 29 October 2015, (b) 0000 UTC 30 October 2015, (c) 1200 UTC 29 October 2015, (d) 1200 UTC 30 October 2015, (e) 0000 UTC 2 November 2015,(f) 0000 UTC 3 November 2015.

Time series from 0000 UTC 28 October 2015 to 0000 UTC 03 November 2015 of the temperature at the centre of the storm at different vertical levels



Time series from 0000 UTC 28 October 2015 to 0000 UTC 03 November 2015 of the temperature at the centre of the storm at different vertical levels (RI indicates Rapid Intensification phase and RD indicates Rapid Decay phase).


CHINA
BANGLADESH
INDIA
BURMA
(MYANMAR)
LAOS
THAILAND
Thank you
Bay of Bengal