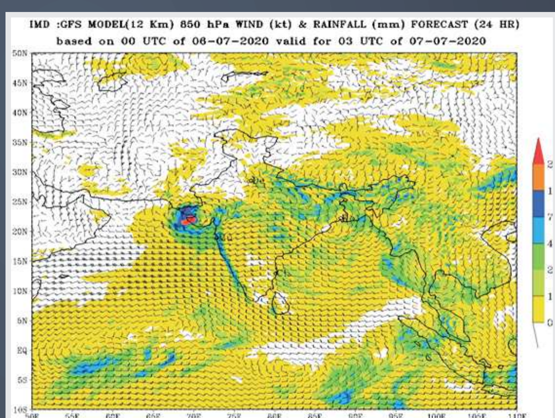
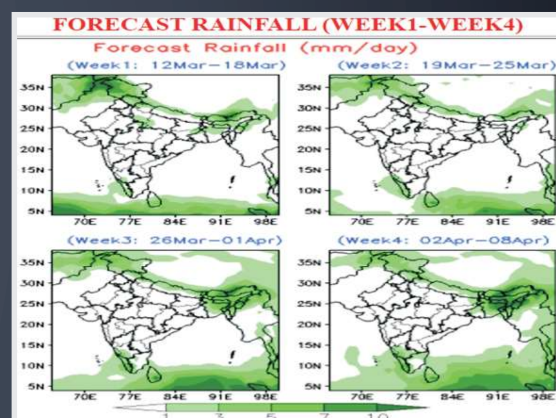
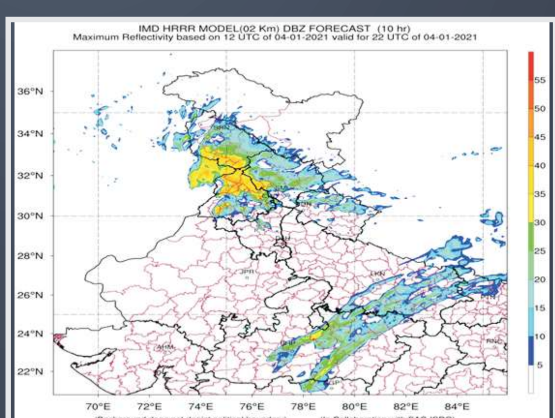
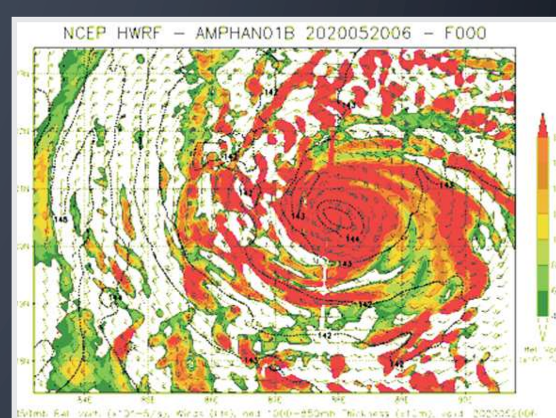
Government of India
Ministry of Earth Sciences
India Meteorological Department

Standard Operation Procedure for Numerical Weather Prediction (NWP) and Forecast Verification









Numerical Weather Division
India Meteorological Department
Ministry of Earth Sciences
New Delhi

March, 2021

Standard Operation Procedure
for
Numerical Weather Prediction (NWP)
and
Forecast Verification

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LIST OF CONTRIBUTORS

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Contents

Preface

Numerical Weather Prediction (NWP) modelling aims at forecasting the future weather by solving a set of governing equations using high power computing systems that describe the evolution of atmospheric parameters presenting the state of the atmosphere. Like worldwide, in India, a beginning on NWP was made towards the development of numerical methods for weather predication in the late fifties. A major boost to NWP in India occurred in late 1980s after India purchased its first Super Computer CRAY-XMP14.

In recent years the Ministry of Earth Sciences (MoES) has strongly supported NWP activities. With the availability of High Power Computing System and collaborative efforts of constituent organizations of MoES like IMD, IITM, NCMRWF and INCOIS, currently NWP division of IMD is operationally running a suite of global and regional numerical models to forecast weather from Nowcasting (a few hours) to the extended range (up to a month) forecasting. IMD generates weather forecasts at Block/District levels up to 5 days in short to medium range with twice a day update. IMD runs coupled models to generate meteorological subdivision levels extended range forecast for next four weeks with weekly update. The forecast of active and break phase of monsoon, high temperature, low temperature etc are predicted up to two weeks. IMD also runs atmospheric-Ocean coupled Hurricane WRF (HWRF) model for cyclone forecasting. In order to meet demands of users sectors like : Agriculture, Power, Hydrology, Tourism, Health etc various customized products based on NWP forecasts are prepared regularly.

This booklet is a consolidated Standard Operation Procedure (SOP) for NWP models run in IMD along with verification procedure for evaluation of NWP model products. It is hoped that the information it contains will be very useful to the NWP modelers & forecasters in operational field.

(Dr. M. Mohapatra)
Director General of Meteorology

Acknowledgements

I am very much thankful to all the Officers and staffs of Numerical Weather Prediction (NWP) Division for their sincere efforts in bringing out this Manual highlighting the details about the operational NWP models and products generated on operational basis as well as about the NWP models verifications aspects in the form a "**Standard Operating Procedure for Numerical Weather Prediction and Forecast Verification**".

I hereby place on record my deep appreciation for the valuable contributions made by Dr. D. R. Pattanaik, Sc.-'F', Head NWP Division, Dr. S. D. Kotal, Sc.-'F', Dr. Ananda Kumar Das, Sc.-'E' , Dr. V. R. Durai, Sc.-'E' and Shri Akhil Srivastava, Sc.-'C' towards preparation, compilation, edition, review and publication of this manual.

I also express my sincere thanks and appreciation to Shri Dinesh Khanna, Publication section for providing technical support in designing and page setting in making the final printable document of this SOP.

Dr. Mrutyunjay Mohapatra

March 2021 **Director General of Meteorology**

Chapter 1

NUMERICAL WEATHER PREDICTION

1.1. Introduction

The advances in Numerical Weather Prediction (NWP) in the last decades have been tremendous: higher accuracy, higher resolution, longer lead-time, wider range of relevant applications. Consequently the emphasis in operational meteorology, hydrology, oceanography and climatology has shifted towards the implementation of increasingly sophisticated and diverse numerical models and applications, for an ever-increasing variety of users.

IMD has also made rapid progress in the operationalization of different Numerical Weather Prediction models to cater to variety of needs specified by the forecaster's and other end users. With the commissioning of High Performance Computing System (HPCS) Aditya and Bhaskara by Ministry of Earth Science in 2015 and subsequent addition in the computing power by commissioning of Mihir and Pratyush HPCS, enabled IMD to operationalize the models on finer resolutions, with increased frequency as well as it also provided infrastructure to run global ensemble models.

To meet the growing operational demands of multiscale forecasts ranging from nowcast to medium range and extended range: global, regional and mesoscale NWP models with state of the art data assimilation procedures for regional models have been made operational at NWP division of IMD HQ. Specialized NWP models dedicated to particular weather events such as Tropical Cyclones and also dedicated to particular locations like Antarctica are also operationalized by NWP division of IMD.

The function of NWP Division has been with the mandate to

(i) Running of operational models like GFS, GEFS, WRF and ERF models.
(ii) Provide NWP guidance for day to day operational forecasts (including nowcast, short to medium-range forecasts and extended range forecast) at various forecasting offices of IMD.
(iii) Provide value-added user specific forecast support
(iv) Ensure regular up-gradation of technology to cope up with standard of other leading International NWP Centres,
(v) Taking up R & D activities related to NWP,
(vi) Customizations of mesoscale (regional) models and cyclone specific regional coupled model
(vii) Data assimilation in high-resolution mesoscale models
(viii) Development of post-processed and downscaled products as per requirement of forecasters and various sectoral applications
(ix) Dynamical-statistical modelling
(x) Conduct thorough testing and evaluation of newly developed techniques before introducing them for operational use and
(xi) Conduct NWP performance verification
(xii) Documentation of performance improvement of the models with time
(xiii) Operanalization and maintenance of NWP webpages

1.2. Organisational Structure

The Division has different with the following responsibilities:

1.2.1. Computer (High power computing) related

Computer Maintenance, procurement, infrastructure development and related coordination and correspondence work, Data management and archival, Networking, Computer Administration and Budget Plan for HQ and NWP Cells at Meteorological Centres.

1.2.2. Model operation

Model Run and generation of various products, coordination & support to day to day operational forecast, model diagnosis, updating and monitoring NWP web page and to trouble shooting.

1.2.3. Research & Development

a) To take up R & D activities related to NWP
b) Development testing and implementation of new algorithms related to data assimilation, model physics, model code, latest new NWP Techniques
c) Development of GIS based value added NWP support system
d) Development of radar and NWP based Nowcast System for major cities
e) Implementation of Air Quality model for major cities of India
f) Implementation of extended range forecast system
g) Post processing and customization of model outputs to generate User Specific Forecasts like District level forecast for Agriculture, Aviation Service, Cyclone Forecast, city forecast, rainfall forecast for river basins, locations specific forecasts (meteograms and epsgrams) etc.
h) Validation and Documentation
i) Training and human resource development for NWP work
j) Technical/Scientific Support to NWP Cells at Meteorological Centres
k) To provide NWP support to various Forecast Demonstration Projects
l) National and international coordination and collaboration

1.2.4. Verification & Documentation

It will conduct day to day NWP performance verifications using standard operation procedure. It will document the performance of different NWP models for severe weathers and also for a whole season.

1.3. Operational NWP System

1.3.1. IMD-GFS T-1534/L64 with Ensemble Kalman Filter (EnKF) component of hybrid Global Data Assimilation System (GDAS)

The IMD-GFS model is run with ~12 km horizontal resolution and 64 hybrid sigma-pressure layers with the top layer centred around 0.27 hPa (around 55 km). The dynamical core of the GFS is based on semi-Lagrangian(SL) spectral global model with state of art dynamics and physics. The initial conditions for IMD-GFS model is generated from the four-dimensional (4D) ensemble-variational data assimilation (DA) system (4DEnsVar) provided by National Center for Medium Range

Weather Forecasting (NCMRWF). This 4DEnsVar data assimilation system has capabilities to assimilate various conventional as well as satellite observations including radiances from different polar orbiting and geo-stationary satellites. The analysis is done 4 times a day (0000, 0600, 1200 and 1800 UTC) to provide first guess to run IMD-GFS model 4 times in a day at 0000, 0600, 1200 and 1800 UTC to generate 10 days forecast during each run. Forecast is made available as soon as the products are generated and on average are available after approximately 4 hrs 30 minute from the model run time. The operational configuration of the GFS and GEFS models are described in the table 1.

Table 1

GFS and GEFS model configuration

Model	GFS / GEFS
Prediction usage	Short Range Prediction
Model Version	V14.1.1.3
No. of ensembles	20 (GEFS) + 1 (GFS)
No. of Levels (Sigma)	64
Description about the Model	a) Spectral model, with Semi-Lagrangian dynamics and Semi-implicit time scheme b) With Near surface SST
Grid description	Reduced Gaussian Linear Grid
Resolution	T1534 (3072 × 1536) ~ 12.5KM
Model time-steps	Dynamics : 900 sec Physics : 450 sec
Radiation time-steps	1 Hour for both LW and SW
Deep Convective Parameterization	Scale- and Aerosol-aware deep convection (SAS)
Shallow Convective parameterization	Scale- and Aerosol-aware shallow scheme based on mass-flux
Radiation	RRTMG
PBL	EDMF
Microphysics	Zhao – Carr Microphysics
Surface Model	NOAH Land Surface Model
Forecast Length	243 Hours with 3 hourly interval (cycles: 0000 UTC and 1200 UTC Every day for GEFS) 243 Hours 4 times a day for GFS
Initial Condition Perturbations	Ensemble Kalman Filter (ENKF)
Model I/O format	Nemsio
Space requirement	21 TB/cycle (Only forecast) GEFS 2 TB / cycle (only forecast) GFS
Post-Processing	Grib2
Time taken	2.5 Hr. and 1 Hr. for GEFS and GFS respectively

The IMD-GFS based products are generated for meteorological sub-division level, State level and up to district and block level to cater different users. GFS(T-1534) State Level Forecast Products and Meteograms for all Districts and major stations within a State are made available in NWP Website. Specific aviation sector products, forecast for major cities and Meteograms for major cities are also hosted on the website for forecaster's and general public. GFS(T-1534) Aviation Products for Low Level, Mid-Level, High Level, Convective Cloud (Cloud cover, Base, Top), Zero Degree Isotherm, Surface Visibility, 10m Wind Gust, Max. Wind & GPM are available at NWP website. At present approximately 1263 district and synop stations Meteograms are made available based on IMD-GFS on NWP website. IMD-GFS based forecast for specific severe weather events such as Heat Wave and fog forecast related products are also provided to forecaster's. Following is the categories of products currently hosted on the NWP website for IMD-GFS model.

MAIN PRODUCTS

- ***STATE LEVEL FORECAST***
- ***DIAGNOSTIC PRODUCTS***
- ***FORECAST FOR MAJOR CITIES***
- ***METEOGRAMS***
- ***Shri AMARNATH JI YATRA METEOGRAMS***
- ***SKEW-T DIAGRAMS***

AVIATION PRODUCTS

- ***CHARTS***
- ***METEOGRAMS***

RAINFALL FORECAST FOR SUB-DIVISION

- ***ALL INDIA DAILY MEAN RAINFALL FORECAST (10 DAYS)***
- ***RAINFALL DISTRIBUTION FORECAST***
- ***RAINFALL INTENSITY FORECAST***
- ***CUMULATIVE RAINFALL FORECAST***

FOG/POLLUTION PRODUCTS

- ***VENTILATION INDEX (SPATIAL)***
- ***WIND CHILL (SPATIAL)***
- ***PBL HEIGHT (SPATIAL)***
- ***FOG STABILITY INDEX (SPATIAL)***
- ***VENTILATION INDEX (DELHI)***
- ***MIXING HEIGHT (DELHI)***
- ***PBL WIND (DELHI)***

HEAT WAVE PRODUCTS

- ***FORECAST & ANOMALY PRODUCTS***
- ***OBSERVED & ANOMALY PRODUCTS***
- ***MAX./MIN. TEMP. FOR BIHAR (HEALTH SECTOR)***

DISTRICT LEVEL FORECAST
DISTRICT & BLOCK LEVEL FORECAST

The list of products for the GFS model is given in the table 2 described below.

Table 2

List GFS products

Parameter	Level	Frequency	Interpretation
MAIN PRODUCTS			
MSLP-India, MSLP, Rainfall, Rainfall-India	Surface	24h	**MSLP** (Mean surface level pressure) is the surface pressure reduced to sea level. These charts show surface pressure patterns - areas of high and low pressure which are associated with different weather types.
GPM height 500hPa	500 hPa	24h	The (GPM) geopotential height is often used to express the altitude of a specific pressure level above sea level. **Heights** are lower in cold air masses, and higher in warm air masses.
Wind	925, 850, 700, 600, 500, 400, 300, 200, 150, 100 hPa	24h	**Wind** is the air in motion in horizontal having speed and direction at different pressure levels. They are useful for identification and monitoring of cyclonic as well as anti-cyclonic features at different pressure levels.
DIAGNOSTIC PRODUCTS			
10m WIND, GUST(INDIAN REGIONS), 10m WIND, GUST+RH2m, 10m WIND+RH2m, Temperature 2m, RH2m, Temp 2m Tendency, RH 2m Tend, Wind Tendency.	Near Surface	06h	This product gives indication about the different diagnostic parameters like wind, gust, relative humidity etc very close to the surface i.e. at 2 m and 10 m heights.
Moisture Flux, Moisture Flux Convergence, PWC, Supercell Composite Parameter (SCP) Index ,T-Storm Initiation Index ,Total Total Index, Sweat Index , K Index, Lifted Index, CAPE, CIN.	N/A	06h	These parameters are used for forecasting of thunderstorms. Different regions have different threshold for identification and forecasting of thunderstorms.
Divergence (850), Vertical Velocity(850), Vorticity(850)	850 hPa	06h	**Divergence** occurs when a stronger wind moves away from a weaker wind or when air streams move in opposite directions. When **divergence** occurs in the upper levels of the atmosphere it leads to rising air. The **vorticity** and its changes are used to calculate divergence and, through continuity, the vertical motions, which are most important for the **weather**.
Temperature	400, 500, 600, 700, 850, 925 hPa	06h	The temperature is provided at different pressure levels.
Wind Shear	850-200 hPa	06h	**Wind shear** describes how the **wind** changes **speed** and/or direction with height. Wind shear is important to severe thunderstorm forecasting.

Mean Wind	500-300 hPa, 850-300 hPa, 850-500 hPa	06h	This product gives the mean wind between the different pressure levels.
500-1000hPa Thickness	500-1000 hPa	06h	Rain and snow are equally likely when the 500-1000 hPa thickness is about 5225 gpm (or 522 dam). Rain is rare when the 500-1000 hPa thickness is less than 5190 gpm. Snow is extremely rare when the 500-1000 hPa thickness is greater than 5395 gpm.
Vertical Velocity(750)	750 hPa	06h	The amount of upward motion in the atmosphere. 700 mb vertical velocity is simply the velocity of air moving through the 700 mb surface in a vertical direction.
Mean Tropospheric Temperature,Temp. Inversion	N/A	06h	A temperature inversion is a thin layer of the atmosphere where the normal decrease in temperature with height switches to the temperature increasing with height. An inversion acts like a lid, keeping normal convective overturning of the atmosphere from penetrating through the inversion.
AVIATION PRODUCTS CHARTS			
Cloud-Cover, Cloud Base, Cloud Top.	Low, Medium, High, Convective	03h	Different products regarding the amount of cloud, lowest cloud as well as tallest cloud etc are indicated for aviation purposes.
Zero Degree Isotherm, Surface Visibility, 10m Wind Gust, Max. Wind & GPM, Wind 80m, Wind 100m.	Surface and Near Surface.	03h	Zero degree isotherms are important for precipitation type forecasts and infrastructure that is vulnerable to freezing. It helps us to forecast ice, freezing rain, freezing fog, frost and snow etc. **Surface Visibility is** a measure of the horizontal opacity of the atmosphere and very important for aviation purposes. Winds/Gusts at different heights as required for aviation purposes is provided.
Wind and Temperature	FL10, FL15, FL20, FL30, FL60, FL90, FL120, FL150	03h	Wind and temperature at different heights specified in terms of Flight levels are provided for use in weather forecasting specifically for aviation purposes.
ALL INDIA DAILY MEAN RAINFALL FORECAST (10 DAYS)			
All India Daily Mean Rainfall Forecast(10days), Cumulative Sub-div Rainfall Forecast(10days)	Surface	N/A	The average daily rainfall over entire country for next 10 days as well as cumulative rainfall forecast sub-division wise for 10 days are provided. They are very important for agro-meteorological forecasts as well as other water management activities.

CUMMULATIVE RAINFALL FORECAST			
Cum. Rainfall Forecast (Day1-Day3), Cum. Rainfall Forecast(Day4-Day8), Cum. Rainfall Forecast (Day9-Day10)	Surface	N/A	The cumulative rainfall forecast for different duration and forecast periods for guidance to different sectoral applications.
FOG/POLLUTION PRODUCTS			
Ventilation Index(Spatial), PBL Height(Spatial), Wind Chill(Spatial),Fog Stability Index(Spatial), 10m Wind & RH 2m(Spatial),Temperature Inversion(Spatial)	N/A	03h	Different factors affect the formation as well as denseness of formation of fog. These different parameters are provided as guidance to the forecasters for use in fog forecasting.
Ventilation Index(Delhi), Mixing Height(Delhi),PBL Wind(Delhi).	N/A	03h	Ventilation Index is product of the mixing height (m) and the transport wind speed (m/s) used as a tool for air quality forecasters to determine the potential of the atmosphere to disperse contaminants such as smoke or smog.
HEAT WAVE PRODUCTS			
Forecast & Anomaly Products, Observed & Anomaly Products, Max/Min Temp. For Bihar (Health Sector).	N/A	24h	The products generated for heat wave guidance are the forecasted Maximum temperatures, Maximum Temperature anomaly, Maximum Heat Index, Minimum temperatures, Minimum Temperature anomaly and Minimum Heat Index.
GFS METEOGRAM			
Sea Level Pressure , Precipitation, RH, Temperature, 10 m Wind Speed and Gust, 2m RH/ Temp/ Dew Point Temp.	SURFACE & Near Surface.	3 Hourly	The spatial products mentioned above are also generated for point locations in form of meteograms. They contain MSLP, RH, Wind etc for location specific forecasting.
Cloud Cover	Low, Middle, High	3 Hourly	The spatial products mentioned above are also generated for point locations in form of meteograms. They contain cloud cover details for location specific forecasting.
Lifted Index, CAPE	N/A	3 Hourly	The spatial products mentioned above are also generated for point locations in form of meteograms. They contain different thunderstorm related indexes for a particular location for localised thunderstorm forecasting.
Thickness and Wind	1000-500 mb and 1000 millibar-500 millbar	3 Hourly	The spatial products mentioned above are also generated for point locations in form of meteograms. They contain different products such as thickness (GPM) etc for location specific forecasting.

The sample rainfall product as generated from IMD-GFS model is shown in figure below:-

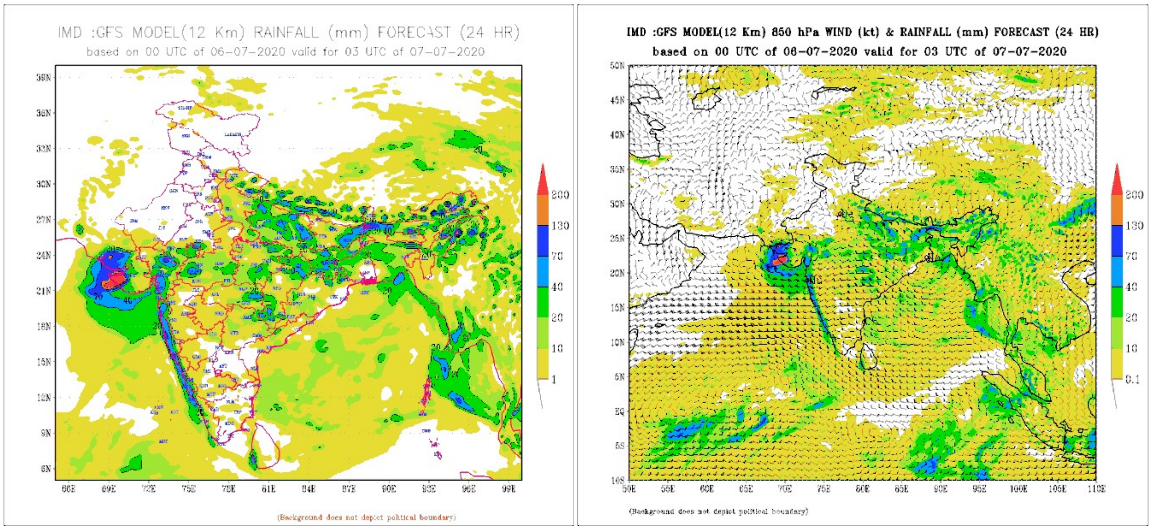


Fig. 1. ***Heavy Rainfall forecast for 6th July, 2020 based on IC of 0000 UTC of 6th July, 2020***

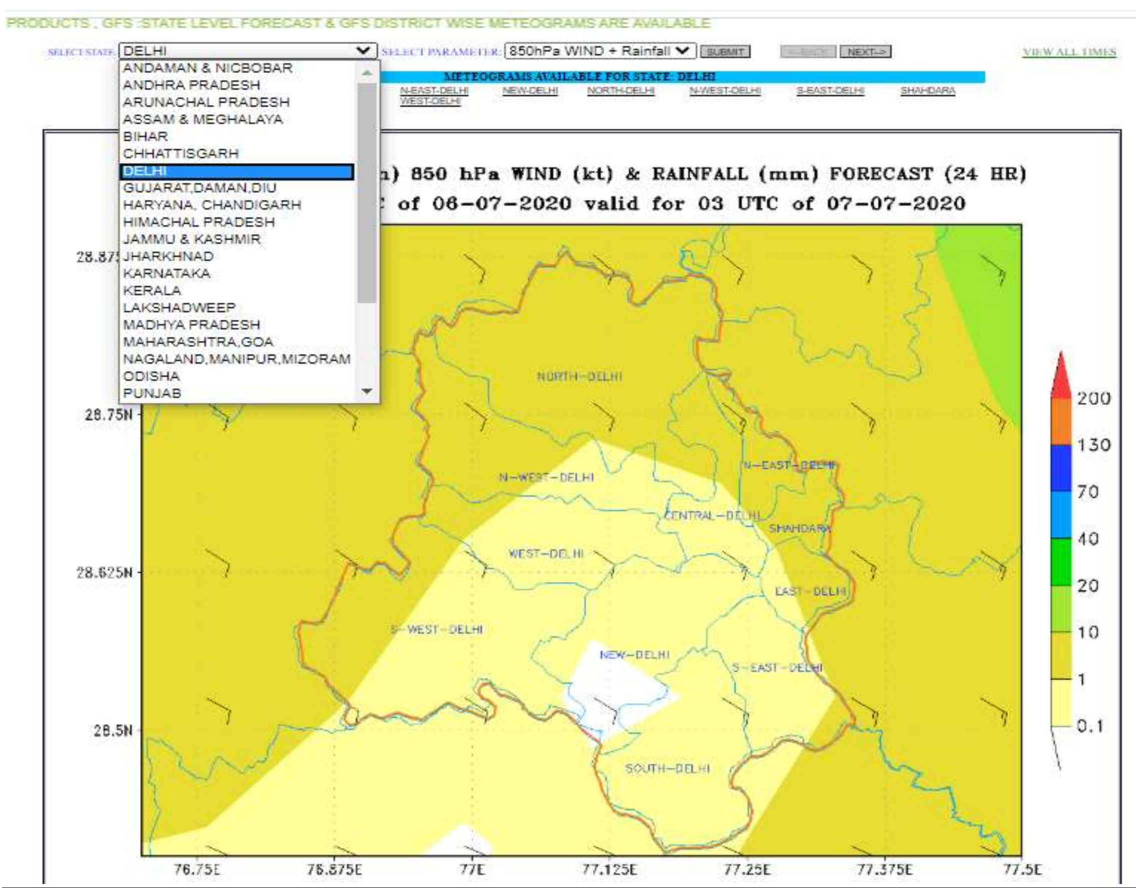


Fig. 2. ***State Level forecast for 6th July, 2020 based on IC of 0000 UTC of 6th July, 2020***

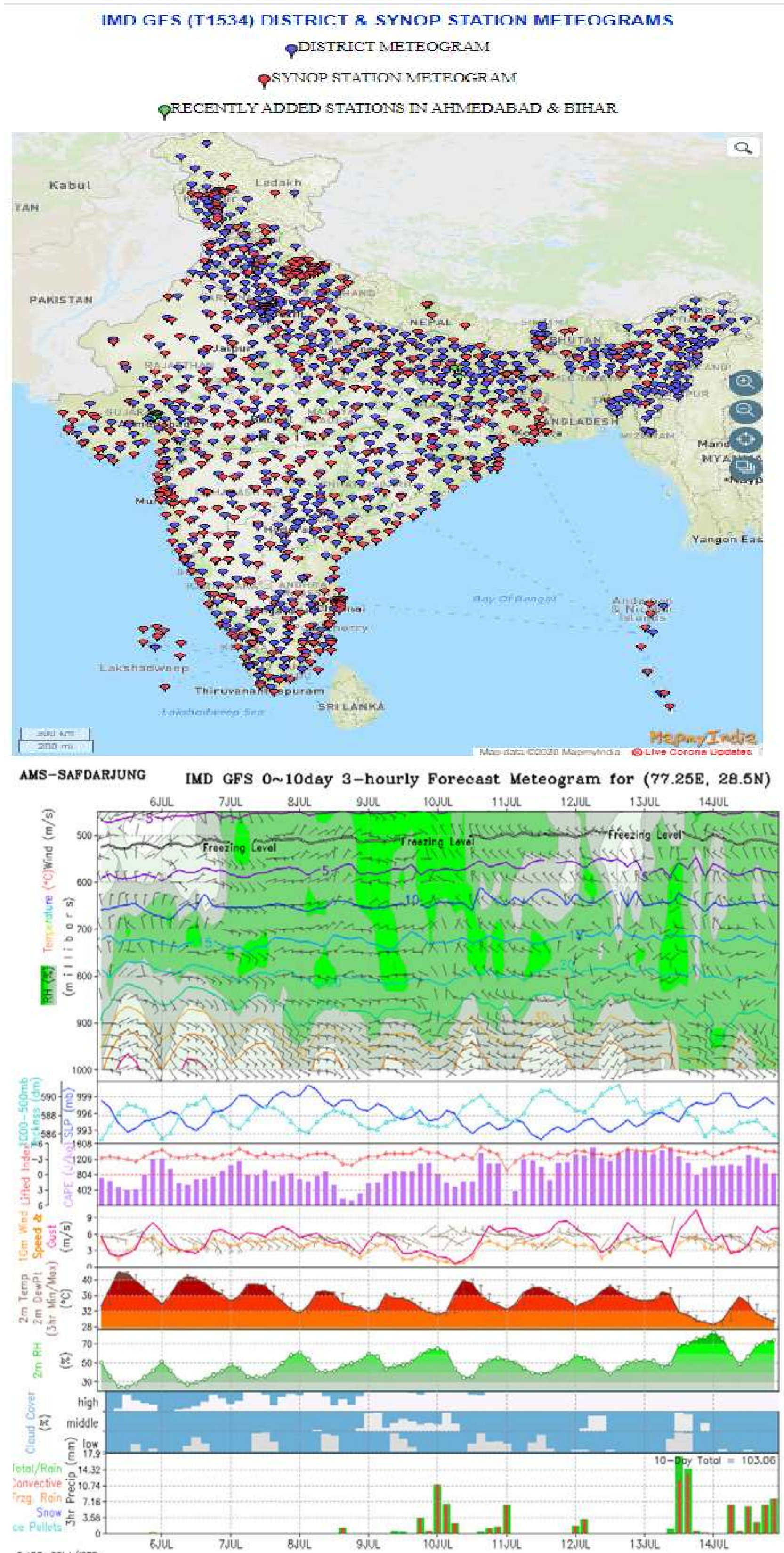


Fig. 3. ***Meteograms locations as generated through IMD-GFS model***

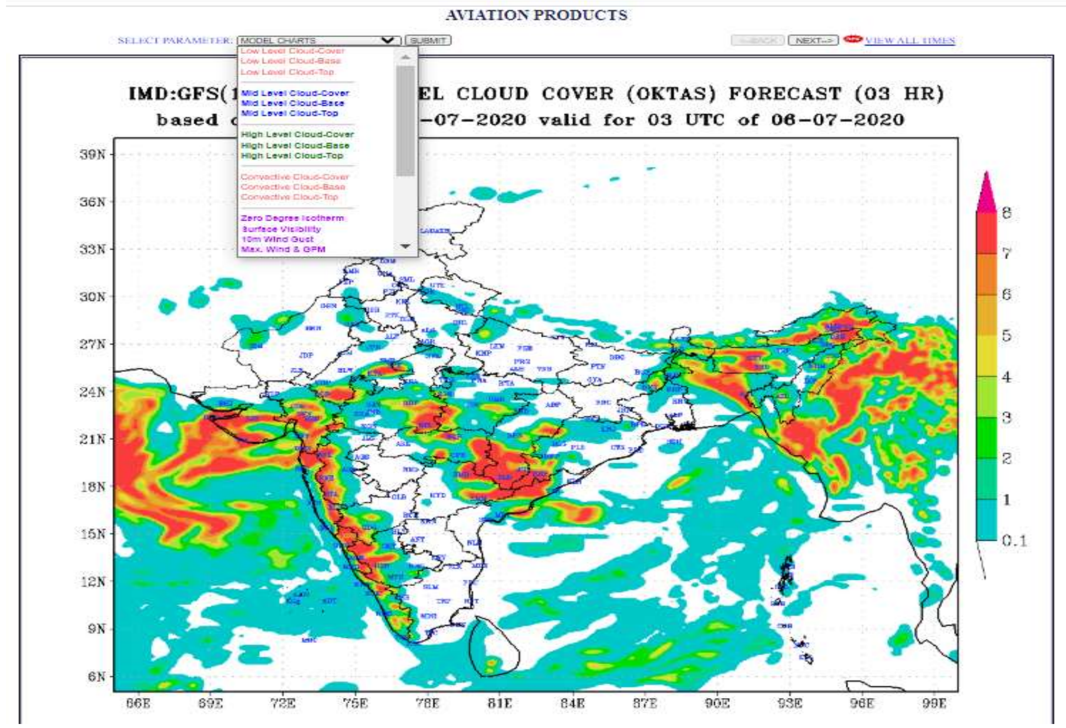


Fig. 4. ***Cloud cover forecasts***

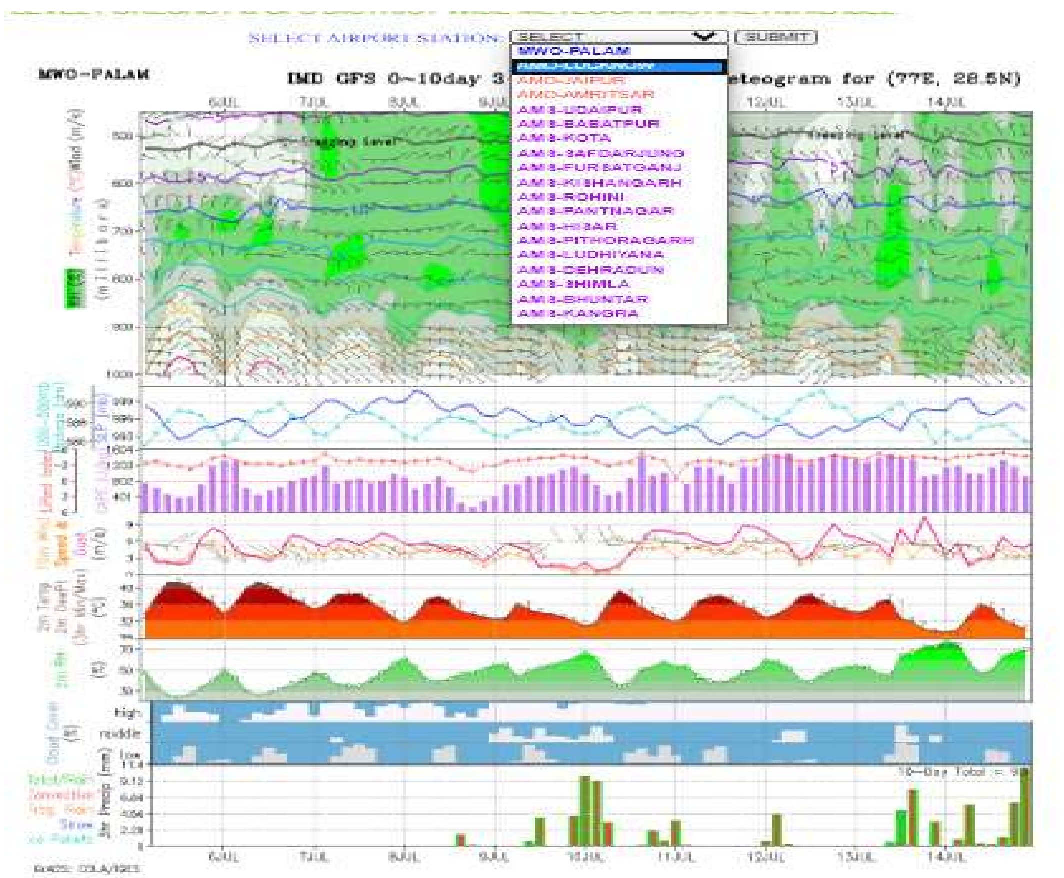


Fig. 5. ***Aviation products generated from IMD-GFS model including Meteograms for MWO, AMO & AMS***

1.3.2. IMD-GEFS T-1534/L64: GEFS is a Semi-Lagrangian T1534 L64 (about 12 km on equator) and 64 hybrid sigma-pressure layers with 21 ensemble members. This high resolution GEFS model is being run twice in a day (0000 & 1200 UTC) to give 10 day operational probabilistic prediction in the short to medium range. At present, in July 2020 the products from 0000 and 1200 UTC cycle are only hosted on NWP website. The initial conditions are generated from the NCEP based Ensemble Kalman Filter (EnKF) component of hybrid Global Data Assimilation System (GDAS). The subdivision wise as well as district and block level probabilistic forecasts are hosted on NWP website for use of forecaster's. The categories of product available on website are (i) **MAIN PRODUCTS, (ii) ANIMATION PRODUCTS. (iii) EPSGRAM and (iv) DISTRICT & BLOCK LEVEL FORECAST.** The product list for the GEFS model is given in the table 3 given below.

Table 3

List of GEFS products

MAIN PRODUCTS			
MSLP, Rainfall-EnsMean, Rainfall-probabilty, Tmax/Tmin	Surface	24h	**MSLP** (Mean surface level pressure) is the surface pressure reduced to sea level. These charts show surface pressure patterns - areas of high and low pressure which are associated with different weather types. The products showing mean of all the members of ensemble model are also provided to guide forecasters in probabilistic forecasting.
GPM height 500 hPa	500 hPa	24h	The (GPM) geopotential height is often used to express the altitude of a specific pressure level above sea level. **Heights** are lower in cold air masses, and higher in warm air masses.
Wind hPa	850, 700, 500, 200 hPa	24h	**Wind** is the air in motion in horizontal having speed and direction at different pressure levels. They are useful for identification and monitoring of cyclonic as well as anti-cyclonic features at different pressure levels.
ANIMATION PRODUCTS			
GPM	N/A	24h	The same as above GPM product in form of a movie/animation.
MSLP, Probabilistic Rain, Rain, Temperature	Surface	24h	The same as above MSLP/probabilistic rain product in form of a movie /animation.
Wind	850, 700, 500, 200 hPa	24h	The same as above wind product in form of a movie /animation.

The sample products from IMD-GEFS model is given below:-

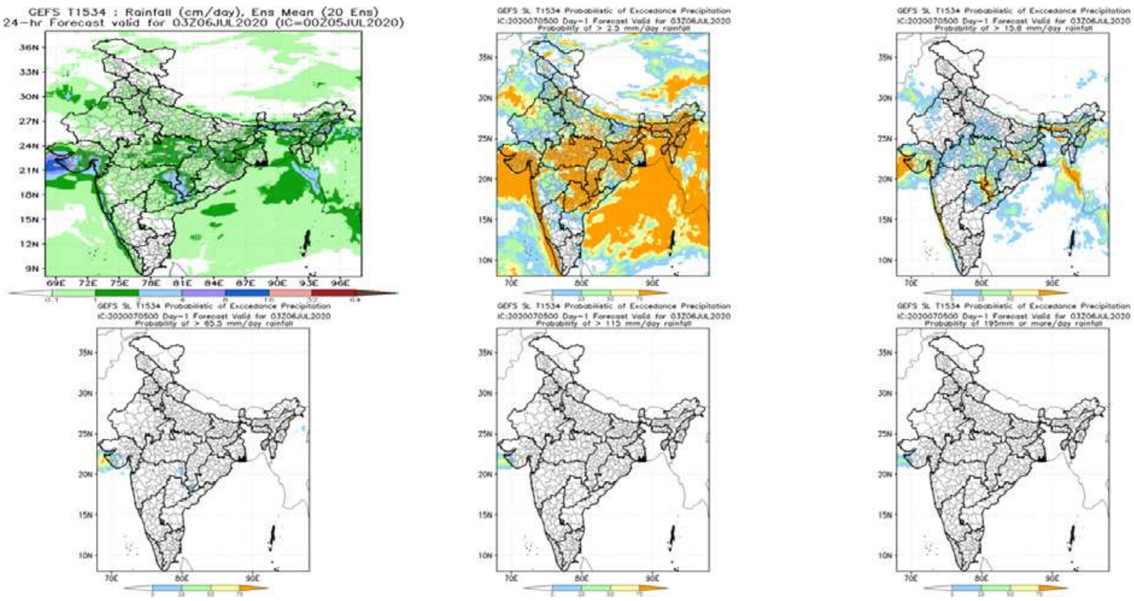


Fig. 6. ***Rainfall Probability forecast for 06th July, 2020 based on IC of 0000 UTC of 5th July, 2020***

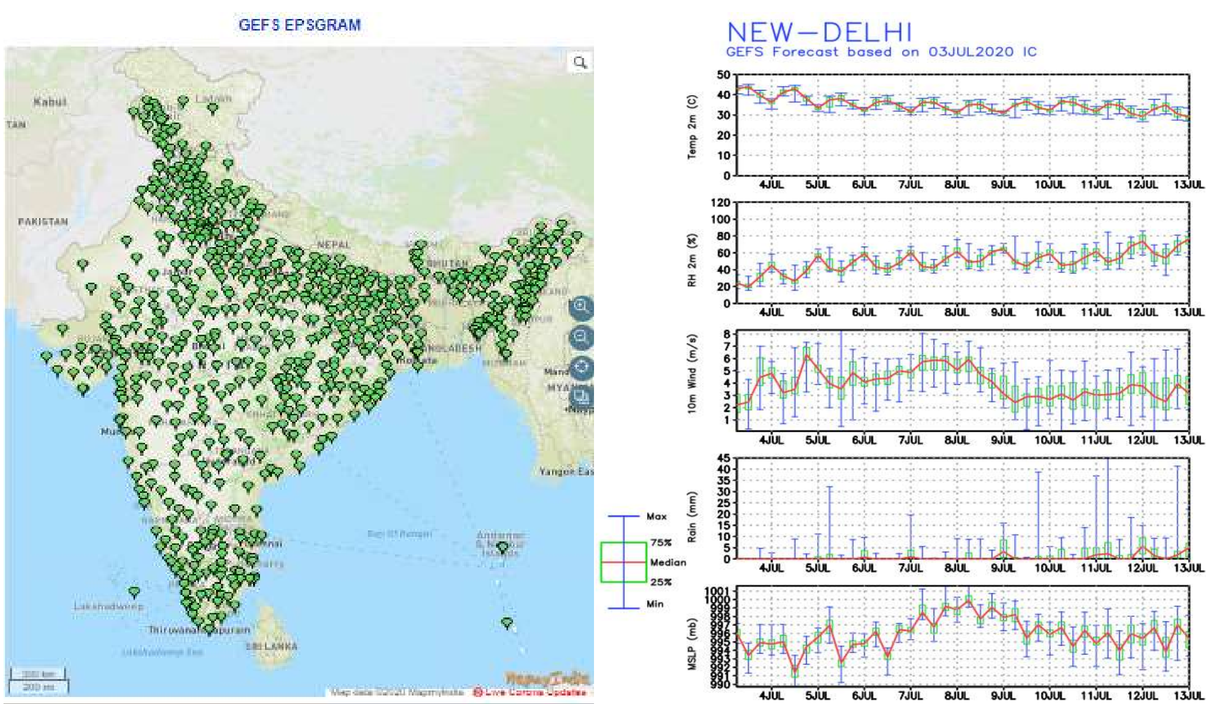
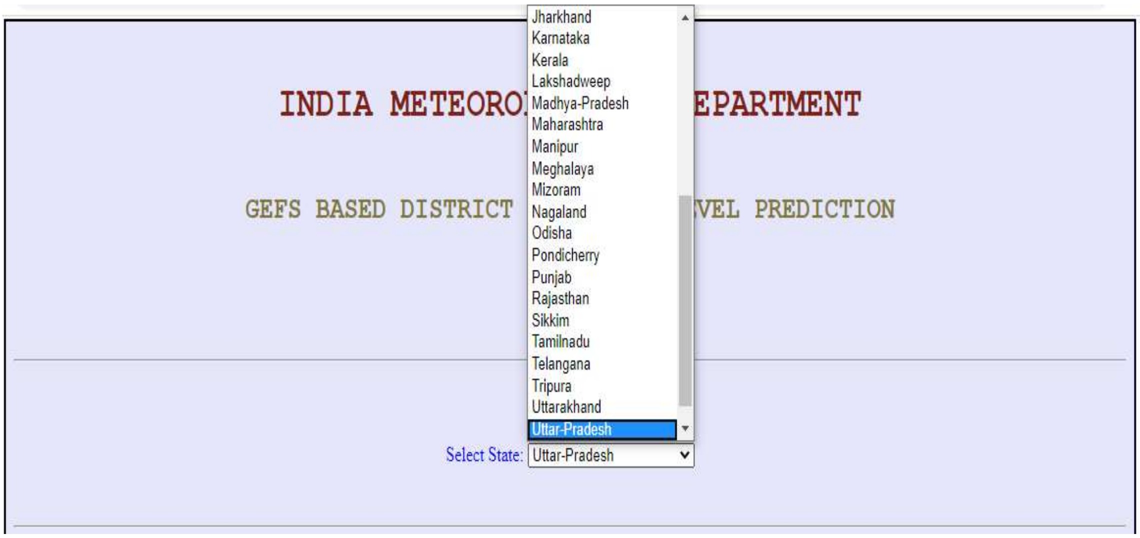
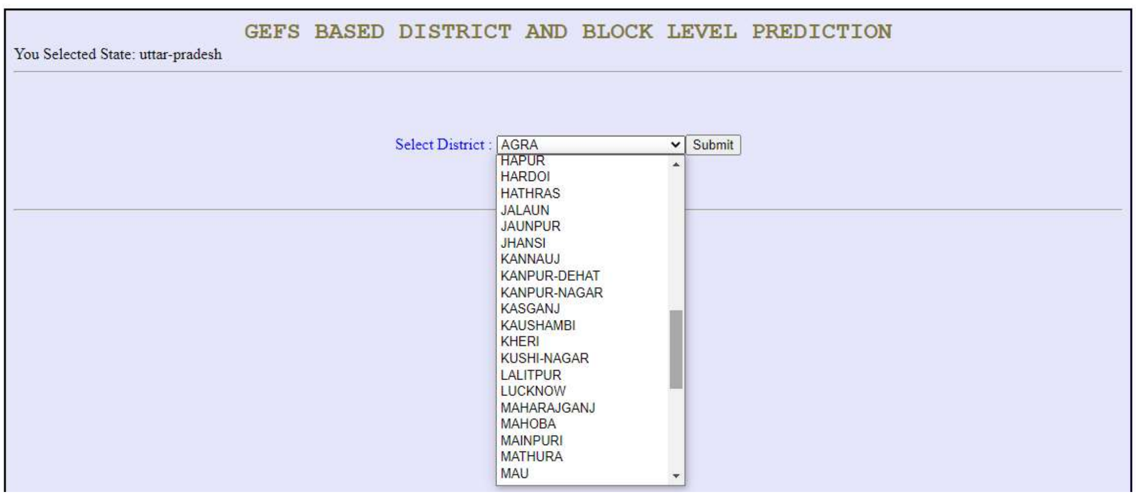
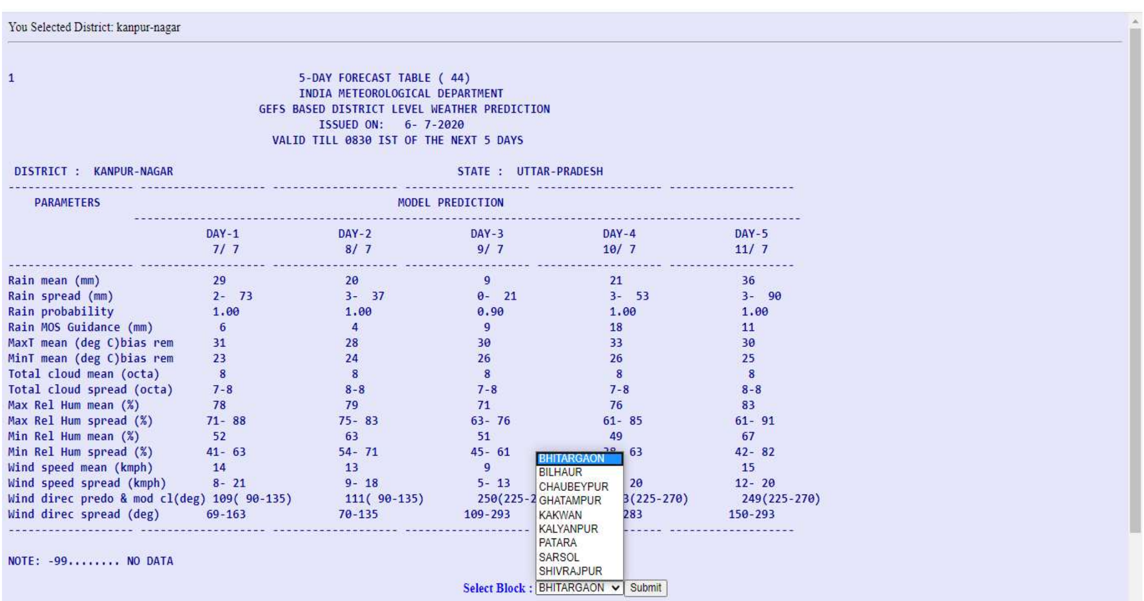


Fig. 7. ***Meteograms as generated through IMD-GEFS model***






You Selected District: kanpur-nagar

1 5-DAY FORECAST TABLE (44)

INDIA METEOROLOGICAL DEPARTMENT

GEFS BASED DISTRICT LEVEL WEATHER PREDICTION

ISSUED ON: 6- 7-2020

VALID TILL 0830 IST OF THE NEXT 5 DAYS

DISTRICT : KANPUR-NAGAR STATE : UTTAR-PRADESH

PARAMETERS	MODEL PREDICTION				
	DAY-1 7/ 7	DAY-2 8/ 7	DAY-3 9/ 7	DAY-4 10/ 7	DAY-5 11/ 7
Rain mean (mm)	29	20	9	21	36
Rain spread (mm)	2- 73	3- 37	0- 21	3- 53	3- 90
Rain probability	1.00	1.00	0.90	1.00	1.00
Rain MOS Guidance (mm)	6	4	9	18	11
MaxT mean (deg C)bias rem	31	28	30	33	30
MinT mean (deg C)bias rem	23	24	26	26	25
Total cloud mean (octa)	8	8	8	8	8
Total cloud spread (octa)	7-8	8-8	7-8	7-8	8-8
Max Rel Hum mean (%)	78	79	71	76	83
Max Rel Hum spread (%)	71- 88	75- 83	63- 76	61- 85	61- 91
Min Rel Hum mean (%)	52	63	51	49	67
Min Rel Hum spread (%)	41- 63	54- 71	45- 61	[illegible] 63	42- 82
Wind speed mean (kmph)	14	13	9	[illegible]	15
Wind speed spread (kmph)	8- 21	9- 18	5- 13	[illegible] 20	12- 20
Wind direc predo & mod cl(deg)	109(90-135)	111(90-135)	250(225-[illegible]	[illegible]3(225-270)	249(225-270)
Wind direc spread (deg)	69-163	70-135	109-293	[illegible]283	150-293

NOTE: -99........ NO DATA

You Selected State: uttar-pradesh

You Selected District: kanpur-nagar

1

5-DAY FORECAST TABLE (481)
INDIA METEOROLOGICAL DEPARTMENT
GEFS BASED BLOCK LEVEL WEATHER PREDICTION
ISSUED ON: 6- 7-2020
VALID TILL 0830 IST OF THE NEXT 5 DAYS

BLOCK : BILHAUR DISTRICT : KANPUR-NAGAR STATE : UTTAR-PRADESH

PARAMETERS	MODEL PREDICTION				
	DAY-1 7/ 7	DAY-2 8/ 7	DAY-3 9/ 7	DAY-4 10/ 7	DAY-5 11/ 7
Rain mean (mm)	23	20	10	22	47
Rain spread (mm)	5- 42	3- 45	0- 25	0- 105	0- 194
Rain probability	1.00	1.00	0.95	0.95	0.95
Rain MOS Guidance (mm)	4	1	3	18	16
MaxT mean (deg C)bias rem	32	27	30	33	31
MinT mean (deg C)bias rem	24	24	26	26	25
Total cloud mean (octa)	8	8	8	8	8
Total cloud spread (octa)	6-8	8-8	7-8	6-8	8-8
Max Rel Hum mean (%)	77	78	70	77	82
Max Rel Hum spread (%)	69- 87	72- 85	60- 85	59- 90	57- 93
Min Rel Hum mean (%)	51	60	51	48	62
Min Rel Hum spread (%)	41- 66	51- 72	45- 57	36- 64	38- 76
Wind speed mean (kmph)	13	13	10	18	15
Wind speed spread (kmph)	5- 20	9- 18	5- 14	14- 24	10- 20
Wind direc predo & mod cl(deg)	98(90-135)	110(90-135)	255(225-270)	251(225-270)	274(270-315)
Wind direc spread (deg)	45-135	71-135	71-290	240-285	23-293

NOTE: -99........ NO DATA

Fig. 8. ***IMD-GEFS based District and Block Level Forecast***

1.3.3. IMD-WRF (ARW) with regional Gridpoint Statistical Interpolation (GSI) based data assimilation : IMD-WRF is run at 3 km resolution twice a day based on 0000 UTC and 1200 UTC observations with initial and boundary conditions from IMD-GFS. Forecast outputs at 3 km resolution are made available after 6 hrs of model run time for next 3 days. The detailed configuration of IMD-WRF model at 3 km resolution is shown in table 4 below:-

Table 4

Operational configuration of WRF model

Model Configuration at 3 km		
Domain	Center: 22.5 N and 81.2 E 1321 X1321	E-W and N-S
Map Projection	Mercator	True at equator
Geophysical data resolution	5 minutes	SourceUSGS
Vertical levels in eta co-ordinate	45 levels	Normalized pressure
Top boundary	50 hPa	
Physics	-	-
Cloud Microphysics	Option 4	WRF Single-Moment 5-class scheme
Radiation – Long-wave	Option 1	RRTM scheme
Radiation – Long-wave	Option 2	Goddard shortwave
Radiation schemes frequency	Every 10 minutes	-
Surface Layer Physics	Option 2	Eta similarity
Surface Physics	Option 2	Noah Land Surface Model
Planetary Boundary Layer	Option 2	Mellor-Yamada-Janjic scheme
PBL scheme frequency	Every time step	-
Cumulus parameterization	Option 5	Grell 3D Ensemble cumulus scheme
Cu Parameterization frequency	Every 5 minutes	-

IMD-WRF based products are generated for meteorological sub-division level and are also covering RSMC domain to cater different users. The forecast for different regions viz. Northwest, Northeast, Central and South India are also hosted on the NWP website. Apart from this hourly forecast are also provided on the website and specific forecast for major cities and their Meteograms are also hosted for forecaster's and general public. At present approximately 523 stations Meteograms are available based on IMD-WRF on NWP website. The categories of products hosted on NWP website with respect to WRF model are given below:-

MODEL CHARTS (03 KM)

REGION-WISE PRODUCTS

DERIVED PRODUCTS

HOURLY PRODUCTS

METEOGRAMS

- ***ALL INDIA***
- ***INDIAN AIRPORTS***
- ***SHRI AMARNATH JI YATRA SITES/J&K***
- ***NEPAL/BHUTAN CITIES/TOWNS***
- ***HIMALAYAN MOUNTAIN***
- ***MATA VAISHNO DEVI SITES***
- ***CHARDHAM YATRA SITES***

AVIATION

- ***AIRPORT METEOGRAMS***
- ***CHARTS FOR LOW FLYING AIRCRAFTS***

Table 5

The list of products generated from the WRF model

MODEL CHARTS			
MSLP,MSLP-India, Rainfall, Rainfall-India	Surface	03/06/24h	**MSLP** (Mean surface level pressure) is the surface pressure reduced to sea level. These charts show surface pressure patterns - areas of high and low pressure which are associated with different weather types.
Wind, Wind-India	925,850,700, 500, 300, 200 hPa	03/06/24h	**Wind** is the air in motion in horizontal having speed and direction at different pressure levels. They are useful for identification and monitoring of cyclonic as well as anti-cyclonic features at different pressure levels.

REGION WISE PRODUCT			
MSLP, Rainfall	Surface	24h	**MSLP** (Mean surface level pressure) is the surface pressure reduced to sea level. These charts show surface pressure patterns - areas of high and low pressure which are associated with different weather types.
Wind	925, 850, 700, 500, 300, 200 hPa	24h	**Wind** is the air in motion in horizontal having speed and direction at different pressure levels. They are useful for identification and monitoring of cyclonic as well as anti-cyclonic features at different pressure levels.
DERIVED PRODUCTS			
Wind 10m+RH2m, Temp. 2m, Temp Inversion 2m, Wind 10m Tend, RH 2m Tend, Temp. 2m Tend.	Near Surface	06h	This product gives indication about the different diagnostic parameters like wind, gust, relative humidity etc very close to the surface i.e. at 2 m and 10 m heights.
Temperature	925,850,700, 600,500, 400 hPa	06h	The temperature is provided at different pressure levels.
Mean Wind	500-300hPa, 850-300 hPa, 850-500 hPa	06h	This product gives the mean wind between the different pressure levels.
Wind Shear	200-850 hPa, 500-850 hPa	06h	**Wind shear** describes how the wind changes **speed** and/or direction with height. Wind shear is important to severe thunderstorm forecasting.
Vorticity, Divergence	850 hPa	06h	**Divergence** occurs when a stronger wind moves away from a weaker wind or when air streams move in opposite directions. When **divergence** occurs in the upper levels of the atmosphere it leads to rising air.

			The **vorticity** and its changes are used to calculate divergence and, through continuity, the vertical motions, which are most important for the **weather**.
Vertical Velocity	850, 750 hPa	06h	The amount of upward motion in the atmosphere. 700 mb vertical velocity is simply the velocity of air moving through the 700 mb surface in a vertical direction.
Potential Vorticity	850, 200 hPa	06h	Potential vorticity (PV) is a quantity which is proportional to the dot product of vorticity and stratification. It is a useful concept for understanding the generation of vorticity in cyclogenesis (the birth and development of a cyclone).
Divergence	200 hPa	06h	Divergence occurs when a stronger wind moves away from a weaker wind or when air streams move in opposite directions. When divergence occurs in the upper levels of the atmosphere it leads to rising air. The rate the air rises depends on the magnitude of the divergence and other lifting or sinking mechanisms in the atmosphere.
PWC, LCL, LFC, CAPE, CIN, Total Total Index, K Index, Ventilation Index, PBLH, Storm-Relative-Helicity	N/A	06h	These parameters are used for forecasting of thunderstorms. Different regions have different threshold for identification and forecasting of thunderstorms.
HOURLY PRODUCT			
Reflectivity, Rain, Storm-Relative Helicity	N/A	01h	Storm-Relative Helicity (SRH) is a measure of the potential for cyclonic updraft rotation in right-moving supercells, and is calculated for the lowest 1 and 3 km layers above ground level. High SRH do suggest an increased threat of tornadoes with supercells.

WRF METEOGRAM

Parameter	Level	Frequency	Interpretation
Rainfall, Heat Index, Relative Humidity, TD & TT, Pressure, Wind Speed	N/A	Hourly	The spatial products mentioned above are also generated for point locations in form of meteograms. They contain MSLP, RH, Wind etc for location specific forecasting.
Wind Speed	1000-300 hPa	Hourly	The spatial products mentioned above are also generated for point locations in form of meteograms. They contain MSLP, RH, Wind etc for location specific forecasting.
WRF-HYSPLIT			
Forward/Backward Trajectory	100, 500, 1000, 2000 m	24 h	This product gives the forward and backward trajectory of an air parcel at different vertical heights.
WRF-POLAR ANTARTICA			
MSLP, Relative Humidity, Wind (10m) & Temp (2m), Snowfall	Surface and Near Surface	24h	The Mean Sea Level pressure, Relative Humidity and wind near to ground are provided for the Indian stations in Antartica (Maitri and Bharti).

The sample rainfall product from IMD-WRF model is shown below :-

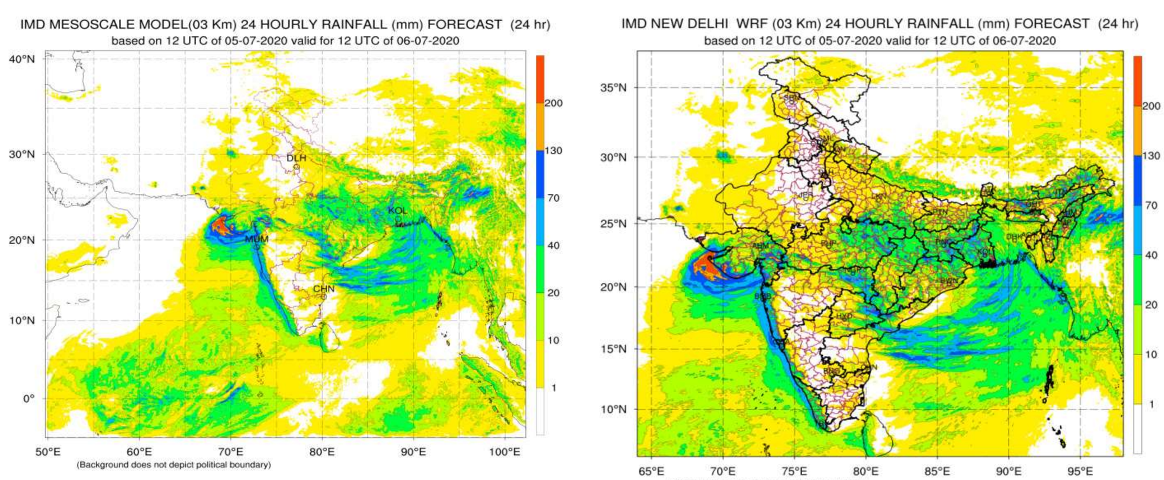


Fig. 9. ***Heavy Rainfall forecast for 6th July, 2020 over Saurashtra & Kutch based on IC of 1200 UTC of 5th July 2020***

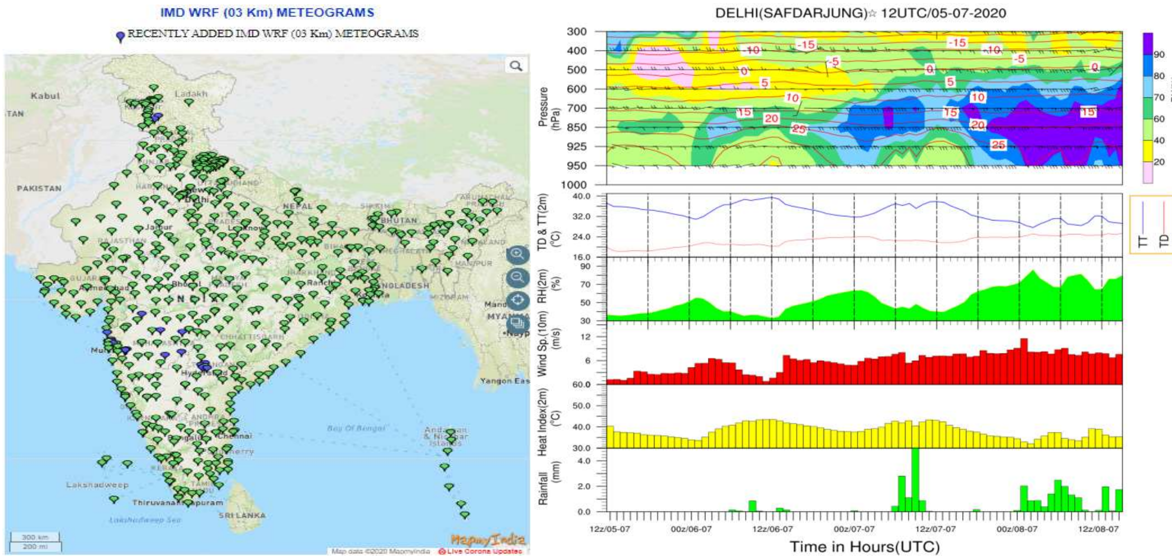


Fig. 10. ***Meteograms as generated through IMD-WRF model***

1.3.4. Polar WRF model is run operationally for prediction over Antarctica at 09 km horizontal resolution. The products are provided particularly for Indian stations at Antarctica i.e. BHARATI & MAITRI. The model is run two times a day and produce forecast for next 2 days. The Meteograms are also provided for Indian Stations at BHARATI & MAITRI. The configuration of the model is given table 6.

Table 6

Operational configuration of Polar WRF model

Domain	**Center at 70.85°S and 11.44° E**	**E-W and S-N 600 × 600**
Map Projection	Polar Stereographic	True at 70.0 °S and pole
Geo-physical data resolution	5 minutes	Source USGS
Vertical levels in eta co-ordinate	38 levels	Eta co-ordinate/normalized pressure
Top boundary	50 hPa	
Physics		
Cloud Microphysics	Option 4	WSM 5 class scheme
Radiation physics-Long-wave	Option 1	RRTM scheme
Radiation Physics-Short-wave	Option 1	Dudhia Scheme
Radiation Scheme Frequency	Every 60 minutes	
Surface-layer Physics	Option 1	MM5 Surface layer scheme
Surface Physics	Option 2	Noah Land Surface Model
Planetary boundary Layer	Option 99	MRF scheme
PBL scheme Frequency	Every time step	
Cumulus Physics	Option 3	Grell-Freitas scheme
Cumulus Physics frequency	Every 5 minutes	

The sample products from Polar WRF model are given below:-

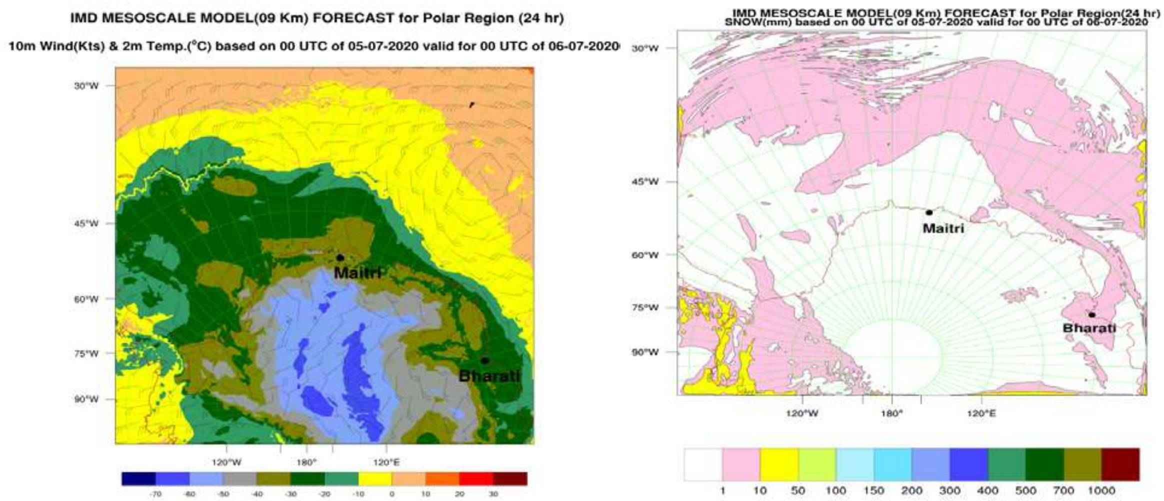


Fig. 11. ***10m wind, 2m Temp and Snowfall forecast for 05th July, 2020 over Antarctica based on IC of 0000 UTC of 5th July, 2020***

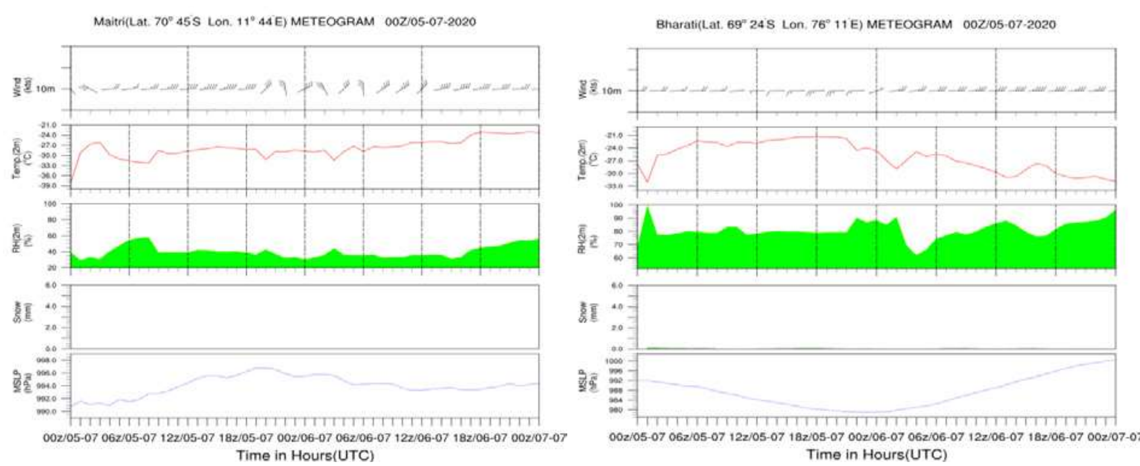


Fig. 12. ***Meteograms for BHARATI & MAITRI stations of Antarctica***

1.3.5. WRF Hysplit Trajectory model is been operationally run for major Indian Cities to provide the backward as well as forward trajectory of any air parcel. The Sample backward and forward trajectory forecast is shown below:-

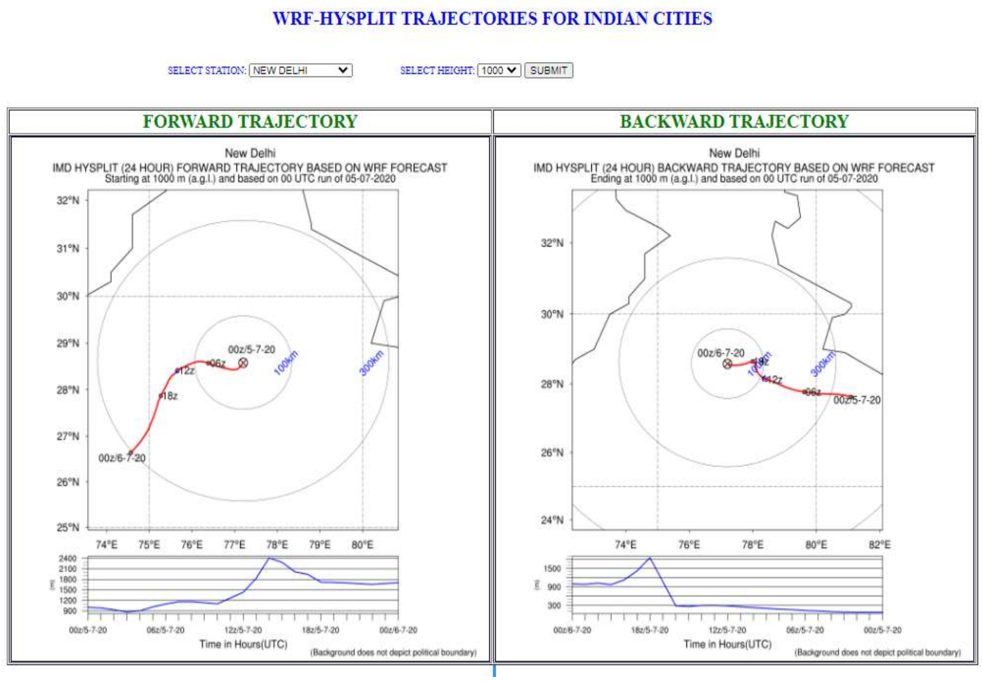


Fig. 13. ***HYSPLIT model forecast for Delhi based on IC of 0000 UTC of 5th July, 2020***

1.3.6. The Hurricane WRF (HWRF) modelling system

The HWRF modelling system is implemented in IMD based on MoU between MoES and NOAA. The HWRF version H217 has been ported on the MHIR HPCS with horizontal resolution of 18 km for parent domain and 6 km & 2 km for intermediate and innermost nested domains following the center of cyclonic storm. The model is running with 61 vertical levels with parent domain, intermediate and innermost domain covering area of 80° × 80°, 24° × 24° and 7° × 7° respectively. The special feature modified for tropical cyclone forecasting includes vortex initialization and correction, GSI based regional data assimilation, coupler for two way coupling between atmosphere and ocean components and fine-tuned physical parameterization schemes. This model is customized specifically to forecast the track, intensity and structure of tropical cyclones. The HWRF modelling system uses the dynamics and infrastructure from the NMM WRF modelling system. It uses physics that are proven to be better for the tropics. Also, at this time, it is an Ocean coupled model system with a Moving two-way interactive nest, and advanced data assimilation. IMD is operationally running ocean coupled HWRF models during Tropical Cyclone events with two ocean models viz. POM-TC and HYCOM. HYCOM initial conditions are provided through INCOIS where as POM-TC is initialized based on climatology. It is run 4 times a day in cyclic mode with GSI based (hybrid-EnVar) assimilation (80 members) with 6 hourly cycles in cycling mode. The operational configuration is given in the following table 7.

Table 7

HWRF Operational Configuration

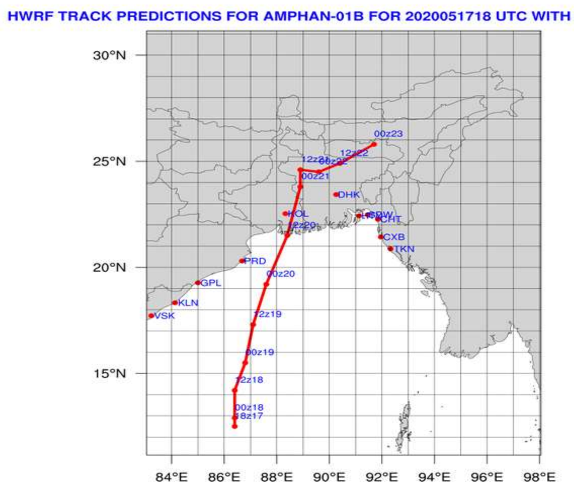
Domain-Parent	Center:- Storm Center Size:- 80° × 80° Grid Spacing:- 18 Km Grid Points:-288 × 576
Intermediate Nest (Moving)	Center:- Storm Center Size:- 24° × 24° Grid Spacing:-06 Km Grid Points:-265 × 532
Inner Most Nest (Moving)	Center:-Storm Center Size:- 7° × 7° Grid Spacing:- 02 Km Grid Points:- 235 × 472
Map Projection	Rotated Latitude and Longitude
Vertical Levels In Hybrid Pressure Sigma Coordinates	61
Top Boundary	10 hPa
Cloud-Microphysics	Ferrier-Aligo Cloud Microphysics
Radiation	Rapid Radiative Transfer Model For General Circulation Models (RRTMG)
Surface Layer Physics	Modified Geophysical Fluid Dynamics Laboratory (GFDL) Surface Layer
Surface Flux Calculation	The Monin-Obukhov
Represent The Land Surface	The Noah Land Surface Model
Planetary Boundary Layer	Global Forecasting System (GFS) Eddy-Diffusivity Mass Flux
Cumulus Parametrization	Scale-Aware Arakawa-Schubert

The information about the ocean coupling in HWRF modelling system is given in table 8 below.

Table 8

Ocean Model	POM	HYCOM
Dynamics & Configurations	Hydrostatic, free-surface, primitive equations on C grid	
	1/12-degree	
	Rectangular Projection	Mercator Projection
	40 vertical sigma level	41 vertical Hybrid isopycnal-Z levels
Mixing Physics	Mellor-Yamada 2.5 closure	KPP (K-Profile Parameterization)
Initialization	Monthly GDEM3 Climatology + daily NCEP SST + Feature Model	6 hourly HYCOM analysis from INCOIS-RTOFS
Lateral Boundary	Adjusted T/S fields	6 hourly 2D and 3D INCOIS-RTOFS forecasts

Some sample products generated from HWRF modelling system utilized by forecaster's for tropical cyclone predictions are given below:-



Dt/Hr.	Lat.	Lon.	MSLP	Vmax
18z17	12.5	86.4	969.	64.
00z18	12.9	86.4	967.	65.
12z18	14.2	86.4	955.	104
00z19	15.5	86.8	945.	108
12z19	17.3	87.1	943.	95.
00z20	19.2	87.6	929.	111
12z20	21.5	88.4	928.	114
00z21	23.8	88.9	956.	58.
12z21	24.6	88.9	987.	44.
00z22	24.5	89.6	998.	33.
12z22	24.9	90.4	1003	27.
00z23	25.8	91.7	1007	18.

Fig. 14. ***HWRF generated track & intensity of Super Cyclone AMPHAN based on IC of 18 UTC of 17th May, 2020***

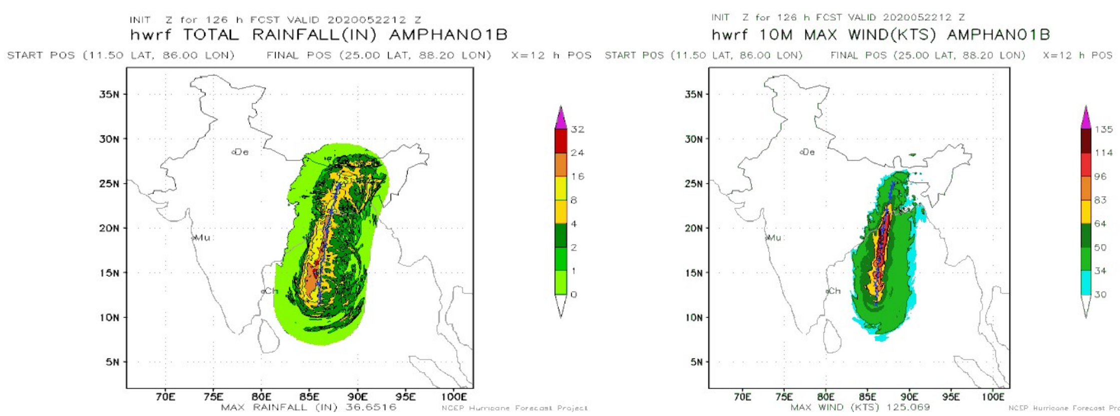
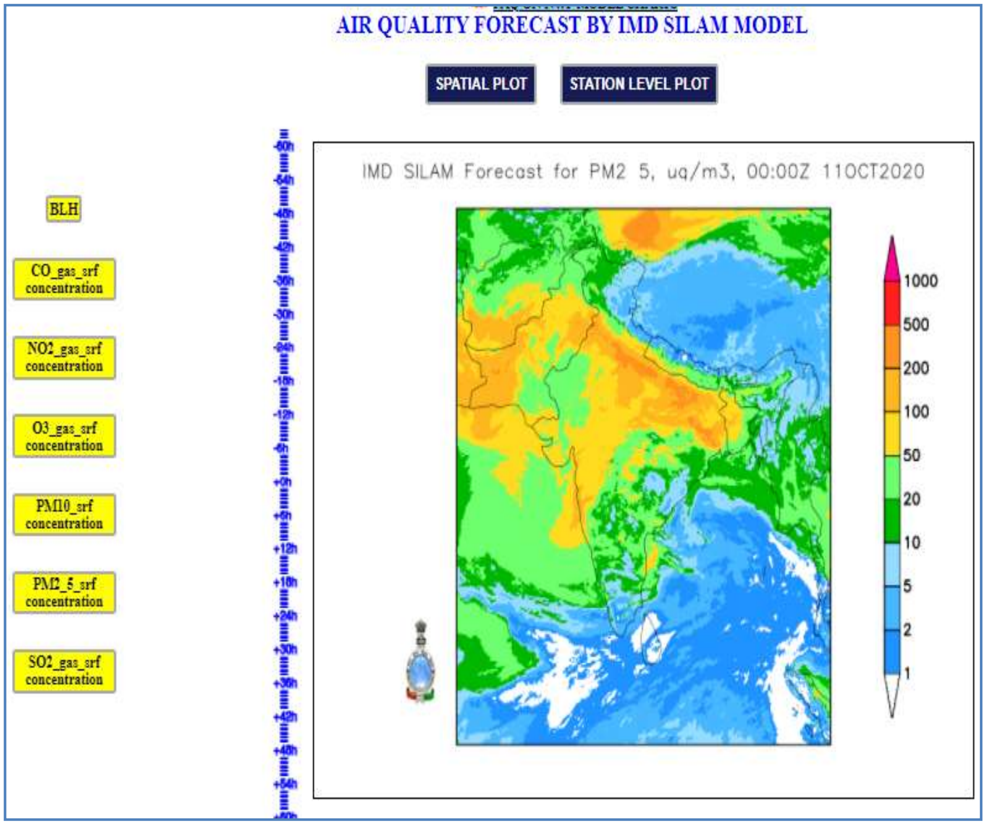


Fig. 15. ***HWRF model generated Rainfall and Wind swath for super cyclone AMPHAN based on IC of 1200 UTC of 22nd May, 2020***

1.3.7. IMD has also operationalized SILAM model for air quality forecasting services

SILAM is a global-to-meso-scale dispersion model developed for atmospheric composition, air quality, and emergency decision support applications, as well as for inverse dispersion problem solution. The model incorporates both Eulerian and Lagrangian transport routines, 8 chemico-physical transformation modules (basic acid chemistry and secondary aerosol formation, ozone formation in the troposphere and the stratosphere, radioactive decay, aerosol dynamics in the air, pollen transformations), 3- and 4-dimensional variational data assimilation modules. SILAM source terms include point- and area- source inventories, sea salt, wind-blown dust, natural pollen, natural volatile organic compounds and nuclear explosion. At present it is run once a day in IMD. The sample products from SILAM model for spatial distribution of PM2.5 and Carbon Mono Oxide (CO) hosted on NWP website are given below:-



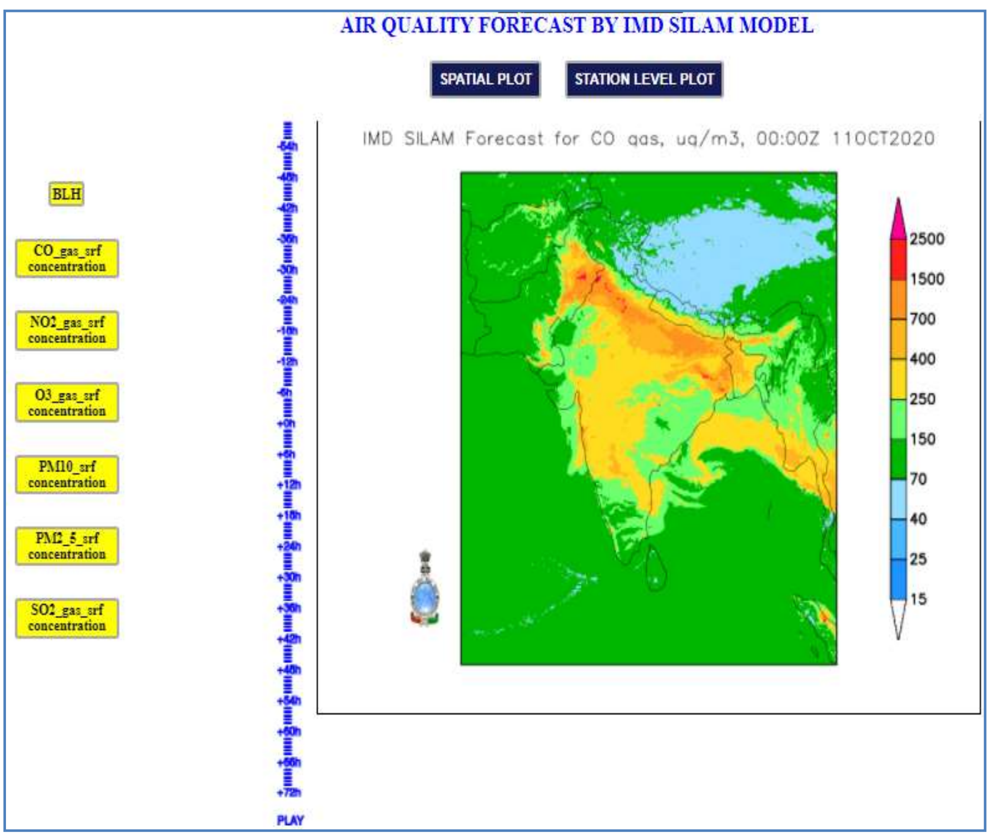


Fig. 16. ***(a) SILAM generated PM 2.5 and CO forecast based on IC on 0000 UTC of 11th October, 2020***

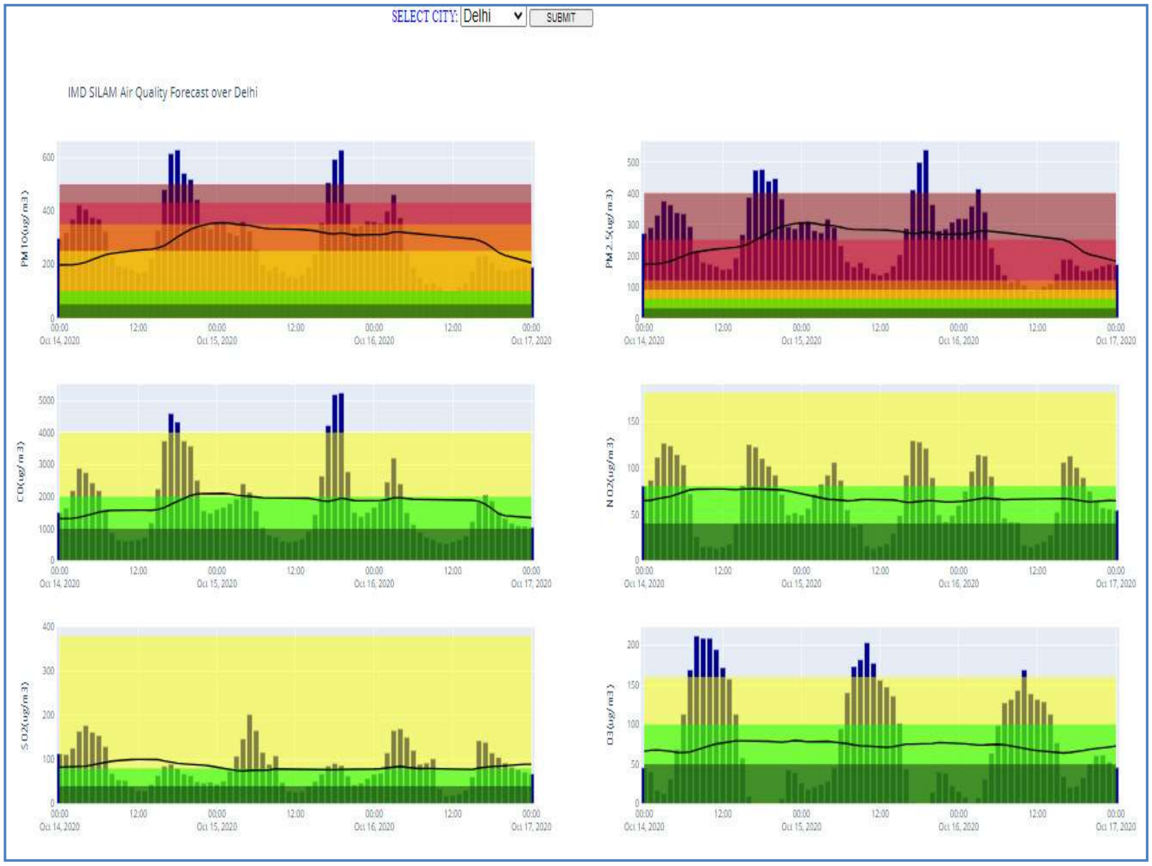
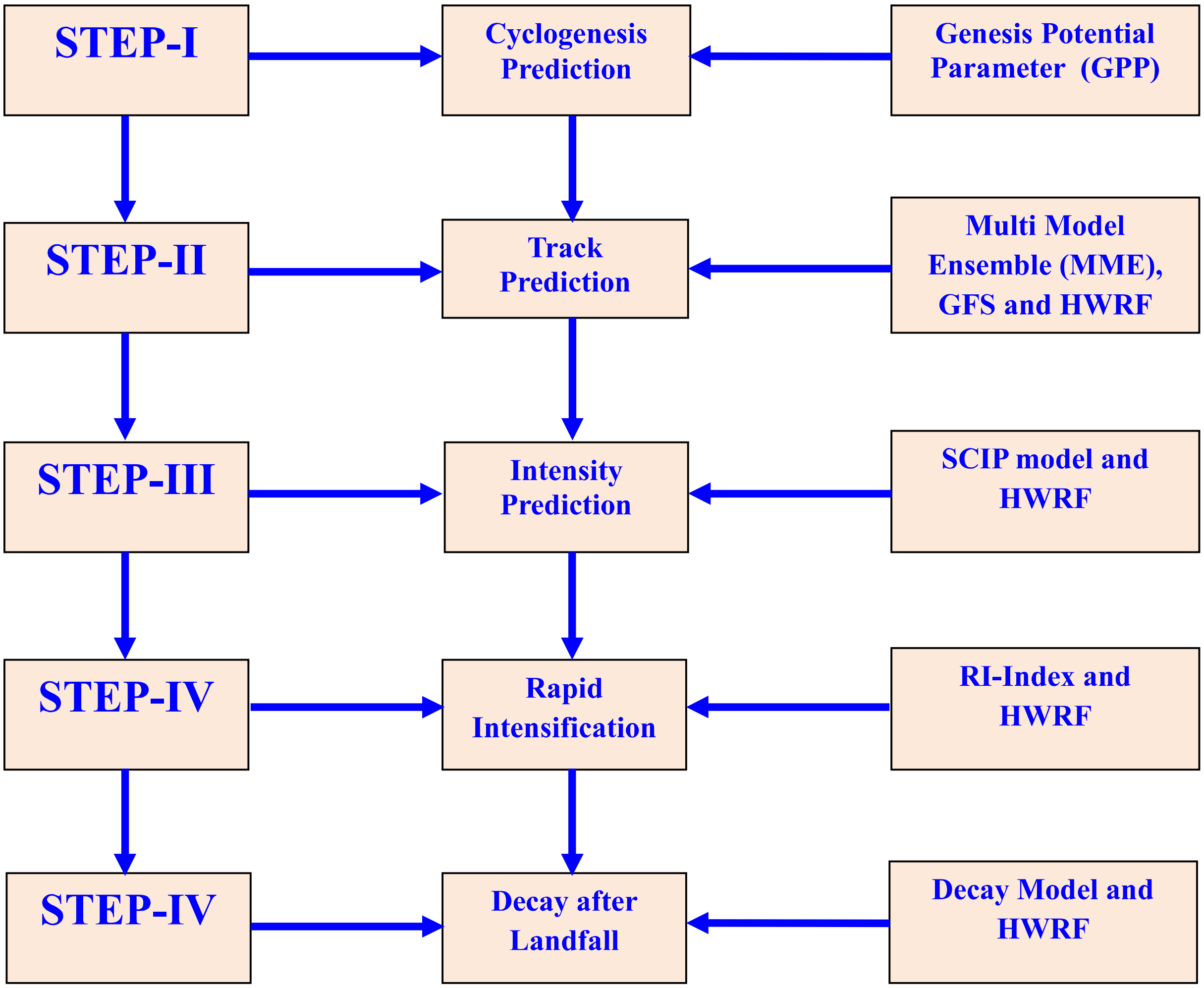


Fig. 16. (b) ***IMD SILAM generated station level plot for Delhi showing different air pollution parameters***

1.3.8. NWP based objective forecast products for cyclone forecast Guidance

The Cyclone guidance and forecasting typically follows the following steps based on the NWP guidance.



Tropical Cyclone Genesis potential Parameters are generated everyday based on 0000 UTC and provides the guidance for any cyclogenesis during next 7 days. The sample GPP parameter as provided on the website is given below:

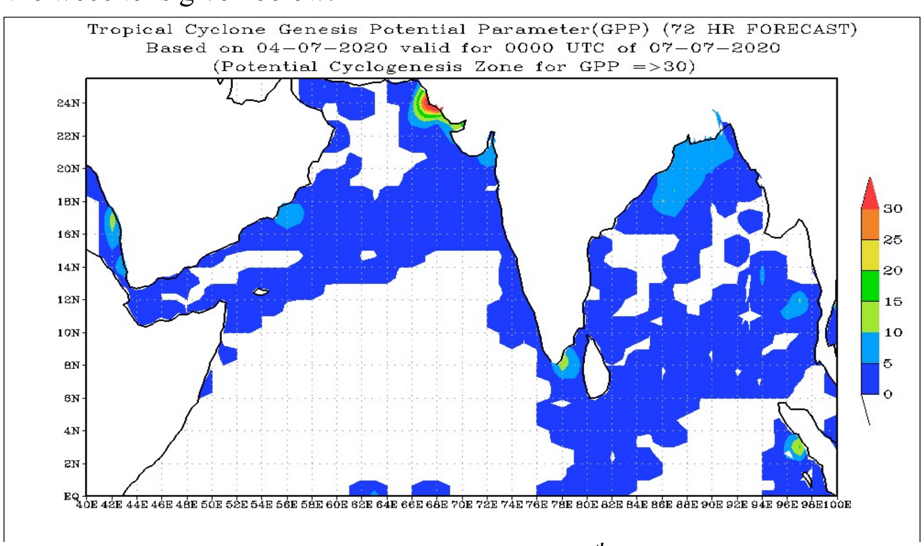
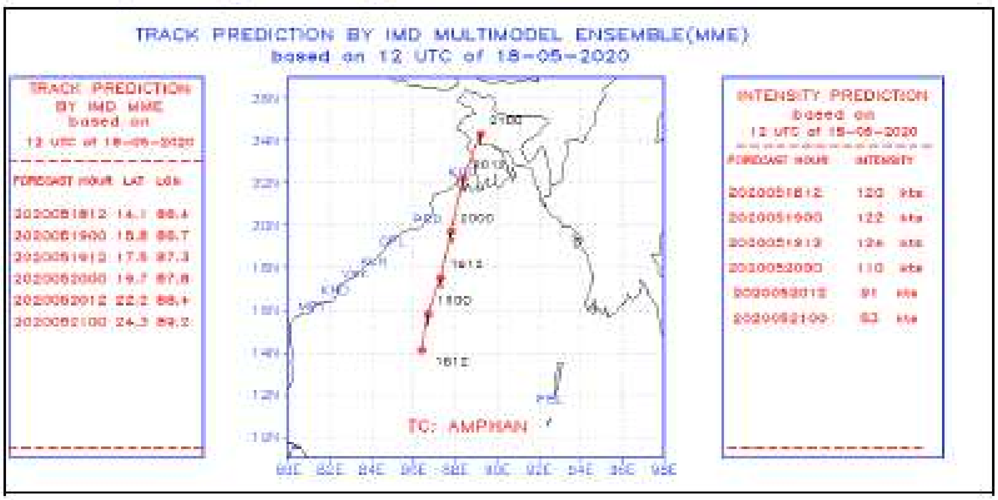


Fig. 17. ***GPP Parameter for 0000 UTC of 7th July, 2020 based on IC of 0000 UTC of 4th July, 2020***

Along with the GPP potential the NWP division also provides the Multi-model Ensemble (MME) based forecast product regarding the tropical cyclones track, intensity and rapid Intensification. These MME products are provided during the entire duration of tropical cyclone, i.e., from cyclogenesis phase to post landfall phase. These products are generated two times a day based on 0000 UTC and 1200 UTC model forecasts. NWP division also provides the post landfall guidance of tropical cyclones based on Decay model. The following figure shows the sample MME forecast provided for Super Cyclone AMPHAN and also the Decay model based post-landfall scenario for Super Cyclone AMPHAN.

NWP inputs for tropical cyclone "AMPHAN" over the Bay of Bengal based on 1200 UTC of 18th May 2020

(A) MME TRACK, INTENSITY, RI FORECAST: MME track forecast, Intensity and RI forecast for tropical cyclone "AMPHAN" over the Bay of Bengal based on 12 UTC of 18th May 2020 are given in the figure below:



(C) INTERPOLATED 6-HOURLY MME TRACK POSITIONS OF TROPICAL CYCLONE "AMPHAN" BASED ON 1200 UTC 18.05.2020:

Lead Time (h)	LAT	LON
00	14.1	86.4
06	14.9	86.5
12	15.8	86.7
18	16.6	87.0
24	17.5	87.3
30	18.6	87.5
36	19.7	87.8
42	20.9	88.1
48	22.2	88.4
54	23.2	88.8
60	24.3	89.2

Fig. 18. ***MME based Track, Intensity and Rapid Intensification forecast product based on IC of 12 UTC of 18th May, 2020***

POST-LANDFALL INTENSITY PREDICTION BY DECAY MODEL*

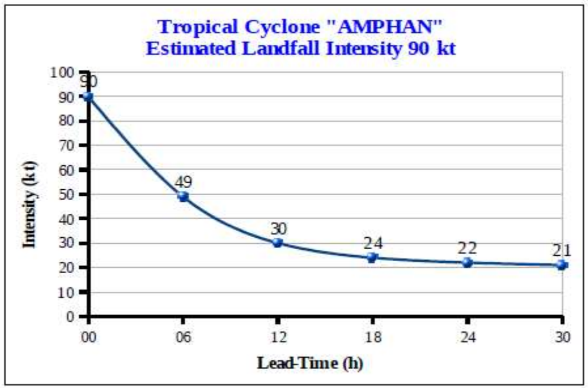


Fig. 19. ***Post Landfall Outlook for Super Cyclone AMPHAN with landfall intensity of 90 Knots***

1.3.9. Extended Range Forecast

A coupled model with a suite of models from CFSv2 coupled model has been developed, implemented and operationalized in IMD for generating operational Extended Range Forecast products for different users. This suite of models are (i) CFSv2 at T382 (≈ 38 km) (ii) CFSv2 at T126 (≈100 km) (iii) GFSbc (bias corrected SST from CFSv2) at T382 and (iv) GFSbc at T126. The Multi-model ensemble (MME)of the above suite is run operationally for 32 days based on every Wednesday initial condition with 4 ensemble members to give forecast for 4 weeks for days 2-8 (week1; Friday to Thursday), days 09-15 (week2; Friday to Thursday), days 16-22 (week3; Friday to Thursday) and days 23-29 (week4; Friday to Thursday). On met subdivision level the category forecasts upto two weeks are being used for agro-advisory purpose. Fig. 20 shows the operational hindcast and forecast run setup for the ERF.

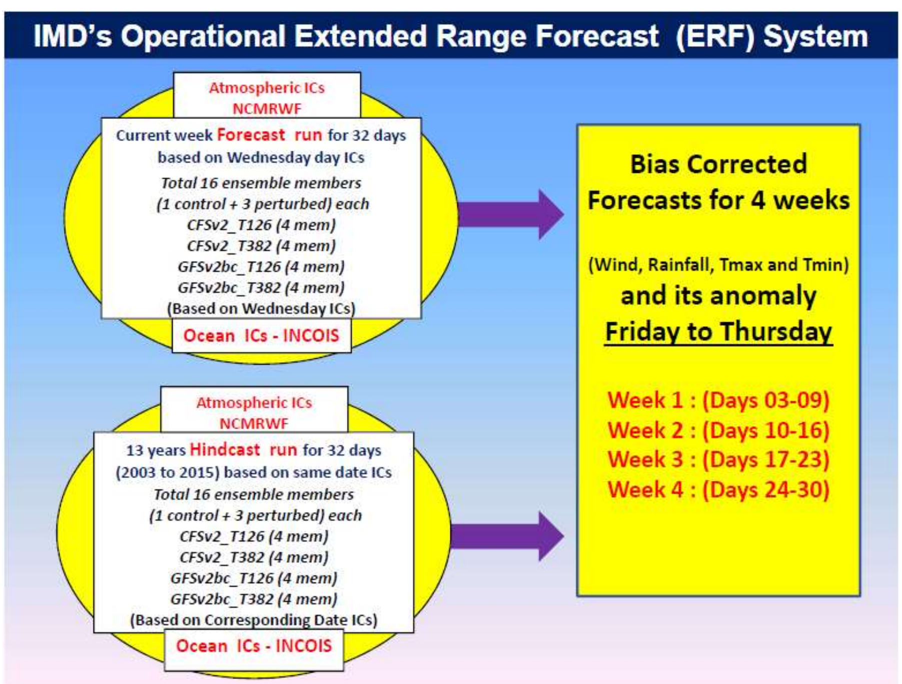


Fig. 20. ***IMD's operational ERF setup***

The products available on NWP website related to extended range products is as follows:

EXTENDED RANGE FORECAST

MME(CFSv2/GFSbc)

- **COUPLED MODEL BULLETIN**
- **ANIMATION PRODUCTS**
- **04 WEEK PRODUCTS**
- **WEEK WISE PRODUCTS**
- **SUB-DIVISION WISE PRODUCTS**
- **HOT DAY & HEAT WAVE**
- **MJO FORECAST**
- **CYCLOGENESIS PROBABILITY**
- **PRODUCTS OVER INDO-PACIFIC**
- **IMD ERF WEEKLY PPT.**
- **DOCUMENTATION**

The list of products from the extended range forecasting system is given in table placed below.

EXTENDED RANGE FORECAST			
ANIMATION PRODUCT			
Wind & Rain, Tmax, Tmin, Tmax Anomaly, Tmin Anomaly	Surface	24h	The animation product related to Wind, Rainfall, Maximum Temperature, Minimum Temperature as well as their anomaly are generated.
04 WEEK PRODUCTS			
MSLP, Rainfall, Temp. Min., Temp. Max., RH(2m)	Surface and Near Surface	Weekly	**MSLP** (Mean surface level pressure) is the surface pressure reduced to sea level. These charts show surface pressure patterns - areas of high and low pressure which are associated with different weather types as a average representation on a weekly basis.
Vorticity, Divergence	850hPa	Weekly	**Divergence** occurs when a stronger wind moves away from a weaker wind or when air streams move in opposite directions. When **divergence** occurs in the upper levels of the atmosphere it leads to rising air. The **vorticity** and its changes are used to calculate divergence and, through continuity, the vertical motions, which are most important for the **weather**. The weekly average of vorticity and divergence are generated at 850 hPa height.
Wind	850,500, 200 hPa	Weekly	**Wind** is the air in motion in horizontal having speed and direction at different pressure levels. There average weekly pattern is generated at different pressure levels.
Vertical Wind Shear	N/A	Weekly	**Wind shear** describes how the wind changes **speed** and/or direction with height. Wind

			shear is important to severe thunderstorm forecasting and this product gives weekly average projection of same.
WEEK WISE PRODUCT			
Rain Mean, Tmax Mean, Tmin Mean, Rain Anomaly, Rain Anomaly(%Dep.), Rain Anomaly(Sub-Division), Tmax Anomaly, Tmin Anomaly, Tmax Threshold Maps.	Surface	Weekly	Weekly average spatial distribution of Rainfall, mean Temperature (minimum & maximum) along with rainfall and temperature anomaly on subdivision scale is generated.
HOT DAY & HEAT WAVE			
Animation,Spatial Plot,Daily Forecast Tmax.		24h	Daily plots of forecast of maximum temperature and their animation is provided to guide the heatwave forecasting activities.
CLIMATE HEALTH PRODUCTS			
Min. Temp., Max. Temp.	11-12, 14-15,16-19 Deg C and 33-39 Deg C	Weekly	Minimum and Maximum Temperatures are generated for health sector services.
MJO FORECAST			
MISO Animation, MISO Spatial Plot, MISO Phase Plot, MJO Animation, MJO Spatial Plot MJO Phase Plot.	N/A	24h and Weekly	Monsoon intra-seasonal oscillation (MISO) represents a quasi-periodic occurrence of rainfall spells over India during summer monsoon (June-September) associated with large-scale circulation and convection.
CYCLOGENESIS PROBABILTY			
Animation and Spatial Plot	N/A	Weekly	Weekly plots showing the spatial distribution as well as animation of cyclogenesis probability is provided to predict the cyclogenesis event in extended range duration.
PRODUCTS OVER SOUTH ASIA			
Rain, Tmin, Tmax and Wind	Surface and wind at 850, 500, 200 hPa	Weekly	Special products for south asian region are provided representing rainfall, Minimum/ Maximum Temperature and wind at surface and different pressure levels.
SEVERE WEATHER PRODUCTS			
Rainfall, T Maximum, T Maximum Anomaly, Cyclone Probability	Surface	Weekly	Severe weather products such as Rainfall, Maximum Temperature and its anomaly along with cyclone formation probability is generated on a weekly basis.

The sample product generated for extended range forecast is given below:

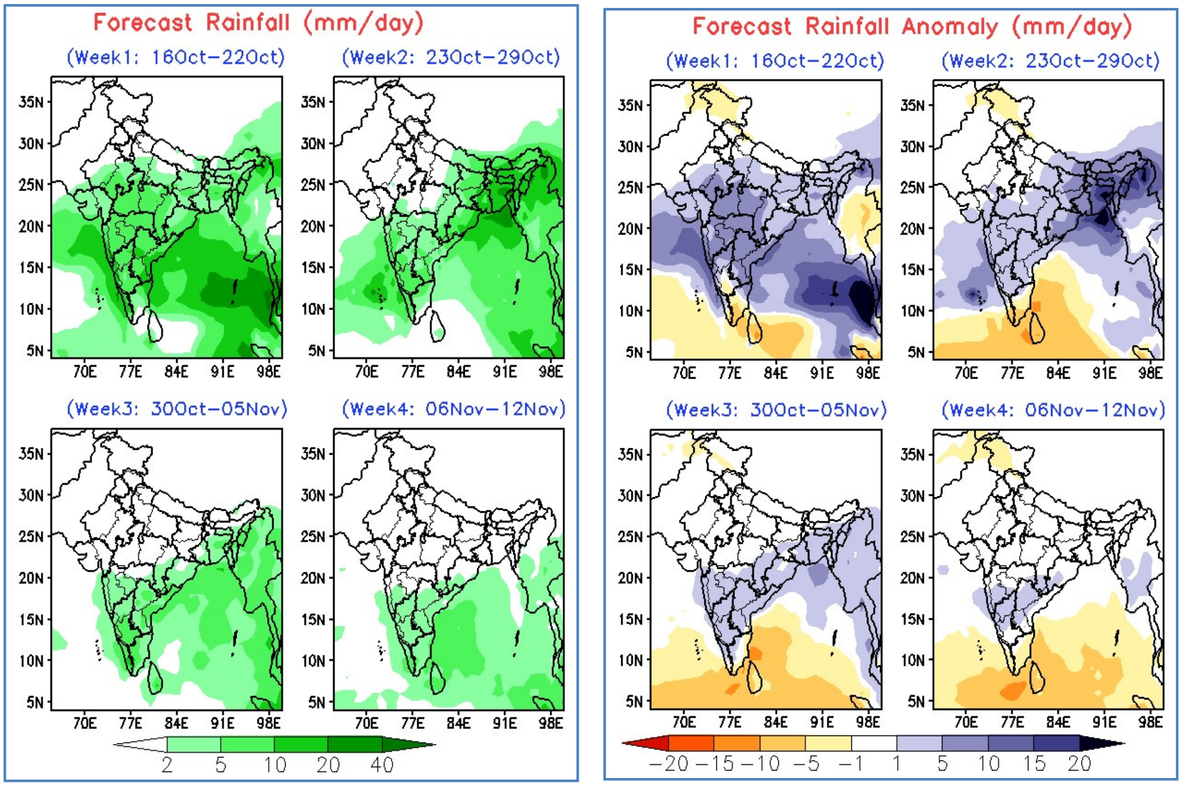


Fig. 21. ***(Left) Observed and forecast rainfall anomaly for the weak phase of monsoon for the target week of 12-18 July, 2019 with three weeks lead time (10 July, 03 July and 26 June ICs). (Right) Same as 'left' but for the active target week of 26 July-01 August, 2019***

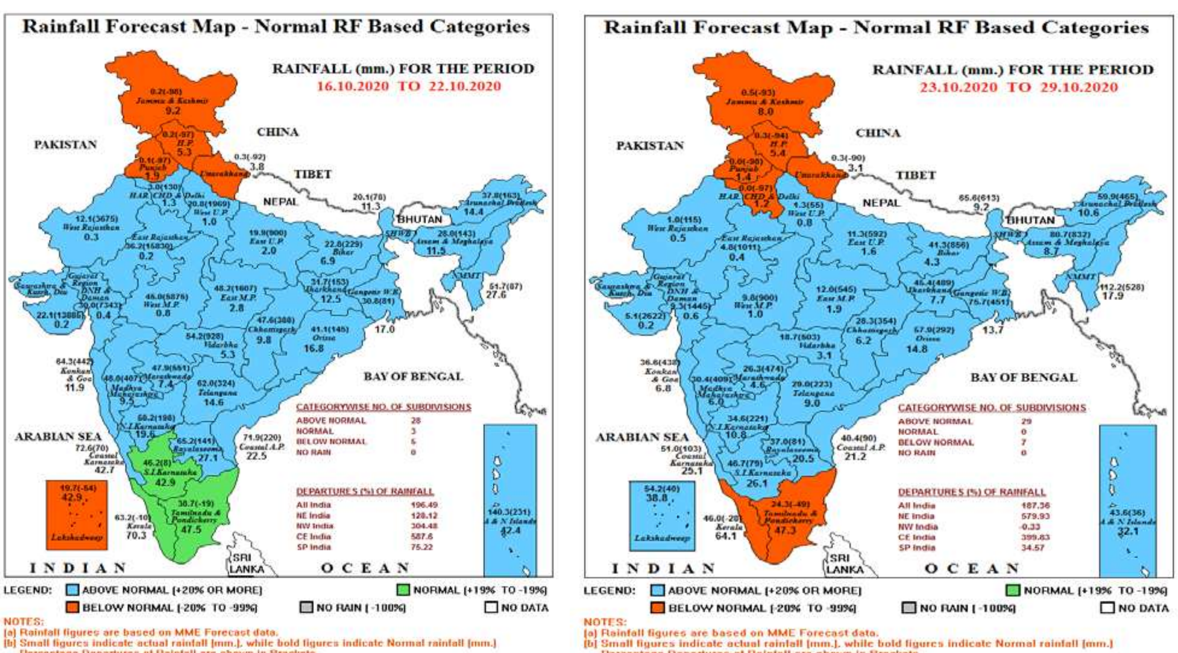


Fig. 22. ***Met-subdivision level forecasts of rainfall departure for two weeks***

MME WEEKLY RAINFALL FORECAST
RAINFALL DEPARTURE (%) WITHIN SUB-DIVISION DURING NEXT 04 WEEKS

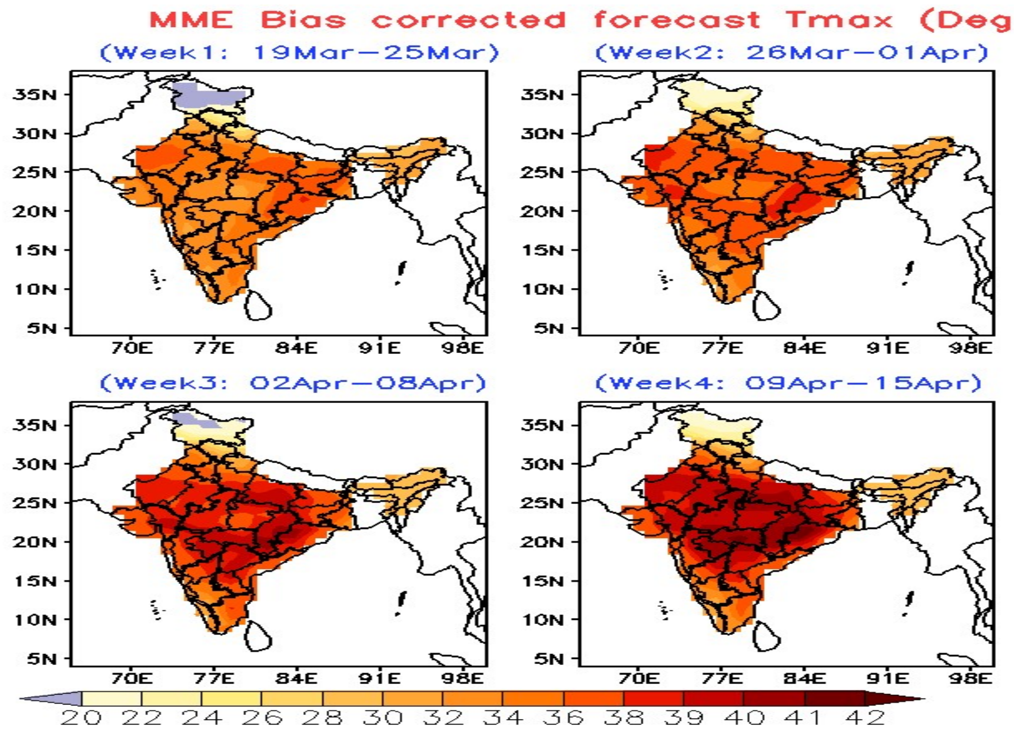
BASED ON 14-10-2020

S.NO.	SUB-DIVISION	WEEK-1	WEEK-2	WEEK-3	WEEK-4
1	A & N ISLAND	230.62	35.77	-23.64	-53.84
2	ARUNACHAL PRADESH	162.62	464.63	64.89	-47.10
3	ASSAM & MEGHALAYA	142.58	831.57	246.88	-76.91
4	N M M T	87.36	527.53	209.90	-27.06
5	SHWB & SIKKIM	77.73	612.56	30.15	-36.57
6	GANGETIC WEST BENGAL	80.98	451.26	217.35	-33.75
7	ORISSA	144.67	291.69	194.79	74.86
8	JHARKHAND	152.79	488.57	229.75	-27.92
9	BIHAR	228.98	856.25	103.31	-59.93
10	EAST UTTAR PRADESH	899.90	591.77	51.84	-99.69
11	WEST UTTAR PRADESH	1,969.37	55.19	-7.57	-99.67
12	UTTARAKHAND	-91.65	-90.21	-61.80	-75.26
13	HAR.CHD & DELHI	130.45	-97.04	-14.38	-99.00
14	PUNJAB	-97.05	-98.16	-11.32	-98.87
15	HIMACHAL PRADESH	-96.87	-94.05	-64.70	-79.52
16	JAMMU & KASHMIR	-97.60	-93.27	-63.16	-76.74
17	WEST RAJASTHAN	3,675.55	114.95	19.16	-56.73
18	EAST RAJASTHAN	3,675.55	114.95	19.16	-56.73
19	WEST MADHYA PRADESH	5,877.11	899.66	20.06	-50.46
20	EAST MADHYA PRADESH	1,607.31	545.39	84.29	-63.27
21	GUJARAT REGION	7,348.74	1,444.53	62.60	40.94
22	SAURASHTRA & KUTCH	7,348.74	1,444.53	62.60	40.94
23	KONKAN&GOA	442.21	438.20	223.77	194.89
24	MADHYA MAHARASHTRA	407.12	408.84	197.11	127.12
25	MARATHWADA	550.68	473.51	223.83	141.02
26	VIDARBHA	928.39	503.45	247.70	142.96
27	CHHATTISGARH	388.40	354.43	403.21	121.16
28	COASTAL ANDHRA PRADESH	219.96	90.36	114.37	21.67
29	TELANGANA	323.53	222.83	332.57	143.81
30	RAYALASEEMA	140.80	80.87	96.96	35.04
31	TAMILNADU & PONDICHERY	-18.53	-48.54	-22.90	-37.08
32	COASTAL KARNATAKA	70.24	102.61	114.30	77.33
33	N.I.KARNATAKA	197.86	220.78	234.77	166.28
34	S.I.KARNATAKA	7.57	78.60	143.84	40.61
35	KERALA	-10.03	-28.31	19.75	-16.88
36	LAKSHADWEEP	-53.95	39.64	-59.03	-69.70

RAINFALL DEPARTURE (%)

	REGIONS	WEEK-1	WEEK-2	WEEK-3	WEEK-4
1	ALL INDIA	196.49	187.36	84.35	1.40
2	NORTH EAST INDIA	128.12	579.93	176.45	-40.92
3	NORTH WEST INDIA	304.48	-0.33	-43.43	-78.48
4	CENTRAL INDIA	587.60	399.83	182.35	84.16
5	SOUTH PENINSULAR INDIA	75.22	34.57	63.86	7.85

Met sub-division wise rainfall departures for 4 weeks



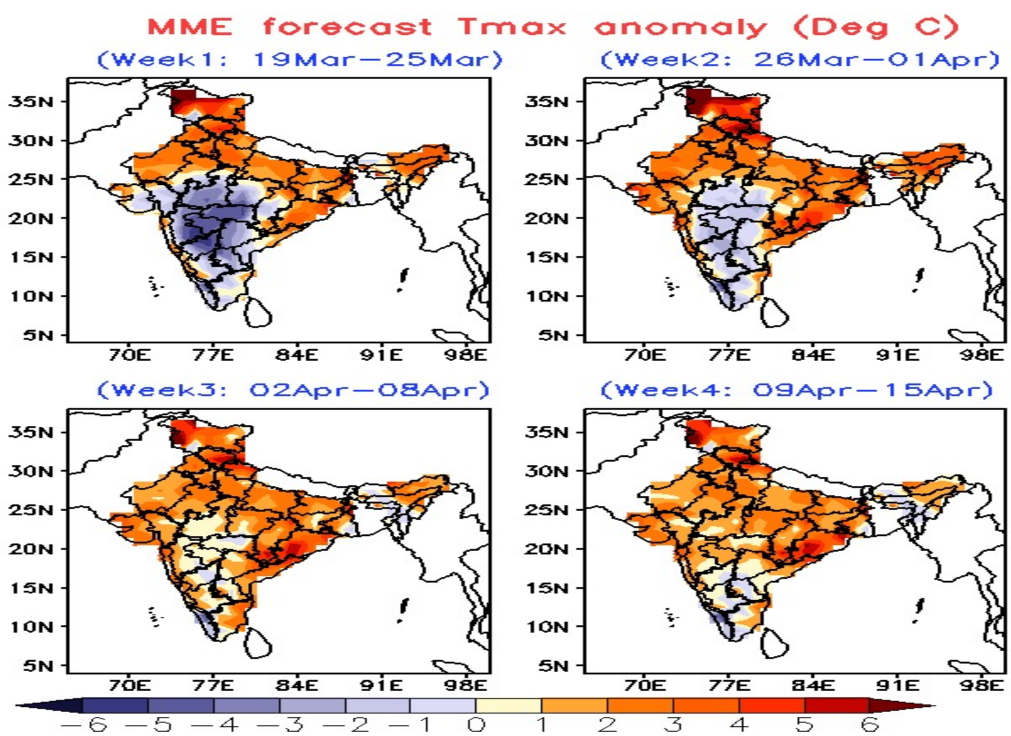
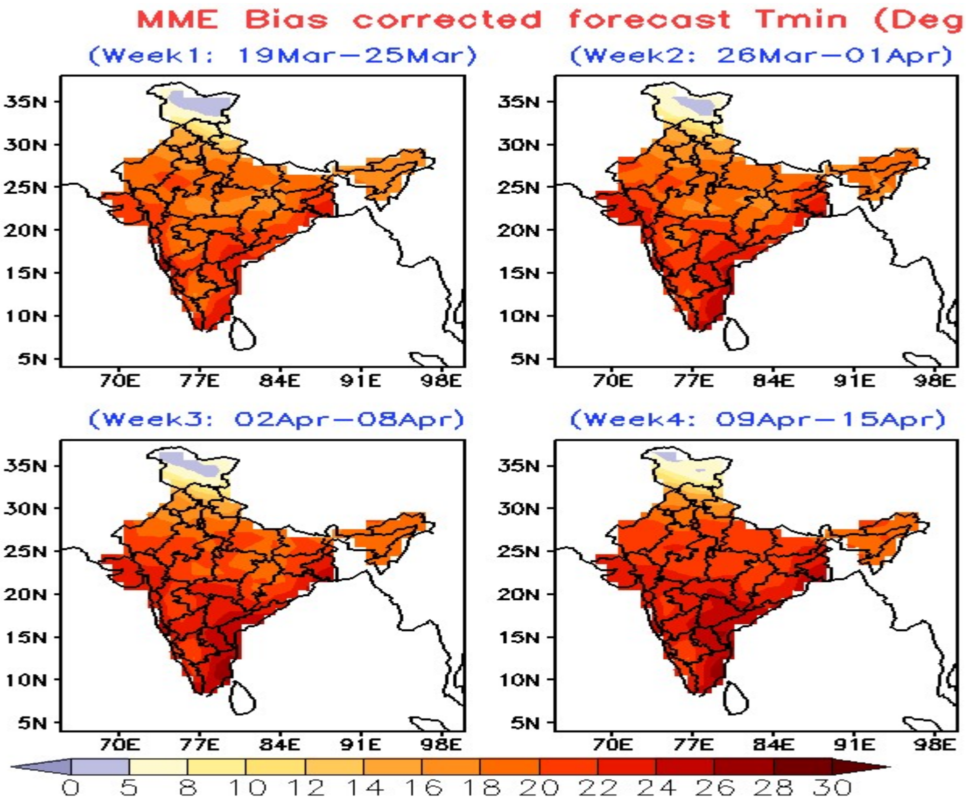


Fig. 23a. ***Maximum Temperature (Tmax) anomaly for week four weeks based on IC of 17 March, 2021***



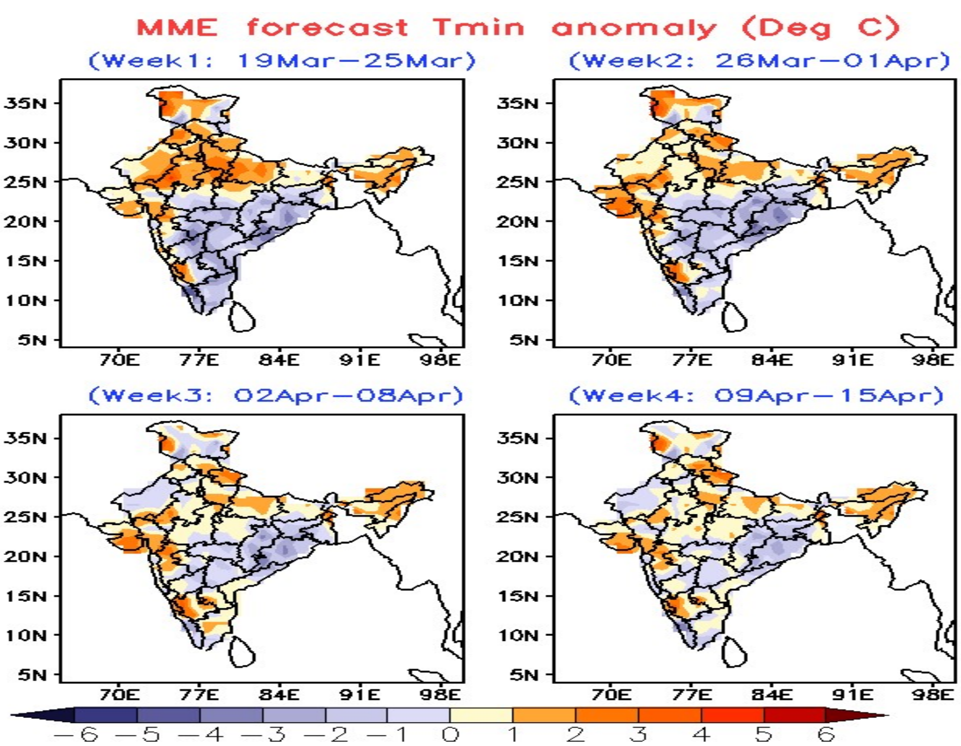


Fig. 23b. ***Minimum Temperature (Tmin) anomaly for week four weeks (IC of 14 Oct, 2020)***

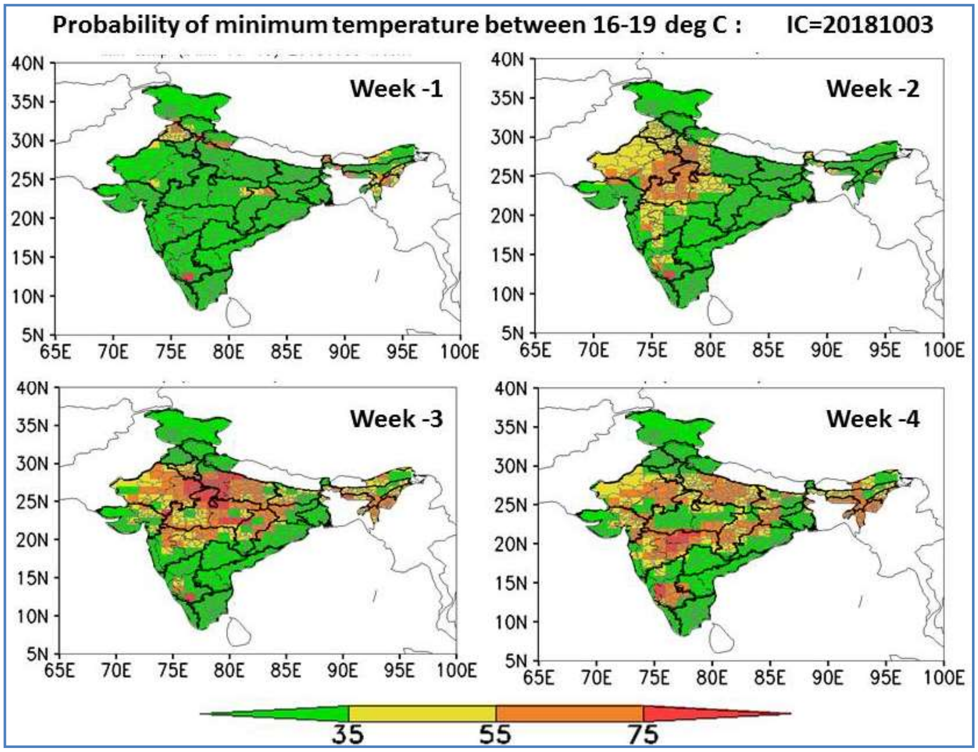


Fig. 24a. ***Probability of Minimum Temperature (Tmin) between 16-19C for guidance in health sector***

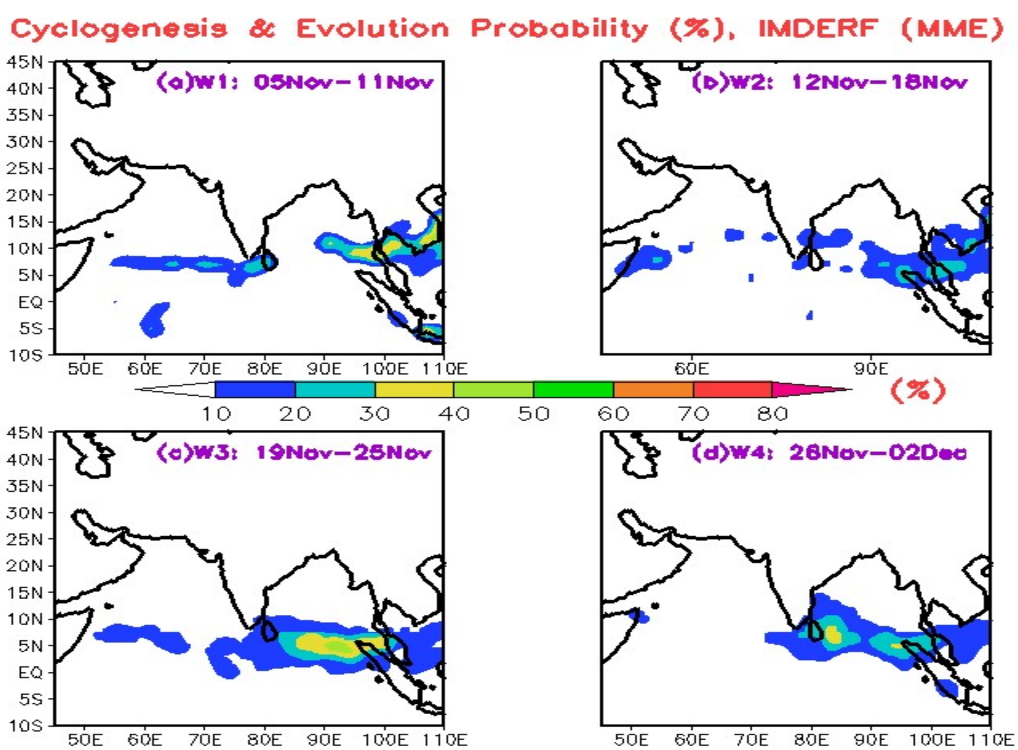
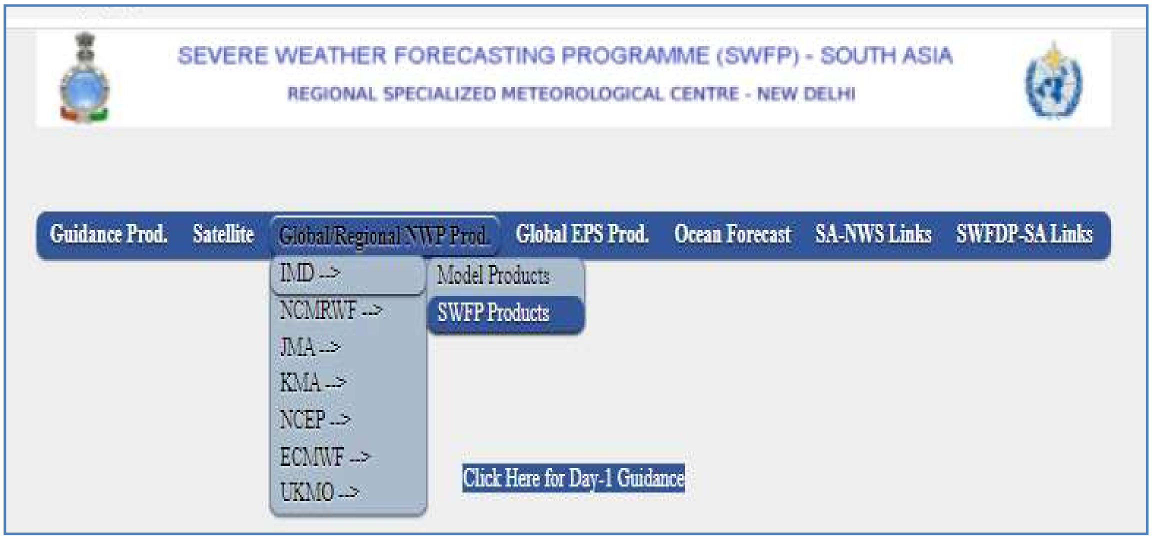


Fig. 24b. ***Cyclogenesis probability forecast for 4 weeks based on 04 Nov, 2020***

1.3.10. Severe Weather Forecasting Project (SWFP) - South Asia Website

NWP division of IMD is also catering to the needs of international users specifically from south Asian regions. For this purpose NWP division of IMD is also participating in the Severe Weather Forecasting Demonstration Project (SWFDP). Various products are made available on the SWFDP link available through NWP website. IMD-WRF Meteograms are made available for SWFDP-SA for countries Bangladesh, Bhutan, India, Maldives, Myanmar, Nepal and Srilanka. Following products are made available through IMD's NWP division:-. Customized NWP and EPS products from 8 modelling centres (IMD, NCMRWF, JMA, KMA, NCEP, ECMWF and UKMO) are available in one location along with other date from SATMET division of IMD and INCOIS. The Guidance products are prepared for 5 days based on these NWP/EPS models outputs.



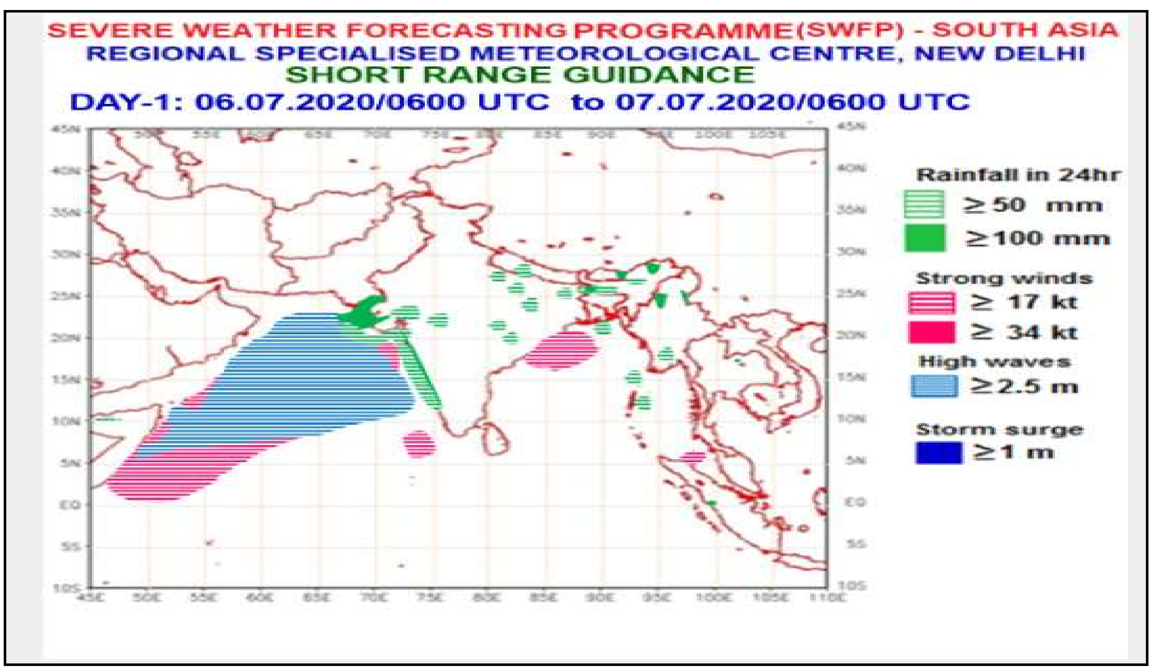


Fig. 25. ***Severe Weather Forecasting Programme Short Range Guidance***

In addition to the above products, the severe weather products in three different time scales (Short range, medium range and extended range).

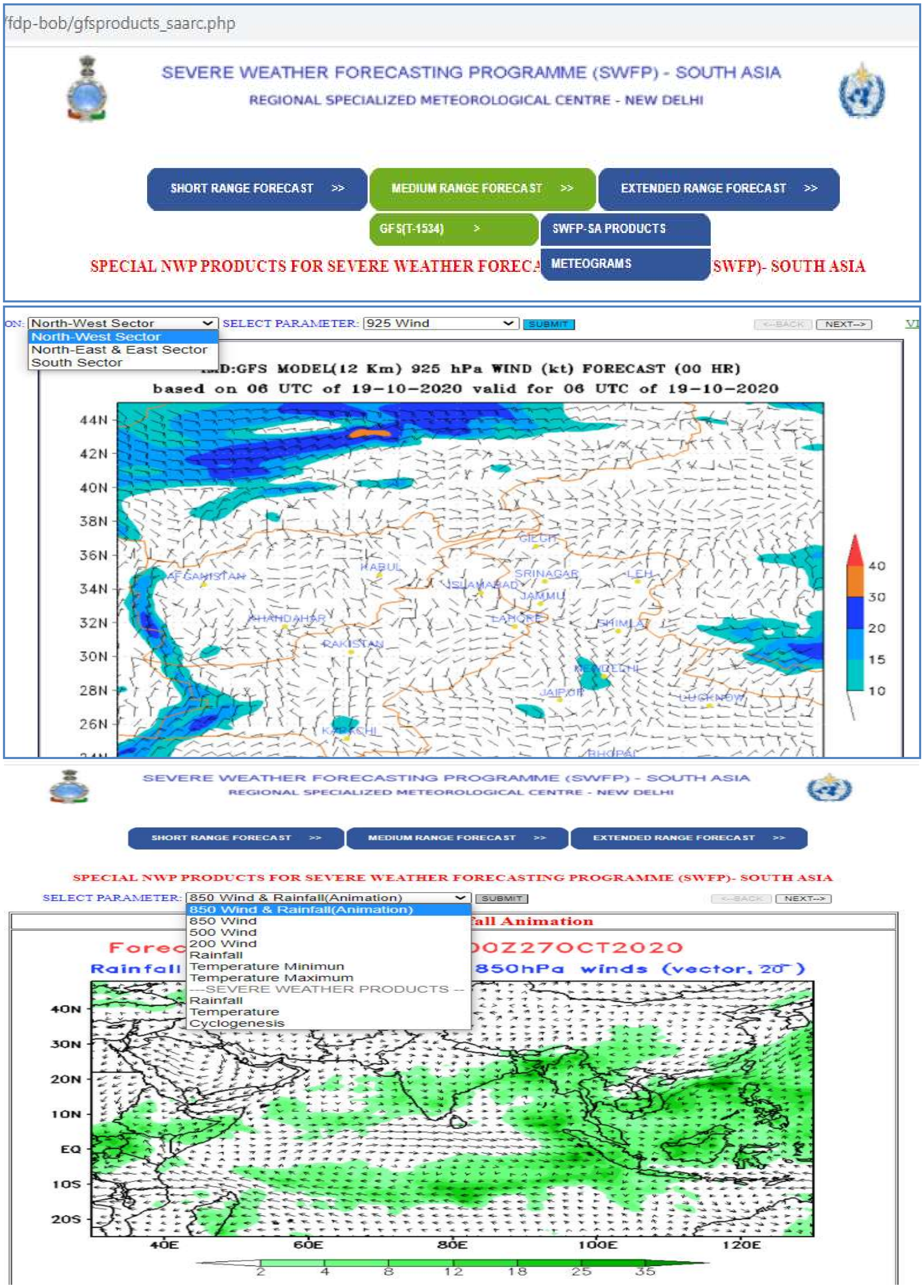


Fig. 26. *Severe Weather Forecasting Programme Short Range Guidance*

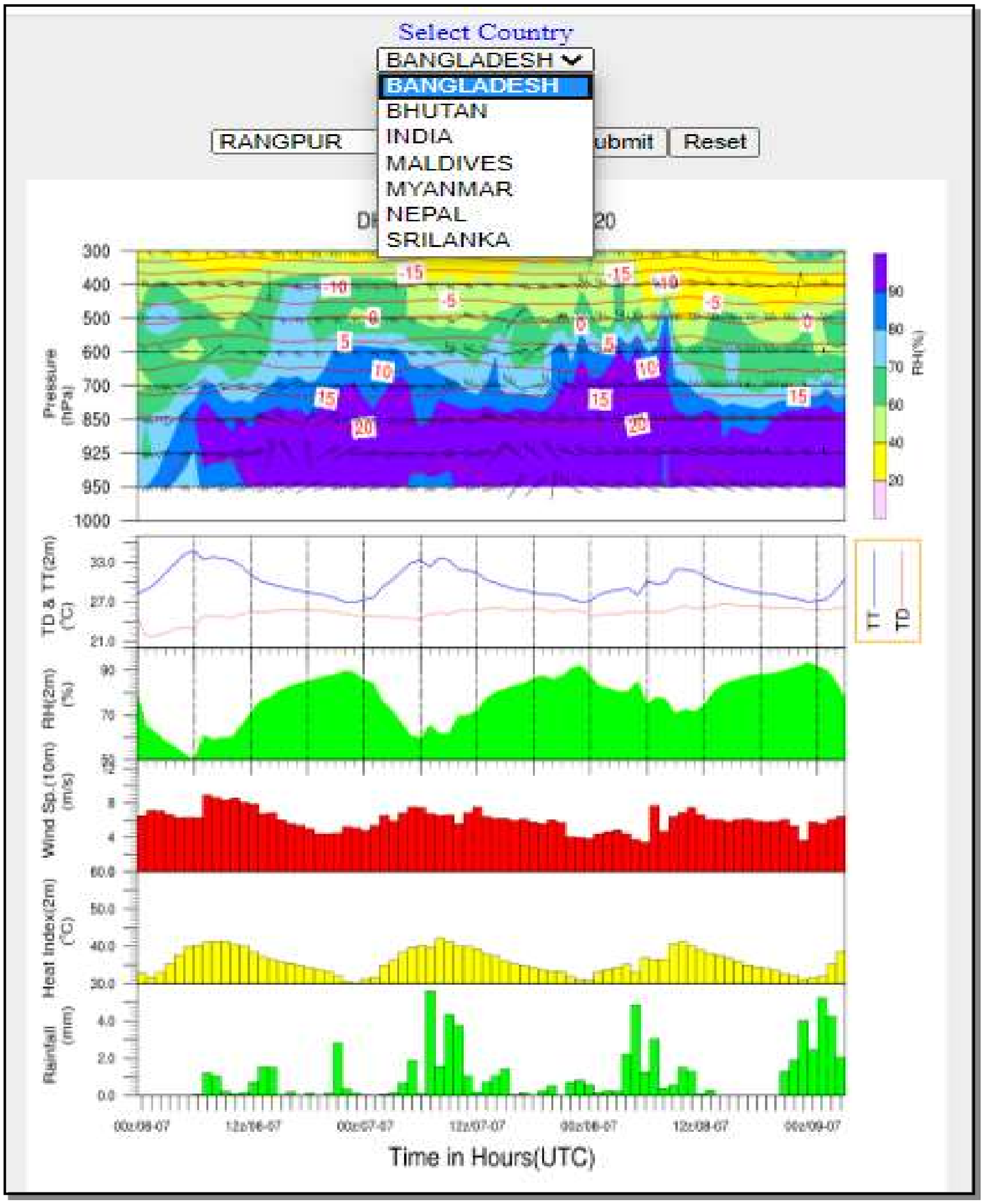


Fig. 27. ***IMD-WRF based meteogram for South Asian Countries as part of SWFDP Project***

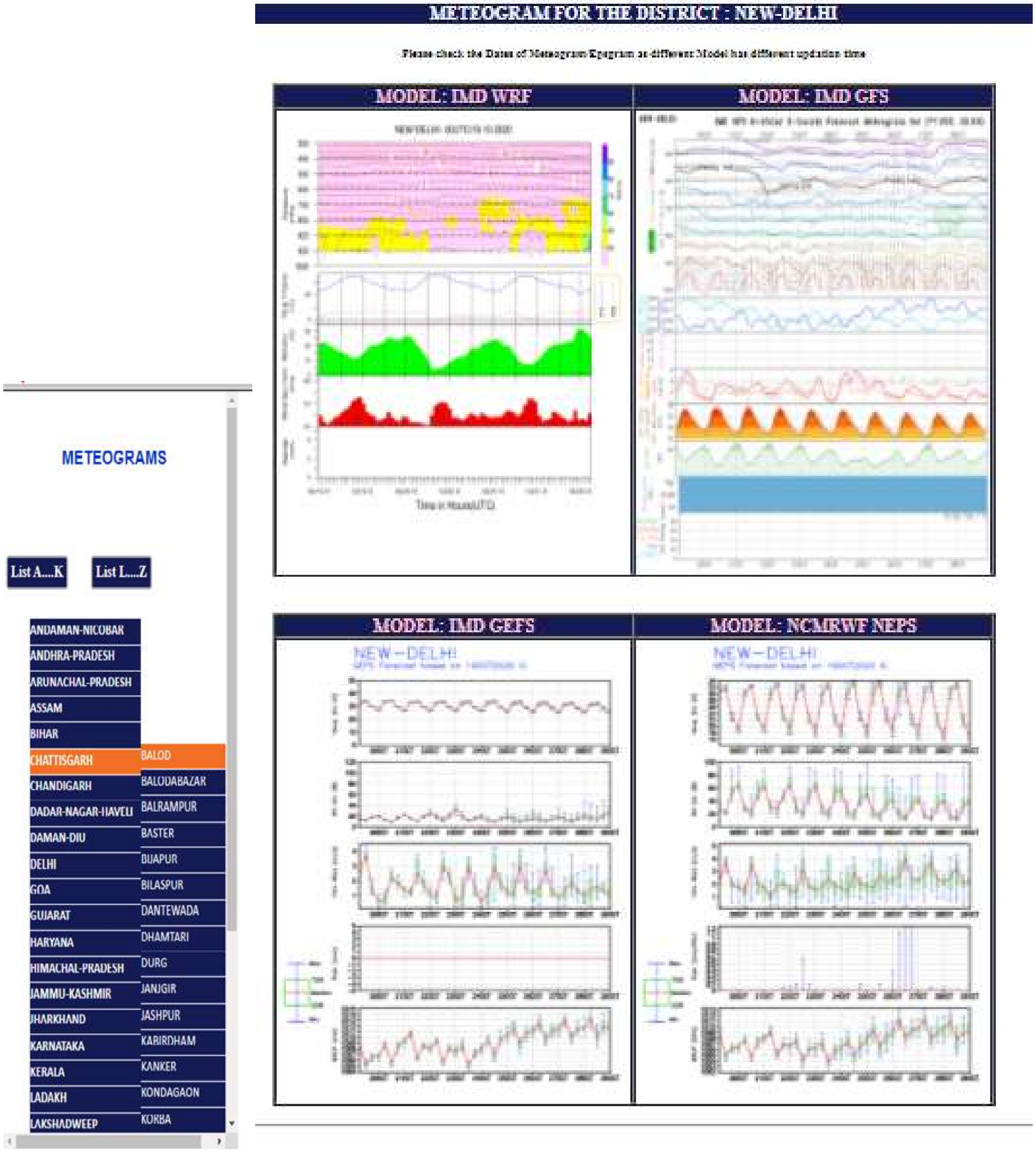


Fig. 28. ***Severe Weather Forecasting Programme Short Range Guidance***

For all the districts head quarters the METEOGRAMS/EPSGRAMS from IMD WRF, GFS, GEFS and NCMRWF models are put in one locations for the use by forecasters.

1.4. Documentation and verification

Performance of all models will be documented and verified as per standard procedure. The performance reports are brought out time to time and are also published in monsoon report.

1.5. **Users** : NWP products are used by a large number of end users and general public. Following is the brief account of major users of NWP generated products.

S.No.	User Name	Type of Forecasts
1.	***Agro-met services***	Five days quantitative District Level Forecasts of *rainfall, max , min temperature, cloud cover, surface humidity and winds* *Block level around 6400+ are being generated*
2.	***Cyclone Services***	MME based Cyclone track, genesis potential parameter and intensity prediction; Triple nested HWRF (v 3.8) (18, 6,2 Km)
3.	***Aviation services***	Flight level temperature and wind forecast map, Meteograms of 68 Airports
4.	***Hydro-logical Services***	MME based gridded daily rainfall forecasts at 25 km resolution, WRF (3 km) gridded rainfall at 3 hourly interval
5.	***Nowcast and city forecast***	SWIRLS, WRF/GFS based city forecasts.
6.	***Public weather service***	Direct and derived graphics NWP charts
7.	***Polar Met Service***	Polar WRF at 9 km resolution for IMD stations in Antarctica
8.	***Highway forecast***	Location specific temperature/wind/rainfall Forecasts along certain National Highway
9.	***Pilgrimage***	Amarnathji, Kedarnath, Badrinath, Kailash mansarovar (pilgrims)
10.	***Mountaineering expedition***	Location specific Forecasts
11.	***Power sector***	Experimental sectoral forecast of temperature
12.	***Health sector***	Yet to be implemented (Extreme Humidity, temperature and weather -Hourly Forecast). Temperature forecast for Health Sector for Bihar state is already made available on NWP website.

1.6. NWP User Data Management

Category of Data: ***ASCII***, *BUFR, NetCDF, GRIB, PNG, GIF*

- *Direct Model Outputs*
- *Model Derived Graphics Plot & Data*
- *Processed data:*
- *Aviation Products*
- *District Level Forecast*
- *Time Series Data*
- *Meteograms*
- *Amarnath, Chardham Yatra Forecast*
- *National Highway Forecast*
- *Antarctica Forecast*
- *Aviation Products*
- *Block Level Gridded Data:*
- *2 Dimensional*
- *3 Dimensional Lat & Long Pressure Level*

Uninterrupted Data from NWP division is supplied for Daily Operational Services to various agencies as given below:

- ✓ Indian Air Force
- ✓ Central Water Commission (CWC)
- ✓ The Regional Integrated Multi-Hazard Early Warning System (RIMES)
- ✓ Flood Management Information System Cell (FMISC) in Bihar, UP
- ✓ Watershed Organization Trust (WOTR)
- ✓ Geological Survey of India (GSI)
- ✓ National Disaster Management Authorities (NDMA)
- ✓ SDMA in Kerala, Andhra Pradesh, Odisha, Telangana.
- ✓ Power System Operation Corporation Limited (POSCO)
- ✓ Uttar Pradesh Power Corporation Limited, UPPCL, Lucknow
- ✓ Directorate of Wheat Development (DWD), Ghaziabad
- ✓ The Bhakra-Nangal Dam
- ✓ Indian Institute of Remote Sensing (IIRS), Dehradun
- ✓ Water Resource Department (WRD), Punjab
- ✓ Center for Snow and Avalanche Study Establishment (SASE)
- ✓ Polar Met Services (PMS)
- ✓ The National Highways Authority of India (NHAI)
- ✓ Kolkata Environmental Improvement Investment Programme (KEIIP) For R&D Purposes: DRDO, TERI, NRSC, IGCAR, IIT's,
- ✓ Flash Flood Guidance Cell (Hydromet Division, IMD)

Chapter 2

NWP FORECAST VERIFICATION

The basic philosophy of forecast verification:

i. to monitor forecast quality - how accurate are the forecasts and whether forecast is improving over time?
ii. to improve forecast quality - the first step toward getting better is identifying the reasons of wrong forecast.
iii. to compare the quality of different forecast systems - to what extent does one forecast system give better forecasts than another, and in what ways is that system better?
iv. Documentation of error statistics for better guidance to the forecasters.

2.1. Verification of quantitative precipitation forecasts (QPFs) from operational NWP models

The purpose of this document is to recommend a standard methodology for verification of QPFs from NWP models. These recommendations apply to the verification of direct model output precipitation forecasts as well as forecasts which have been subjected to post-processing (MSLP, Geopotential height (Z), Temperature (T), Relative humidity (RH), Wind speed (V) etc.).

2.1.1. Spatial matching

The primary interest of the NWP modelling community is anticipated to be model-oriented verification. Model-oriented verification includes processing of the observation data to match the spatial and temporal scales of the observations to those scales resolvable by the model. It addresses the question of whether the models are producing the best possible forecasts given their constraints on spatial and temporal resolution. Cherubini et al. (2002) showed that gridded, "upscaled", observations representing rainfall averaged over a gridbox are more appropriate than synoptic "point" observations for verification of models which produce areal quantities as opposed to grid point values.

Users of forecasts typically wish to know their accuracy for particular locations. They are also likely to be interested in a more absolute form of verification, without limiting the assessment to those space and time scales resolvable by the model. This is especially relevant now that some models are run at very high resolution, and direct model output is becoming increasingly available to the public via the internet. For this user-oriented verification it is appropriate to use the station observations to verify model output from the nearest grid point (or spatially interpolated if the model resolution is very coarse compared to the observations). Verification against a set of station observations that have been quality-controlled using model-independent methods, is the best way of ensuring truly comparable results between models.

Both approaches have certain advantages and disadvantages with respect to the validity of the forecast verification for their respective targeted user groups. The use of gridded observations addresses the scale mismatch and also avoids some of the statistical bias that can occur when stations are distributed unevenly within a network. A disadvantage is that the gridded data are not "true" observations; that is, they contain some error associated with smoothing and insufficient sampling. Station data are true observations, unadulterated by any post-processing, but they usually contain information on finer scales than can be reproduced by the model, and they under-sample the spatial distribution of precipitation. Both approaches give important information on forecast accuracy for their respective user groups.

It is proposed that verification may be done both against.

i) Gridded observations (model-oriented verification) on a common 1° (or 0.5°) latitude/longitude grid.
ii) Station observations (user-oriented verification).
iii) Time scales

The forecasts of 24-h accumulation rainfall as the basic quantity to be verified. This approach is based on the large number of 24h rainfall observations available from national rain gauge networks.

2.1.2. Stratification of data

Stratifying the samples into quasi-homogeneous subsets helps to tease out forecast behaviour in particular regimes. For example, it is well known that forecast performance varies seasonally and regionally.

It is proposed that verification data and results be stratified by:

i) Lead time (24h, 48h, 72h, 96h, and 120h) for Regional and Global model (upto 6h for nowcasting against the nowcast model analysis rainfall).
ii) Season (winter, pre-monsoon, monsoon and post-monsoon)
iii) Region (sub-division wise / average over a quasi-homogeneous region)
iv) Observed rainfall (24-h accumulation rainfall, mm/day) threshold.

Table 2.1

Rainfall category

S. No.	Terminology	Rainfall range
1.	Very light rainfall	Trace -2.4
2.	Light rainfall	2.5-15.5
3.	Moderate rainfall	15.6-64.4
4.	Heavy Rainfall	64.5- 115.5
5.	Very Heavy Rainfall	115.6-204.4
6.	Extremely heavy rainfall	≥ 204.5 mm
7.	Exceptionally Heavy Rainfall	When the amount is a value near about the highest recorded rainfall at or near the station for the month or season. However, this term will be used only when the actual rainfall amount exceeds 12 cm

2.1.3. Verification methods

i) *Forecasts of rain meeting or exceeding the specified thresholds*

For binary (yes/no) events, an event ("yes") is defined by rainfall greater than or equal to the specified threshold; otherwise it is a non-event ("no"). The joint distribution of observed and forecast events and non-events is shown by the categorical contingency table, as represented in Table 2.7 in Annexure 1.

The elements of the table, hits, false alarms, misses, and correct rejections, count the number of times each forecast and observed yes/no combination occurred in the verification dataset. A large number of verification scores may be computed from these four values. Reporting the number of hits, false alarms, misses, and correct rejections for each of the rain thresholds specified in Table 2.1 is mandatory.

The term **categorical** refers to the yes/no nature of the forecast verification at each grid point. Some threshold (as per Table 2.1) can be considered to define the transition between a rain versus no-rain/range of rain event. Then at each grid point, each verification time the scores can be computed.

The list of recommended scores includes: (their brief descriptions can be found in Annexure 1 based on Categorical contingency table 2.7)

Where,

H = Hits, F = False alarm, M = Misses, Z = Correct rejections

(a) Frequency bias (bias):

$$BIAS = \frac{F+H}{M+H} \quad (1)$$

The desirable value for bias is 1, indicating an unbiased forecast where the event is forecast exactly as often as it is observed. When bias is greater than 1, the event is over forecast When bias is less than 1, the event is under forecast.

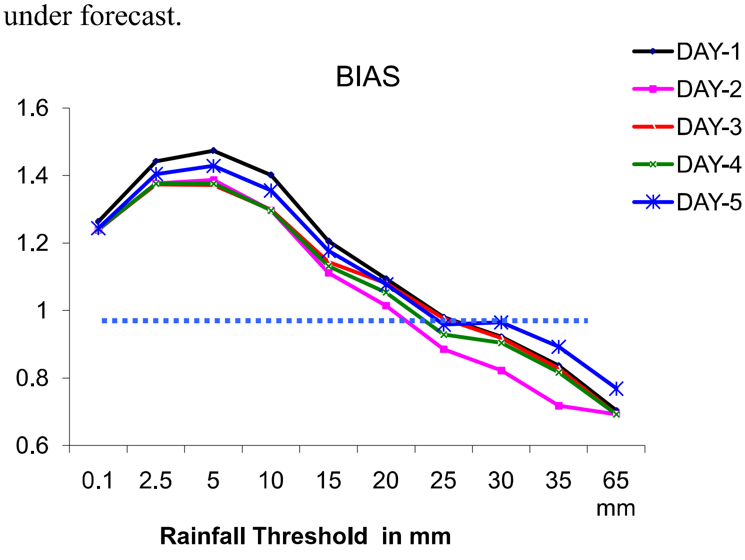


Fig. 2.1. ***Rainfall bias for 1 -to day-5***

The bias score is equal to the number of rain forecasts divided by the total number of observations of rain. Thus the bias score is a measure of the relative frequency of rain forecasts compared with observations. Fig. 2.1 shows the day-1 -to day-5 bias of the GFS T574 model. The day-1 forecast over predict (bias >1) rainfall event in all the rainfall threshold range. From day-2 -to day-5, the bias of T574 over predicts (bias >1) in the low threshold ranges up to 20 mm and close to 1.0 around rainfall threshold of 15 mm/day, while it over predict very slightly (bias ≈1) rainfall event in the higher threshold ranges for day-2 -to day-5 forecast

Threat score (critical success index):

$$TS = \frac{H}{H + M + F} \qquad (2)$$

The threat score (TS) measures the fraction of observed and/or forecast events that were correctly predicted (Range : 0 to 1. Perfect score : 1).

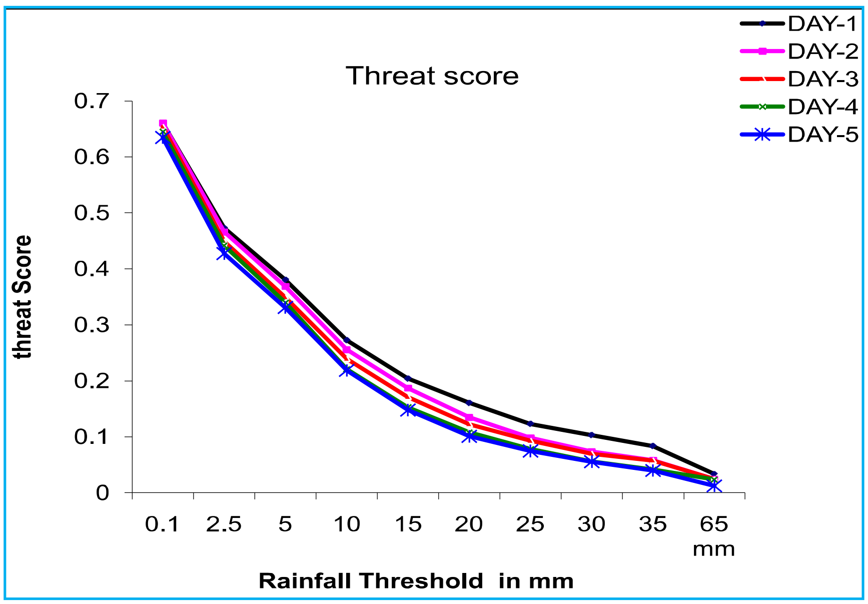


Fig. 2.2. ***Rainfall threat score***

Probability of detection (POD)

$$POD = \frac{H}{H + M} \qquad (4)$$

The probability of detection (POD) is equal to the number of hits divided by the total number of rain observations; thus it gives a simple measure of the proportion of rain events successfully forecast by the model (Range : 0 to 1. Perfect score : 1).

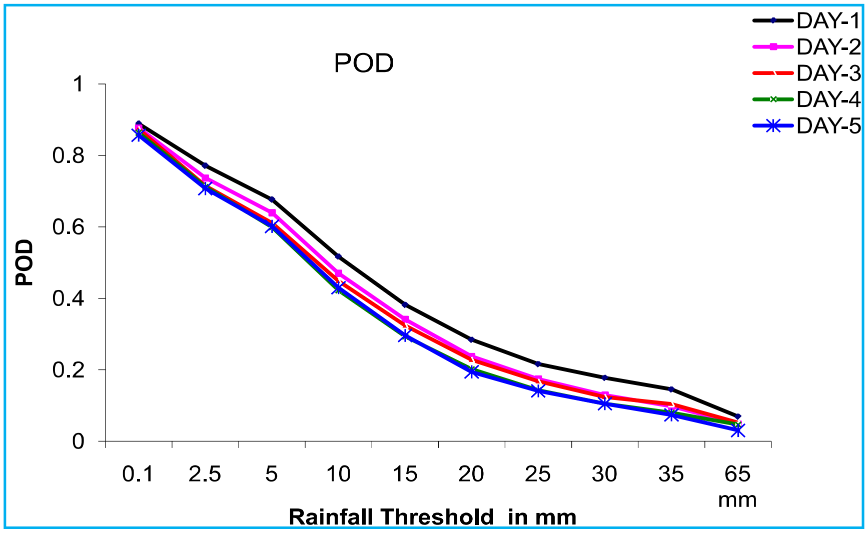


Fig. 2.3. ***POD of Rainfall forecast***

From Figure **POD**, it is seen that the probability of detection is more than 60% for rainfall threshold value of 10 mm/day for all the day-1, day-3 and day-5 forecast, while it is further below for higher rainfall threshold values (>10 mm/day) forecast. It is also seen that skill is a strong function of the rainfall intensity and forecast lead time (day-1 to day-5), with the POD decreasing from more than about 50% for 10 mm/day over most parts of the country to less than 50% for higher rainfall threshold values (>10 mm/day) forecast in the forecast. Higher values of POD more than 50% are observed over most parts of the country for forecasting rainfall of less than 10 mm/day.

POFD=F/(Z+F), also known as the false alarm rate, measures the fraction of false alarms given the event did not occur(Range: 0 to 1. Perfect score: 0).

False alarm ratio (FAR):

$$FAR = \frac{F}{H+F} \qquad (5)$$

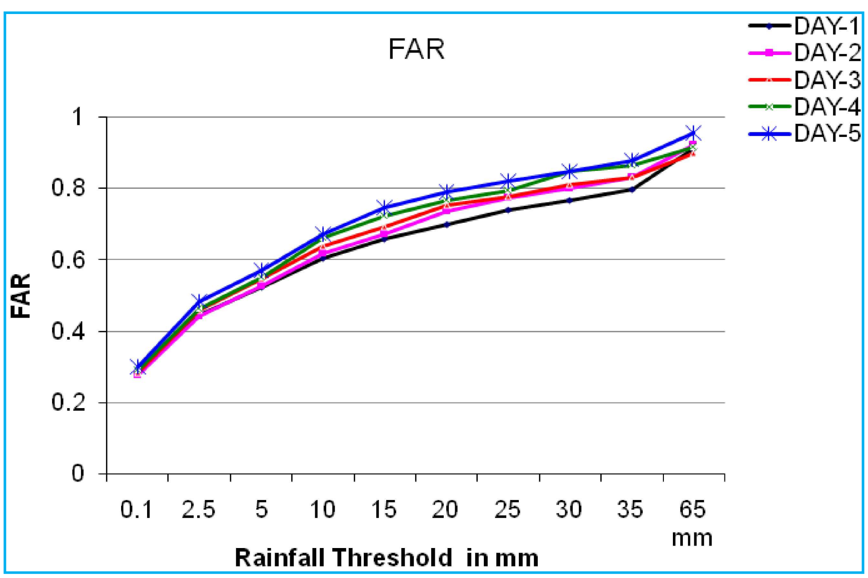


Fig. 2.4. ***FAR of Rainfall forecast***

False Alarm Ratio (FAR) gives a simple proportional measure of the model's tendency to forecast rain where none was observed (Range: 0 to 1. Perfect score: 0). For perfect prediction, the value of this parameter should be 0.0. In the present case, FAR is smaller for classes with a lower class mark, but increases markedly with an increase in class mark, and is practically 1 for class marks above 65 mm (1.0 in.).

Equitable threat score (Gilbert skill score)

$$ETS = \frac{H - H_{random}}{H + M + F - H_{random}} \qquad \text{Where} \qquad H_{random} = \frac{(H+M)(H+F)}{total} \qquad (3)$$

The Equitable threat score (ETS) measures the fraction of observed and/or forecast events that were correctly predicted, adjusted for hits associated with random chance .For example, it is easier to correctly forecast rain occurrence in a wet climate than in a dry climate.

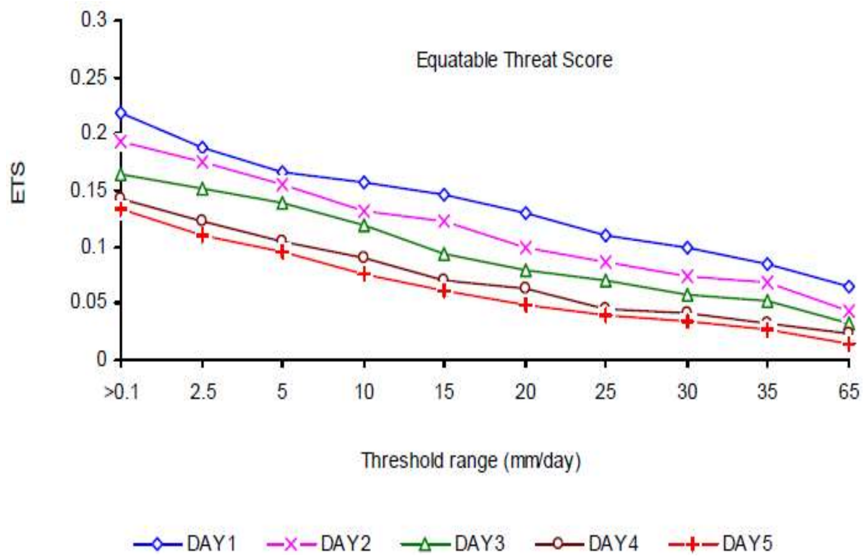


Fig. 2.5. ***Equitable threat score of Rainfall forecast***

Among the wide variety of performance measures available for the assessment of skill of deterministic precipitation forecasts, the equitable threat score (ETS) might well be the one used most frequently. The *ETS* is often used in the verification of rainfall in NWP models because its "equitability" allows scores to be compared more fairly across different regimes. If the ETS = 1, it indicates that there is no error in the forecasting. ETS = 0 indicates that none of the grid points are correctly predicted .One disadvantage perceived by the current authors is that the reference accuracy for a random forecast in the ETS is dependent on the properties of the model being verified. The ETS skill for the model, day-1 and day-2 forecasts of precipitation have significant skill for precipitation in lower threshold and it falls off rapidly for larger precipitation amounts and also for longer lead time (day-3 to day-5).

ii) ***Forecasts of rain amount***

Other statistics measure the quality of forecasts of a continuous variable such as rain amount (WWRP2009-1, WMO/TD-No. 1485, page-9). As discussed previously, some continuous verification scores are sensitive to outliers. One strategy for lessening their impact is to normalize the rain amounts using a square root transformation (Stephenson et al., 1999) (square root of rain amounts). The verification quantities are computed from the square root of the forecast and observed rain amounts, then inverse transformed by squaring, if necessary, to return to the appropriate units. As the resulting errors are smaller than those computed from un-normalized data it is necessary to indicate whether the errors or scores apply to normalized or un-normalized data.

The suggested scores are listed below, while their brief descriptions can be found in Annexure 1:

a) Mean observed
b) Mean error (ME)
c) Root mean square error (RMSE)
d) Corrélation coefficient (r)
e) Mean absolute error (MAE)
f) Mean square error (MSE)

(a) Mean observed

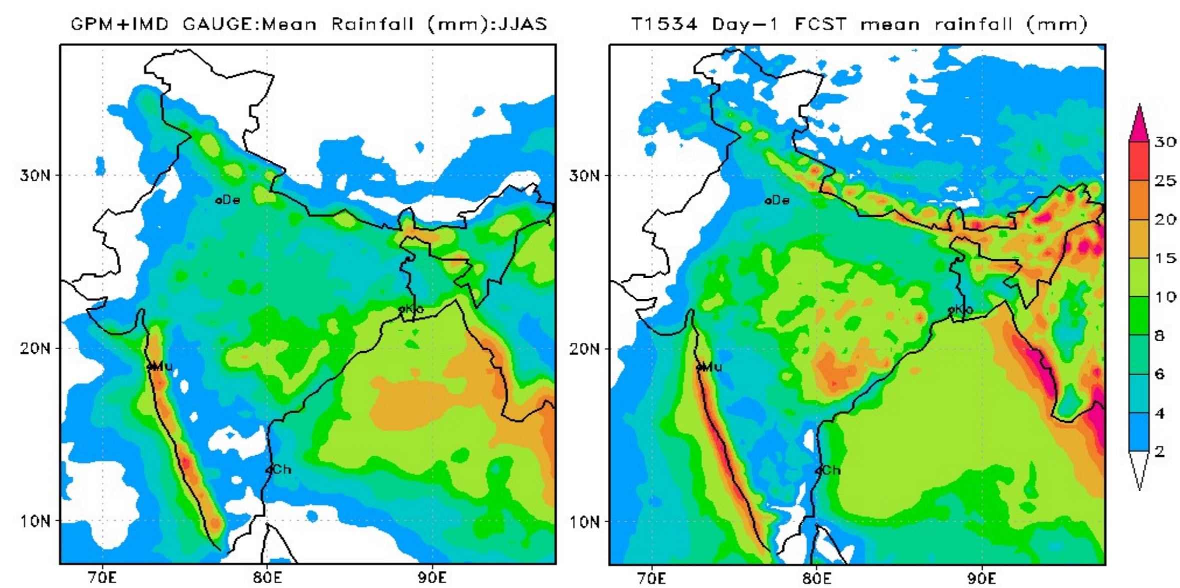


Fig. 2.6. ***Spatial distributions of seasonal (JJAS) mean observed rainfall and Day-1 forecast rainfall (mm/day) from GFS T1534***

For a numerical model of the atmosphere to be successful in predicting summer monsoon precipitation over India, the first step is to reproduce the observed characteristic patterns in the seasonal accumulated values. The forecasts by this model, in general, could reproduce the heavy rainfall due to topographical forcing along the west coast and over North East India and along the foot hills of the Himalaya. The other large seasonal total precipitation due to dynamical forcing produced by the generation of cyclonic circulations over the eastern regions is also seen in the model prediction. The region of less precipitation over North-West India to the west of the country and over South-East Peninsular regions is also noticed in model forecasts. However, some spatial variations in magnitude are noticed. The spatial distribution pattern of model predicted rainfall is closer to the corresponding observed field.

(b) Mean error (ME)

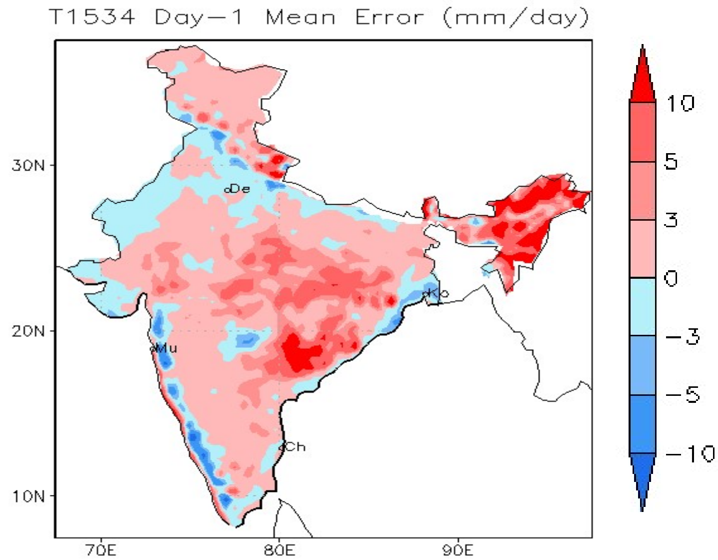


Fig. 2.7. ***Seasonal Mean Error (ME) (mm/day) of GFS T574***

The spatial distribution of seasonal mean error (forecast-observed) rainfall (mm/day) based on Day-1 forecast of *GFS* forecast over Indian monsoon region for monsoon 2019 is depicted in the above Figure. The mean errors is 5 mm/day over most parts of the country except over North-eastern region and over the domain of monsoon low (Orissa and adjoining coastal areas of Andhra Pradesh) where it is in the order of +5 to +10 mm/day. Also the rainfall was negative of the order -6 mm/day over some parts over west coast of India and east coastal regions. In general, GFS model mostly over estimate rainfall over northeast India and underestimate rainfall over North West India.

(c) Root mean square error (RMSE)

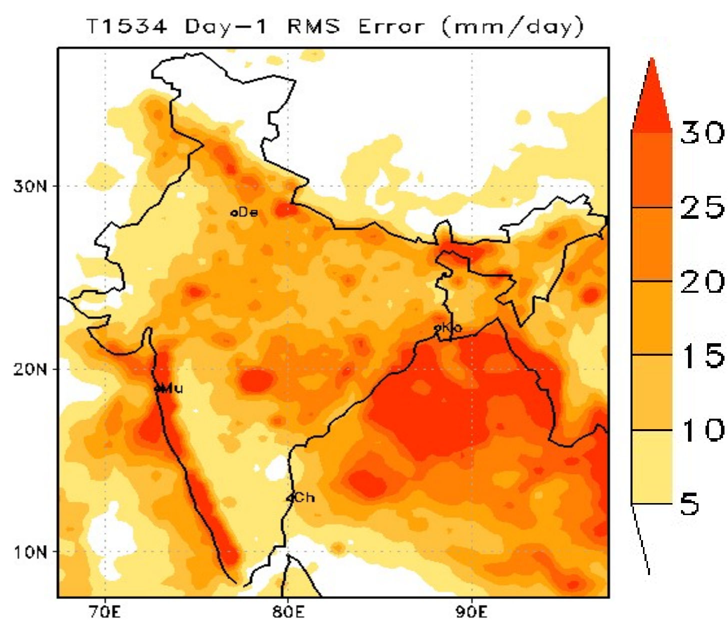


Fig. 2.8. ***Seasonal Root Mean Squared Error (RMSE in mm/day) of GFS T574 Day-1 Forecast over Indian monsoon***

RMSE is a measure of the random component of the forecast error. The values of rmse are higher over the regions where the daily rainfall variability is also high. The less rmse over southern peninsular India indicates that the day to day rainfall variability over this region is small as compared to other regions. The rmse of day-forecasts of the model has a magnitude between 10 and 25 mm, except over the Sub Himalayan West Bengal (SHWB), west coast of India and some pockets of central India where the magnitude of rmse exceeds 30 mm. The spatial distribution of rmse pattern of day-1 forecast is consistent with the area of maximum and minimum rainfall forecast values.

(d) corrélation coefficient (*r*)

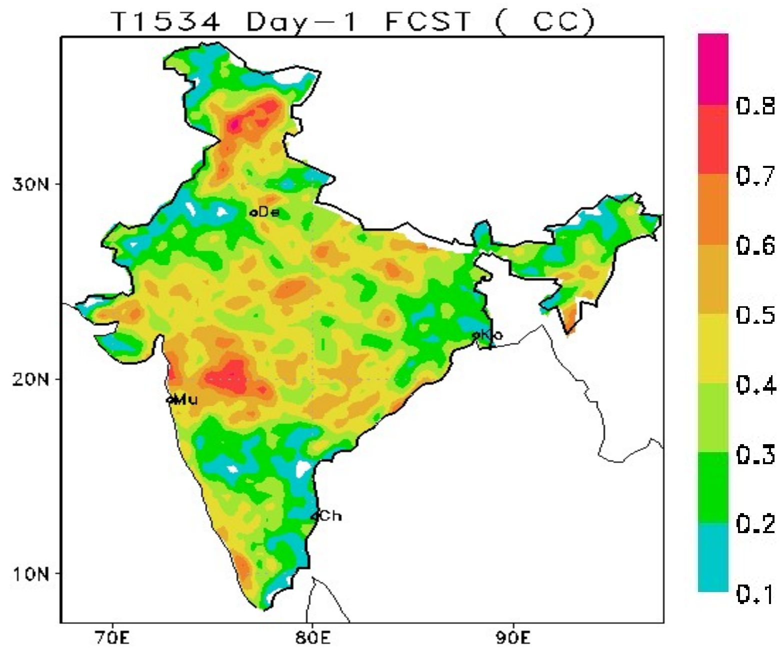


Fig. 2.9. ***Spatial distribution of correlation coefficient (CC) between the observed and the model predicted rainfall for Day-1 forecast of GFS T1534***

The spatial distribution of the values of CC decreases with longer forecast length. This indicates that the trend in precipitation in the day-1 to day-3 forecasts of the model is in good phase relationship with the observed trend over a large part of the country. The CC exceeding 0.4 is considered to be good for precipitation forecast. The magnitude of CC decreases with the forecast lead time, and by day-5 CC values over most of India are between 0.1 and 0.4 except a small portion over NE India and west coast of India. The CC values are comparatively higher over the west coast of India in all the day-1 to day-5 forecasts.

The list of recommended scores includes: (their brief descriptions can be found in Annexure – 1).

a. Frequency bias
b. Proportion correct (PC)
c. Probability of detection (POD)
d. False alarm ratio (FAR)
e. Probability of false detection (POFD)
f. Equitable Threat score (ETS)

ii) *Forecasts of rain amount*

Other statistics measure the quality of forecasts of a continuous variable such as rain amount (WWRP2009-1, WMO/TD-No. 1485, page-9). As discussed previously, some continuous verification scores are sensitive to outliers. One strategy for lessening their impact is to normalize the rain amounts using a square root transformation (Stephenson et al., 1999) (square root of rain amounts). The verification quantities are computed from the square root of the forecast and observed rain amounts, then inverse transformed by squaring, if necessary, to return to the appropriate units. As the resulting errors are smaller than those computed from unnormalised data it is necessary to indicate whether the errors or scores apply to normalized or un-normalised data.

The suggested scores are listed below, while their brief descriptions can be found in Annexure 1.

a. Mean observed
b. Sample standard deviation (s)
c. Mean error (ME)
d. Mean absolute error (MAE)
e. Mean square error (MSE)
f. Root mean square error (RMSE)
g. (Product moment) corrélation coefficient (r)

2.1.4. Quantitative precipitation forecast (QPF) verification by CRA method

Any good quantitative precipitation forecast (QPF) correctly predicts the area, amount/intensity and the location. Errors can occur in all of the three quantities. However, it is difficult to determine the source(s) of error using traditional verification statistics over the model domain. Traditional verification methods focus on matches between the forecast and observations at individual stations or grid points, and do not consider the spatial relationship between the points. In addition, it may be difficult to interpret the verification results for a given spatial forecast when there is more than one feature of interest in the domain. When we verify a spatial forecast by eye, we compare the mapped forecast and observations side by side, generally focussing on one or more features of interest. The first things we notice are whether each feature was forecast to be in the right place, and whether it had the correct size, shape, and magnitude.

Contiguous rain area (CRA) verification is an intuitive approach that quantifies the results of "eyeball", or visual, verification. It focuses on individual weather systems as opposed to the entire domain, enabling the errors in each event to be separately assessed. It verifies the properties of the forecast entities against the properties of the corresponding observed entities. A big advantage of this approach over more traditional verification methods is that the location error of the forecast entity can be quantified.

CRA method isolates systems or features of interest and evaluates their properties, namely, location, size, intensity, and pattern. It was one of the first methods to measure errors in predicted location and to separate the total error into components due to location, volume, and pattern errors (Ebert and McBride, 2000; Ebert and Gallus, 2009).

A CRA is defined for an observation/forecast pair based on a user specified isohyet (rain rate contour) in the forecast and/or the observations. It is the union of the forecast and observed rain entities as illustrated in Fig. 2.10. This simple approach is used to match a forecast rain system with an observed rain system under the assumption that they are associated with a common synoptic disturbance/situation, which is reasonable for monsoon rain events. During the monsoon season, large parts of India regularly receive rainfall in the range up to 1 cm/day. It was found that choice of lower rainfall thresholds of 1, 2, and 5 mm/day contour frequently spread the CRA across large geographical areas, merging rainfall due to unrelated rain systems. The CRAs defined by higher thresholds of 10, 20, 40 and 80 mm/day are used to better isolate the heavy rain events of interest in the study.

Apart from the measuring errors in predicted location, the CRA method decomposes the total error into components due to errors in location, volume, and pattern. The location errors in the model forecasts suggest issues with predicted flow and the model dynamics. The volume and pattern errors possibly emanate from physics and thermodynamics. The steps involved in the CRA technique are described in Ebert and Gallus (2009). A brief summary of the procedure is given below.

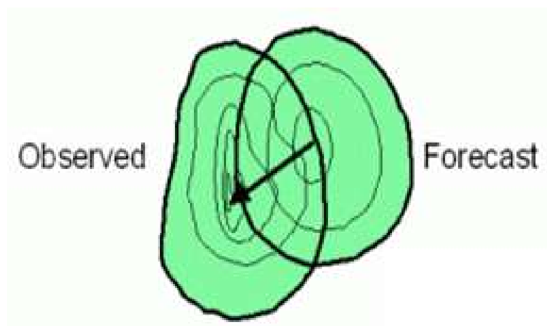


Fig. 2.10. ***CRA formed by overlap of forecast and observations***

Firstly, the CRA objects are identified in observation and forecast pair for a threshold (e.g., 10 mm/day). In the next step, a pattern matching technique is used for estimating the location error. Here the forecast field is horizontally translated over the observed field until the best match is obtained. The geometric distance between the centers of gravity (COG) in the observed and estimated fields forms the location error or vector displacement. The best match between the two entities can be determined either: (a) by maximizing the correlation coefficient, (b) by minimizing the total squared error, (c) by maximizing the overlap of the two entities, or (d) by overlaying the centers of gravity of the two entities. For a good forecast, all of the methods will give very similar location errors. In the present study, the best match is determined by maximizing the correlation, as was also done by Ebert and Gallus (2009). The mean squared error (MSE) and its decomposition (location error, volume error and pattern error) are computed as shown below (see Grams et al., 2006, for details of the derivation).

$$MSE_{Total} = MSE_{Displacement} + MSE_{Volume} + MSE_{Pattern} \quad (1)$$

where the component errors are estimated as

$$MSE_{Displacement} = 2S_F S_O\, (r_{OPT} - r),$$

$$MSE_{Volume} = (F - O), \quad (2)$$

$$MSE_{Pattern} = 2S_F S_O\, (1 - r_{OPT}) + (S_F - S_O)^2$$

In the above expressions F and O are the mean forecast and observed precipitation values after shifting the forecast to obtain the best match, S_F and S_O are the standard deviations of the forecast and observed precipitation, respectively, before shifting. The spatial correlation between the original forecast and observed features (r) increases to an optimum value (r_{OPT}) in the process of correcting the location via pattern matching. The number of 'good matches' corresponds to the number of forecasts that matched well with observations when the optimum correlation (r_{OPT}) was (statistically) significantly greater than zero (accessed via two-tailed t-test).

Example : ***CRA Verification and Decomposition of Day-3 Forecast Rainfall valid on 24th Jul 2018***

Fig. 2.11 shows the CRA verification for GFS Day-3 rainfall forecast valid on 24th Jul 2018. This CRA is bounded by the domain from 21° - 26.25°N and 73.25° – 80.75°E which has 435 grids common to observation and Day-3 forecast. the original forecast object had a poor match with observed object (CC= -0.063 and RMSE= 58mm which is 100% higher than observed mean rain of 29 mm). Original forecast was located to 0.5° Lon and 1.25° Lat to the south west of observed position (vector displacement of 1.3°). The best match (r_{OPT}) between the objects is obtained by shifting the forecast slightly to the north east (indicated by red arrow in Fig. 7). Pattern error (42.6%), displacement error (31.9%) and Volume error (25.4%) contribute to total error. The highest rainfall amount in GFS it is 270mm as against 131mm in observations. Thus, in GFS volume error contributed significantly to the total error for this case on 24th July 2018.

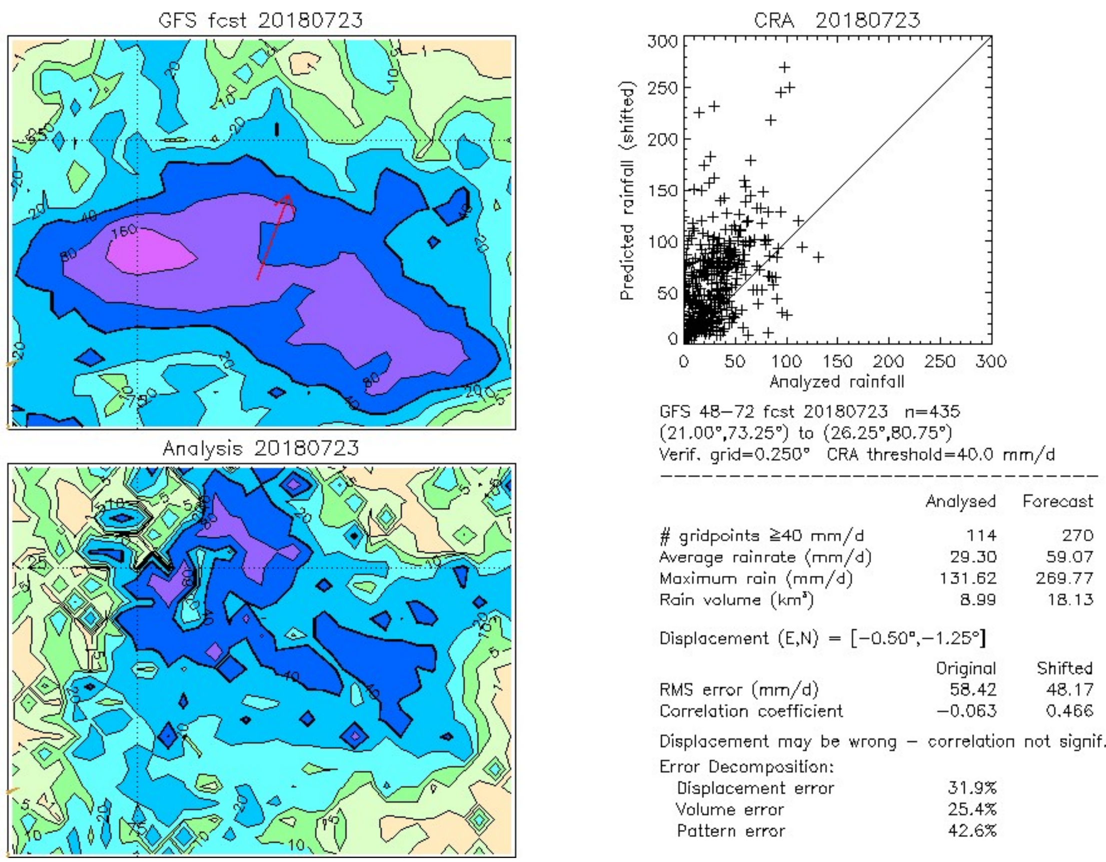


Fig. 2.11. ***CRA Verification for GFS : Day-3 (upper) and Analysis (Lower) rainfall valid on 24th Jul, 2018***

2.1.5. Ensemble Based Probabilistic Forecast Verification

a. QPE probability forecast verification

The skill of the QPE probability forecasts can be assessed by computing the Brier score (BS) (Wilks 2006). The Brier score is computed using the formula

$$BS = \frac{1}{N}\sum_{i=1}^{N}(p_i - o_i)^2$$

p_i: Forecast probability; o_i: Observed occurrence (0 or 1)

in which *p* is the probability that was forecast, *O* the actual outcome of the event (*O* = 0 if it doesn't happen and 1 if it happens) and N is the number of forecasting instances. For example, when RI is observed, a forecast probability of 50% would yield a BS = 0.25 [i.e., $(0.50\text{-}1.0)^2$]. The BS is 0 and 1 for the best and worst score achievable respectively.

QPE probability forecasts for the following threshold values per day to be verified:

i. QPF = 0 mm (No rain)
ii. QPF = Trace - 2.4 mm (very light rain)
iii. QPF = 2.5 - 15.5 mm (light rain)
iv. QPF = 15.6 - 64.4 mm (Moderate rain)
v. QPF = 65.5 - 115.5 mm (Heavy rain)
vi. QPF = 115.6 - 204.4 mm (very heavy rain)
vii. QPF > 204.5 mm (extremely heavy rain)

The same methodology can used to obtain the BS for the climatological forecasts. The skill of the forecast can be evaluated using the Brier skill score (BSS) (Wilks 2006):

$$BSS = 1 - \frac{BS}{BS_{clim}}$$

where BS is the Brier score of the probabilistic forecasts and BS_{clim} is the Brier score of the climatological forecasts. Thus, positive values of BSS indicate higher skill than climatology while negative values indicate no skill.

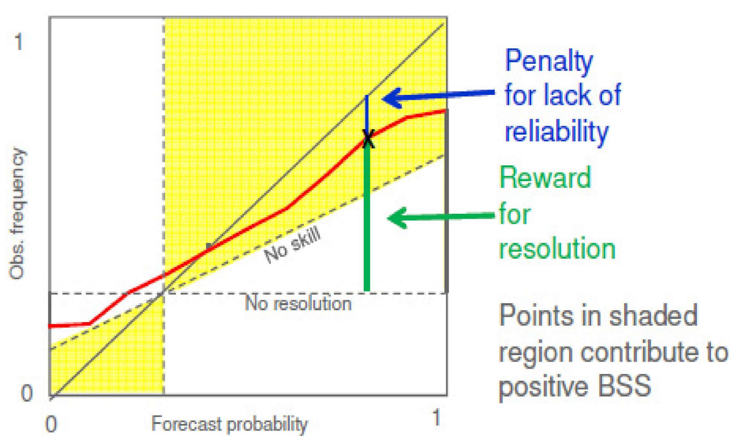


Fig. 2.12. ***BSS diagram***

The Brier score can be decomposed into 3 additive components (Murphy 1973):

$$BS = \underbrace{\frac{1}{N}\sum_{k=1}^{K} n_k (p_k - \bar{o}_k)^2}_{\text{reliability}} - \underbrace{\frac{1}{N}\sum_{k=1}^{K} n_k (\bar{o}_k - \bar{o})^2}_{\text{resolution}} + \underbrace{\bar{o}(1-\bar{o})}_{\text{uncertainty}}$$

☐*Reliability*: measures the average agreement between the forecast values and the observed values.

☐*Resolution*: is defined as the ability of the forecast to resolve the set of events into subsets with different frequency distributions.

☐*Uncertainty*: is the variability of the observations. The greater the *uncertainty*, the more difficult the forecast will tend to be. The uncertainty term depends only on the variability of the observations and is not influenced by the forecast quality. When an event is either very frequent (usually occurs) or infrequent (does not usually occur, for example: a rare event) the uncertainty term is close to zero. On the other hand, when there is more variability seen in the occurrence of an event (for example, it happens 50 % of the time) then the uncertainty associated with the happening of the event is high. For a perfect forecasting system the uncertainty term should be the same as resolution.

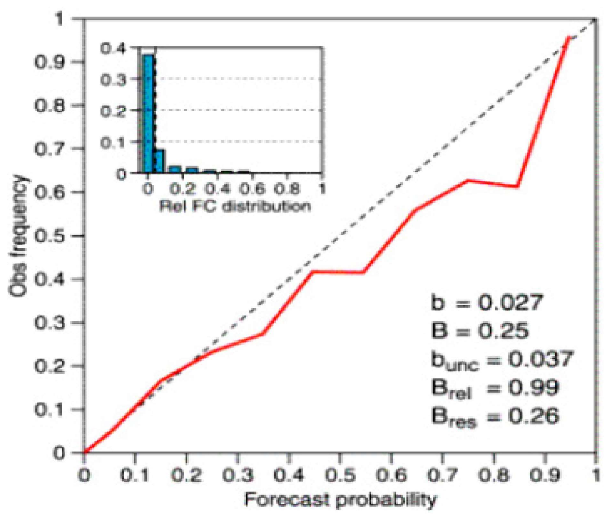


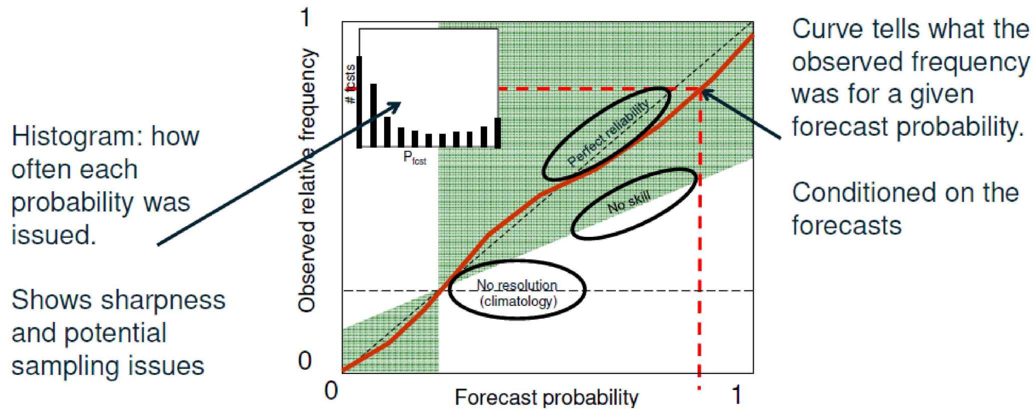
Fig. 2.13. ***Reliability diagram***

Reliability diagram measures deviation of the curve from the diagonal line – error in the probabilities. The diagonal line is the perfect line for a reliable forecast and the further you get from this line the worse the forecast.

Dichotomous forecasts Measures how well the predicted probabilities of an event correspond to their observed frequencies (reliability).

→ Plot observed frequency against forecast probability for all probability categories

→ Need a big enough sample



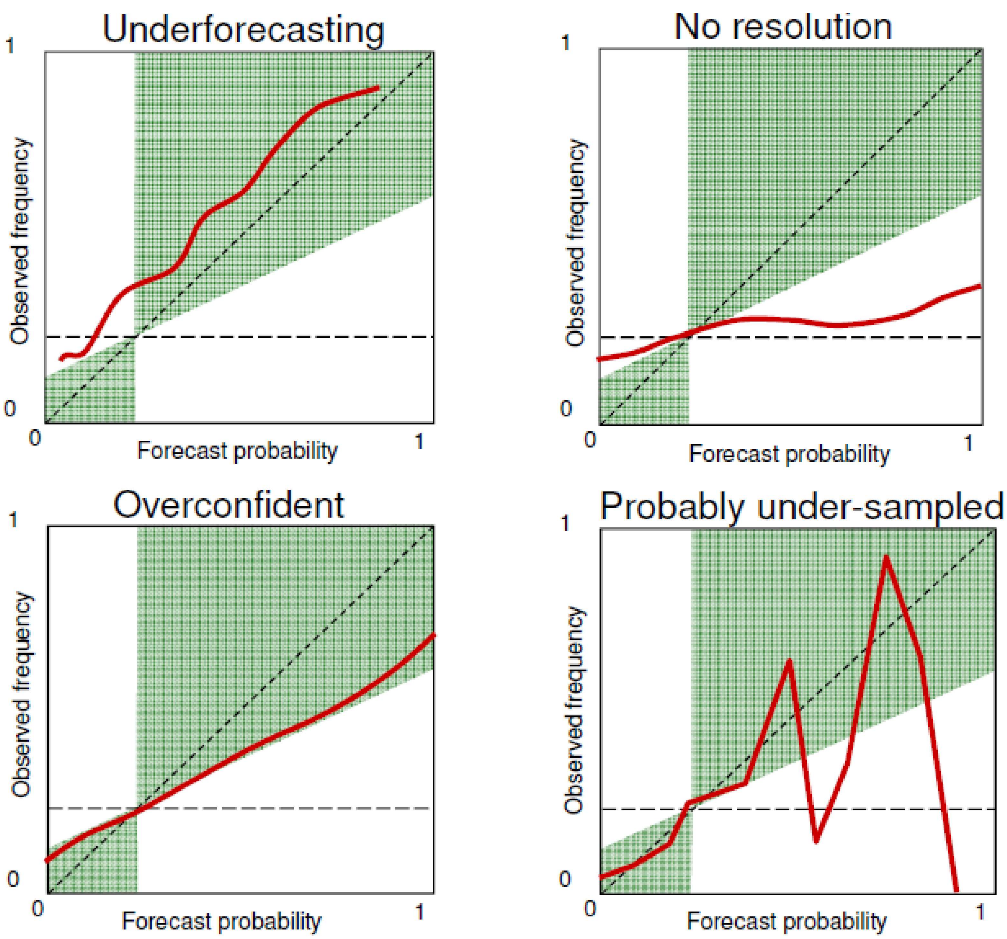


Fig. 2.14. ***Interpretation of reliability diagrams***

Resolution term : measures deviation of the curve from the sample climate horizontal line – indicates degree to which forecast can separate different situations.

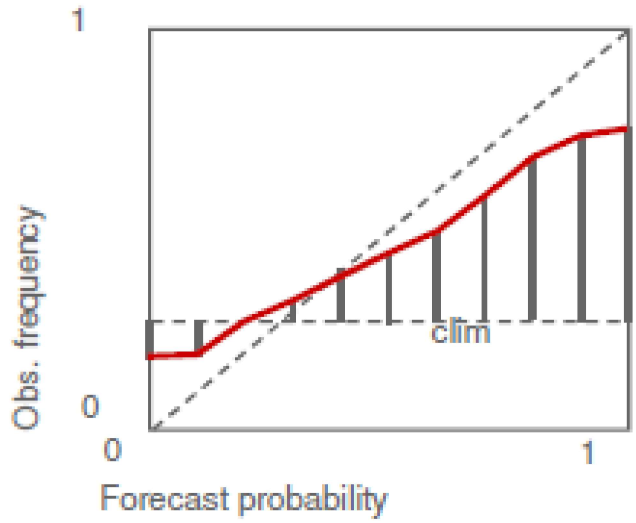


Fig. 2.15. ***Resolution diagrams***

b. **Relative Operating Characteristic (ROC):**

Measures the ability of the forecast to discriminate between events and non-events (discrimination).
• Plot hit rate *vs* false alarm rate using a set of varying probability thresholds to make the yes/no decision.

Close to upper left corner – good discrimination

Close to or below diagonal – poor discrimination

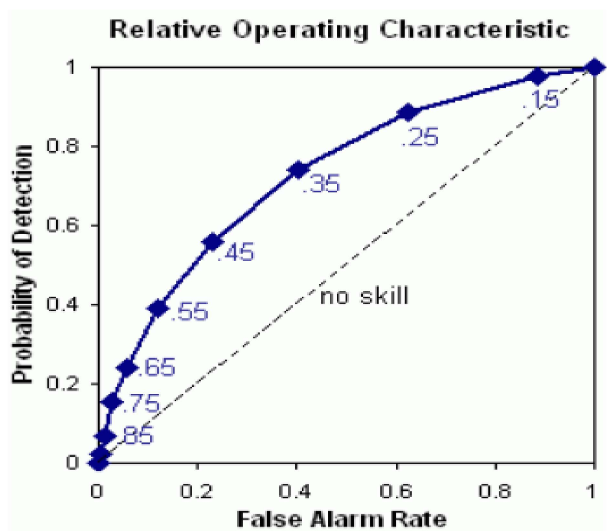


Fig. 2.16. ***Relative operating characteristic curve***

Area under curve ("ROC area") is a useful summary measure of forecast skill.

• ROC skill score : ROCS = 2(ROCarea-0.5)
• The ROC is conditioned on the observations
• Reliability and ROC diagrams are good companions

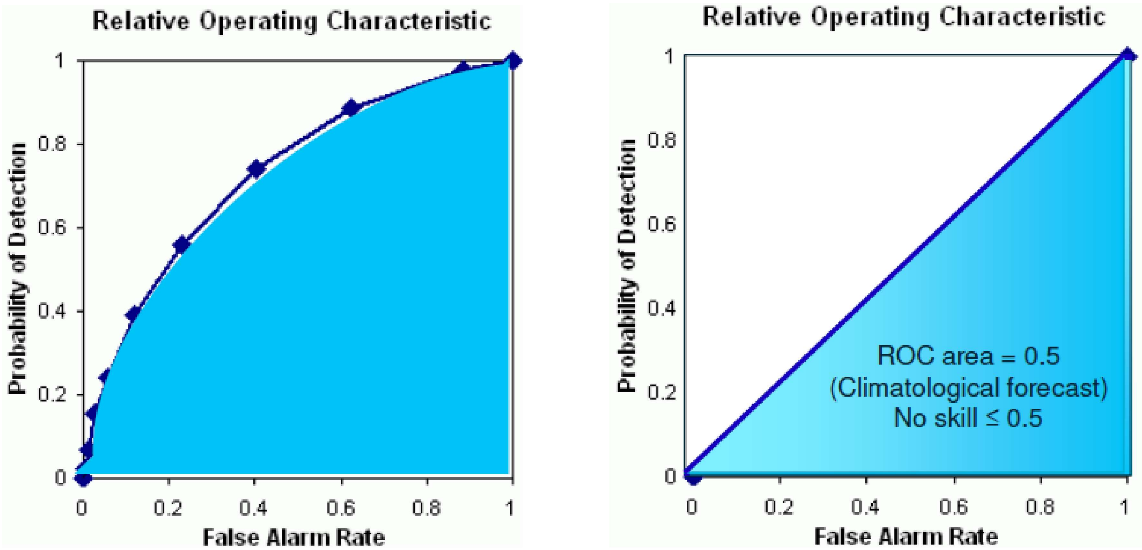


Fig. 2.17. ***Analysis of Relative operating characteristic curve***

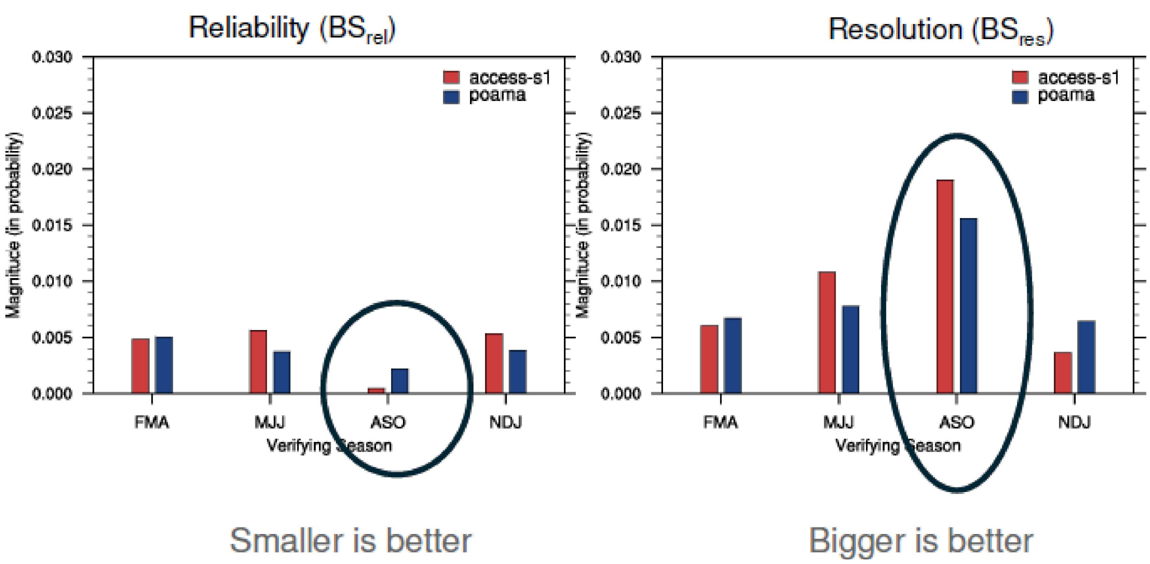


Fig. 2.18. ***Probability seasonal mean rainfall above-normal***

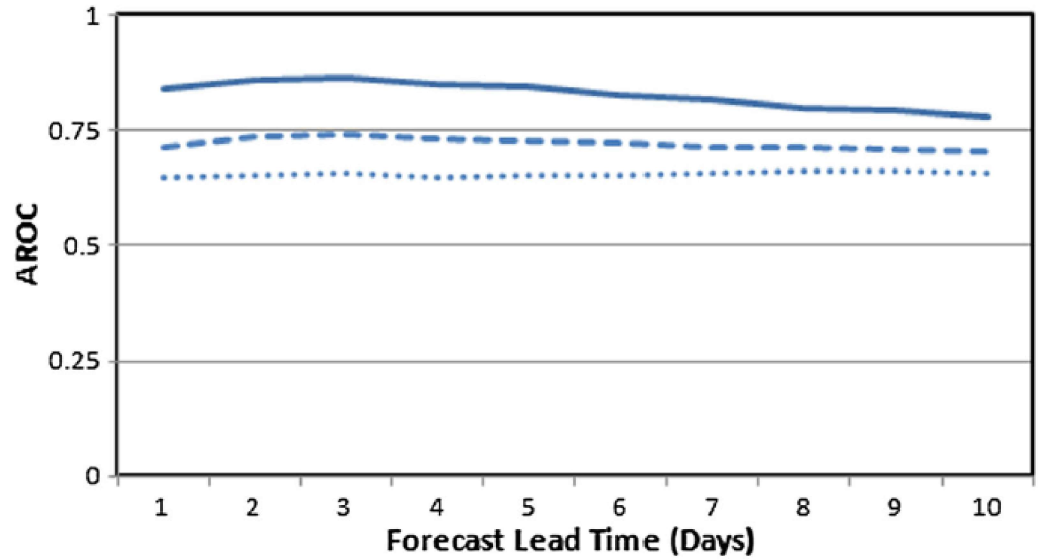


Fig. 2.19. ***Area under the ROC for all regions for a 10 mm/day rainfall thresholds***

b. ***Root mean square error (RMSE) and SPRD (ensemble spread):***

RMS errors of the ensemble mean measure the distance between forecasts and analyses (or observations). SPRD (ensemble spread) is calculated by measuring the deviation of ensemble forecasts from their mean. Fig. 2.1. is an example of a display of RMSEs and ensemble spread (SPRD) for a forecast. Usually, SPRD is defined as:

$$SPRD = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}(\overline{f} - f(n))^2}$$

Where $\overline{f} = \frac{1}{N}\sum_{n=1}^{N} f(n)$ is for the ensemble mean and f is for the ensemble forecast.

In general, an ideal ensemble forecast will be expected to have the same size of ensemble spread as their RMSE at the same lead time in order to represent full forecast uncertainty. But most of the ensemble systems are under dispersed (less spread) for longer lead times due to an imperfect model system (or physical parameterizations) and other things. Therefore, a stochastic process should be introduced to increase ensemble spread for longer lead-time forecasts.

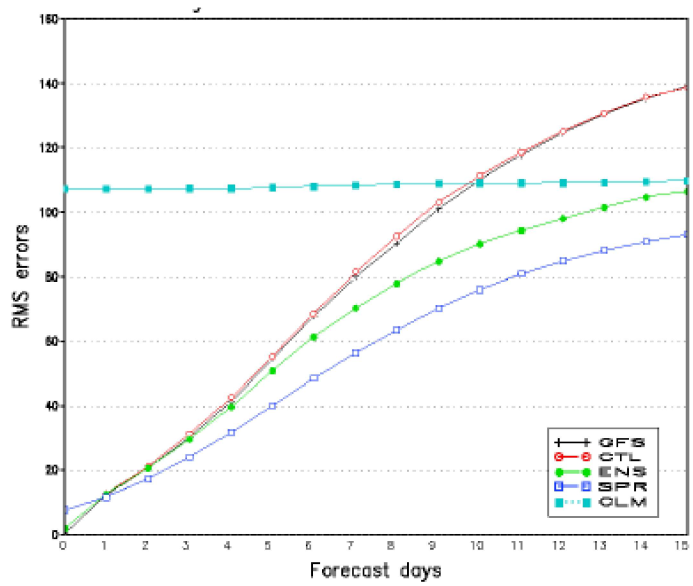


Fig. 2.20. ***RMSE for ensemble mean (blue) and ensemble spread (green) for 500hPa geopotential height, compared to the GFS (black) and ensemble control (CTL, red) RMSEs. The top curve (cyan) is for RMSE of climatology***

Spread-skill evaluation

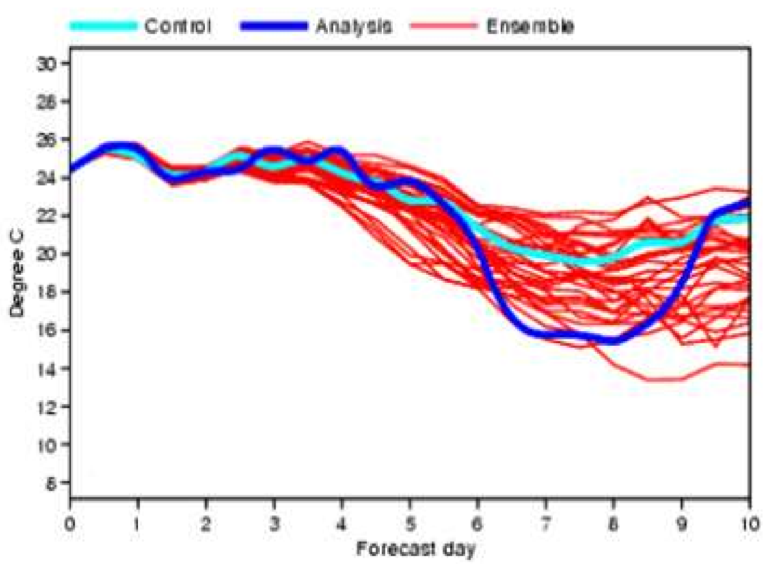


Fig. 2.21. ***Ensemble forecast***

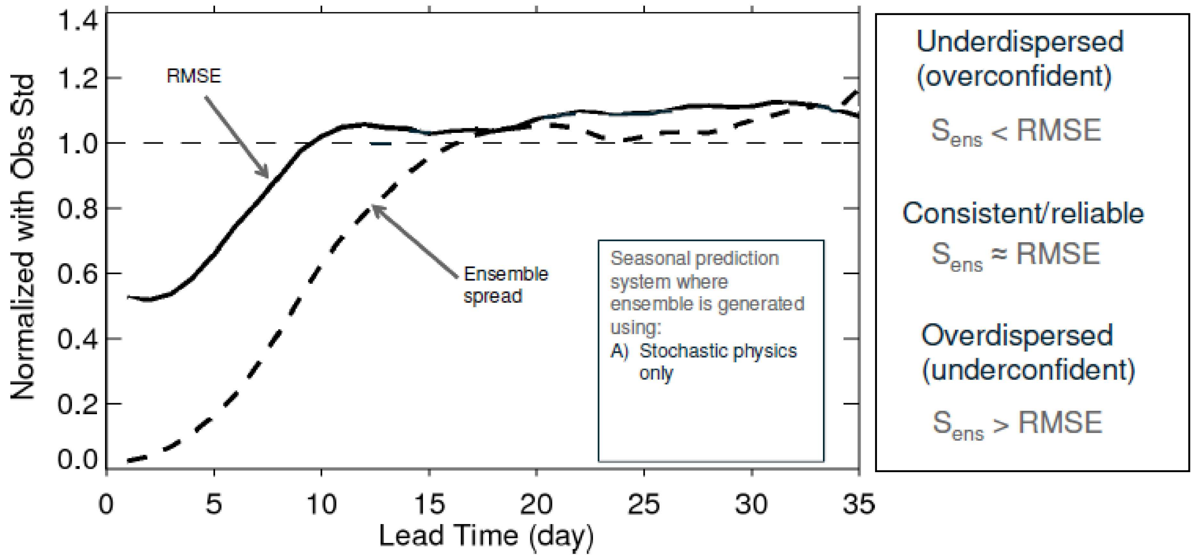


Fig. 2.22. ***Spread-skill diagram***

2.1.6. Reporting guidelines

The QPF verification will be most useful to users if the results are available in a timely fashion via the internet. It will be useful to users (e.g., forecasters) to understand the bias of a model for a rainfall event and in time and space scale.

i) Information about verification

Models included in the verification

For each model: Name and origin, Initialisation time (s) & Spatial resolution of grid

ii) Display of verification results

Graphical products are generally easier to digest than tables full of numbers.

Suggestions for graphical products for various regions are:

a. Plot of scores for multiple models/seasons/rain thresholds as a function of lead time
b. Plot of scores for multiple models/lead times/rain thresholds as a function of season (time series)
c. Plot of scores for multiple models/seasons/lead times as a function of rain threshold
d. POD versus FAR for multiple models as a function of rain threshold/lead times
e. Bar chart of scores as a function of model, lead time, season and rain threshold.
f. Box plot of daily scores as a function of model, lead time, season and rain threshold.

Some examples of graphical verification products (Figs. 2.27 & 2.28) are shown in Annexure-1.

2.2. Verification of surface and upper air parameters from operational NWP models

The plots of bias and RMS error (RMSE) statistics of MSLP, Geopotential height (Z), Temperature (T), and Wind speed (V) forecast may be calculated for different regions (sub-division/gridbox) as per Table 2.2 below. Grid point interpolation to the latitude and longitude of the observation and average over a quasi-homogeneous region may be used.

2.2.1. Geopotential height (Z), Temperature (T), RH, MSLP and Wind speed (V)

For all models, the forecast Geopotential height at 500 hPa, Temperature and RH at 850 hPa, Wind speed at 850 hPa & 200 hPa and MSLP may be verified directly against the observed/analysis values for all forecast hours (24h, 48h, 72h, 96h 120h,). The Table 2.3 may directly follow the map (Fig. 2.16).

2.2.2. Surface Wind Vector BIAS and RMSE

For all models, the forecast 10-m wind may be verified (BIAS and RMSE) directly against the observed/analysis values for all forecast hours (24h, 48h, 72h, 96h, 120h,) for various regions/subdivision using following Table 2.4. Fig. 2.16 may also be plotted for graphical representation.

2.3. Synoptic Verification of NWP products

i) To identify events when genesis of synoptic scale systems such as ridge/trough/circulation/low pressure systems are correctly/incorrectly (false as well as missing) predicted, comparing with actual synoptic charts.
ii) To identify positional error between observed and forecast position of any synoptic system
iii) To write a report every week & month.

2.4. Verification of Tropical cyclone forecast from operational NWP models

Model fields: Tropical cyclone forecast verification consists of three components, (a) Genesis prediction errors, (b) Positional errors, and (c) Intensity prediction errors.

2.4.1. Verification of Genesis prediction

NWP models can predict cyclogenesis 3 to 7 days in advance. Genesis Potential Parameter (GPP) could also predict the potential of a cyclone formation at its early stages of development. Therefore it is important to verify their performances based on success and false alarm rate. The following scores may be calculated based on a categorical contingency Table 2.7 (Annexure 1), similar to rainfall.

a. Probability of detection (POD)
b. False alarm ratio (FAR)
c. Proportion correct (PC)
d. Bias (BIAS)
e. Critical success index (CSI)
f. Heidke skill score (HSS)

2.4.2. Verification of positional errors

The direct positional error (DPE) calculated for each model analysis and forecast will give an indication of how well a TC track was forecast, but gives no information as to whether the forecast errors were resulting from a slow or fast bias in the forecast track. In addition, the DPE value alone may not always indicate the skill of the model in forecasting a TC, since in some tropical areas TC tracks are more predictable than in others and individual TCs which take a 'straight-running' track should be easier to forecast than those which take more complex tracks. In order to assess some of these forecast track characteristics a number of other statistics are produced by the verification scheme.

Forecast errors in the east-west and north-south directions can be easily determined from the forecast and observed positions of a TC and are known as the DX and DY errors. However, it is often more useful to know the components of error both along the observed track of the TC and perpendicular to the track.

These errors are known as the along-track (AT) and cross-track (CT) errors. AT errors give an indication of whether a forecast of TC movement is too slow or fast and CT errors can be used to determine whether the model tends to recurve a TC too soon or fail to recurve it soon enough. A diagrammatic explanation of these errors can be found in Fig. 2.24 (Jullian Hemming, 1994. Tropical cyclone forecast verification method. ***NWP Gazette***, Vol.1, No.2, pp2-8).

Table 2.2.

Bias and RMSE of above mentioned parameters

VARIABLE	24-H FCST	48-H FCST	72H FCST	96H FCST	120-H FCST	144-H FCST	168-H FCST
MSLP BIAS and RMSE							
500 mb Height BIAS and RMSE							
850 mb Temperature BIAS and RMSE							
850 mb RH BIAS and RMSE							
850 mb Wind Speed BIAS and RMSE							
200 mb Wind Speed BIAS and Vector Wind RMSE							

Table 2.3.

Bias and RMSE of 10-m wind

REGION	TYPE OF ERROR	VALID AT 24h	VALID AT 48h	VALID AT 72h	VALID AT 96h	VALID AT 120h	VALID AT 144h	VALID AT 168h
	BIAS - RMSE -							

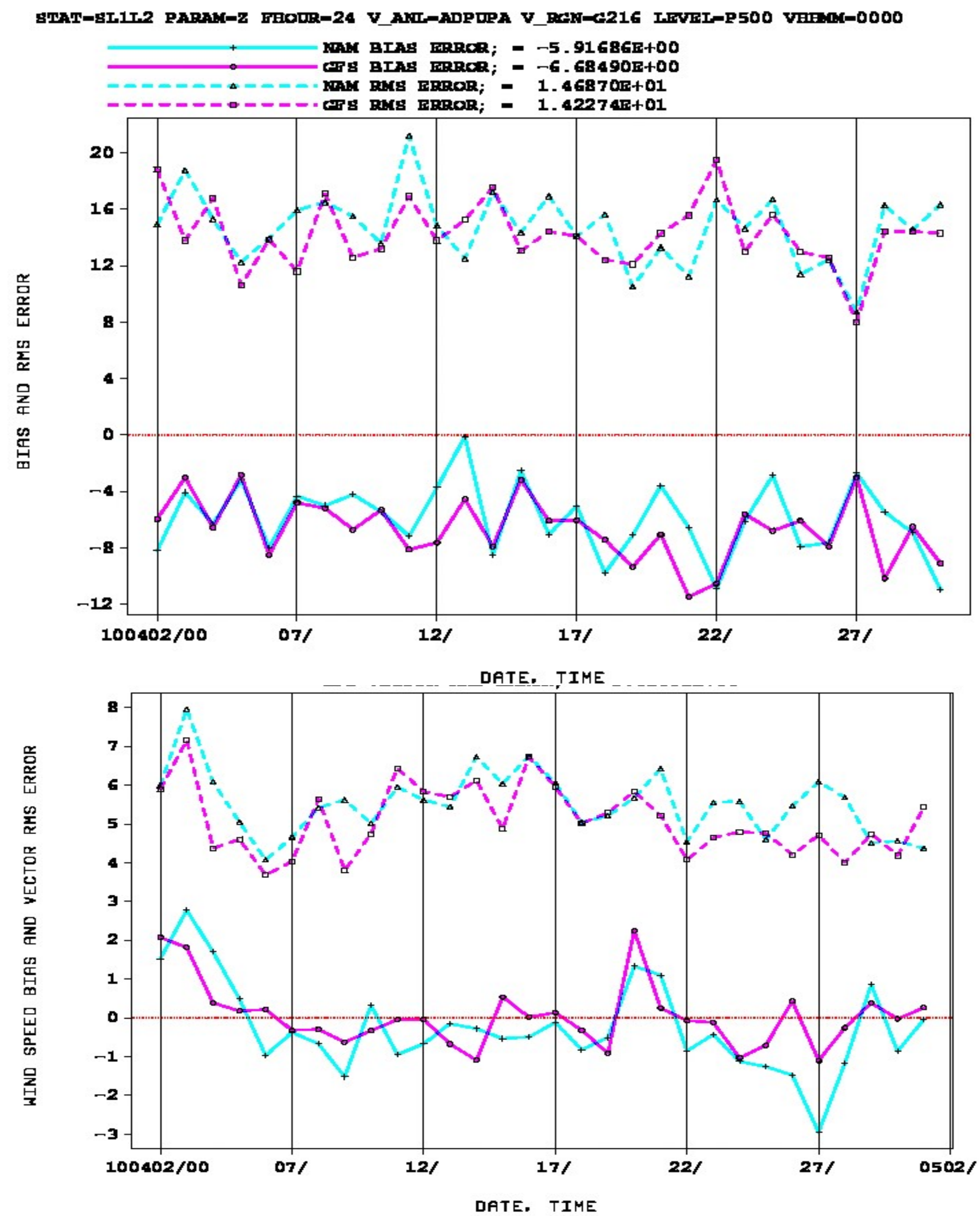


Fig. 2.23. *Time series of Bias and RMSE of 10-m wind*

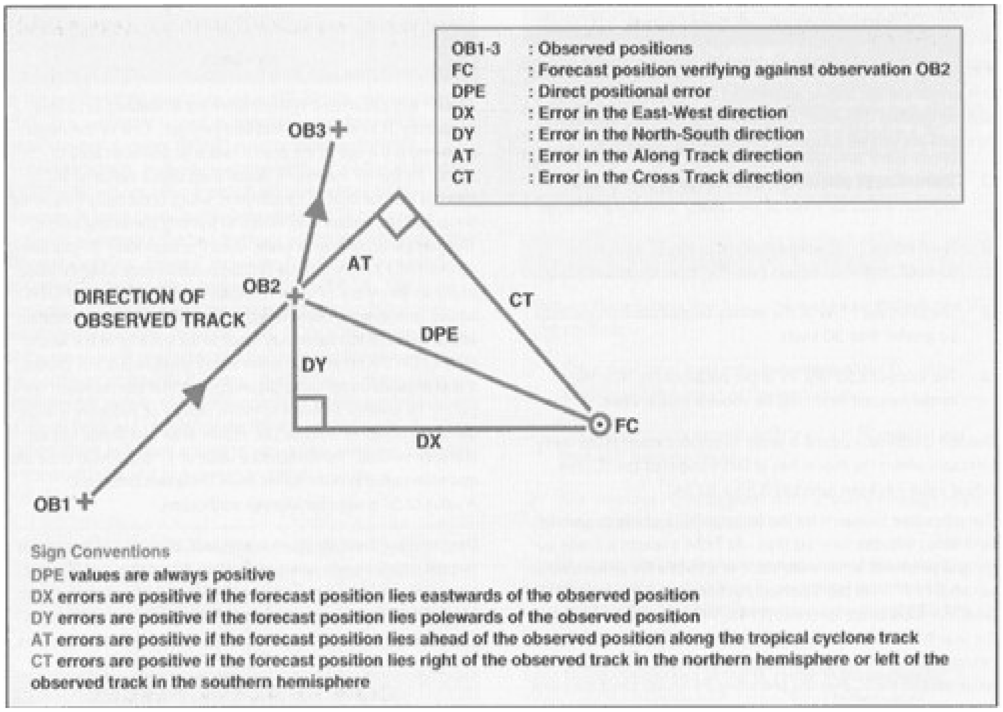


Fig. 2.24. ***Diagrammatic explanation of forecast errors***
(available at http://www.metoffice.gov.uk/weather/tropicalcyclone/method)

AT and CT errors need to be examined together since a negative AT value could indicate a slow bias in forecasts if CT values were not large, but may be associated with a large left- or right-of-track bias if CT values were large. The DP, AT, and CT are related as $DP^2=AT^2+CT^2$.

Several meteorological centres who monitor TCs have developed models which forecast the tracks of TCs up to three days ahead using methods based on past climatology in the area and persistence. These are known as CLIPER models and are generally accepted as a benchmark against which NWP models can be assessed. The Met Office has obtained CLIPER software for all TC basins which has been incorporated into the TC verification scheme. Hence, for each NWP model analysis and forecast which is verified, the equivalent CLIPER forecast is also verified. Values of CLIPER DPE are calculated and if the NWP model values are smaller the model is said to show skill over CLIPER. Skill is defined as a percentage value from the following formula:

(CLIPER DPE - Model DPE)/CLIPER DPE × 100%

Positive skill indicates the model forecast is better than CLIPER. Negative skill indicates the CLIPER forecast is better than the model. Most CLIPER software requires the knowledge of the position of a TC 12 and 24 hours before the analysis time. Hence CLIPER statistics cannot be calculated for the first two forecasts of a storm's life.

The verification system also includes the facility to produce mean statistics for all the parameters above. Mean statistics can be produced for individual storms, a selection of storms, storms grouped by basin or all storms in a year.

Track prediction error at 12h interval may be made as per following Table 2.4.

Table 2.4

Mean track forecast error (DPE, AT, CT) for TC of 2010

Hr	ECMWF	NCEP-GFS	JMA	IMD-GFS	UKMO	WRF	HWRF	MME
12								
24								
36								
48								
60								
72								
84								
96								
108								
120								

Landfall prediction error will be made as per following Table 2.5.

Table 2.5

Landfall position and time error (tt hours before landfall); E=early, D=delay

Cyclone	Lead Time (Hr)	ECMWF		NCEP-GFS		JMA		IMD-GFS		HWRF		MME	
		Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)
MEAN	**-**												

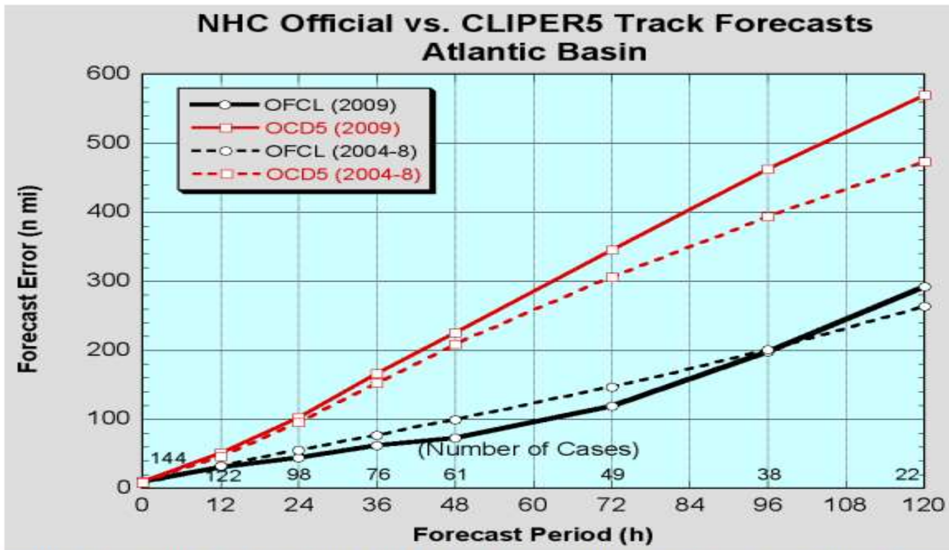
Intensity prediction error at 12h interval may be made as per following Table 2.6.

Table 2.6

Intensity prediction error

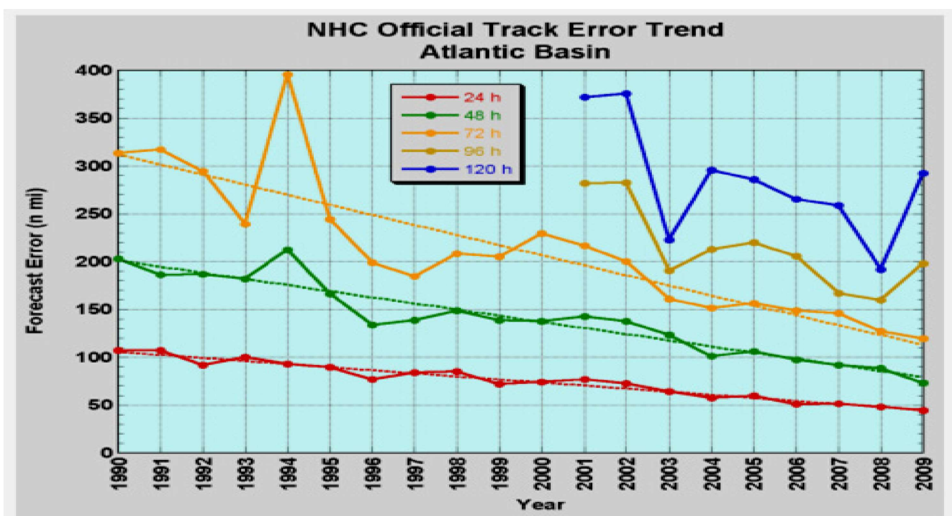
Forecasts hours →			12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
S. No.	TC	Based on date										
Mean absolute error (MAE) (knots)→												

Following type of products (Fig. 2.18) of National Hurricane Center, NOAA may be prepared to present track forecast errors for the North Indian Ocean.



NHC official and CLIPER5 (OCD5) Atlantic basin average track errors for 2009 (solid lines) and 2004-2008 (dashed lines).

(a)

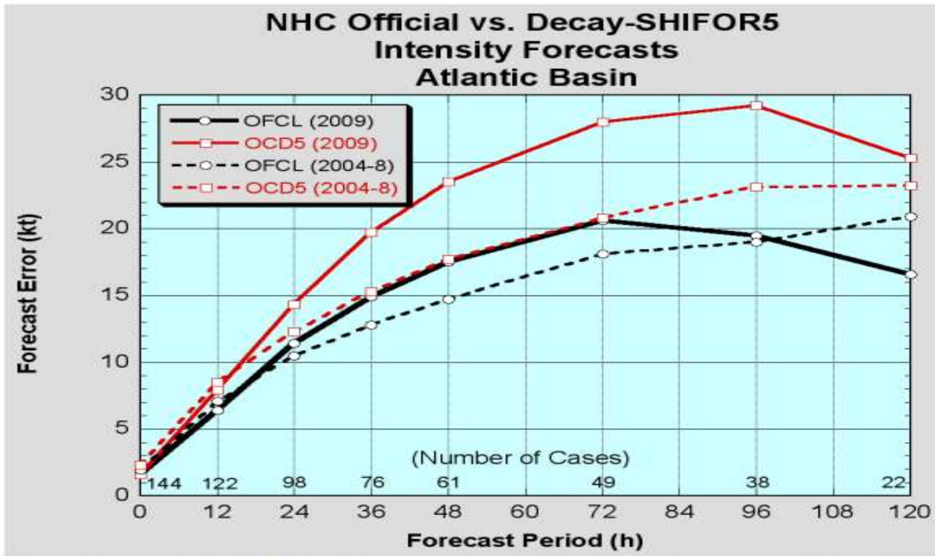


(b)

Fig. 2.25. ***(a) Track forecast errors; (b) Yearly variation of track forecast errors***
(available at http://www.nhc.noaa.gov/verification/verify5.shtml)

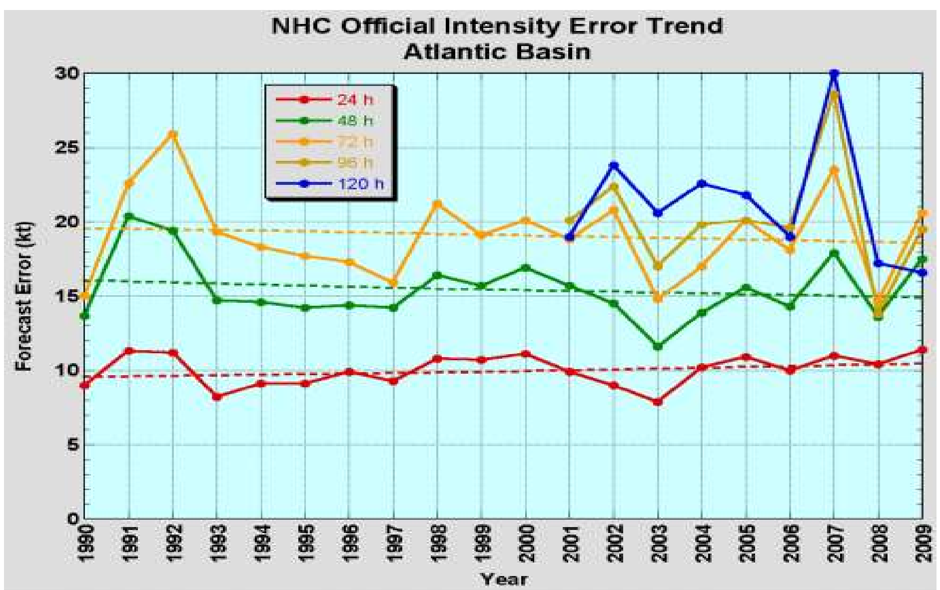
2.4.3. Verification of Intensity errors

Following type of products (Fig. 2.19) may be prepared to present intensity forecast errors for the North Indian Ocean.



NHC official and Decay-SHIFOR5 (OCD5) Atlantic basin average intensity errors for 2009 (solid lines) and 2004-2008 (dashed lines).

(a)



(b)

Fig. 2.26. ***(a) Intensity forecast errors (b) Yearly variation of intensity forecast errors.***
(available at http://www.nhc.noaa.gov/verification/verify5.shtml)

2.5. Proposal

We propose :

i) A separate forecast verification cell in each forecasting unit and NWP division
ii) Verification against climatology and persistency
iii) Monthly weather report
iv) Seasonal report
v) Display of all forecasts performance on IMD website

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http://www.nhc.noaa.gov/verification/

http://www.nhc.noaa.gov/verification/verify5.shtml

http://www.metoffice.gov.uk/weather/tropicalcyclone/method

ANNEXURE – 2.1

SCORES DESCRIPTION

Forecast of rain meeting or exceeding specified thresholds The following scores are based on a categorical contingency table whereby an event ("yes") is defined by rainfall greater than or equal to the specified threshold; otherwise it is a non-event ("no"). The joint distribution of observed and forecast events and non-events is shown by the categorical contingency table, as represented in Table 2.7.

Table 2.7

Categorical contingency table

	Yes	**No**	
Yes Forecast	*Hits (H)*	*false alarms (F)*	***Forecast yes***
no	*Misses (M)*	*correct rejections (Z)*	***Forecast no***

observed yes ***observed no*** ***N= total***

The frequency bias:

BIAS = (H+F)/(H+M), ratio of the yes forecast frequency to the yes observation frequency.

The proportion of correct (PC):

PC = (H+Z)/N, gives the fraction of all the forecasts that were correct. Usually it is very misleading because it credits correct "yes" and "no" forecasts equally and it is strongly influenced by the more common category (typically the "no" event).

The probability of detection (POD):

POD=H/(H+M), also known as Hit Rate (HR), measures the fraction of observed events that were correctly forecast.

The false alarm ratio (FAR):

FAR=F/(H+F), gives the fraction of forecast events that were observed to be non events.

The probability of false detection (POFD):

POFD=F/(Z+F), also known as the false alarm rate, measures the fraction of false alarms given the event did not occur.

The Threat score (TS):

TS = H/(H+M+F), also known as critical success index and hit rate, gives the fraction of all events forecast and/or observed that were correctly diagnosed. Its range is 0 to 1, with a value of 1 indicating a perfect forecast. The TS is relatively frequently used, with good reason. Unlike the POD and the FAR, it takes into account both false alarms and missed events, and is therefore a more balanced score. The TS is somewhat sensitive to the climatology of the event, tending to give poorer scores for rare events. A related score, the Equitable Threat Score is designed to help offset this tendency.

Equitable Threat Score (ETS):

Event Forecast	Event observed		
	Yes	No	Marginal total
Yes	a	b	a + b
No	c	d	c + d
Marginal total	a + c	b + d	a + b + c + d = n

The ETS is given by:

ETS = $(a - a_r) / (a + b + c - a_r)$, where $a_r = (a + b)(a + c) / n$

ETS = (hits - hits expected by chance) / (hits + false alarms + misses – hits expected by chance)
a_r = (total forecasts of the event) * (total observations of the event) / (sample size)

Forecasts of rain amounts:

In the expressions to follow F_i indicates the forecast value for point or grid box, O_i indicates the observed value, and N is the number of samples.

$$\overline{O} = \frac{1}{N}\sum_{i=1}^{N} O_i \qquad \overline{F} = \frac{1}{N}\sum_{i=1}^{N} F_i$$

Another descriptive statistic, the sample *variance (s^2)* describes the rainfall variability

$$s_O^2 = \frac{1}{N-1}\sum_{i=1}^{N}(O_i - \overline{O})^2 \qquad s_F^2 = \frac{1}{N-1}\sum_{i=1}^{N}(F_i - \overline{F})^2$$

The sample standard deviation (s) is equal to the square root of the sample variance, and provides a variability measure in the same units as the quantity being characterized.

$$s_O = \sqrt{s_O^2} \qquad s_F = \sqrt{s_F^2}$$

The *mean error (ME)* measures the average difference between the forecast and observed values.

$$ME = \frac{1}{N}\sum_{i=1}^{N}(F_i - O_i) = \overline{F} - \overline{O}$$

The *mean absolute error (MAE)* measures the average magnitude of the error

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|F_i - O_i|$$

The *mean square error (MSE)* measures the average squared error magnitude, and is often used in the construction of skill scores. Large error carry more weight.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)^2$$

The *root mean square error (RMSE)* measures the average squared error magnitude but gives greater weight to the larger errors.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)^2}$$

The *(product moment) correlation coefficient (r)* measures the degree of linear association between the forecast and observed values, independent of absolute or conditional bias. As this score is highly sensitive to large errors it benefits from the square root transformation of the rain amounts.

$$r = \frac{\sum_{i=1}^{N}(F_i - \bar{F})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N}(F_i - \bar{F})^2}\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}} = \frac{s_{FO}}{s_F s_O}$$

Following Figures (Fig. 2.27 & 2.28) may be plotted for Indian region. POD vs FAR can be plotted by computing POD and FAR using formula as give in Annexure-1 for different threshold rainfall amounts as mentioned in Section 1.2 for various models. The BOX plot can be made by computing RMSE for 5th, 25th, 75th, 95th percentile and Median of number of forecasts (e.g. 120 days forecasts for Monsoon season) for different forecasts hours and different models.

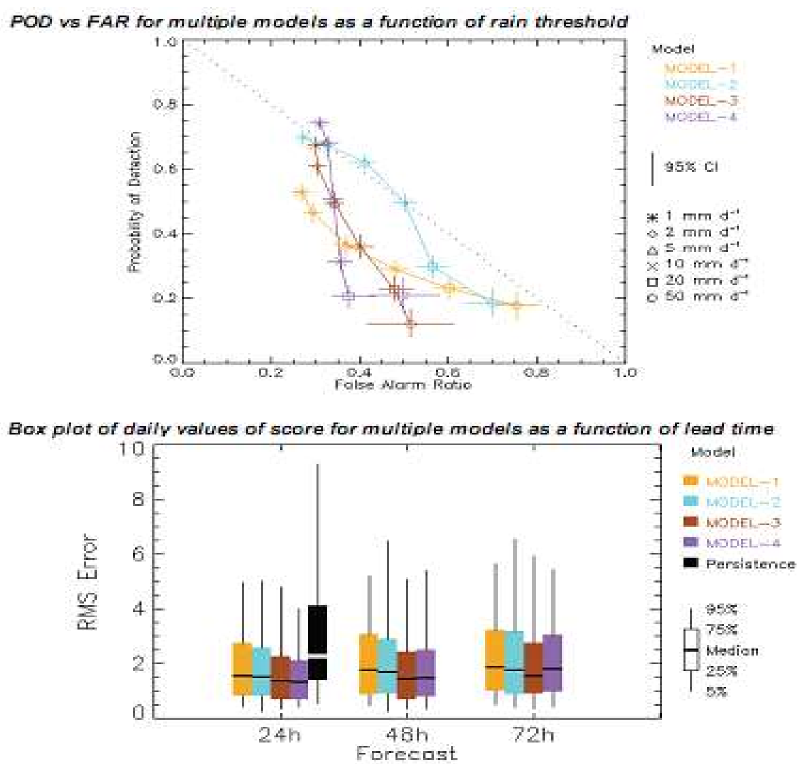
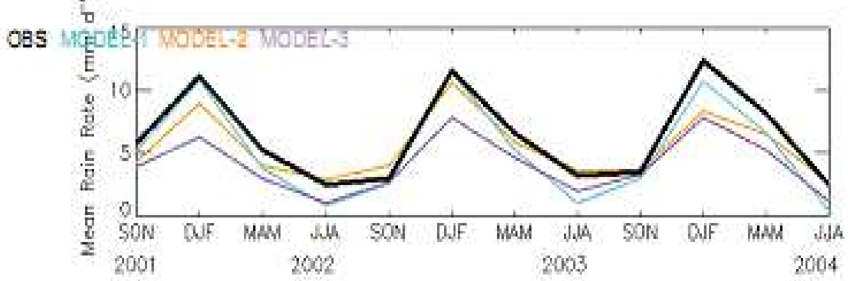


Fig. 2.27. ***(Ref: Recommendations for the Verification and Intercomparison of QPFs and PQPFs from Operational NWP Models-WWRP2009-1, WMO/TD-No. 1485)***

Seasonal time series of forecast and observed mean rainfall



Scatter plot of forecast versus observed rainfall. The dashed line shows the best fit to the data when normalized using a square root transformation

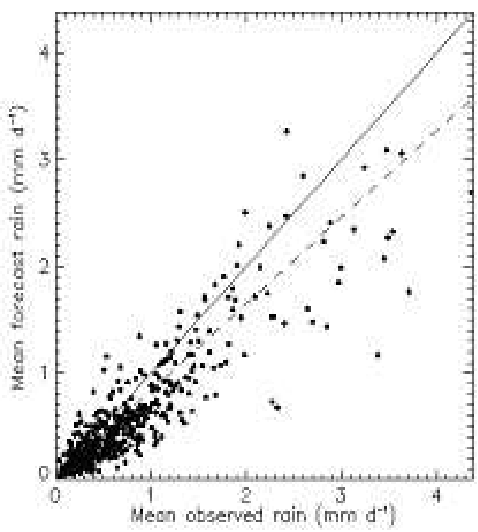
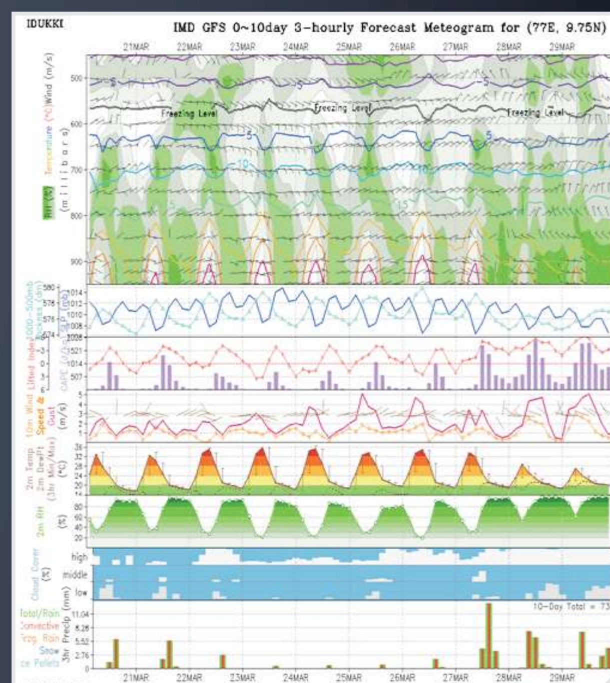


Fig. 2.28. ***(Ref: Recommendations for the Verification and Intercomparison of QPFs and PQPFs from Operational NWP Models-WWRP2009-1, WMO/TD-No. 1485)***

For further details, write to us or visit

Email : **nwp@imd.gov.in; nwp.imd@gmail.com**
Website : **https://nwp.imd.gov.in**



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