Performance of high resolution ensemble prediction system (GEFS at T1534~12.5 km) over Indian region

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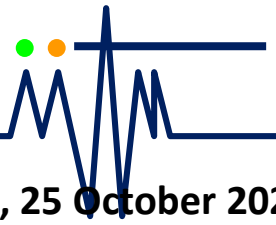
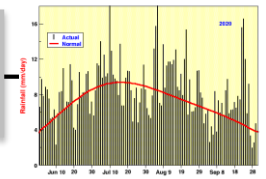


Outline

- **About the GEFS (12km) Modeling System**
- **GFS/GEFS based products**
- **Current status of ensemble forecasting for high impact weather (Cases)**
- **Summary**

Models for earth system relevant processes

Short range
1 km, 48 h
TS
Medium range
12 km, 240 h
Extended range
100, 38 km. 4 wk
Seasonal range
38 km, 10 mons
Decade & Climate
200 km, multi yr



Cumulus clouds

Renewable

TCs, MDs

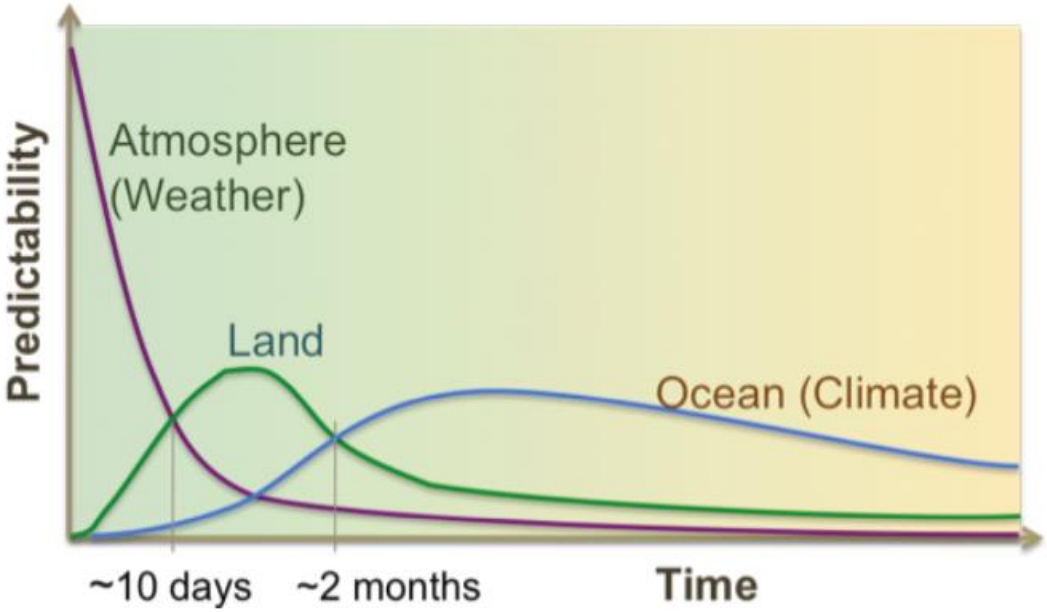
LES Model, DNS

Cloud System Resolving Model (CSRM)
WRF

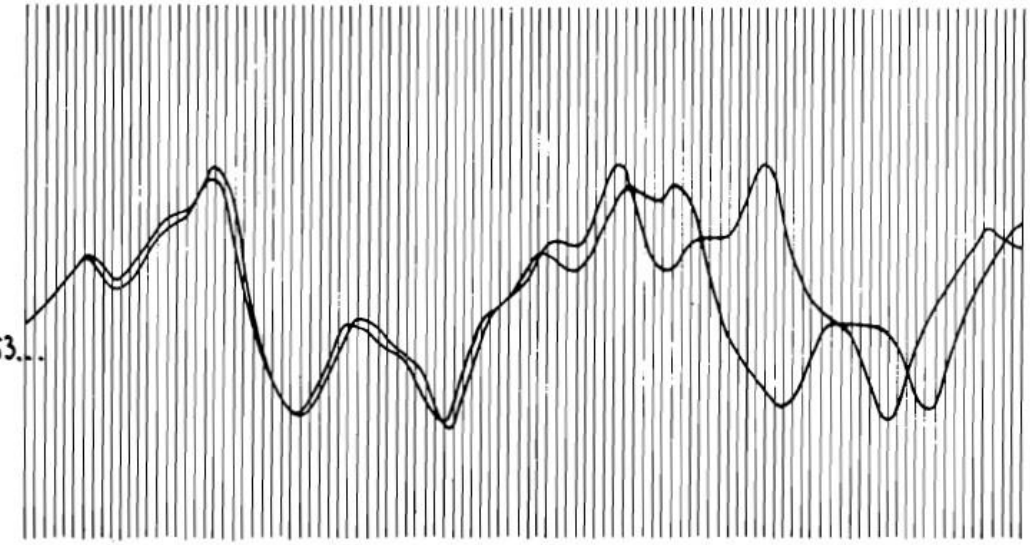
GFS/GEFS GFS/CFS CFS
T1534. 21EM T126/T382 T382

Numerical Weather Prediction (NWP) Model

Global Climate Model



Dirmeyer et al. 2015



HOW TWO WEATHER PATTERNS DIVERGE. From nearly the same starting point, Edward Lorenz saw his computer weather produce patterns that grew farther and farther apart until all resemblance disappeared. (From Lorenz's 1961 printouts.)

Ed. Lorenz
(1917-2008)

APPENDIX 1

The Butterfly Effect

THE FOLLOWING is the text of a talk that I presented in a session devoted to the Global Atmospheric Research Program, at the 139th meeting of the American Association for the Advancement of Science, in Washington, D.C., on December 29, 1972, as prepared for press release. It was never published, and it is presented here in its original form.

Predictability: Does the Flap of a Butterfly's Wings in Brazil Set off a Tornado in Texas?

$$\frac{dx}{dt} = \sigma(y - x)$$

$$\frac{dy}{dt} = x(\rho - z) - y$$

$$\frac{dz}{dt} = xy - \beta z$$

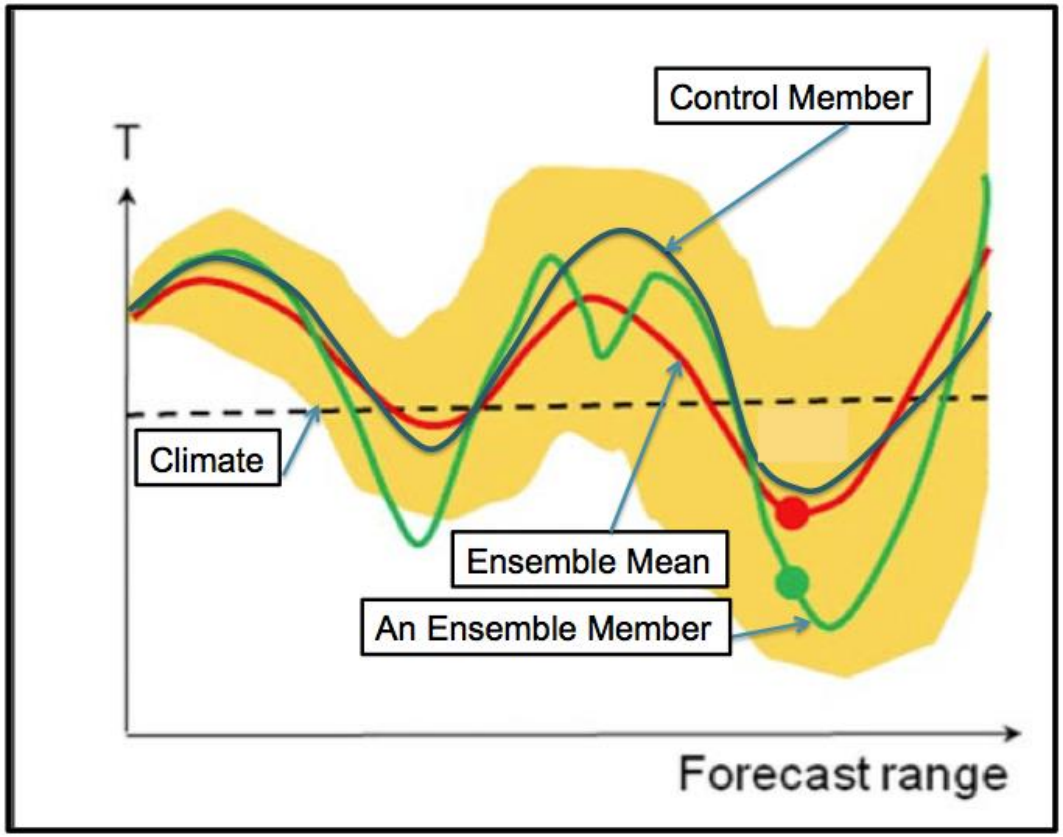
Lorenz's Equation

Lorenz showed that the atmosphere has a finite limit of predictability

Lorenz Attractor:Buterfly effect

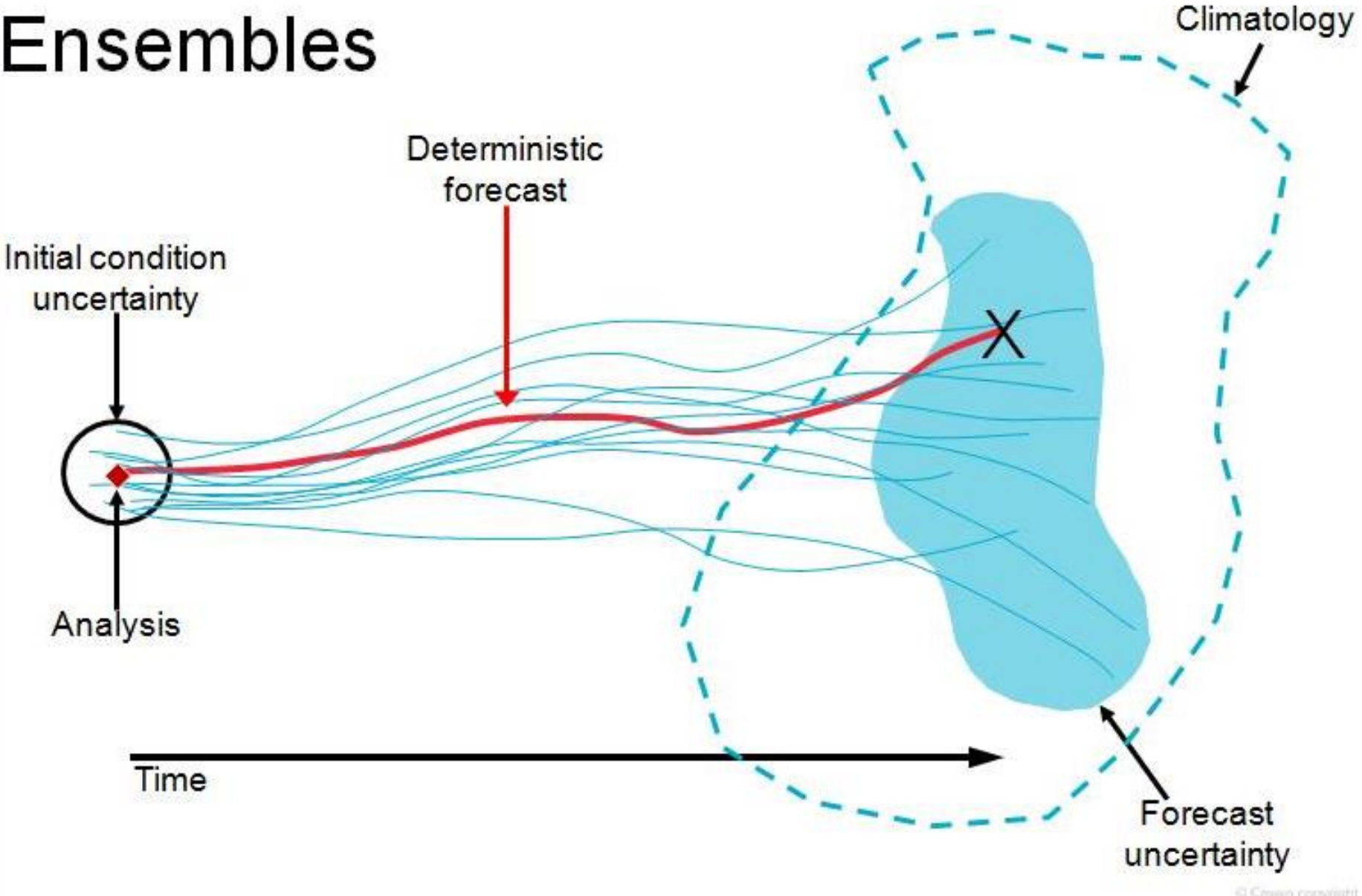
What is an ensemble forecast?

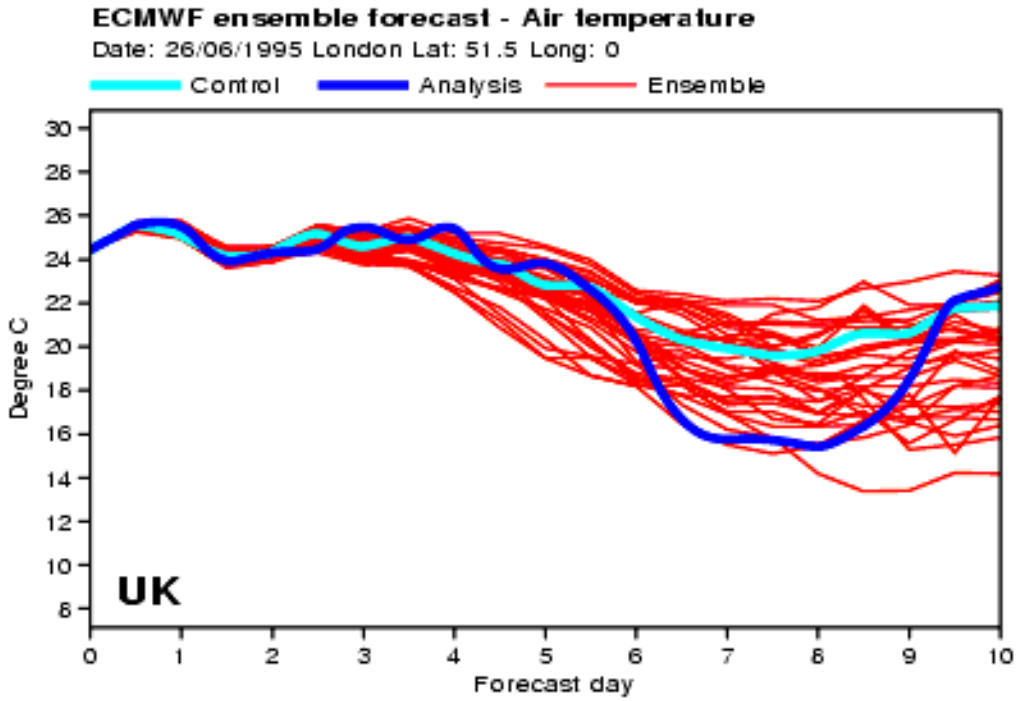
- An ensemble weather forecast is a set of forecasts that present the range of future weather possibilities.
- Multiple simulations are run, each with a slight variation of its initial conditions and with slightly perturbed weather models. These variations represent the inevitable uncertainty in the initial conditions and approximations in the models. They produce a range of possible weather conditions.
- The uncertainty associated with every forecast means that different scenarios are possible, and the forecast should reflect that. Single 'deterministic' forecasts can be misleading as they fail to provide this information.

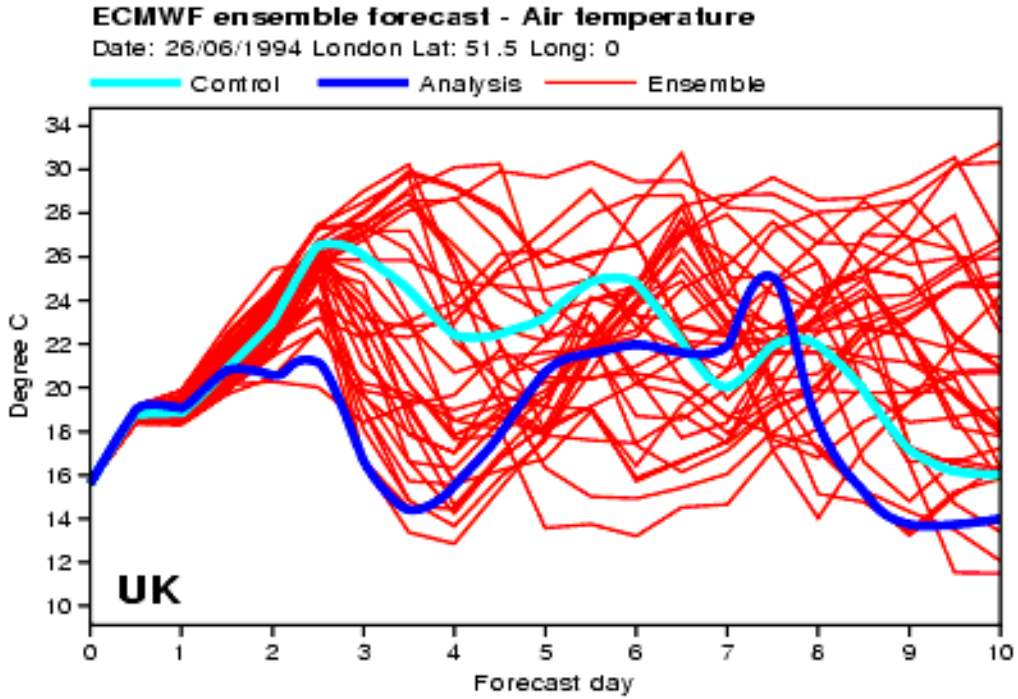


GEFS has 20 ensemble members with 1 Control

Ensembles







Example of error growth

Flowchart of GEFS

GDAS

EnKF – GSI Hybrid Data Assimilation System

Analysis (Control)

Ensemble Initialization method: Ensemble Kalman Filter (EnKF) scheme.

The 6-hr forecasts from the previous cycle

20 Perturbed members

Tropical Storm Relocation (if storm is present)

Centering of the perturbations on the ensemble control analysis (Distributes the spread around analysis instead of Ensemble Mean

FORECAST: 21 members runs for 192 hrs (8 days) GFS Semi-Lagrangian T1534 (approx 12 km at equator); L64 vertical resolution.

The stochastic total tendency perturbation (STTP) to enhance model uncertainty

POST PROCESSING

240 hr (10 days) forecast

Resolution: 0.125°x0.125°

6 hr interval

Products: 21 members, Ensemble mean, Ensemble Spread

The GEFS is running operationally on Mihir HPCS at NCMRWF

The 21 member ensemble forecast takes nearly 90 minutes on 483 nodes

Plus, about 75 minutes for pre and post processing thus total of approximately 165 Minutes

The Global (Ensemble) Forecast Model

Flowchart of deterministic GFS

GDAS

EnKF – GSI Hybrid Data Assimilation System

Analysis(Control)

FORECAST: GFS Semi-Lagrangian T1534 (approx 12 km at equator) L64 vertical resolution, runs for 240 hrs (10 days)

POST PROCESSING

240hr (10 days) forecast

Resolution: Regular grid and Gaussian grid at different resolutions

0.125°x0.125°

About GEFS and GFS Model physics

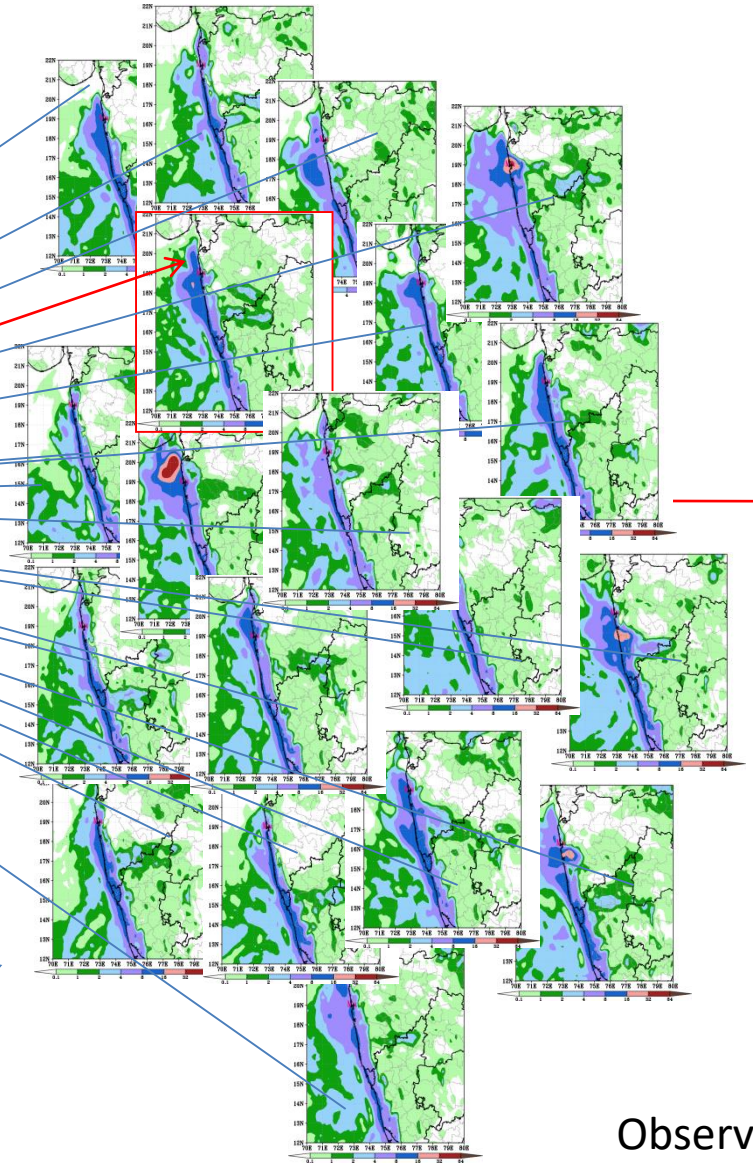
Physics	Description
Convection	Revised Scale Aware Simplified Arakawa-Schubert (RSAS) and mass flux based SAS shallow convection scheme
Microphysics	Zhao-Carr-Moorthi microphysics formulation for grid-scale condensation and precipitation
Gravity Wave Drag	Orographic gravity wave drag, mountain-drag and stationary convective gravity wave drag
PBL	Hybrid Eddy Diffusion Mass flux turbulence/vertical diffusion scheme
Radiation	Solar radiation and IR based on RRTM (originally from AER, modified at EMC) with Monte Carlo Independent Column Approximation (McICA). Cloud fraction for radiation computed diagnostically from prognostic cloud condensate

IC 7 June 2018 00Z: forecast valid for 10 June 2018 00Z (+72h forecast)

Control run shown as →

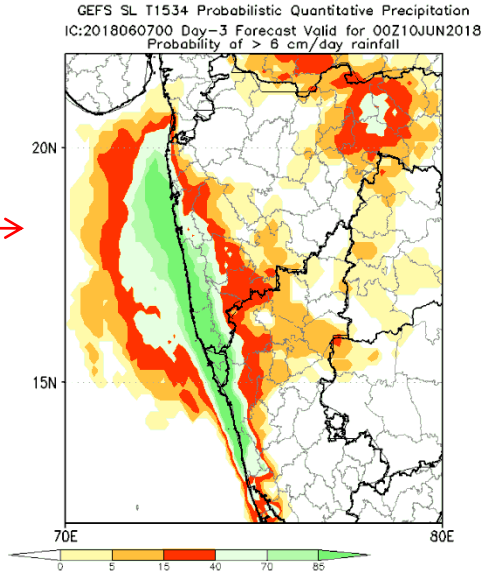
Initial Condition

Analysis

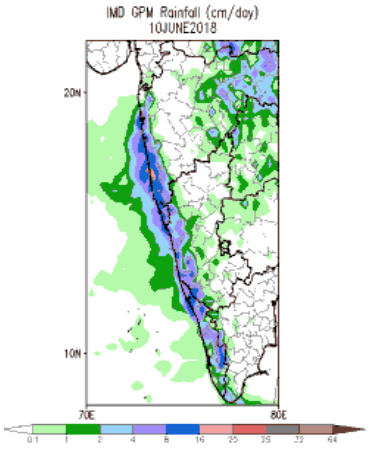


Forecast Uncertainty of different ensemble members which is addressed by computing probability over a certain threshold

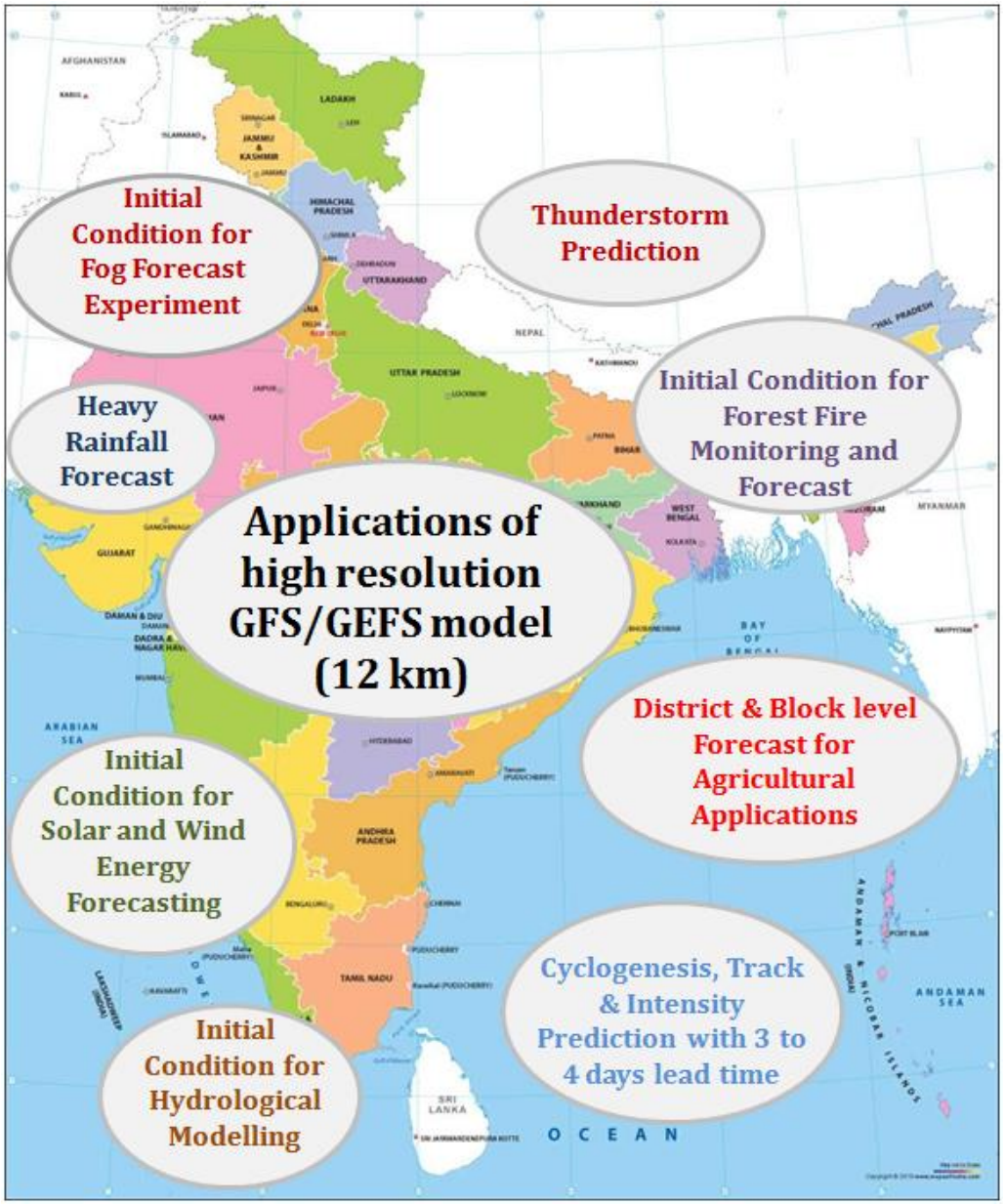
Probability of Rainfall > 6 cm/day

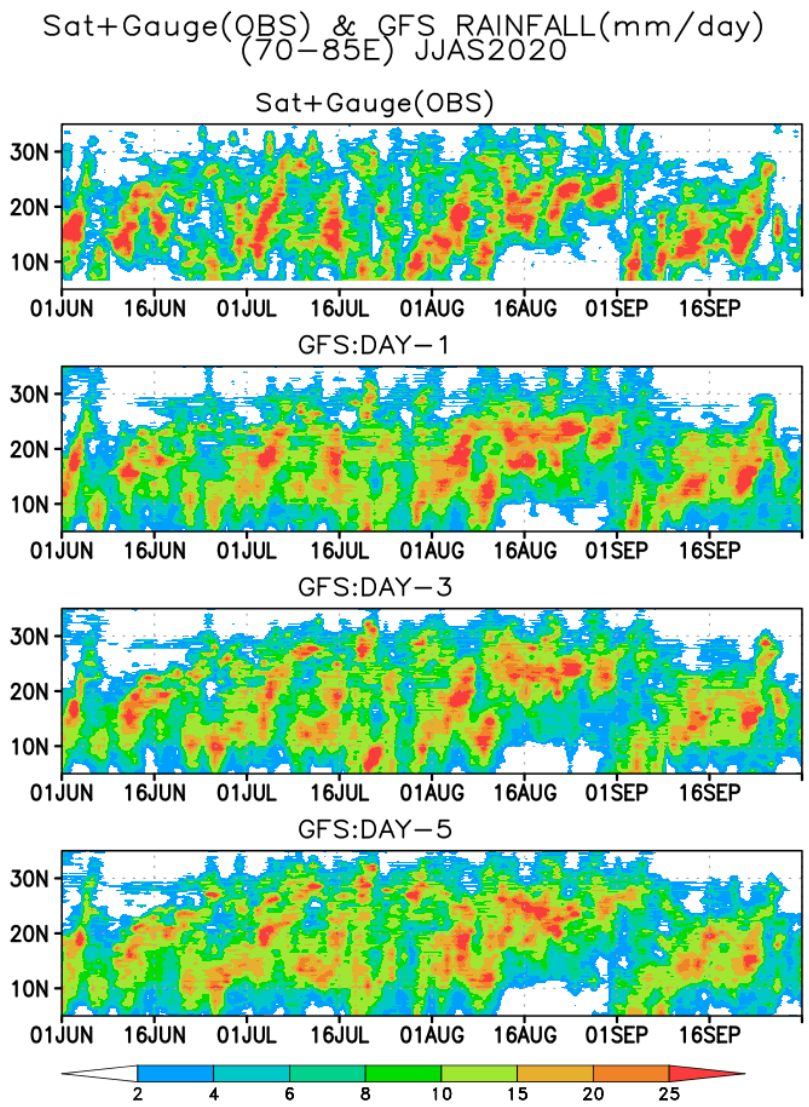


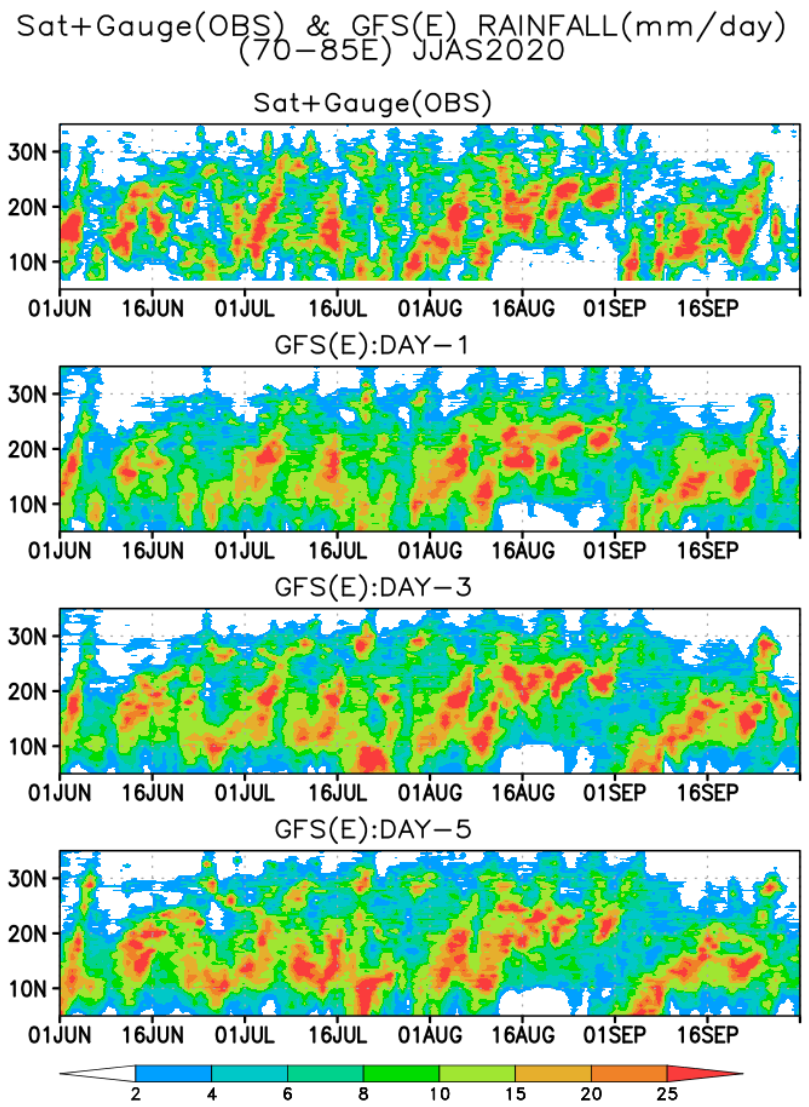
Observed Rainfall



Application of GFS/GEFS products over Indian region

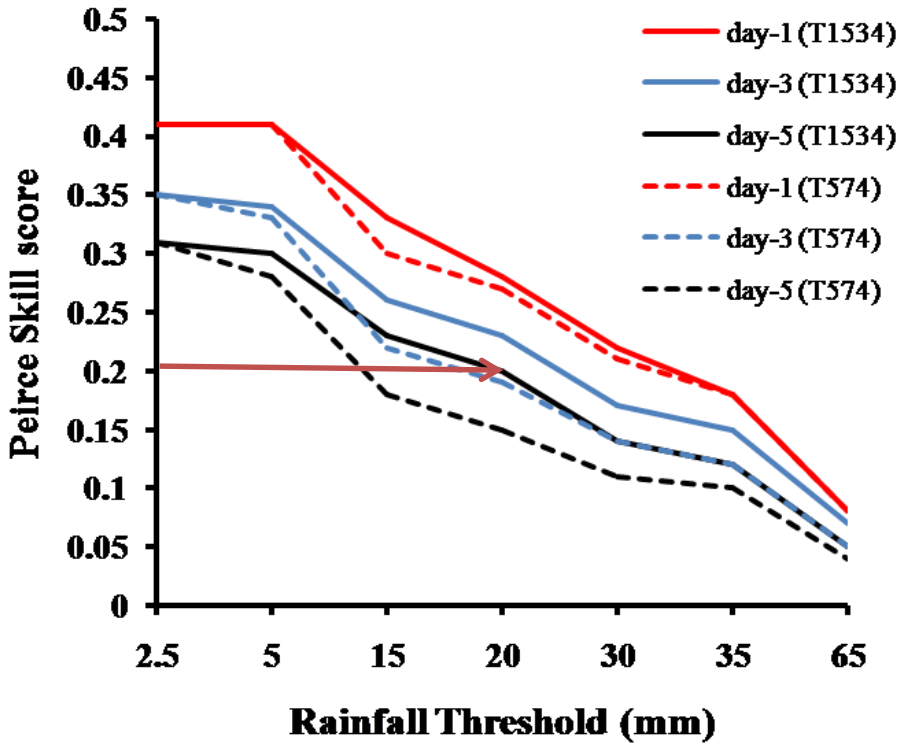




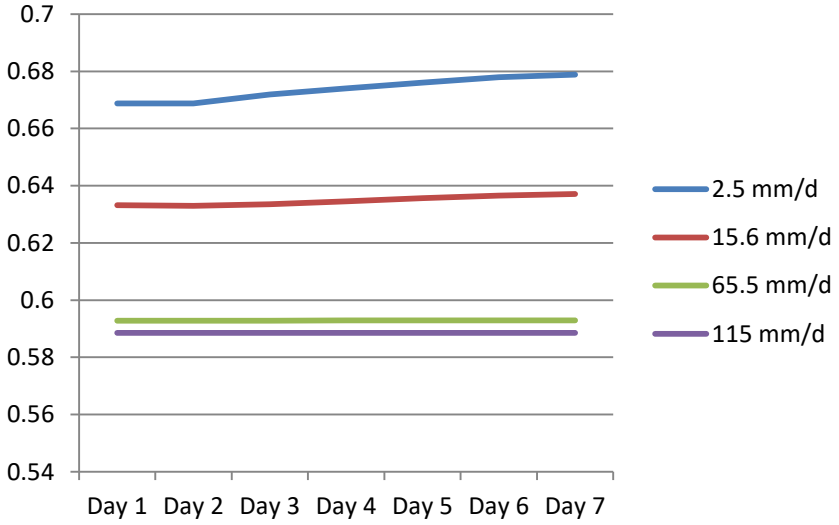


Slide Courtesy: Dr. Raghu

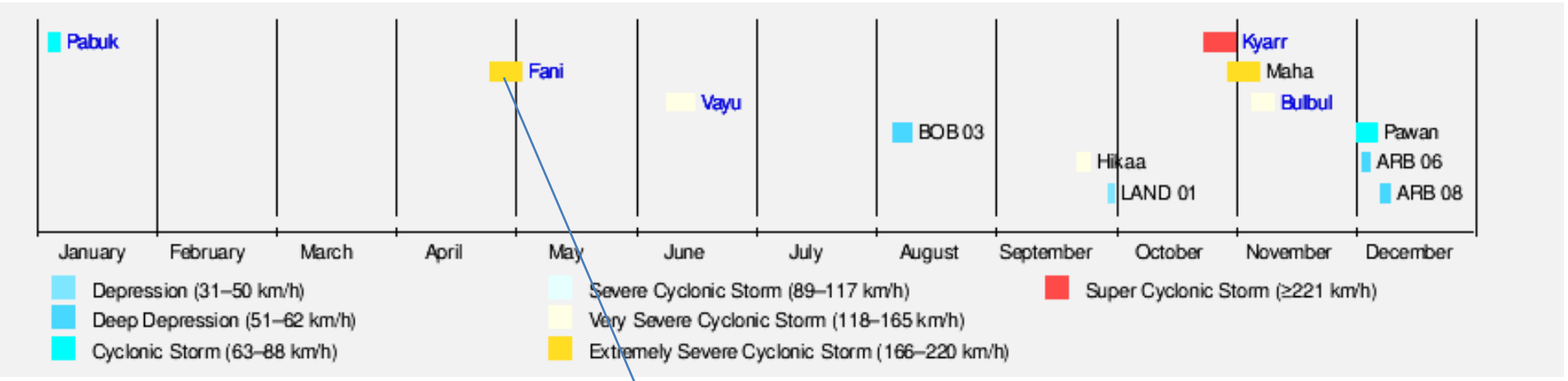
Peirce Skill Score (High Resolution global 12.5 km model gives better skill (The skill of GFS T574 with 3 day lead is now extended to 5 days with T1534 ~12.5 km global GFS

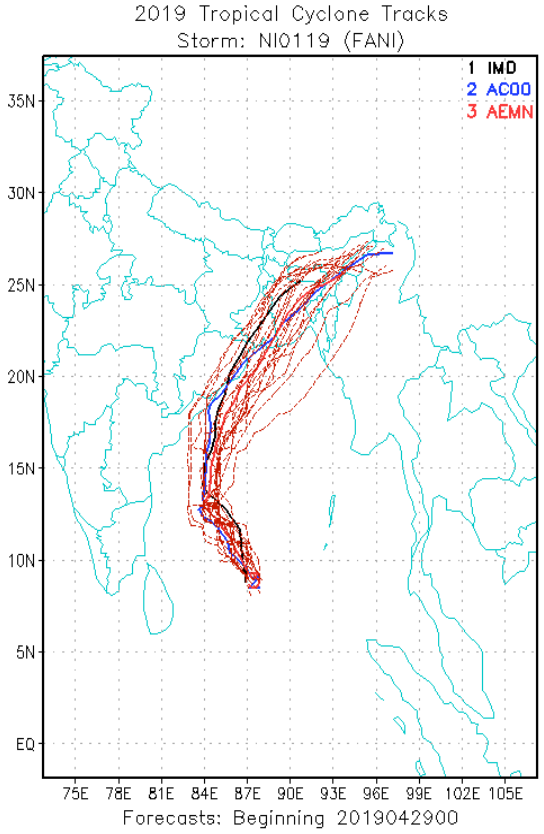


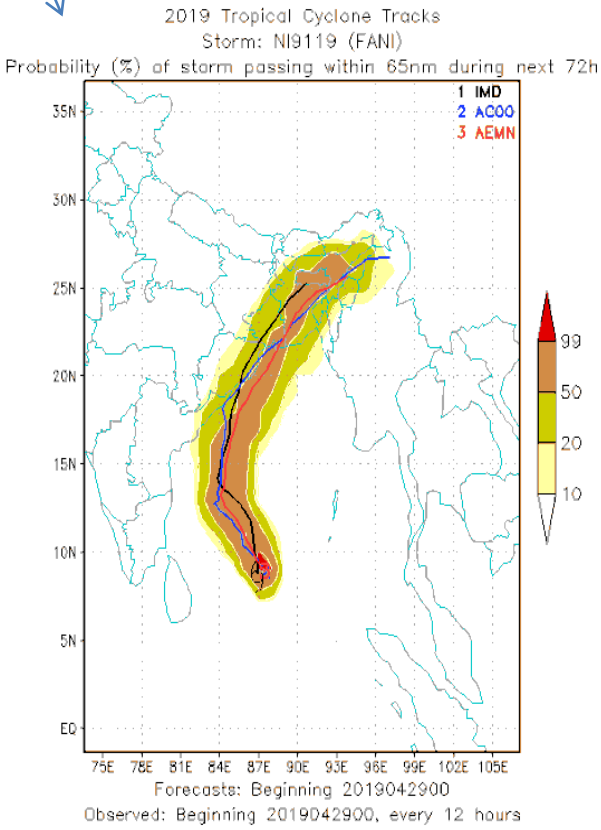
Brier Score GEFS 2018-2020 JJAS



Rao et al. 2019, BAMS







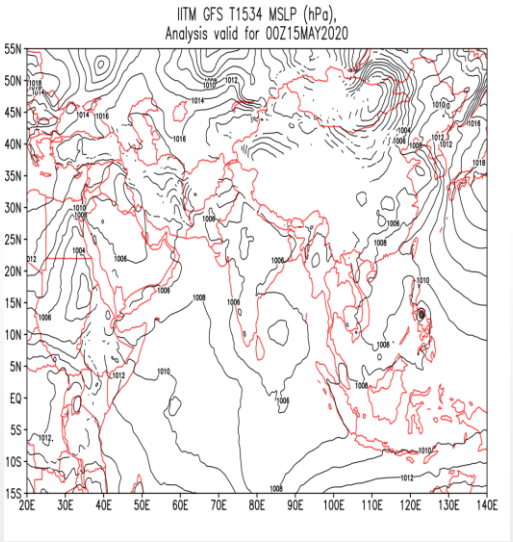
IMD - Observation

AC00 - control run

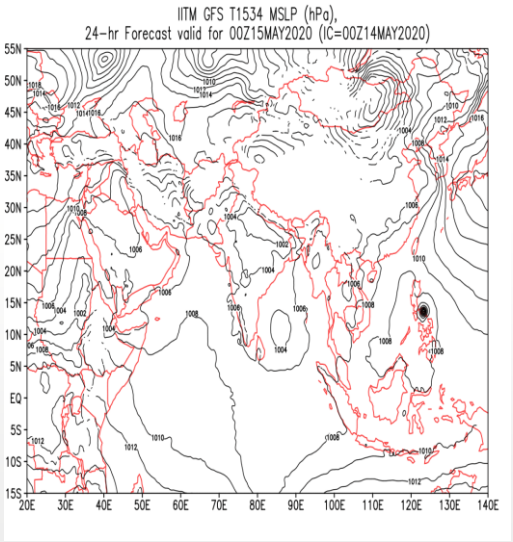
AEMN-Ensemble Mean

---- Ensemble members

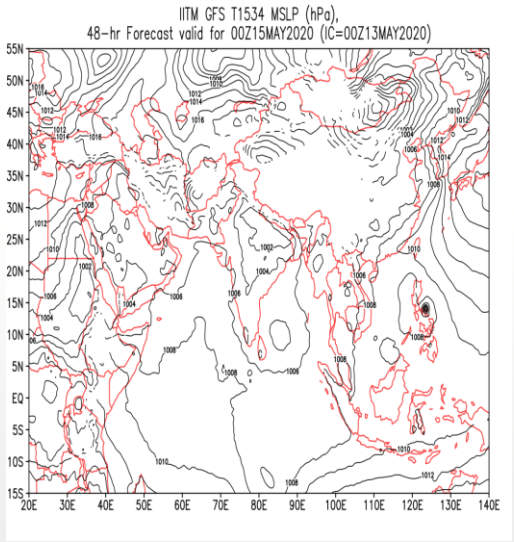
Analysis



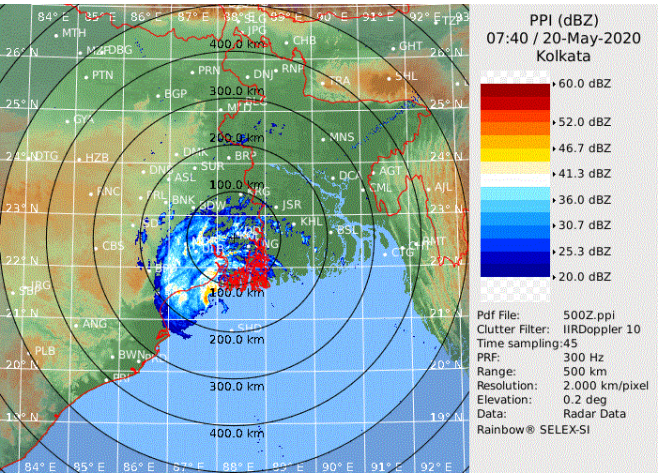
IC: 13 May 2020



IC: 14 May 2020



Super cyclone AMPHAN



Originated as a LPA on 13th May

Concentrated into a depression on 16th May

It underwent Rapid Intensification and reached Super Cyclonic Storm Strength on 18th May.

Weakened slightly and crossed West Bengal – Bangladesh coast as a VSCS on 20th May.

Radar image : IMD

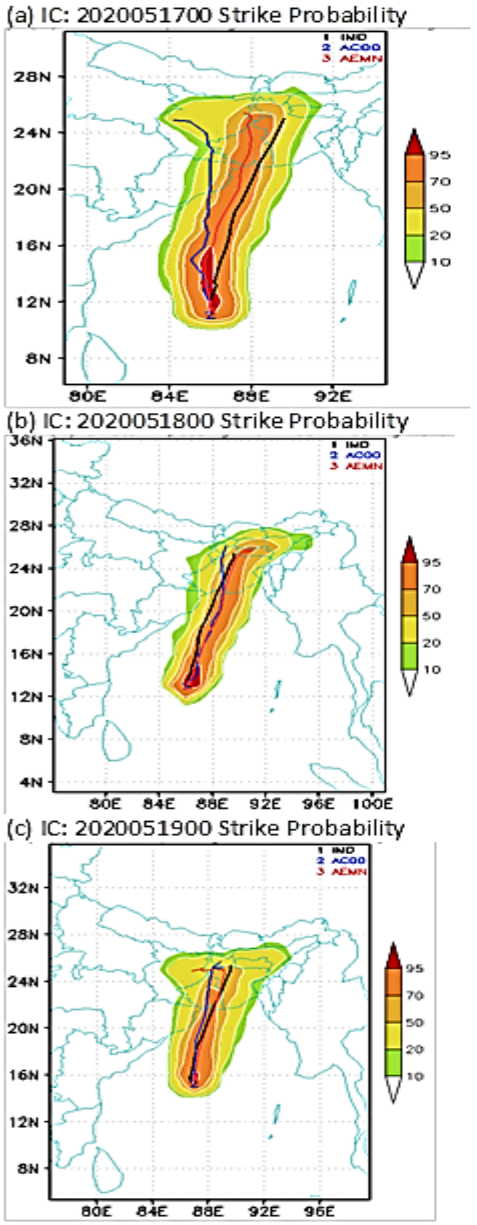
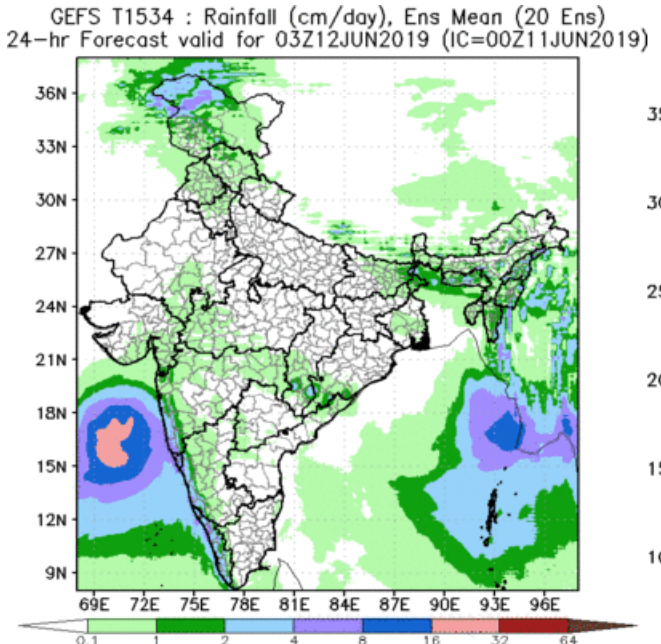
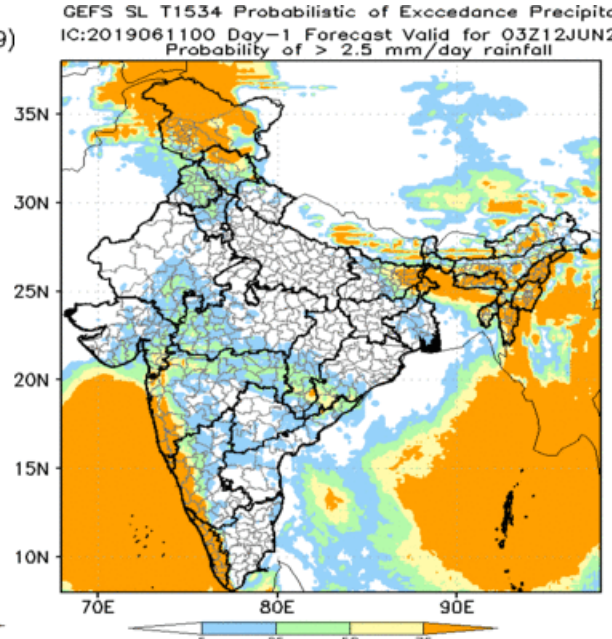
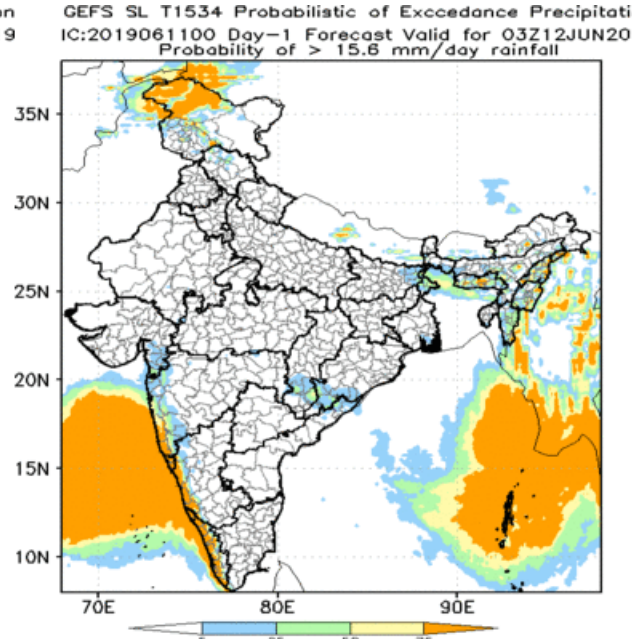


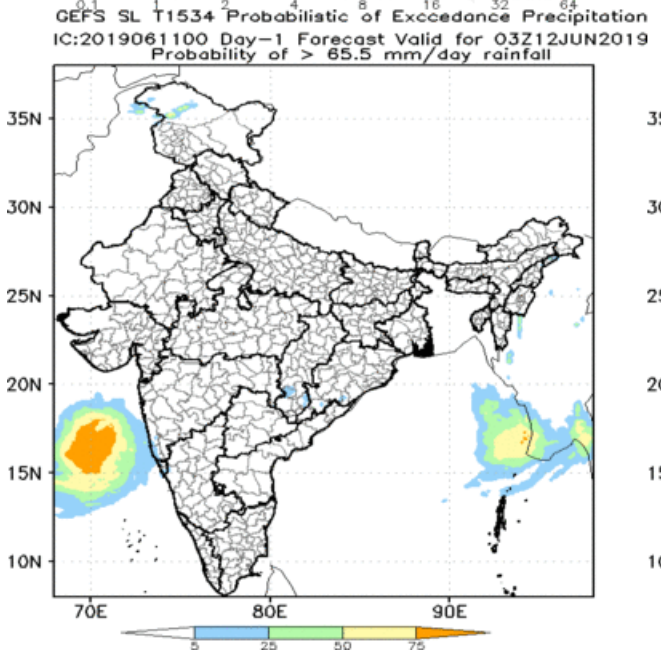
Figure 8: TC AMPHAN (a-c) strike probability, (d-f) Maximum Sustained Wind and Verification of the forecast of (g) track from all the ICs during the lifespan of the AMPHAN.

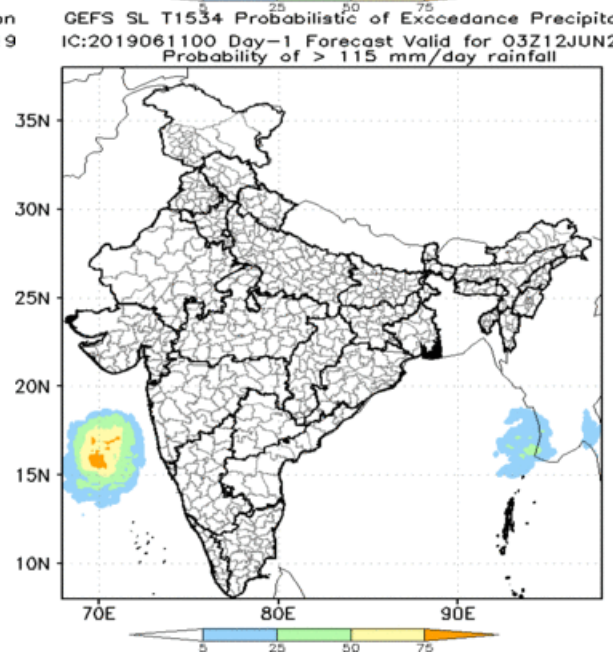
Tropical Cyclone VAYU

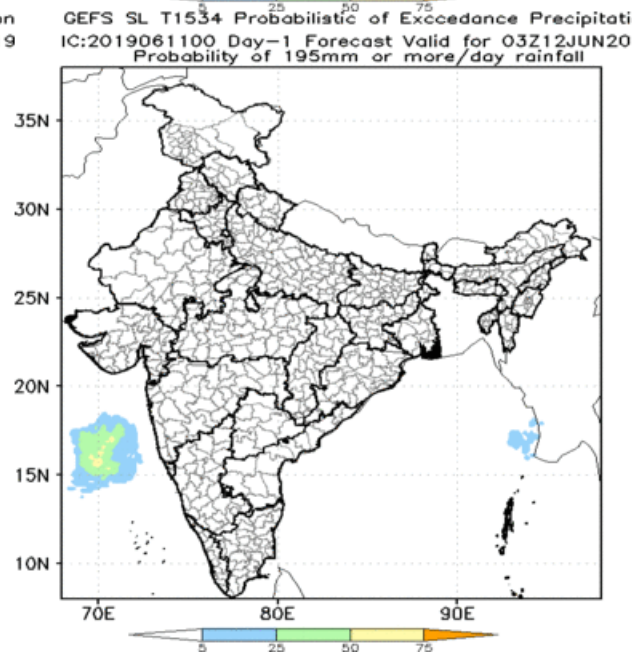




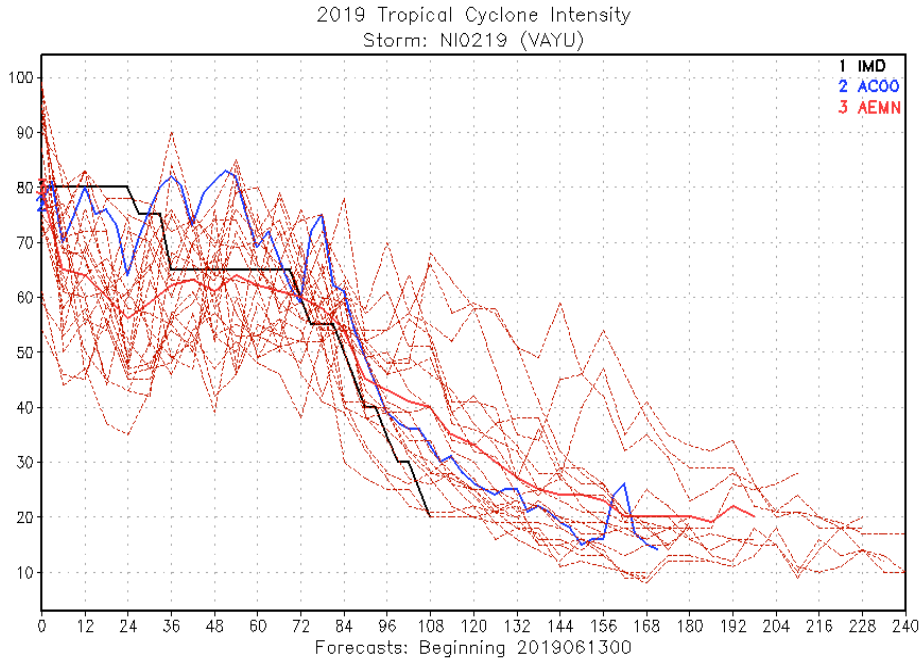


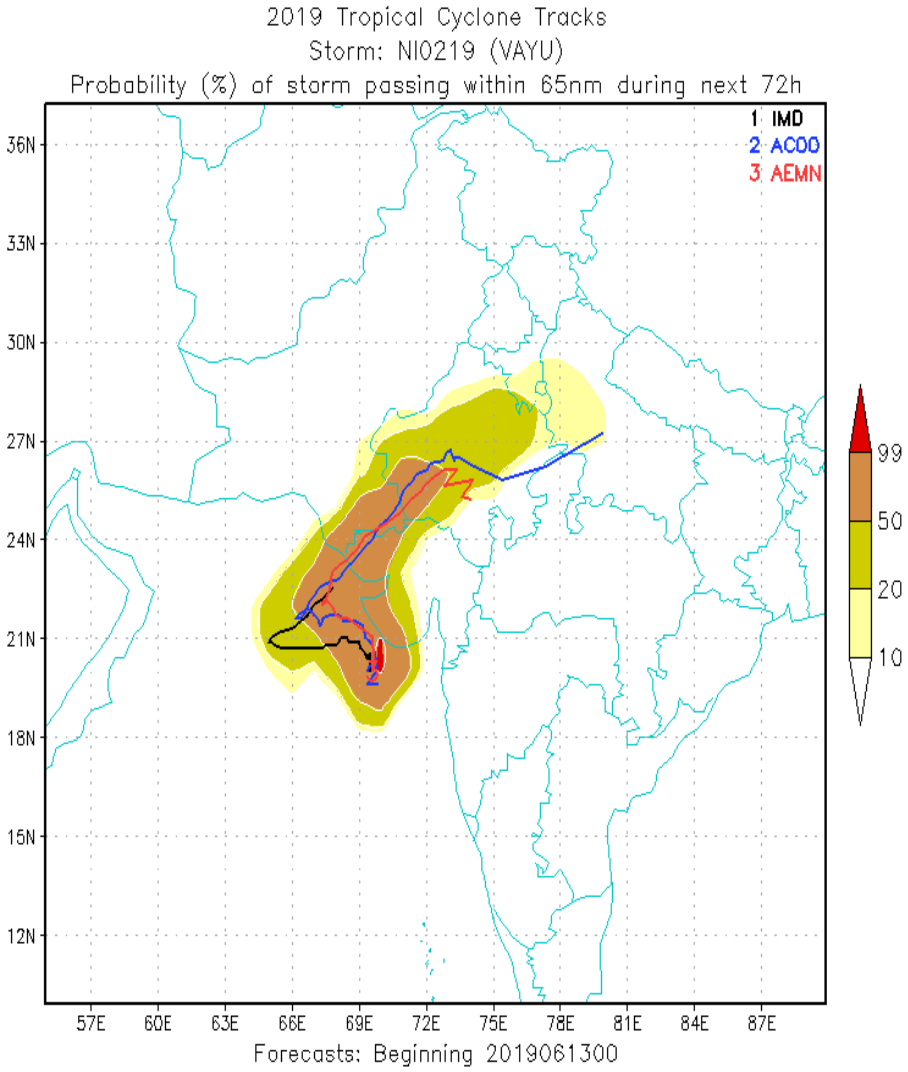


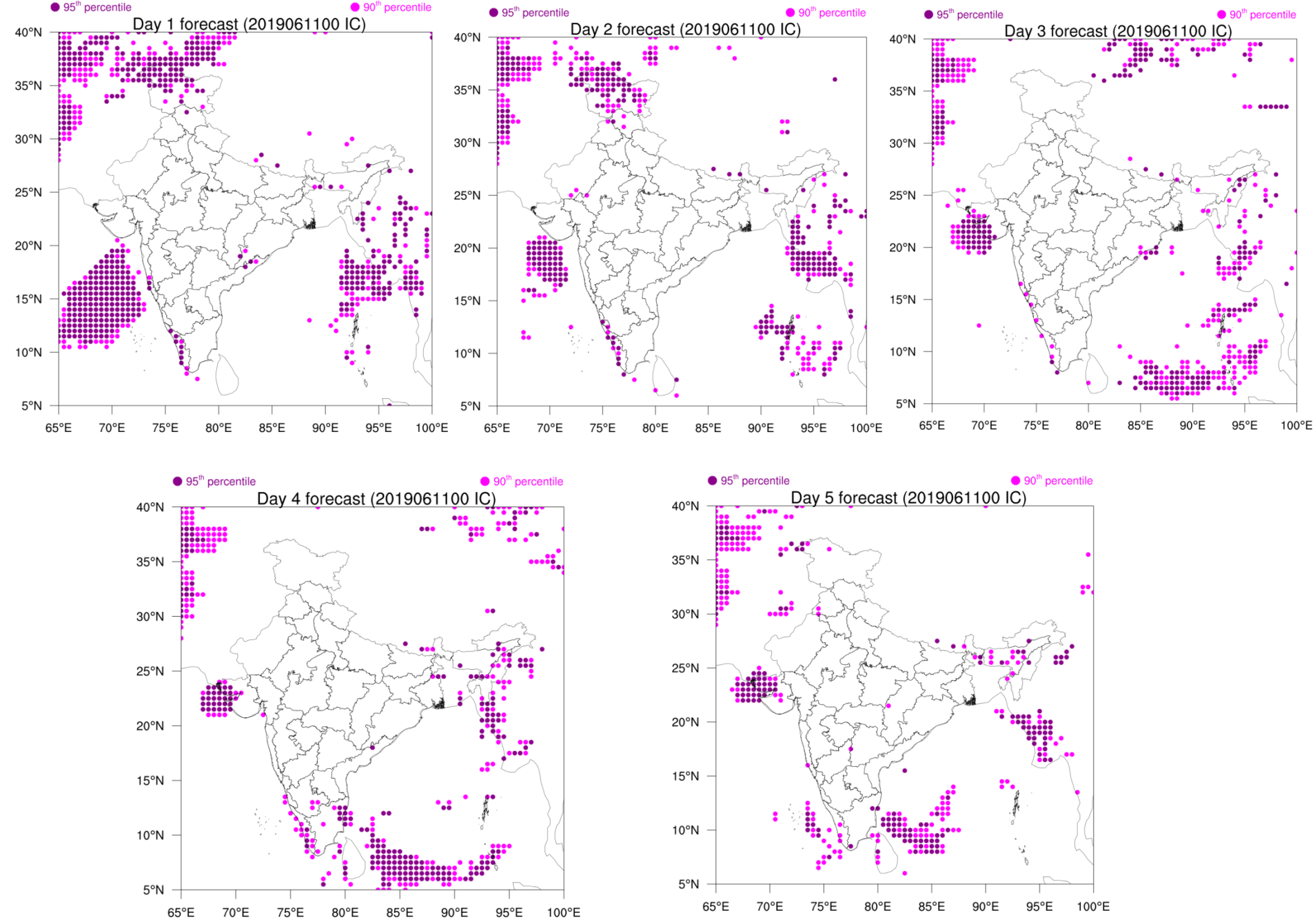




Tropical Cyclone VAYU strike probability and Intensity



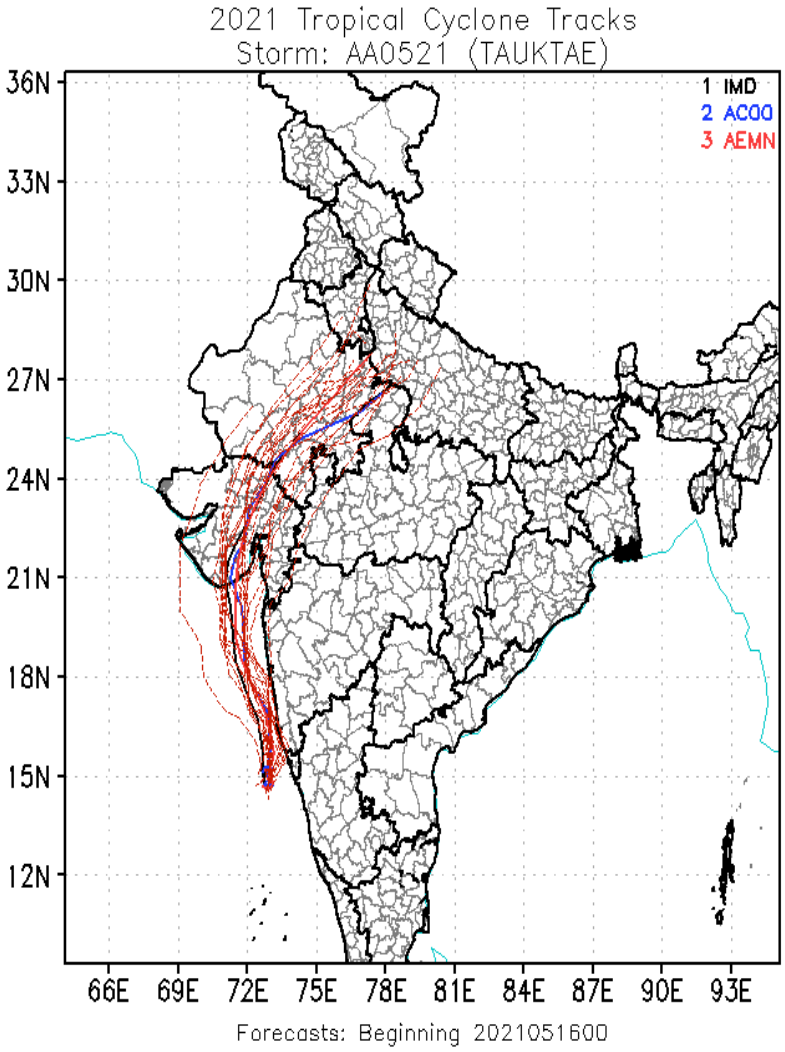



95th percentile
90th percentile
Day 1 forecast (2019061100 IC)
Day 2 forecast (2019061100 IC)
Day 3 forecast (2019061100 IC)
Day 4 forecast (2019061100 IC)
Day 5 forecast (2019061100 IC)
40°N
35°N
30°N
25°N
20°N
15°N
10°N
5°N
65°E
70°E
75°E
80°E
85°E
90°E
95°E
100°E

IC : 2021051600

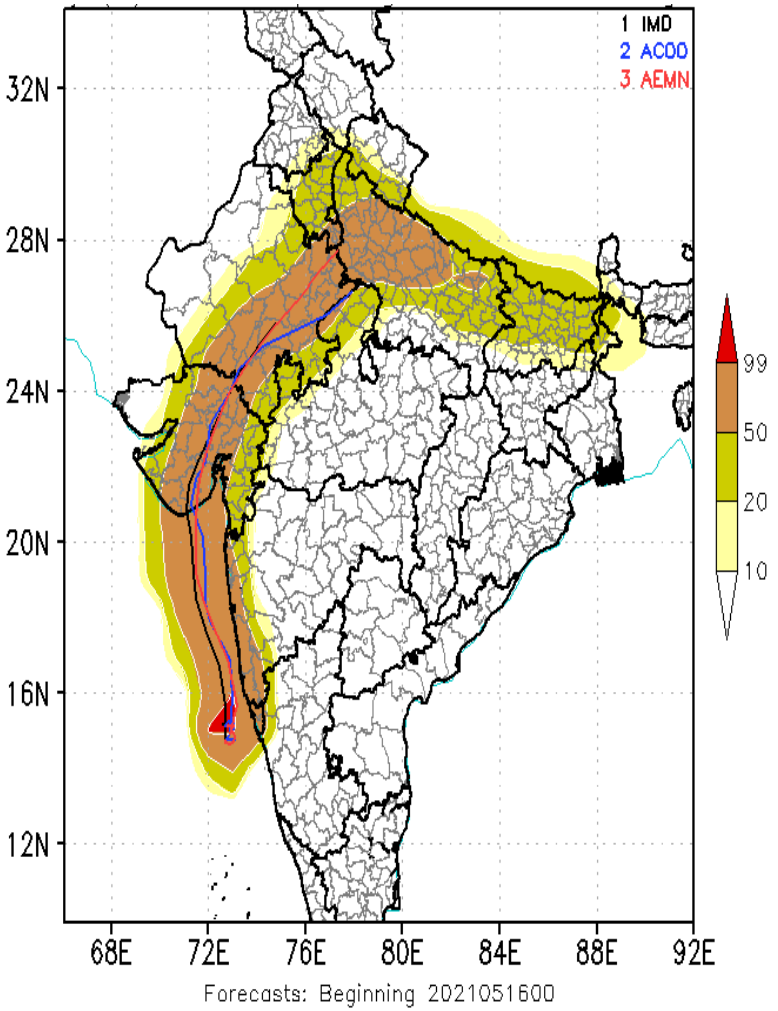
TC “TAUKTE” 14-19 May 2021

Ensemble Tracks

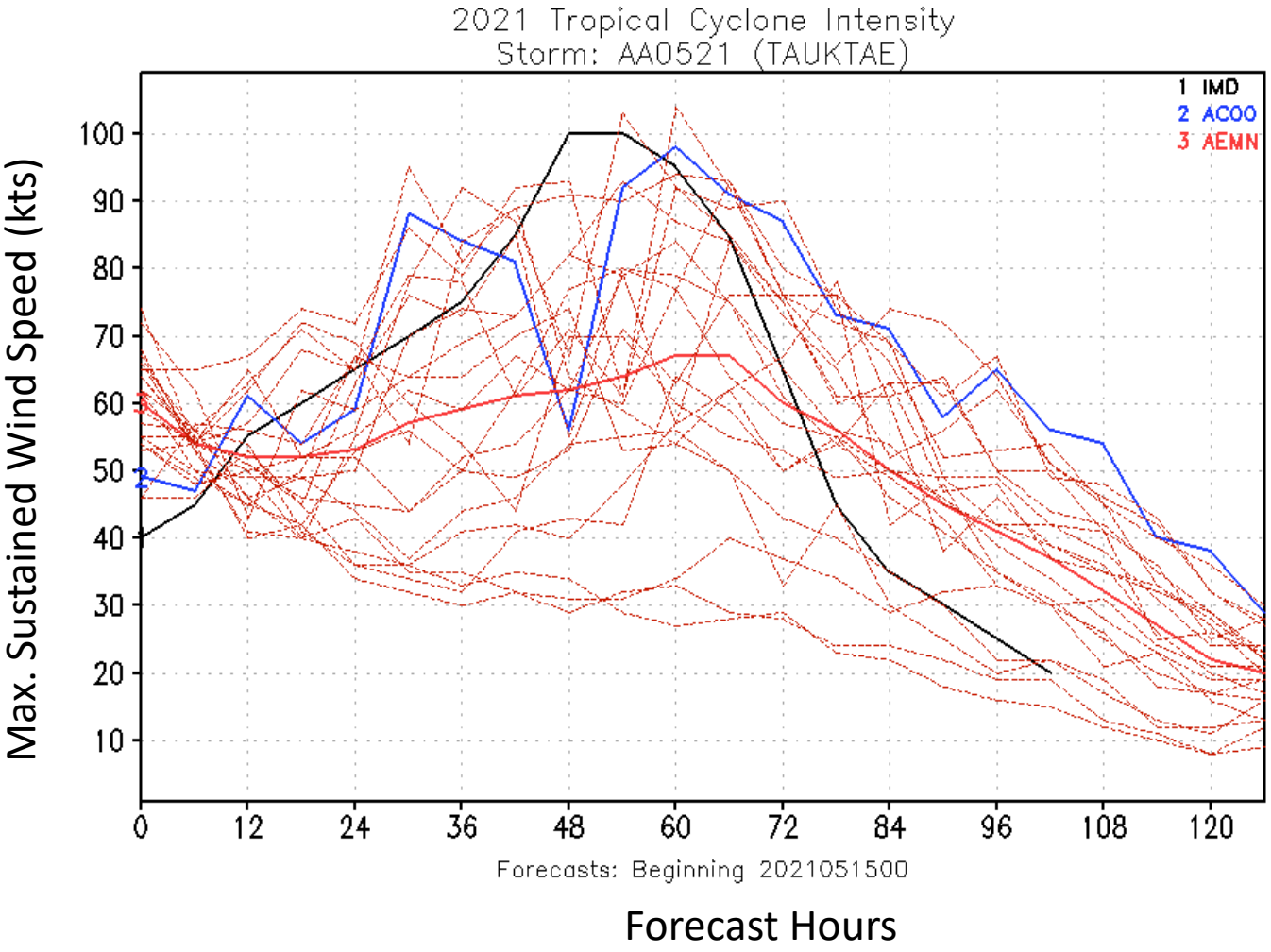


Strike Probability

Probability (%) of storm passing within 65nm during next 96h



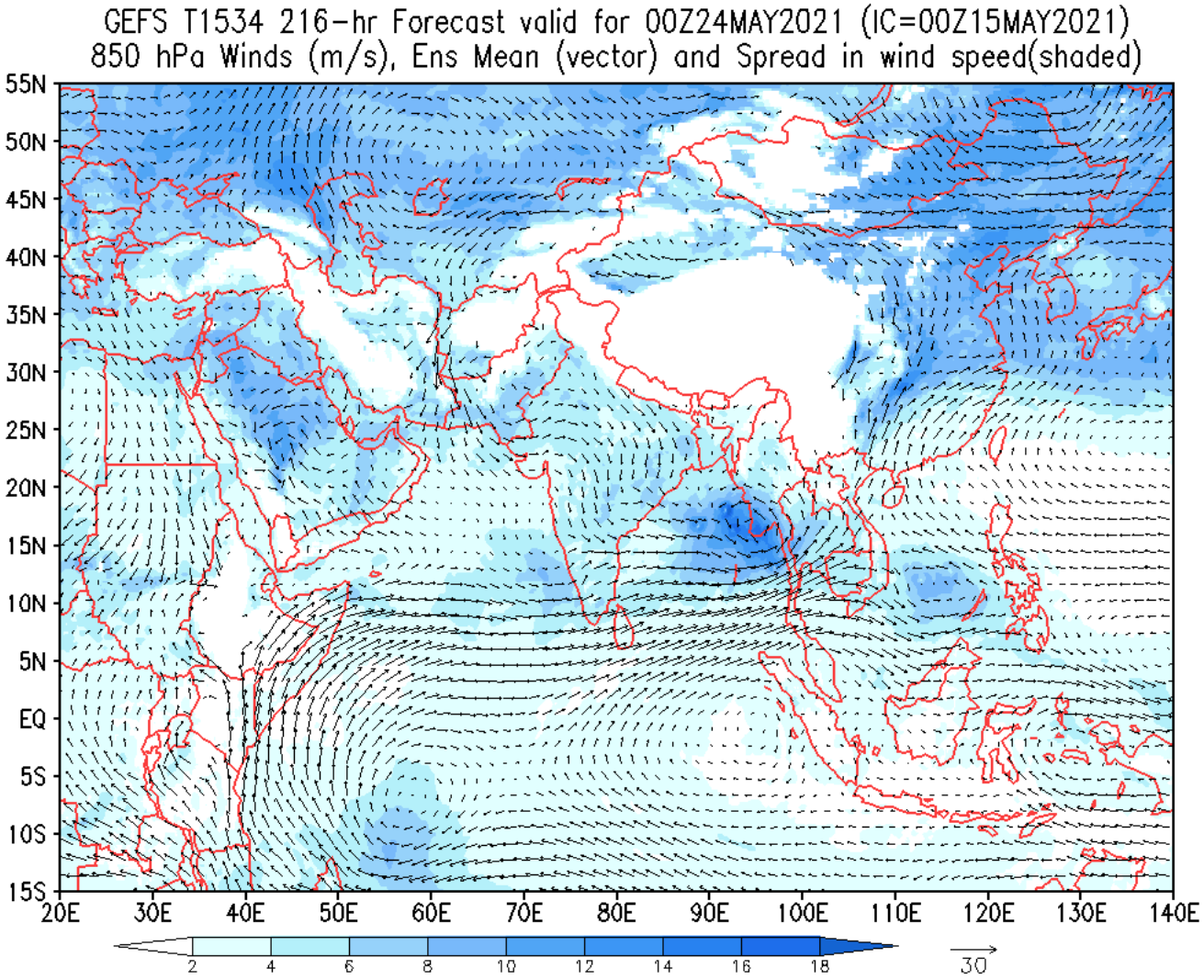
Intensity (Max. Sustained Wind Speed (kts)



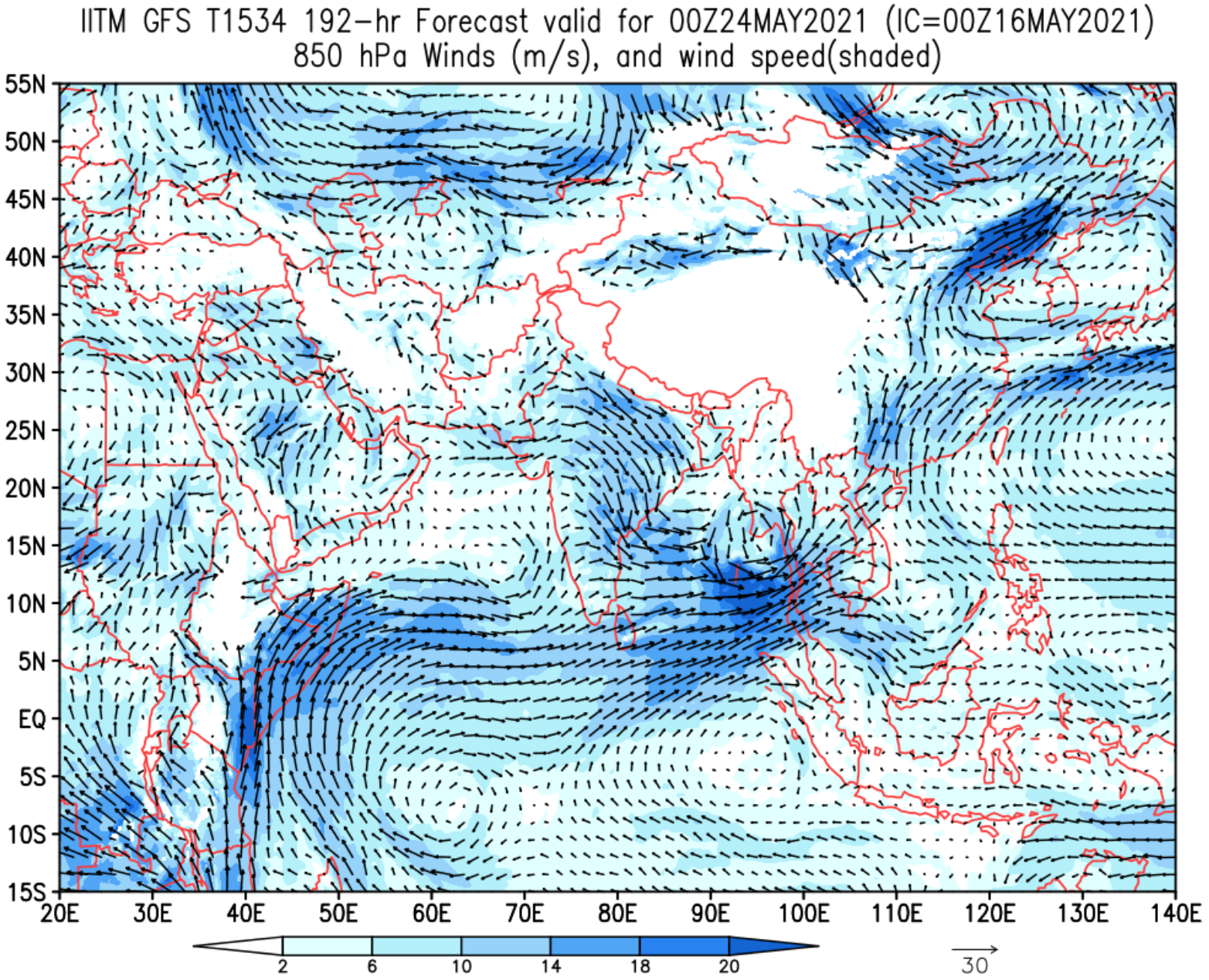
Rainfall associated with cyclone “Yaas”
22-28 May 2021

Early detection

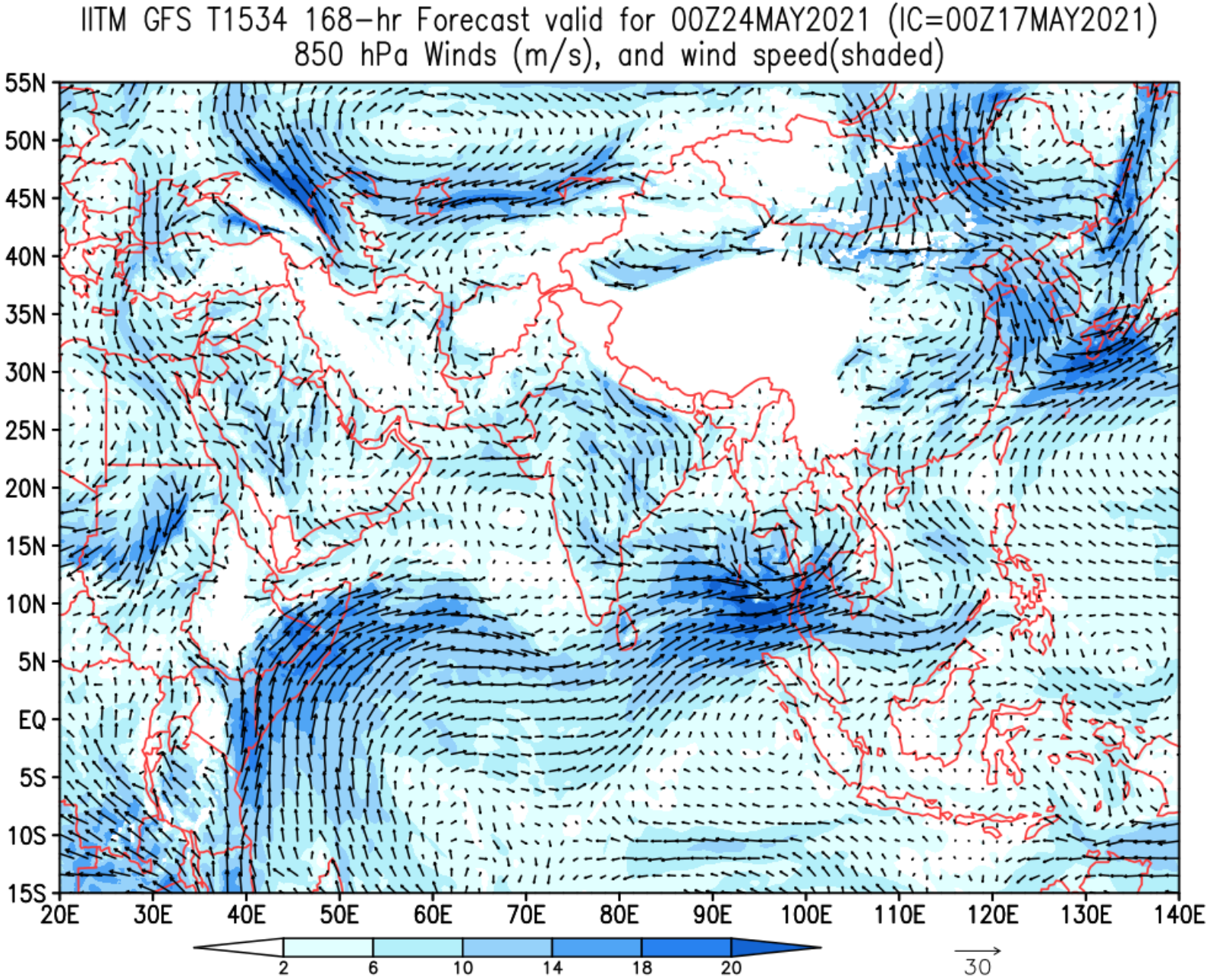
Fcst valid for 24 May based on 15 May 0000Z IC



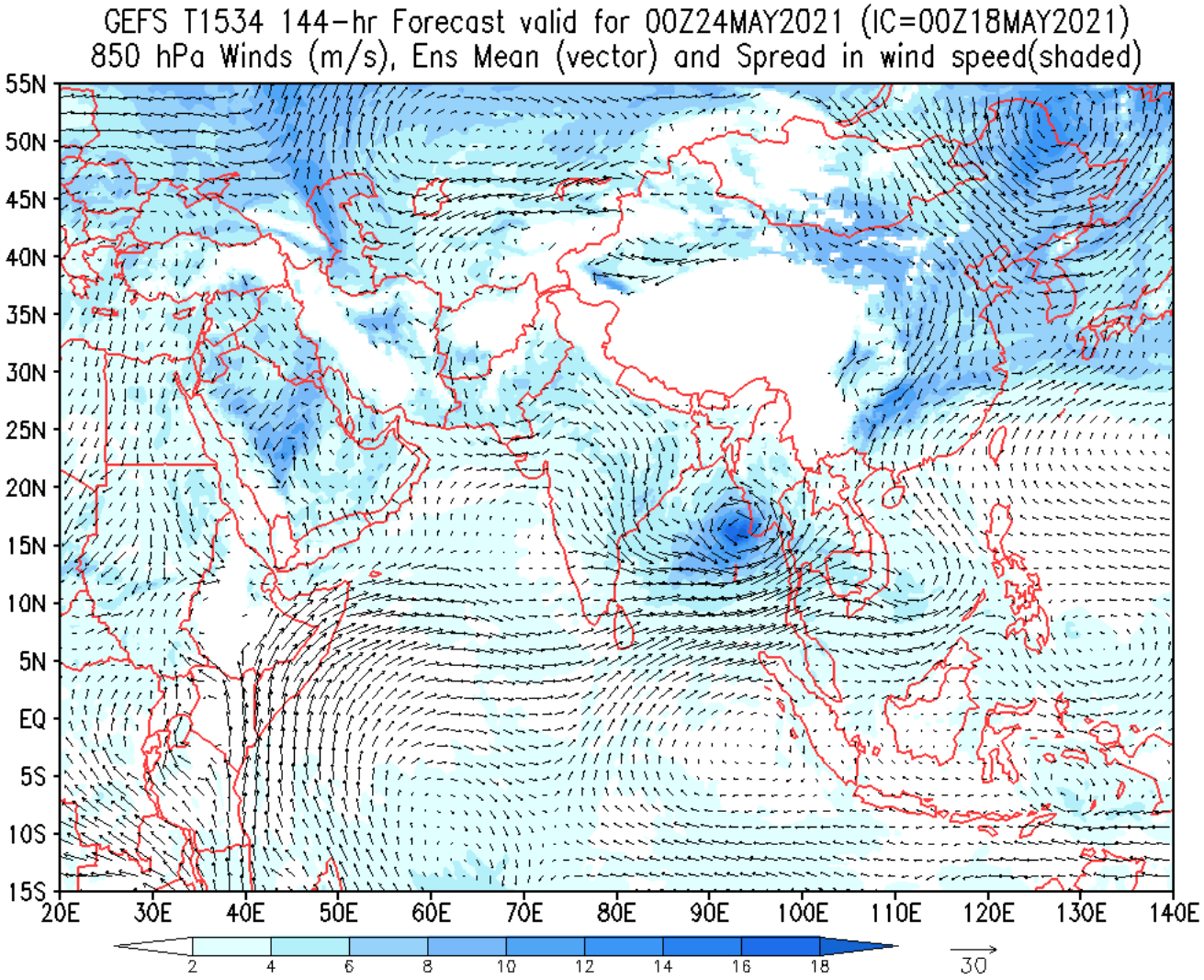
Fcst valid for 24 May based on 16 May 0000Z IC



Fcst valid for 24 May based on 17 May 0000Z IC

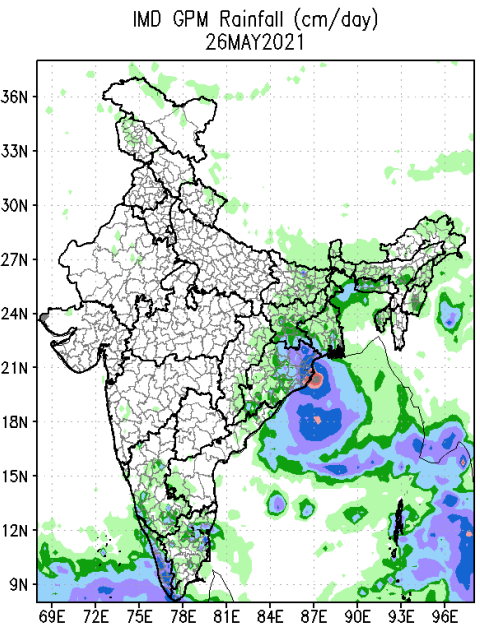


Fcst valid for 24 May based on 18 May 0000Z IC



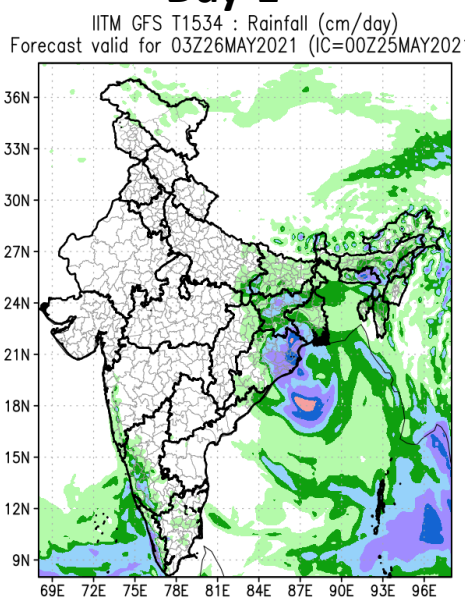
Observed rainfall (cmday^{-1})

26th May

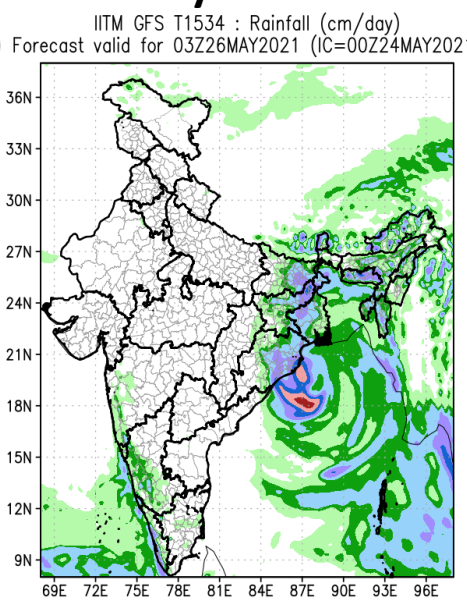


GFS T1534 forecast valid for 26th May

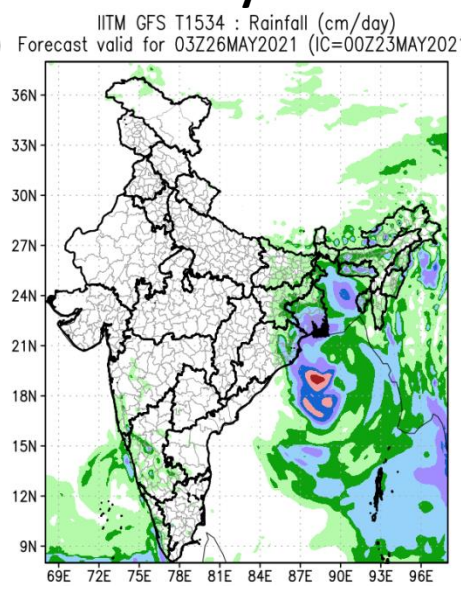
Day-1



Day-2

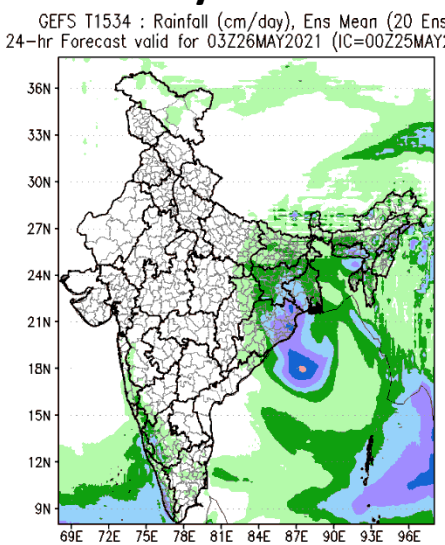


Day-3

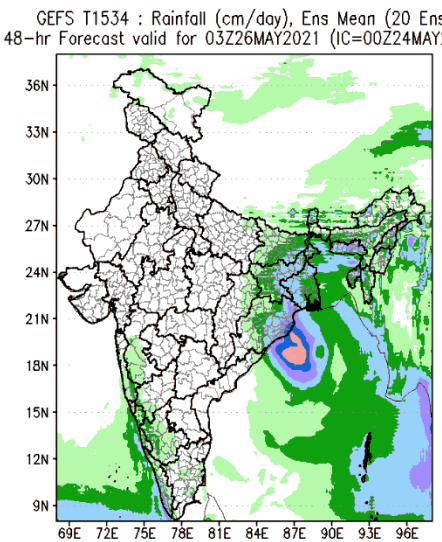


GEFS T1534 forecast valid for 26th May

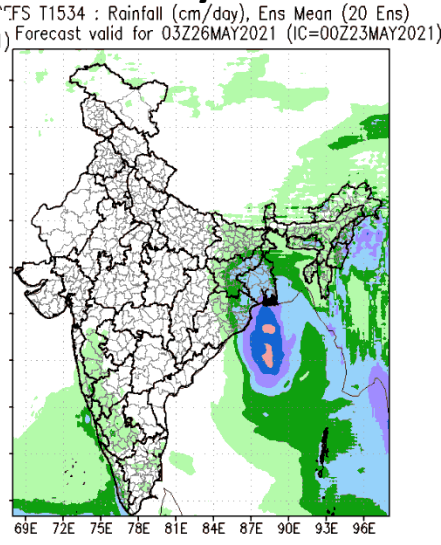
Day-1



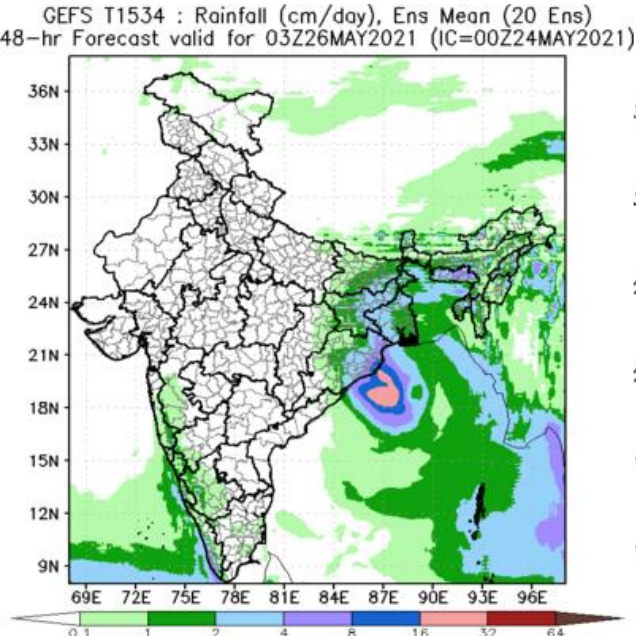
Day-2

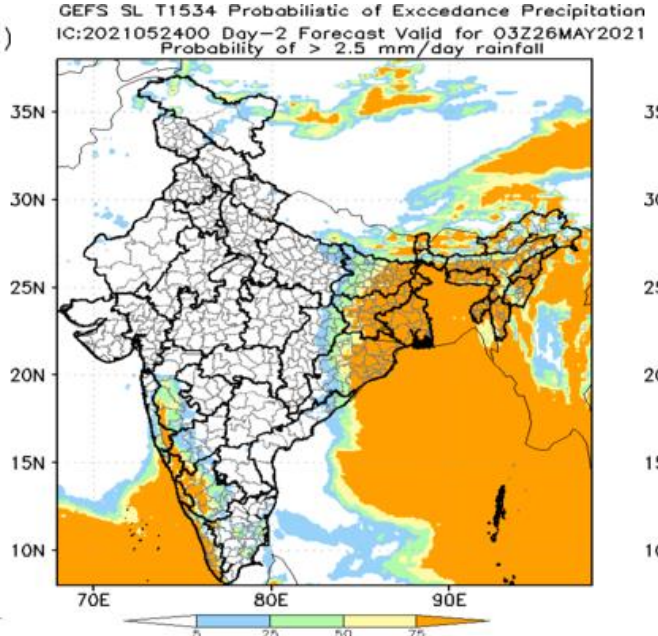


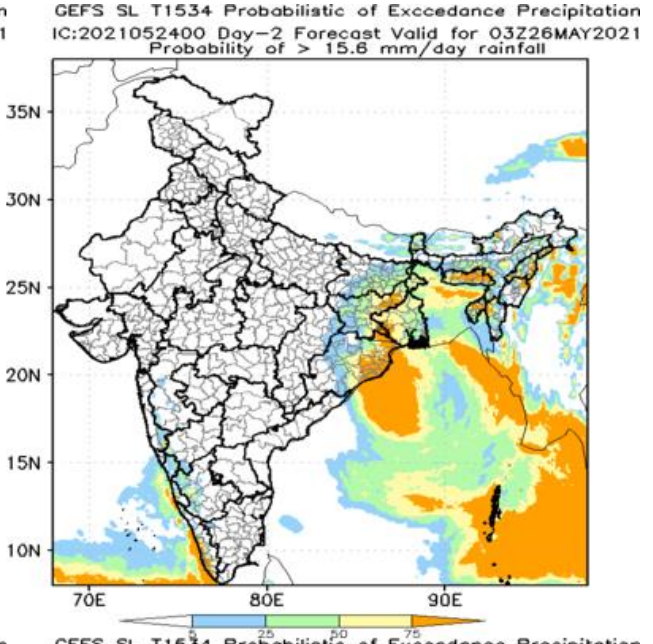
Day-3

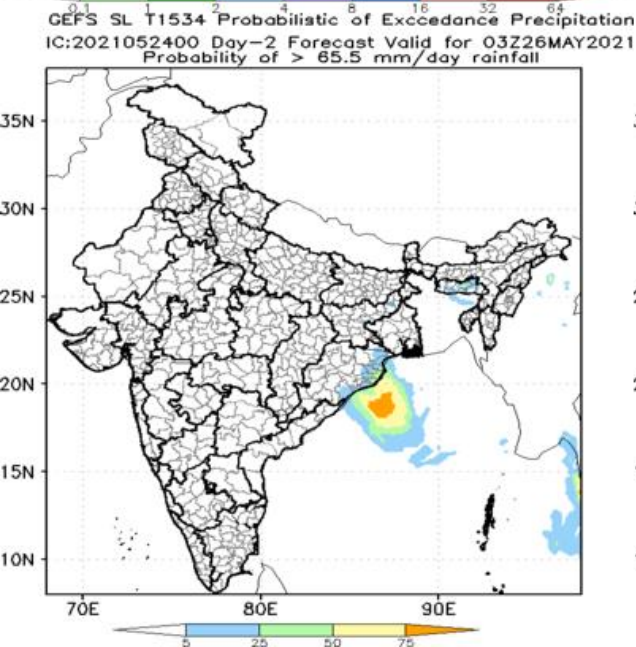


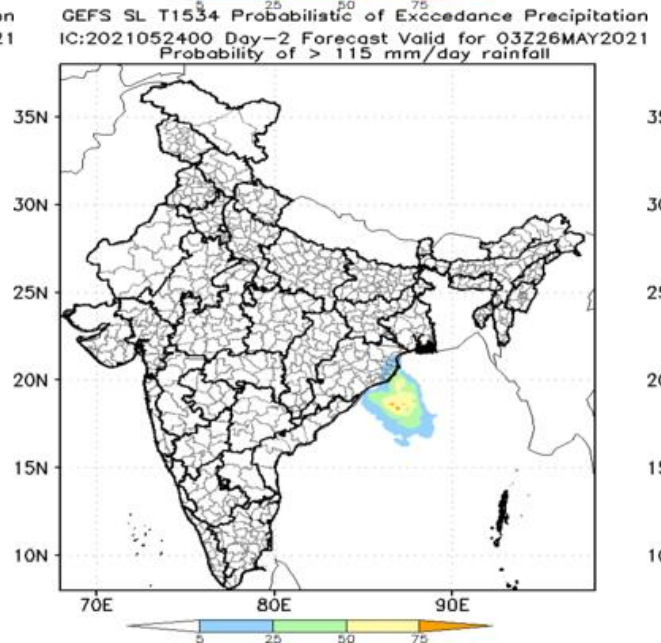
GEFS T1534 Probabilistic rainfall forecast based on 24th May IC valid for 26th May

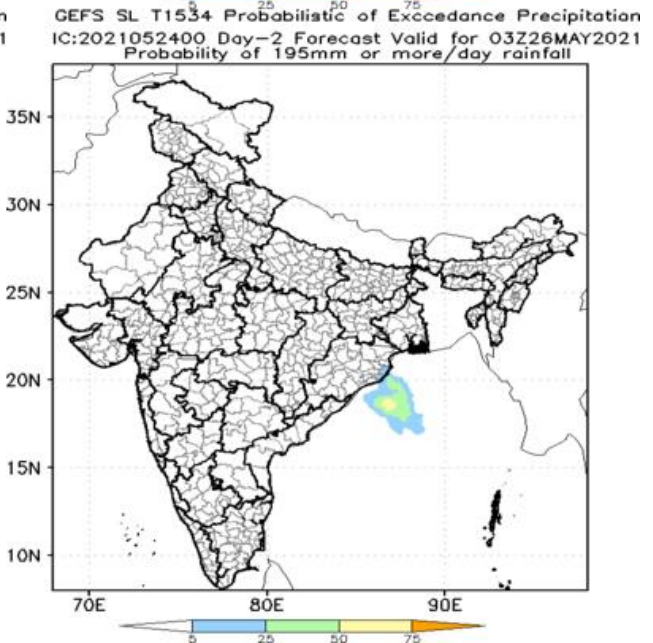


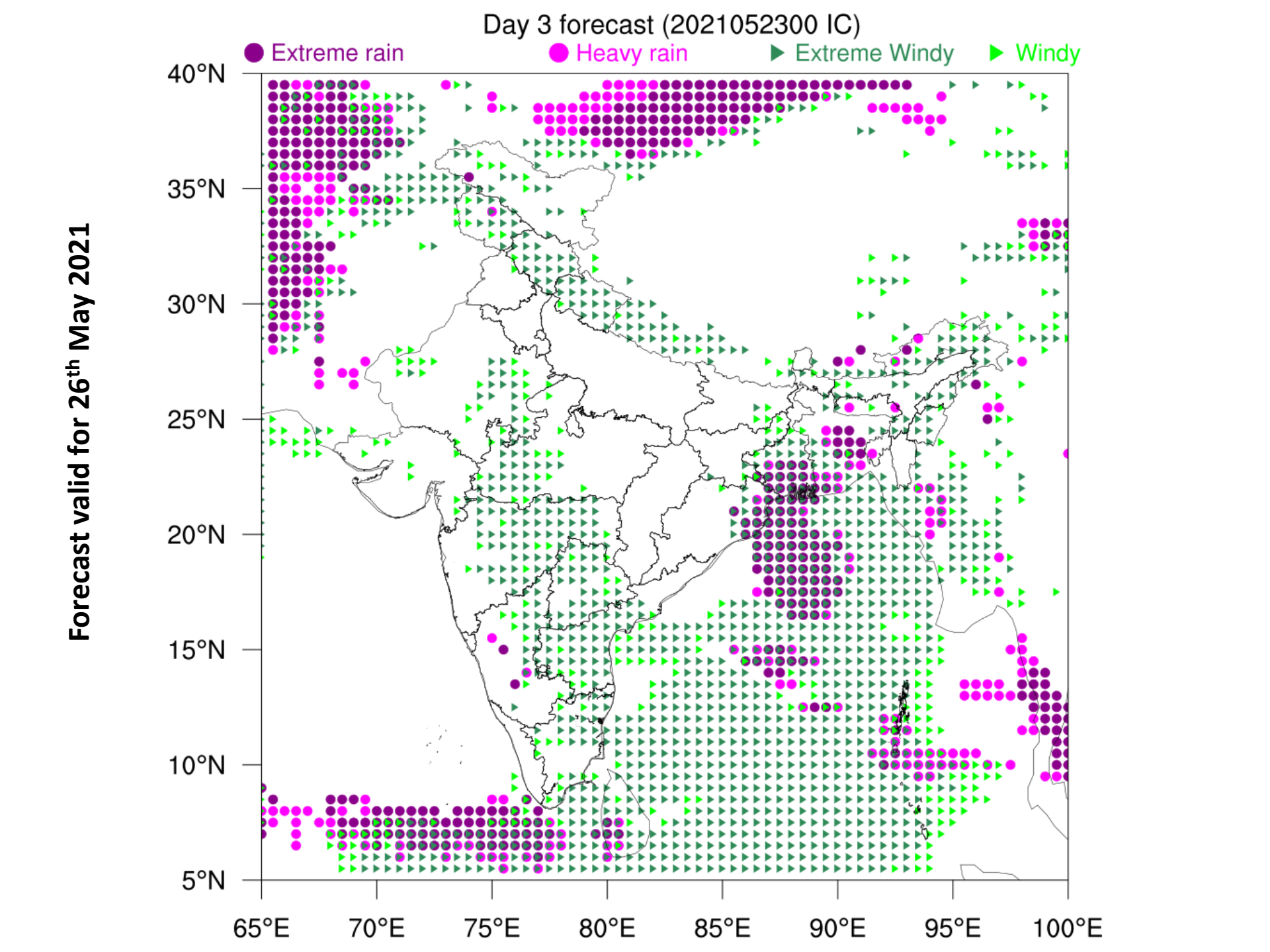




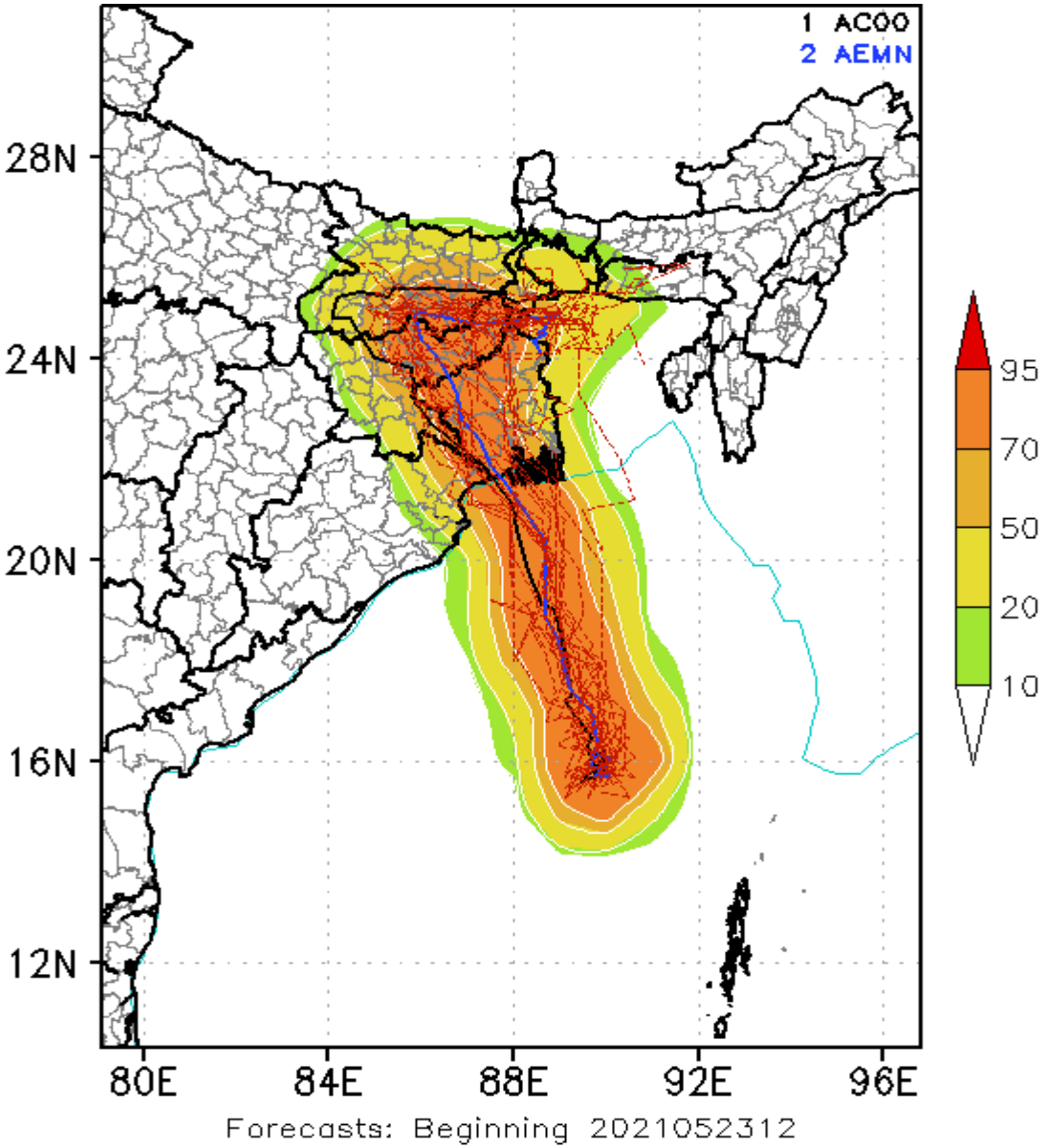




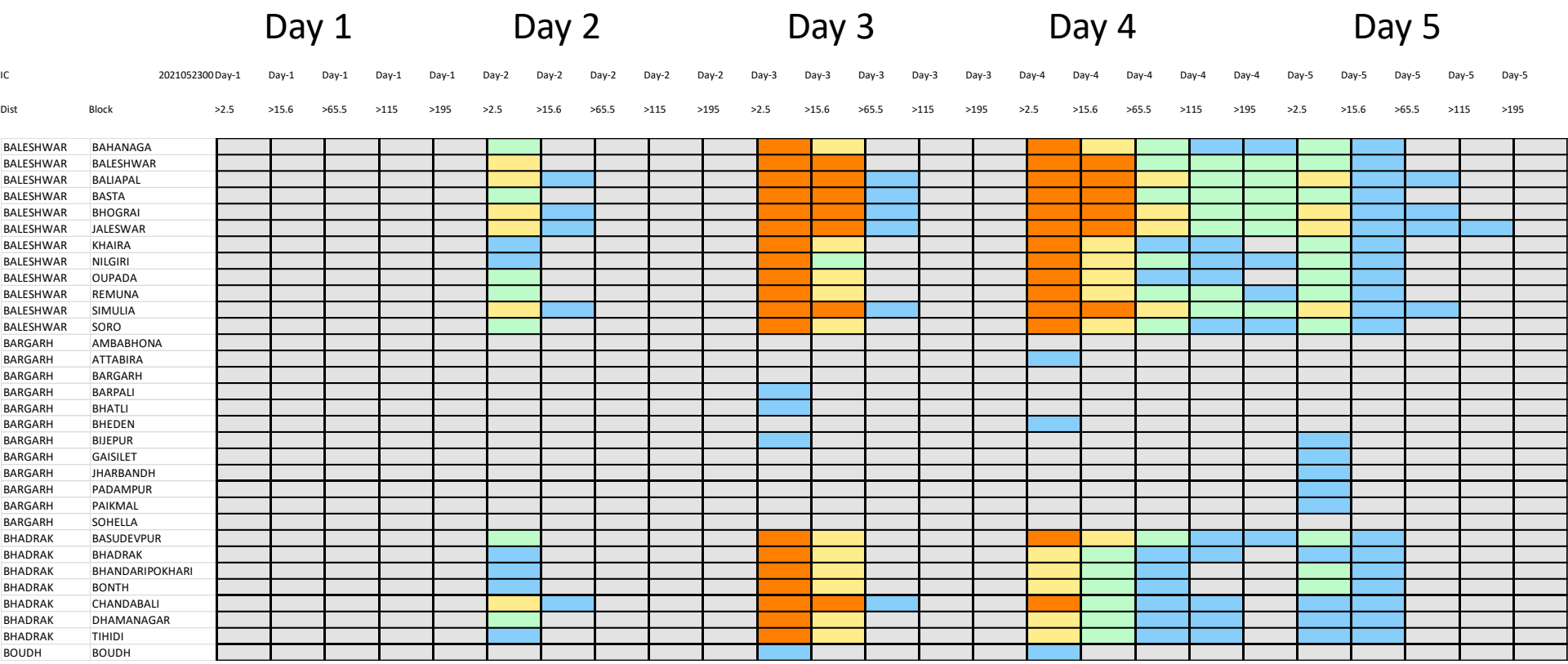


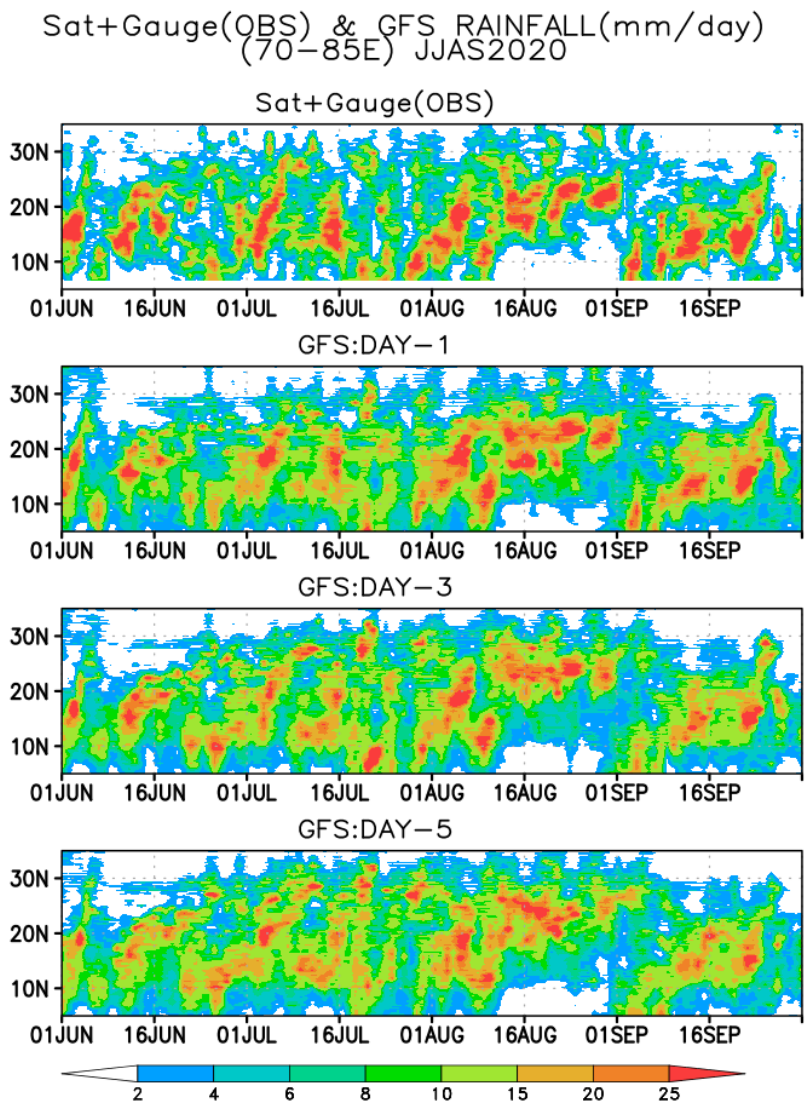

Day 3 forecast (2021052300 IC)
Extreme rain
Heavy rain
Extreme Windy
Windy
Forecast valid for 26th May 2021
40°N
35°N
30°N
25°N
20°N
15°N
10°N
5°N
65°E
70°E
75°E
80°E
85°E
90°E
95°E
100°E

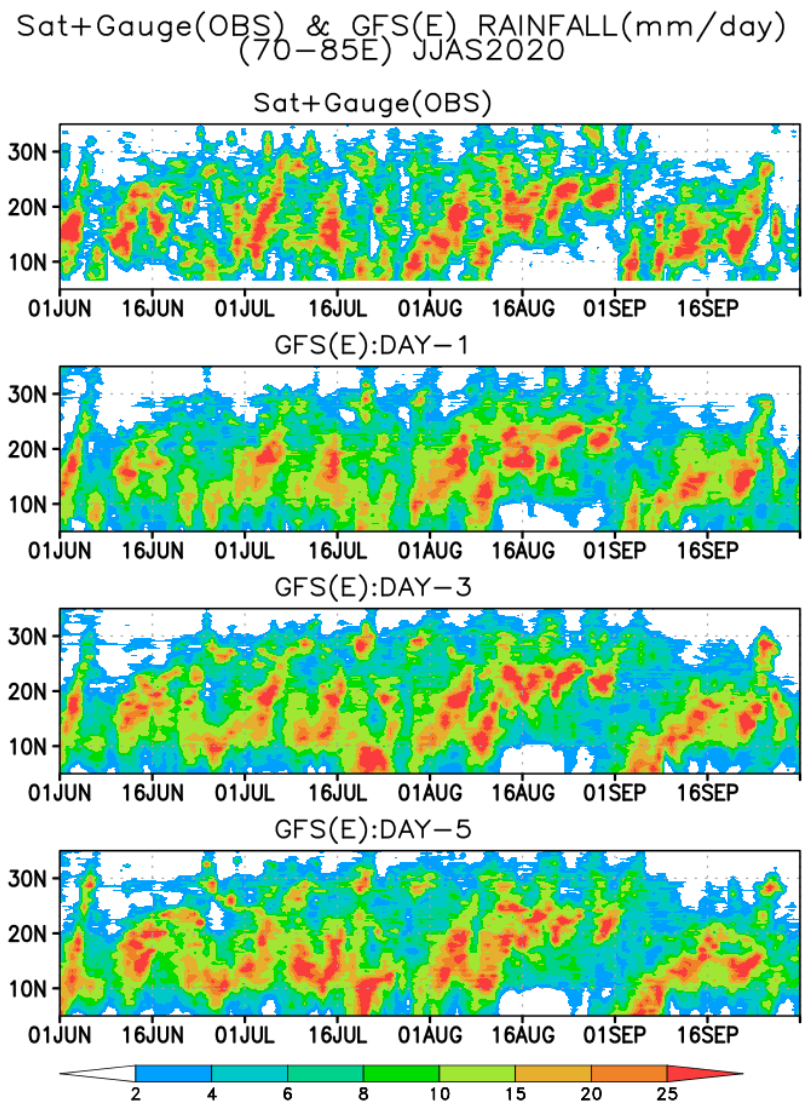
Probability (%) of storm passing within 65nm during next 240hrs



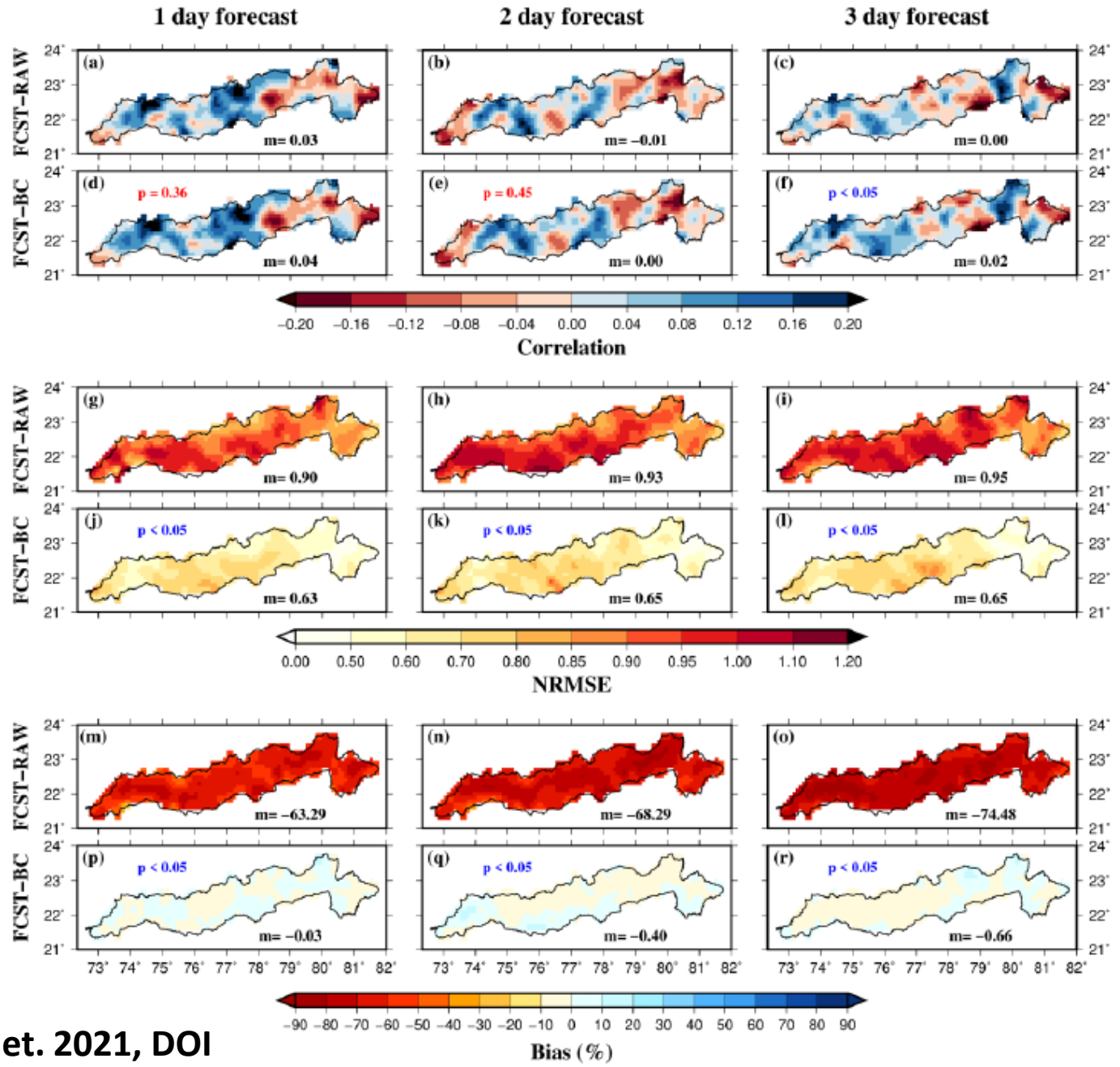
Probabilistic 5 days Forecast of Rainfall over blocks of Odisha with 23 May 2021 0000 UTC IC




Sat+Gauge(OBS) & GFS RAINFALL(mm/day)
(70-85E) JJAS2020
Sat+Gauge(OBS)
GFS:DAY-1
GFS:DAY-3
GFS:DAY-5
30N
20N
10N
01JUN
16JUN
01JUL
16JUL
01AUG
16AUG
01SEP
16SEP
2
4
6
8
10
15
20
25

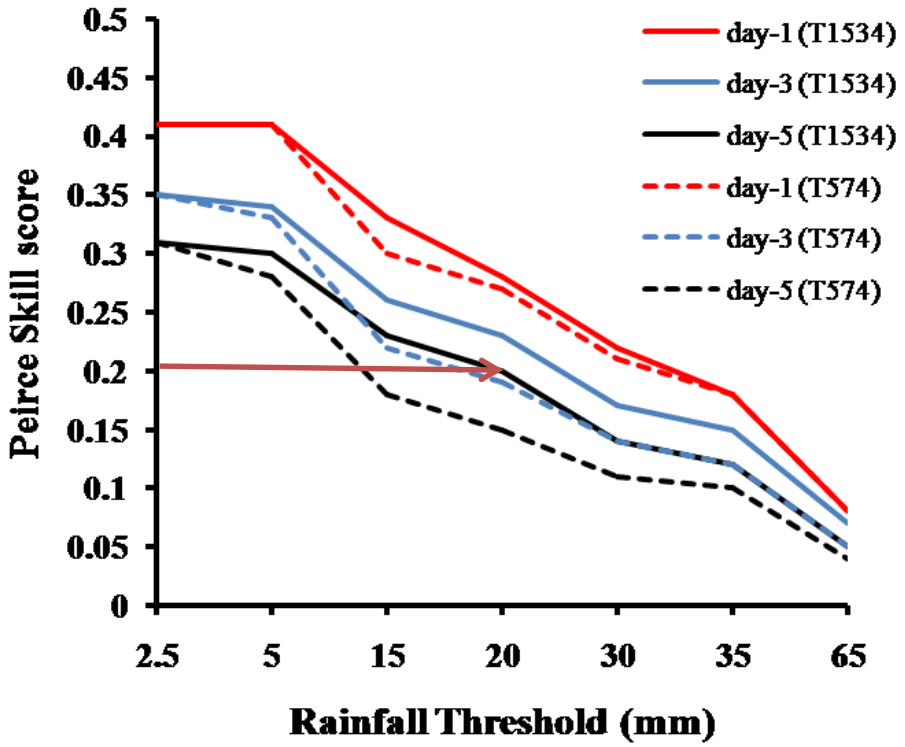

Sat+Gauge(OBS) & GFS(E) RAINFALL(mm/day)
(70-85E) JJAS2020
Sat+Gauge(OBS)
GFS(E):DAY-1
GFS(E):DAY-3
GFS(E):DAY-5
30N
20N
10N
01JUN
16JUN
01JUL
16JUL
01AUG
16AUG
01SEP
16SEP
2
4
6
8
10
15
20
25

Forecast skill of extreme precipitation (exceeding 95th percentile) estimated using the coefficient of correlation, NRMSE, and bias (%) at 1-3 day lead time before (FCST-RAW) and after the bias correction (FCST-BC) during the monsoon season for the 2000-2018 period over Narmada basin

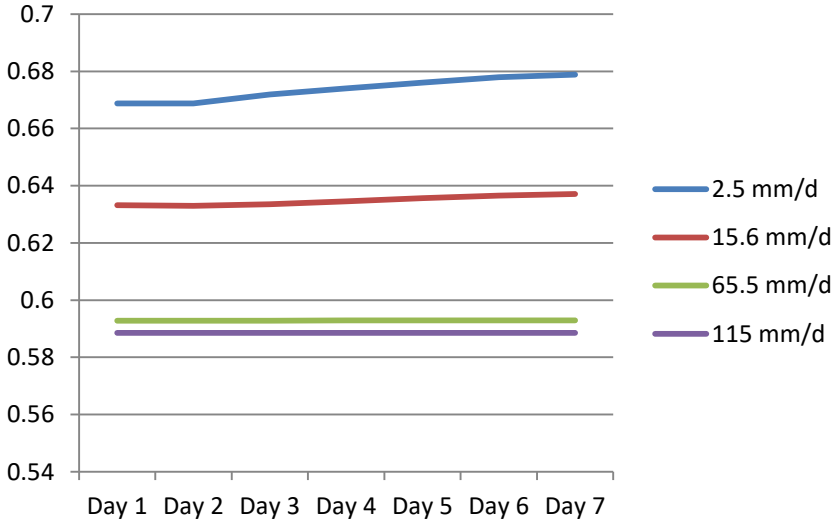


Tiwari et al. J. Hydromet. 2021, DOI 10.1175/JHM-D-20-0235.1.

Peirce Skill Score (High Resolution global 12.5 km model gives better skill (The skill of GFS T574 with 3 day lead is now extended to 5 days with T1534 ~12.5 km global GFS



Brier Score GEFS 2018-2020 JJAS



Rao et al. 2019, BAMS

THE KERALA DELUGE AUGUST 2018

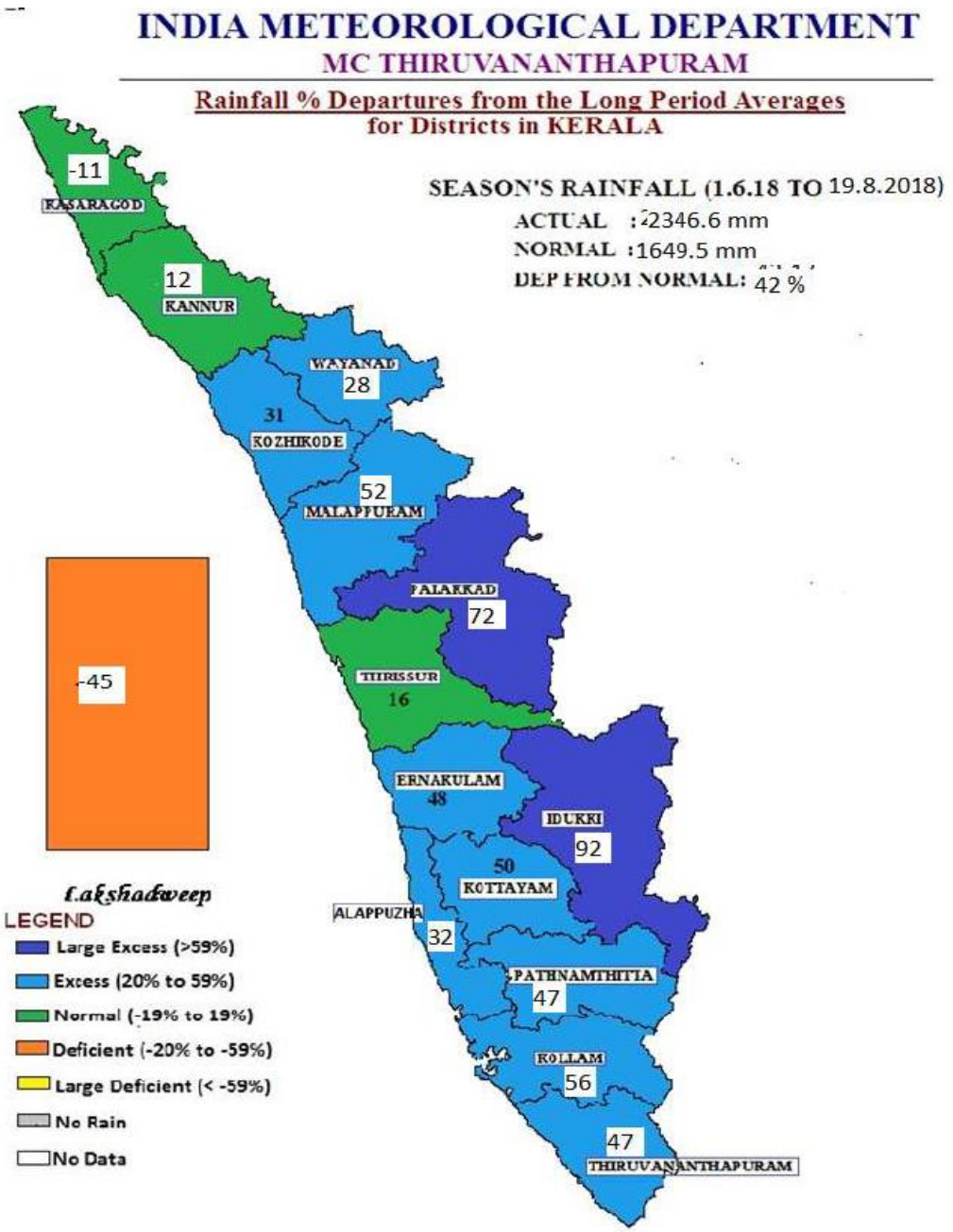
Ref: CWC Report, Sept, 2018

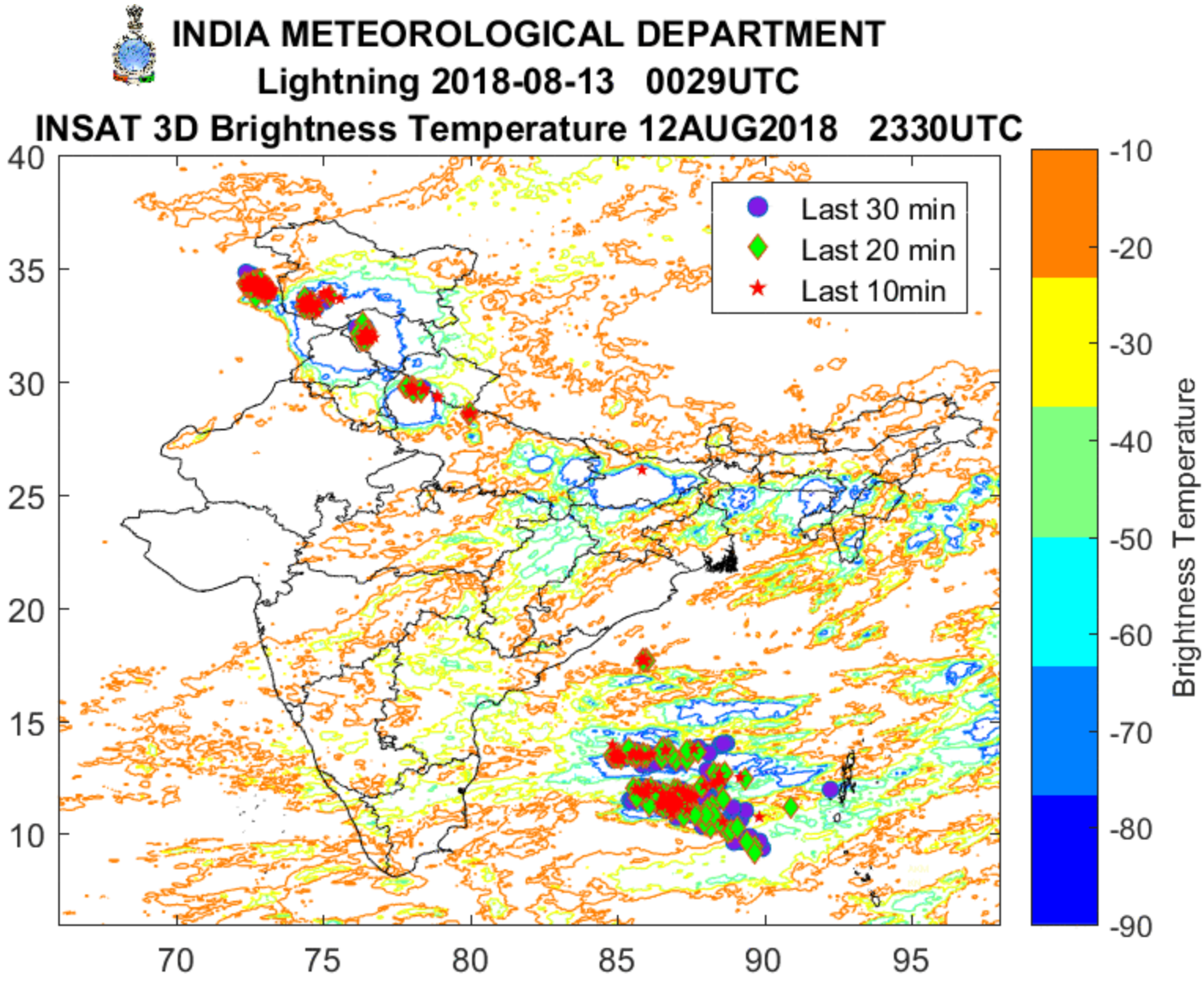
Period	Normal Rainfall	Actual Rainfall	Departure from normal
	(mm)	(mm)	(%)
June, 2018	649.8	749.6	15
July, 2018	726.1	857.4	18
1-19, August, 2018	287.6	758.6	164
Total	**1649.5**	**2346.6**	**42**

Districts	Normal Rainfall (mm)	Actual Rainfall (mm)	Departure from Normal (%)	
Kerala State	1701.4	2394.1	41	Excess
Alappuzha	1380.6	1784	29	Excess
Kannur	2333.2	2573.3	10	Normal
Ernakulam	1680.4	2477.8	47	Excess
Idukki	1851.7	3555.5	92	Large Excess
Kasaragode	2609.8	2287.1	-12	Normal
Kollam	1038.9	1579.3	52	Excess
Kottayam	1531.1	2307	51	Excess
Kozhikode	2250.4	2898	29	Excess
Malappuram	1761.9	2637.2	50	Excess
Palakkad	1321.7	2285.6	73	Large Excess
Pathanamthitta	1357.5	1968	45	Excess
Thiruvananthapuram	672.1	966.7	44	Excess
Thrissur	1824.2	2077.6	14	Normal
Wayanad	2281.3	2884.5	26	Excess

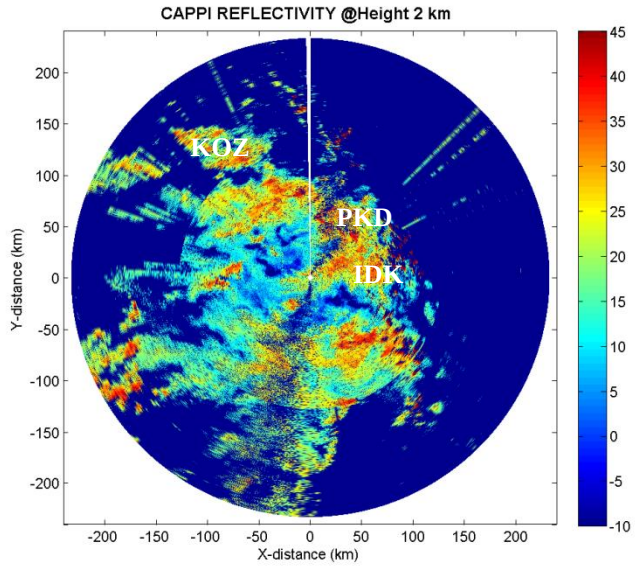
Districts in Kerala:

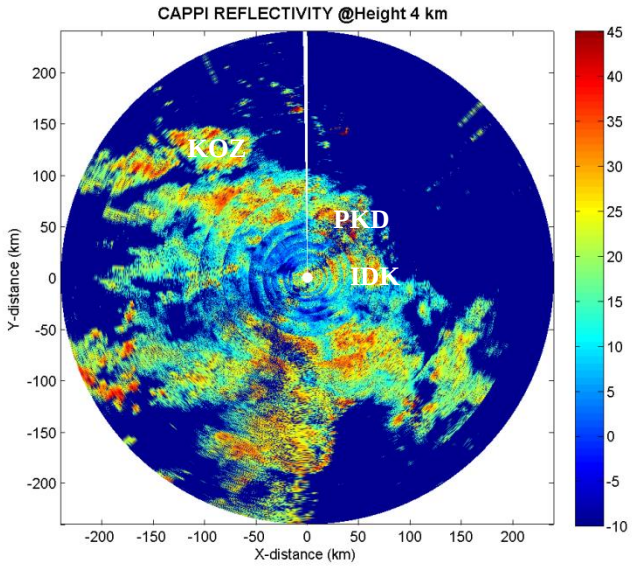
1. Kasargode
2. Kannur
3. Kozhikode
4. Wayanad
5. Malappuram
6. Palakkad
7. Thrissur
8. Ernakulam
9. Idukki
10. Kottayam
11. Alappuzha
12. Pathanamthitta
13.Kollam
14. Thiruvananthapuram

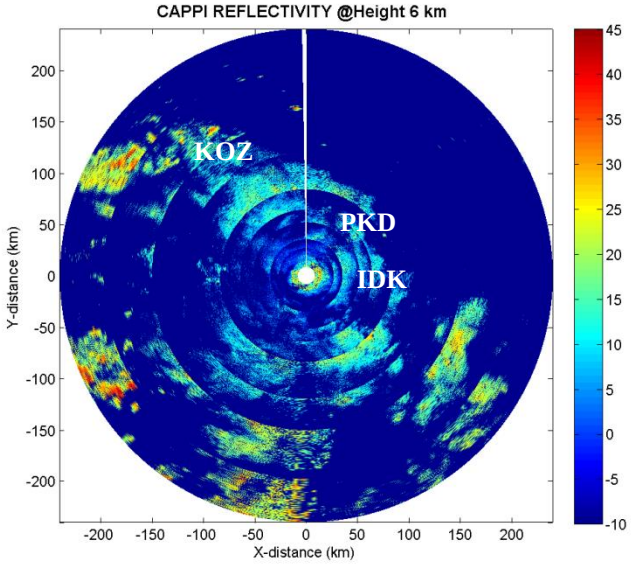


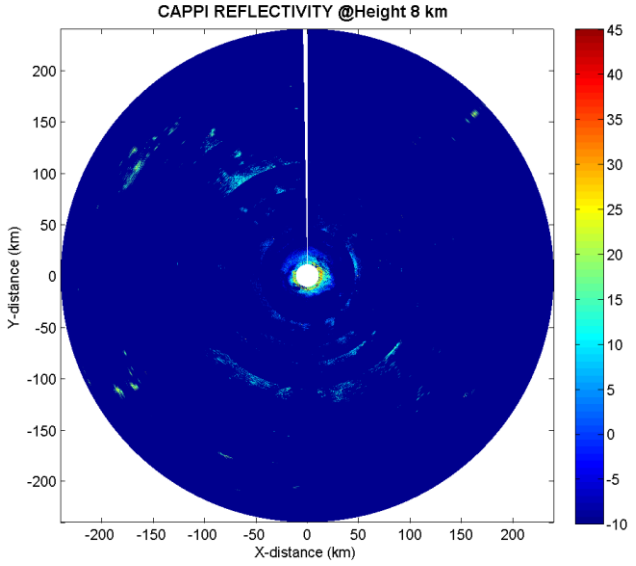


The merged lightening & satellite cloud top temperature operational product is a joint collaboration of IMD, IITM & IAF



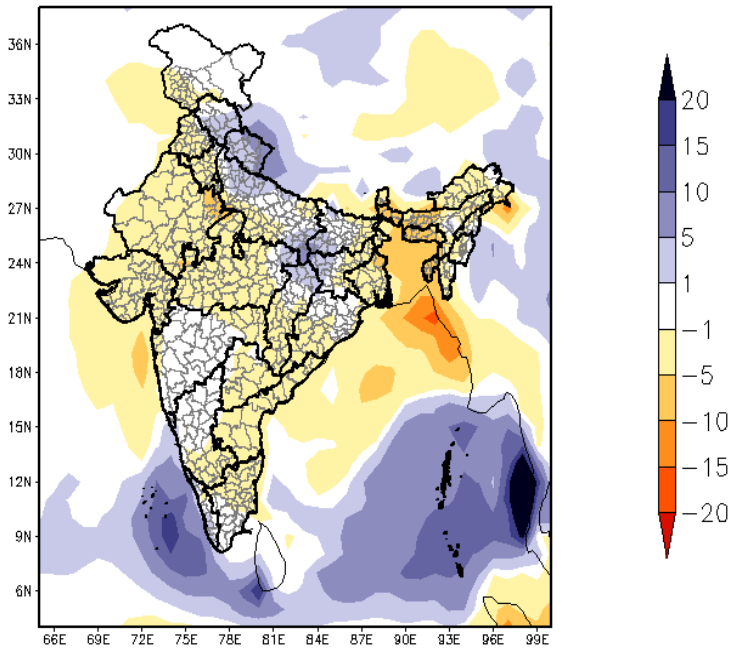




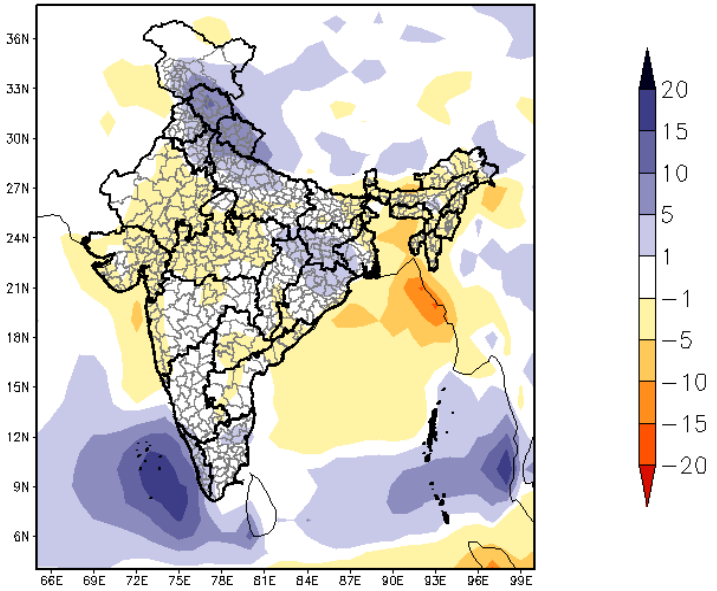


15th August 2018
"DWR_Kochi"

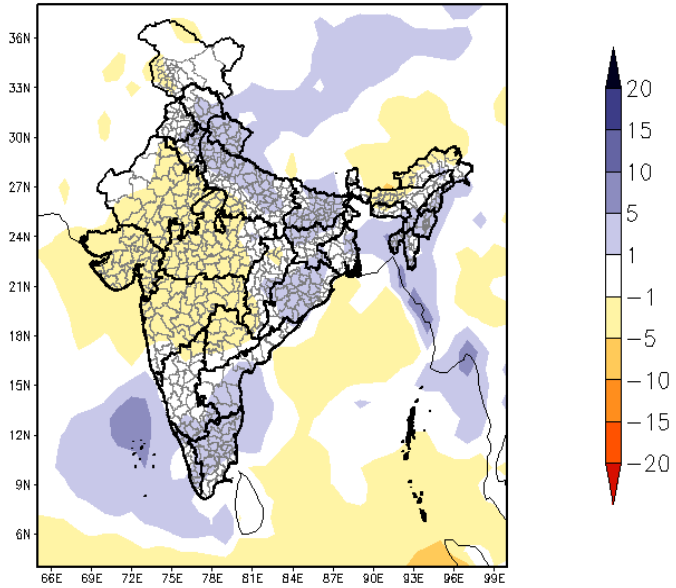
MME Weekly Rainfall Anomaly (mm/day)
(Week1: 10Aug-16Aug)



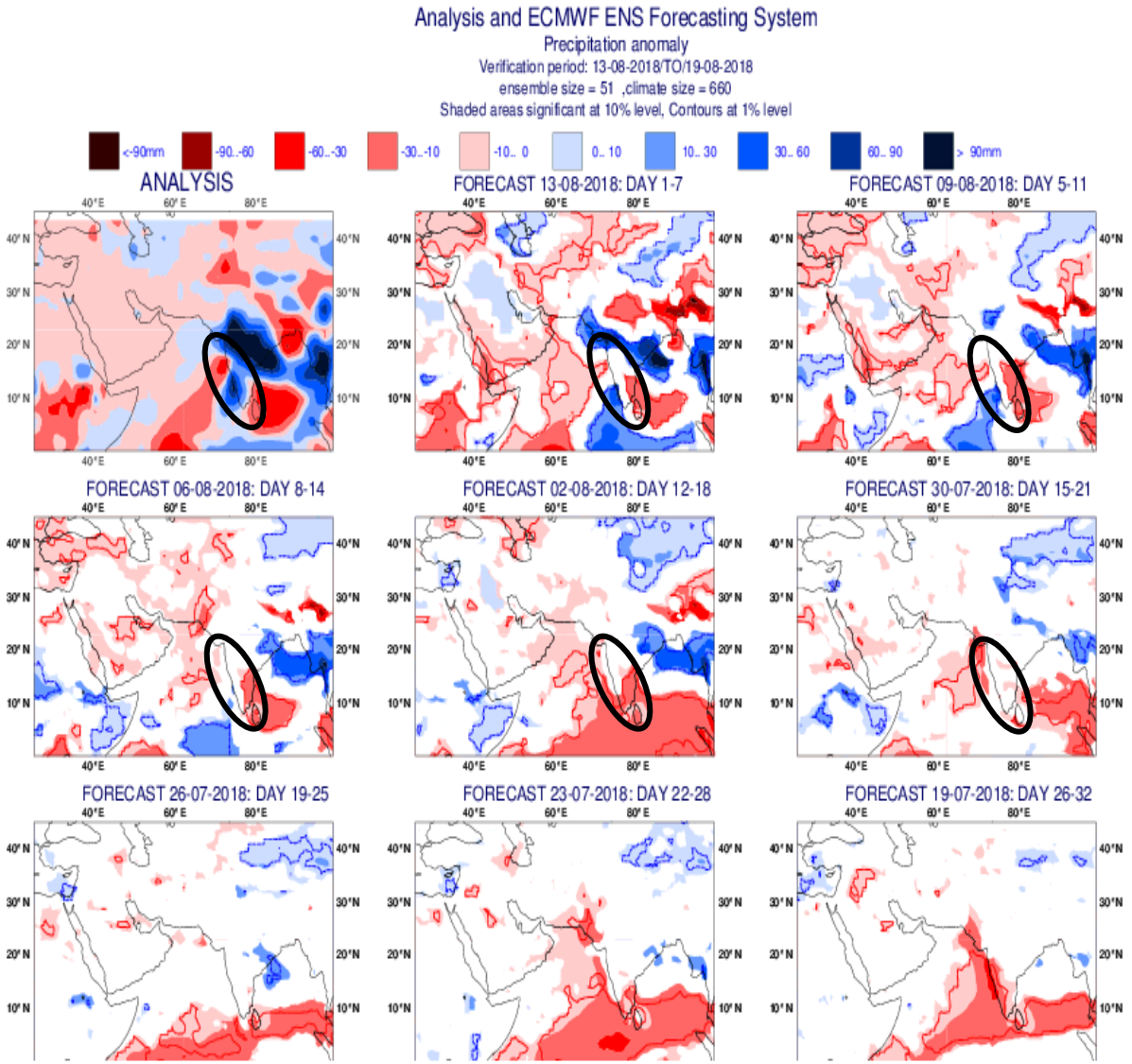
MME Weekly Rainfall Anomaly (mm/day)
(Week2: 10Aug-16Aug)



MME Weekly Rainfall Anomaly (mm/day)
(Week3: 10Aug-16Aug)

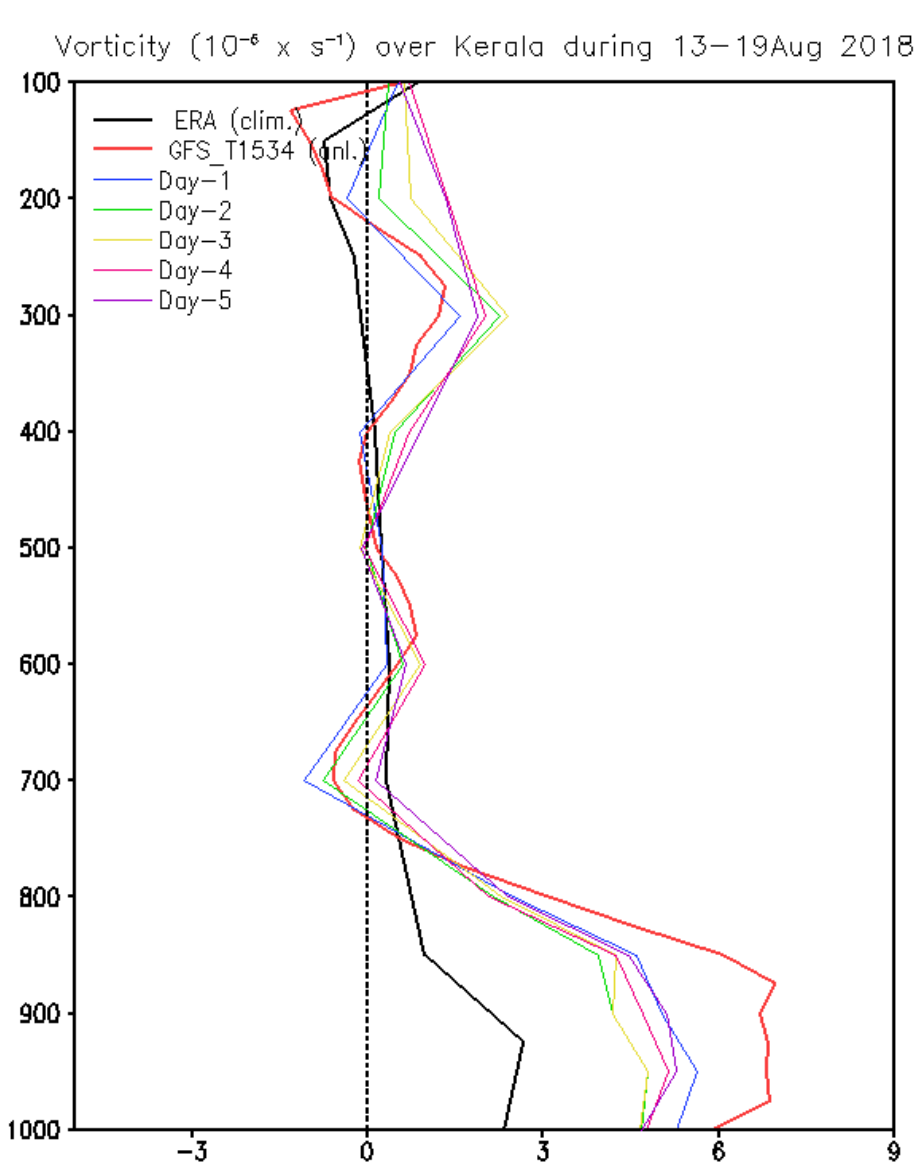


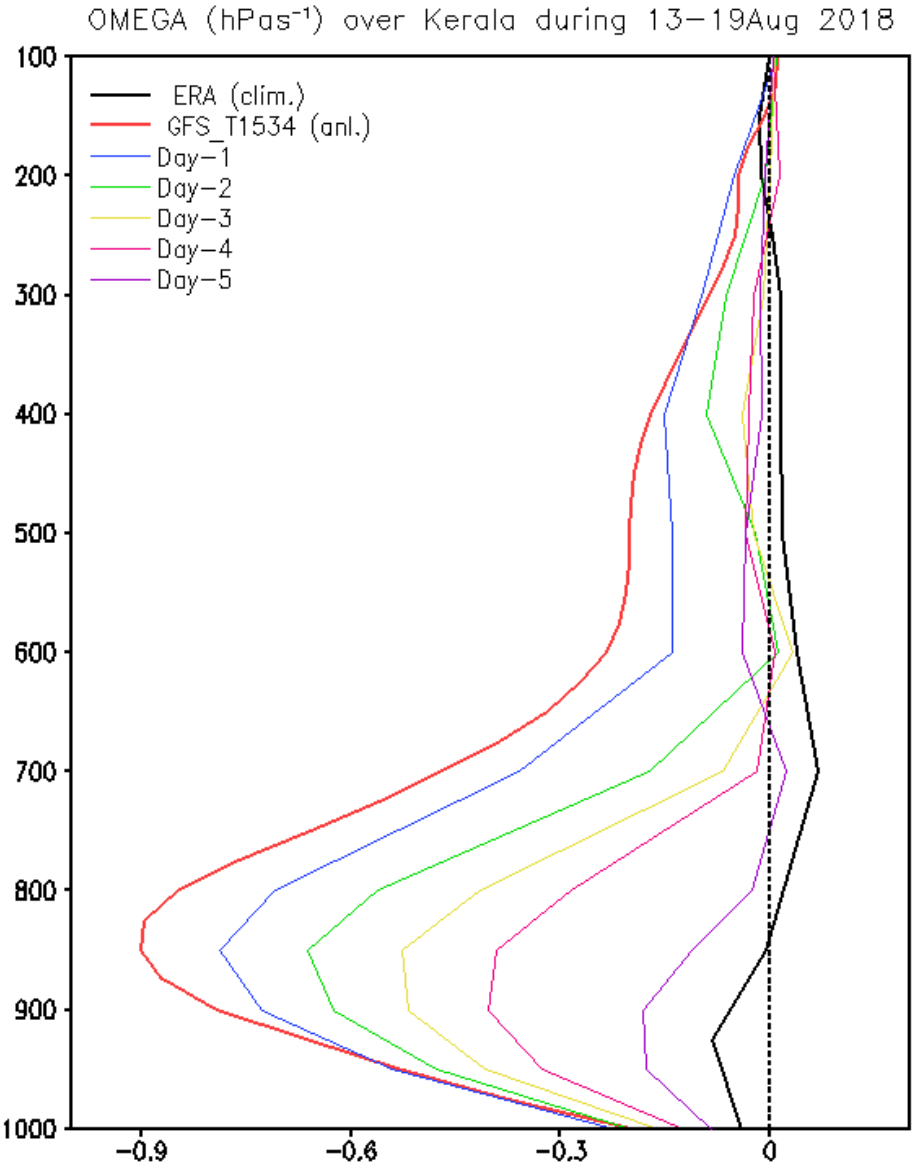
ENS weekly TP fc over India for 20180813-0819



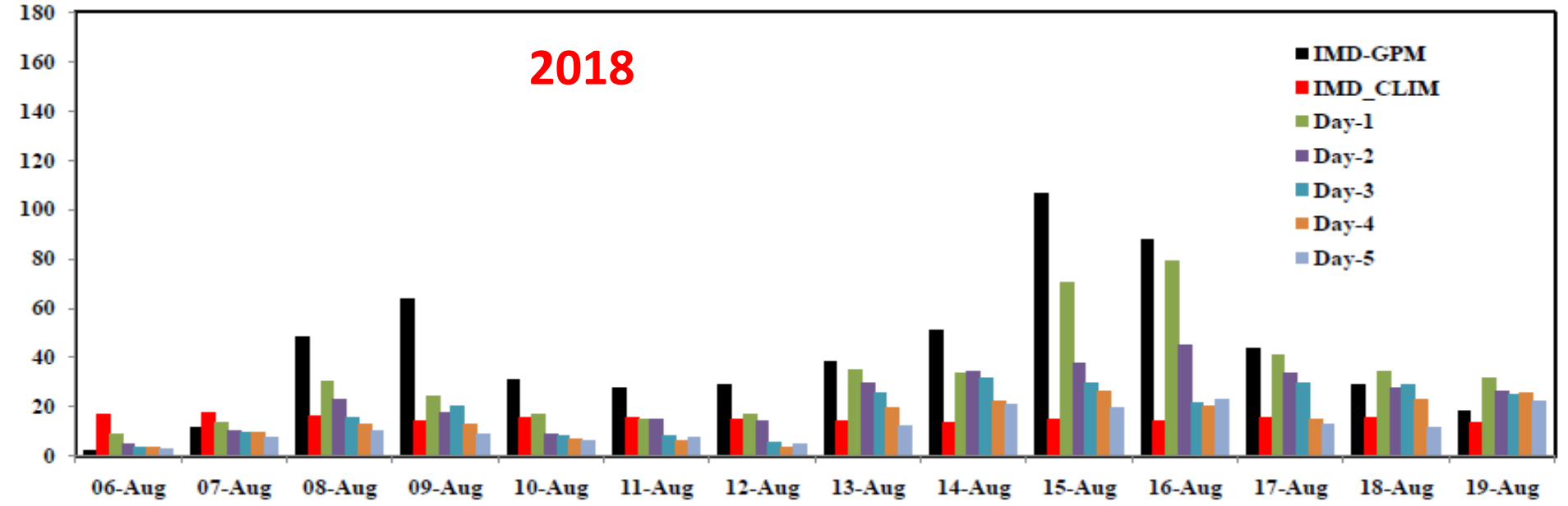
ECMWF

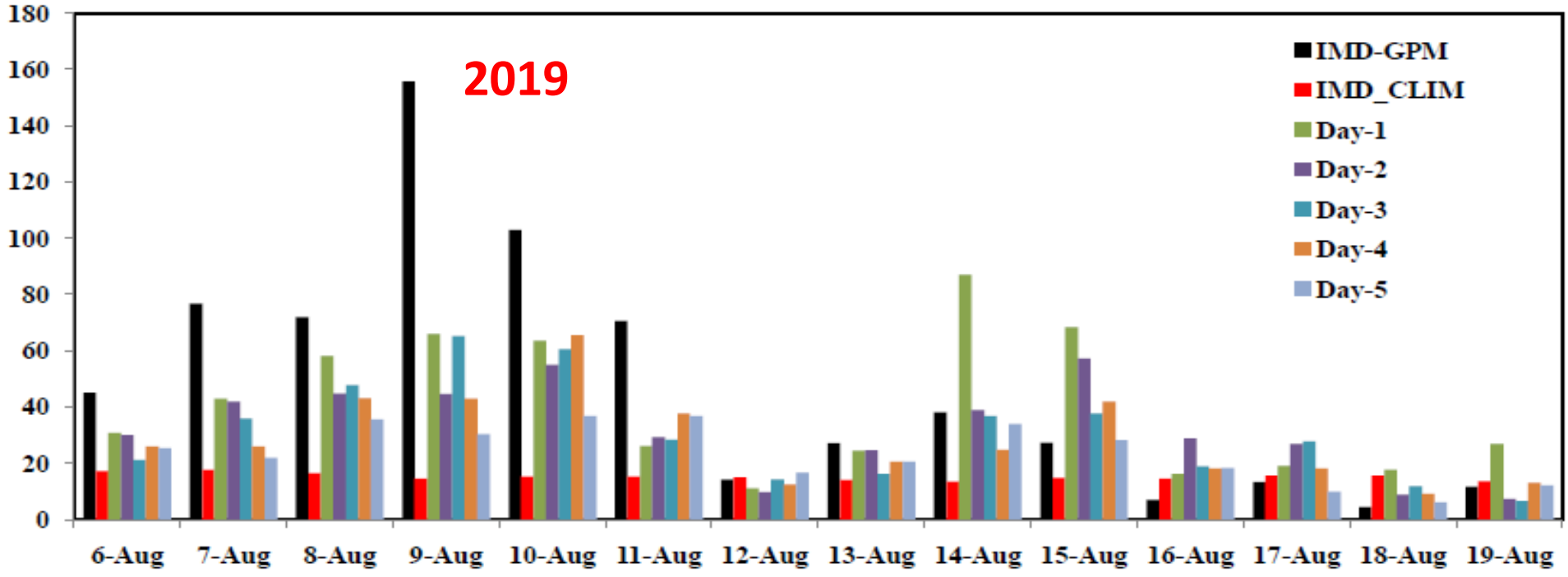
Slide borrowed from Roberto Buizza, ECMWF

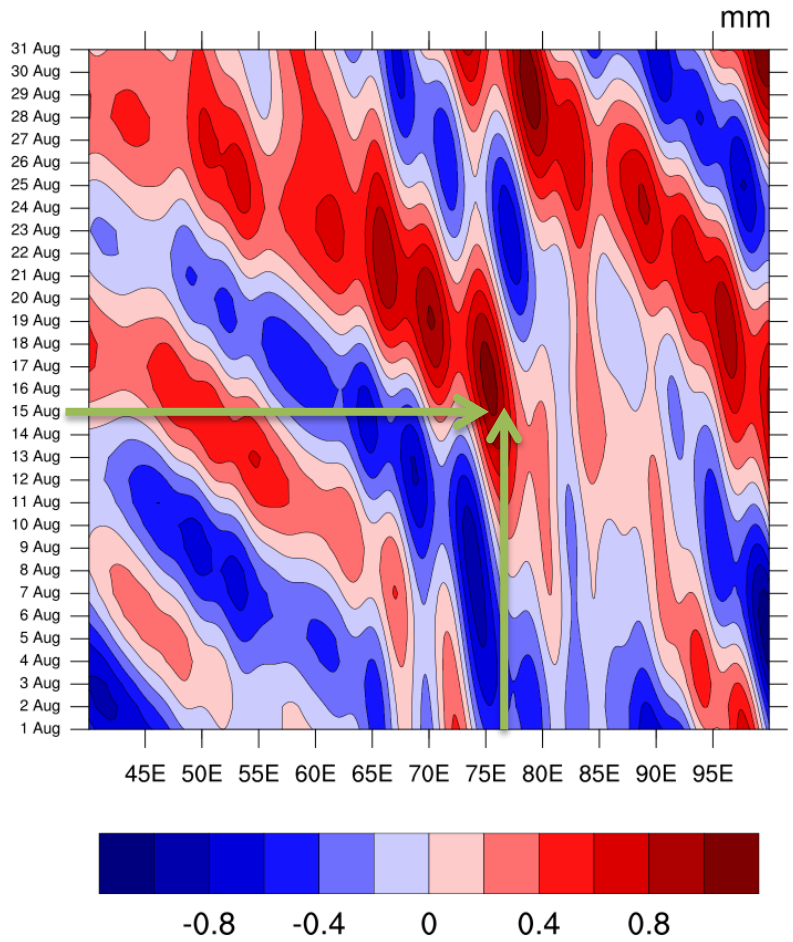

Vorticity (10^{-6} x s^{-1}) over Kerala during 13–19Aug 2018
ERA (clim.)
GFS_T1534 (anl.)
Day–1
Day–2
Day–3
Day–4
Day–5
100
200
300
400
500
600
700
800
900
1000
−3
0
3
6
9


OMEGA (hPas^{-1}) over Kerala during 13–19Aug 2018
ERA (clim.)
GFS_T1534 (anl.)
Day–1
Day–2
Day–3
Day–4
Day–5
100
200
300
400
500
600
700
800
900
1000
−0.9
−0.6
−0.3
0

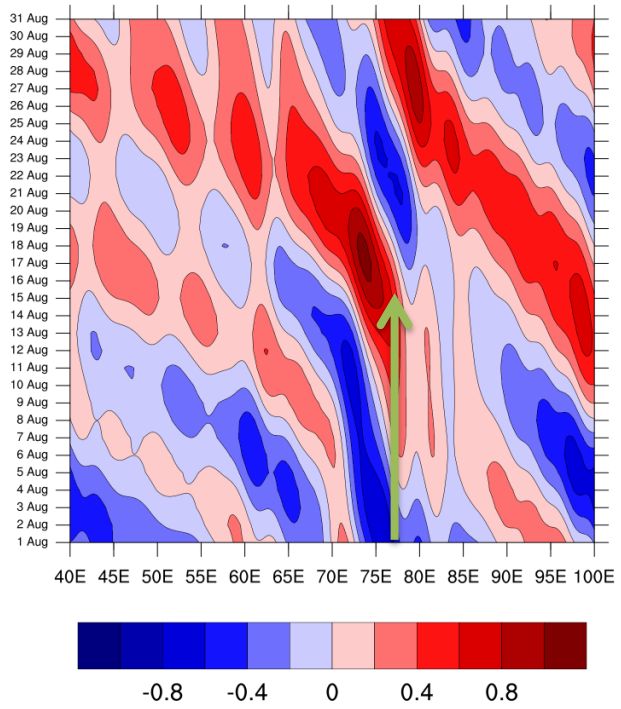
Rainfall (mm/day) time series over Kerala during 06-19Aug from GFS T1534



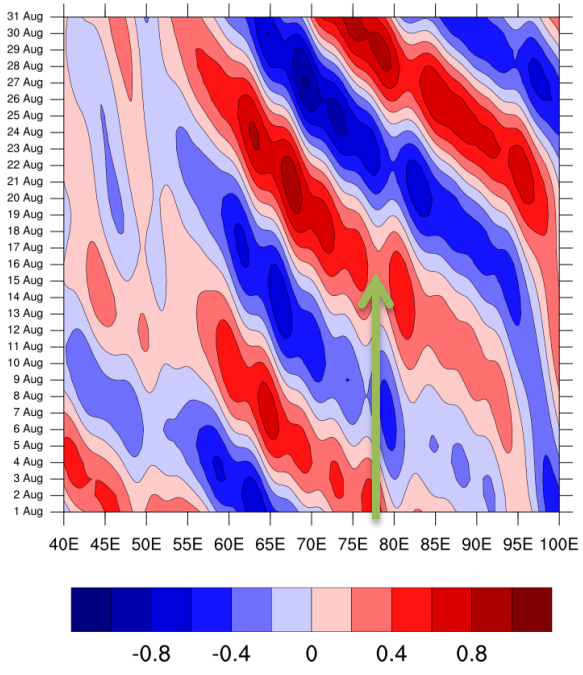




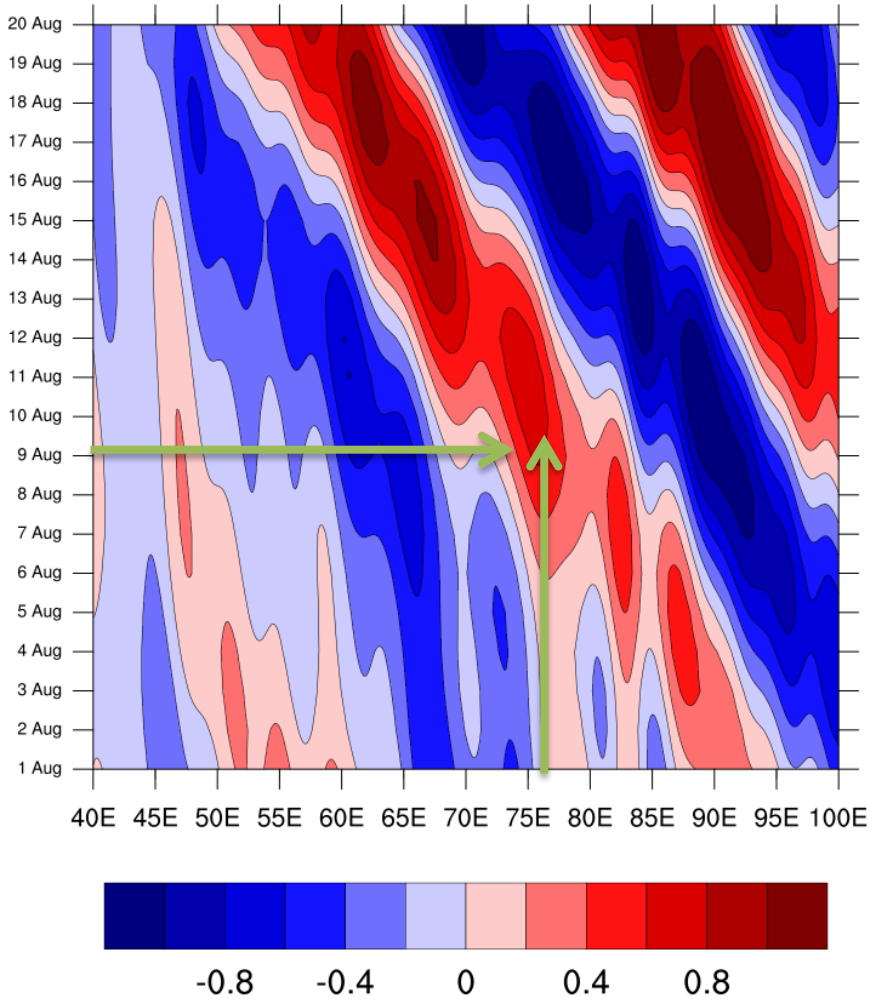
Rossby wave filtered anomaly of rainfall from 1 Aug to 31 Aug 2018



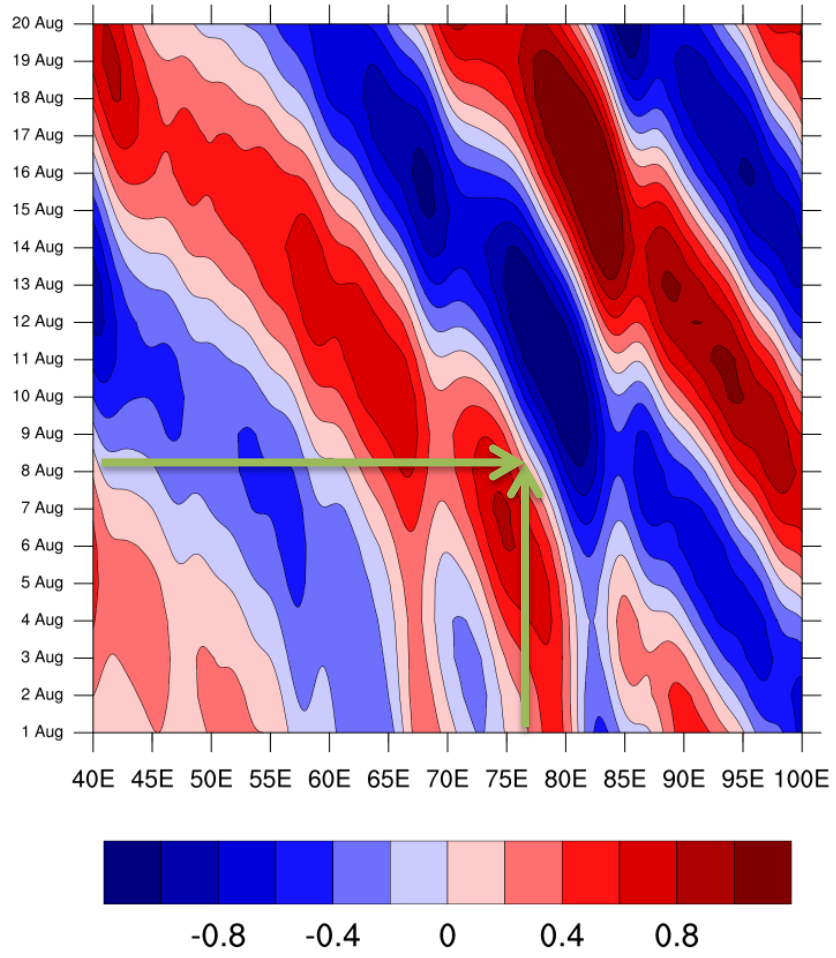
24hr FCST GFS T1534



120 hr FCST GFS T1534

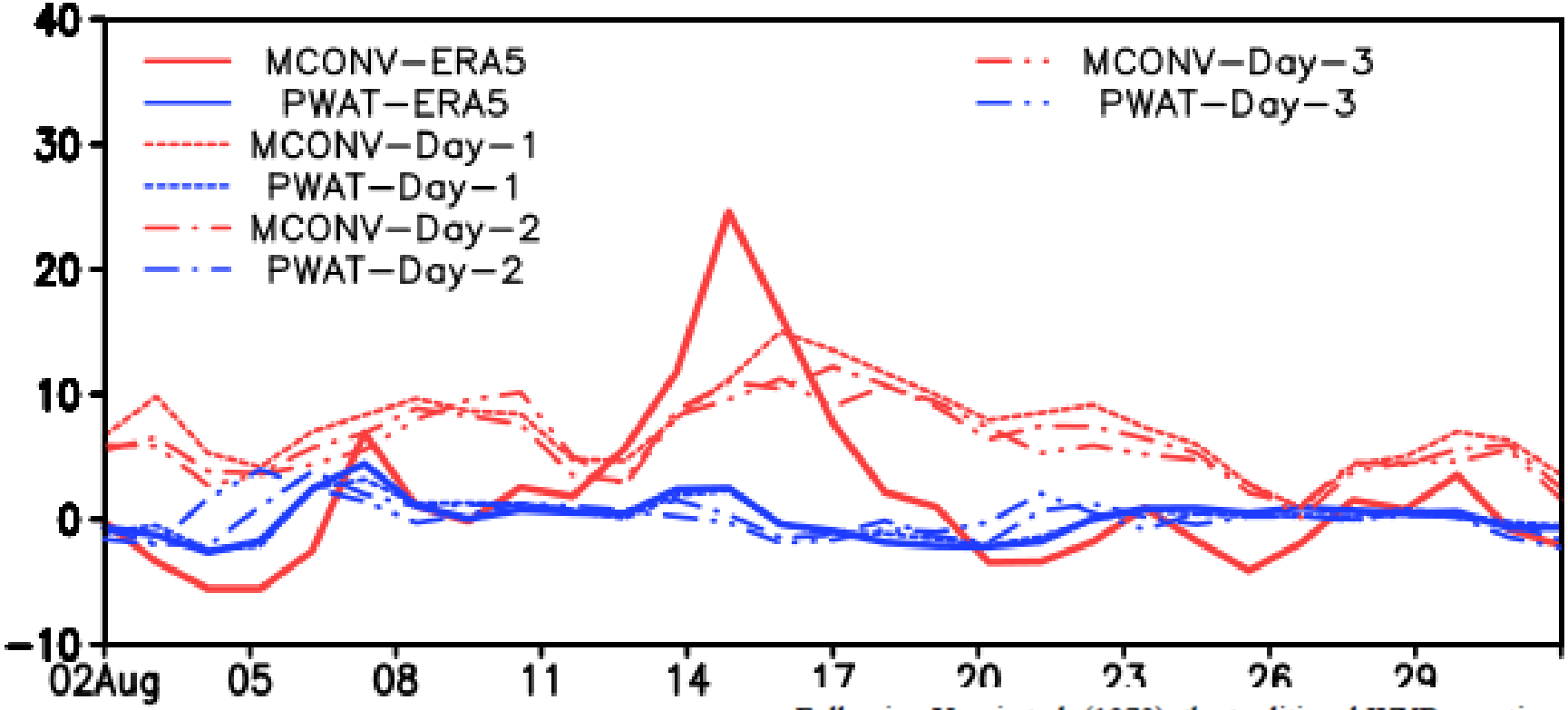


24 hr Forecast Rossby wave filtered anomalous rainfall



120 hr FCST

Vertically integrated moisture convergence and tendency of precipitable water vapour daily (mm/day)



Tendency in PWV is governed by source (moisture convergence) and Sink (Precipitation) terms. Tendency term is relatively small, giving an indication that moisture convergence is balanced by precipitation upto a large extent

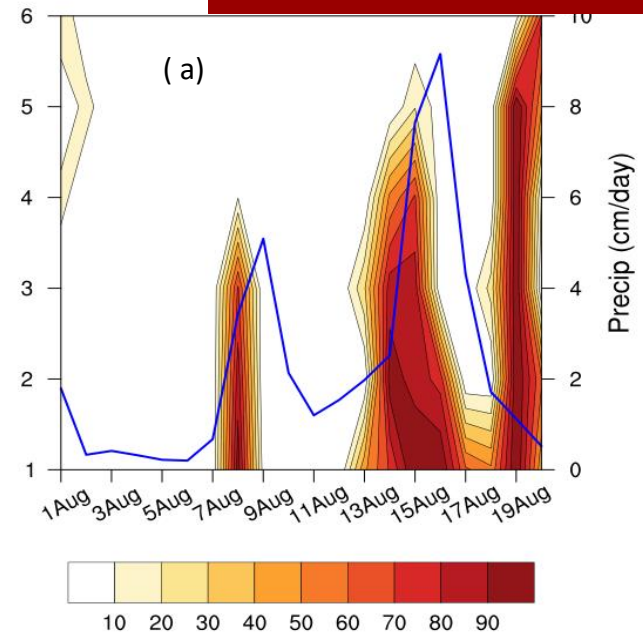
Following Yanai et al. (1973), the traditional WVB equation may be expressed in the following form:

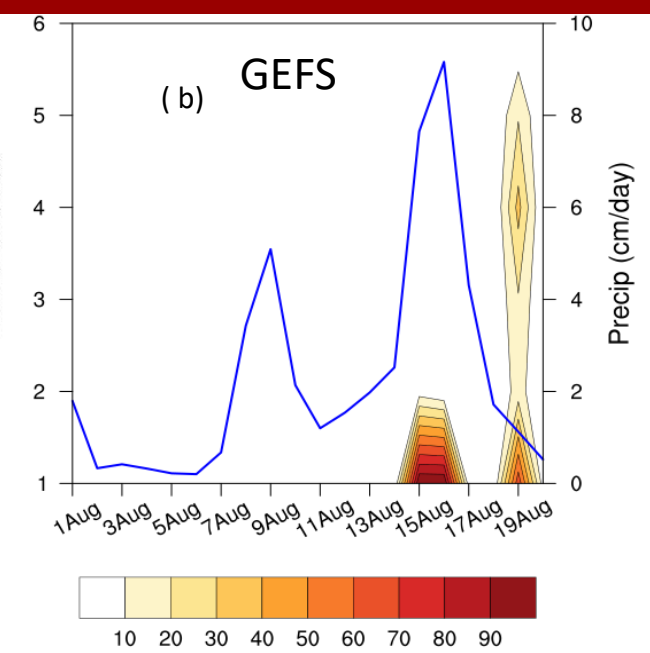
$$\frac{1}{g}\frac{\partial}{\partial t}\int_S^T q\,dp + \frac{1}{g}\int_S^T \nabla \cdot qV\,dp = \mathrm{E} - \mathrm{P}. \qquad (1)$$

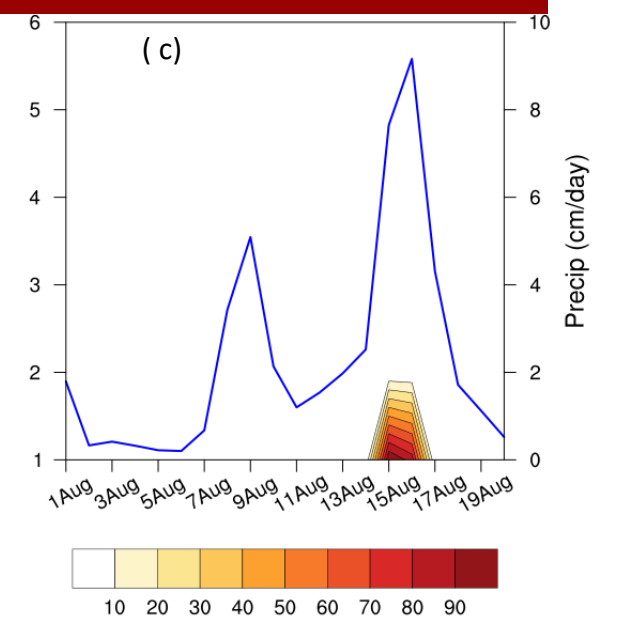
dPW MFD

Where, q is specific humidity, p is atmospheric pressure, V is the horizontal wind vector, g is the acceleration due to gravity, S and T indicate the land/ocean surface and an upper integration limit, respectively, E is the surface evaporation rate, P is precipitation, dPW is the time change of atmospheric water vapor (precipitable water, PW), and MFD is the horizontal moisture flux divergence.

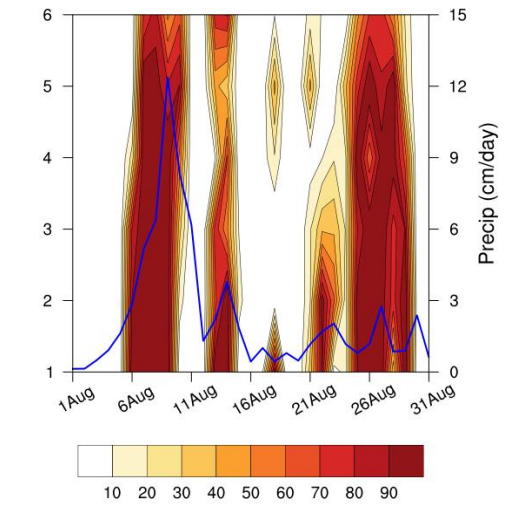
GEFS Probabilistic forecast for Kerala heavy rain during August 2018 and 2019



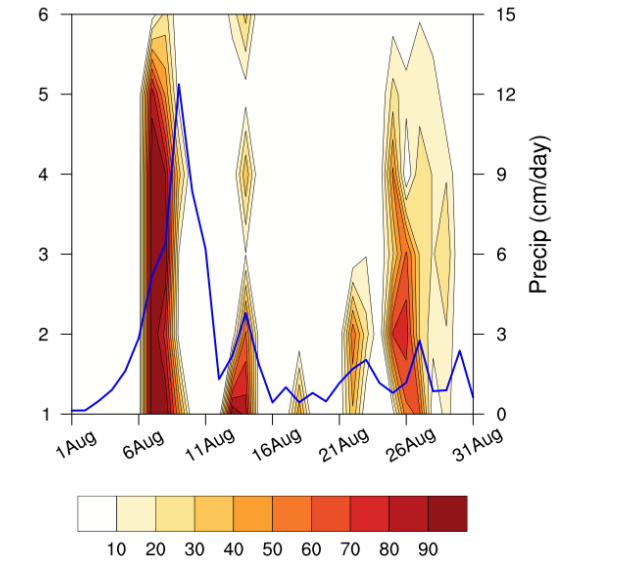




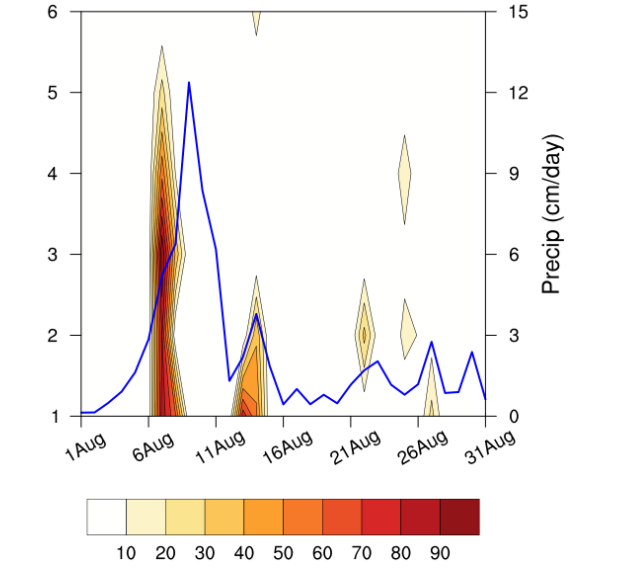
Threshold~Clim +1sd



Clim+2sd

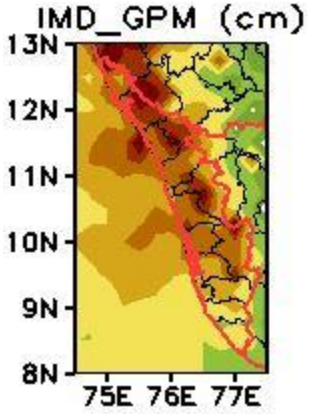


Clim+3sd

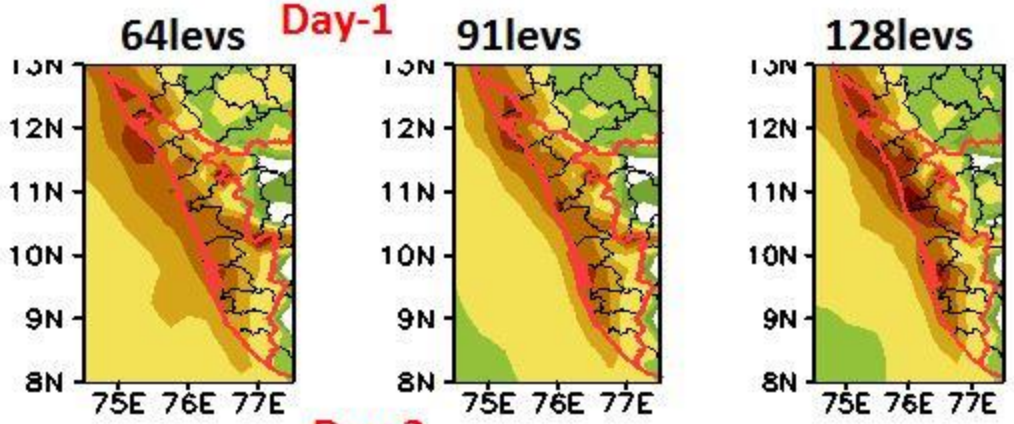


Better skill in 2019 in general is achieved by sorting out/resolving initial condition issues in 2018

Accumulated rainfall (cm) between 01-20th August 2019

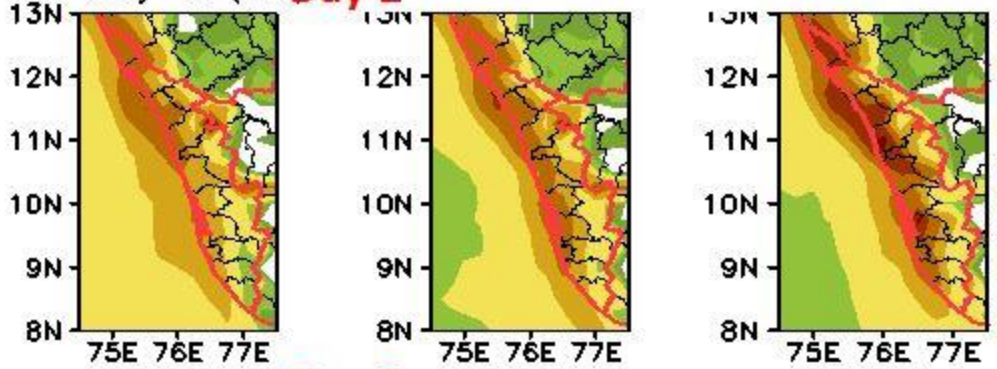


Day-1

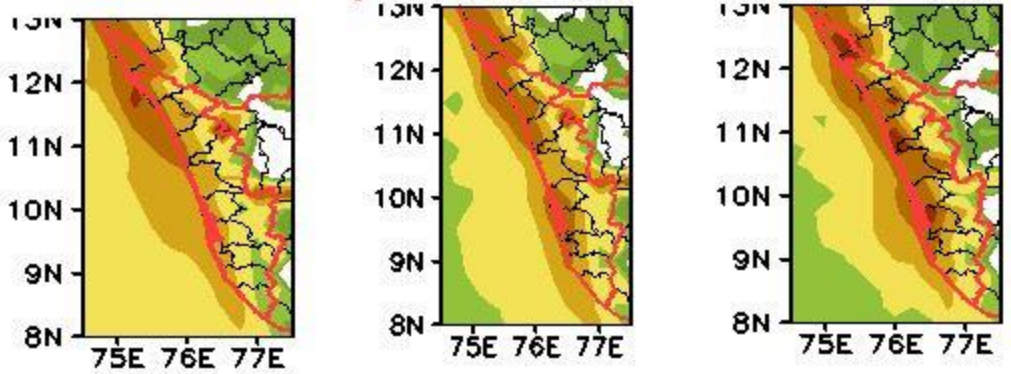


GFS T1534

Day-2



Day-3



Enhanced Vertical Res.

Scale Aware Stochastic Physics

Ensemble/Probabilistic approach

CFS/GFS Vertical levels

CFST62L64

CFST82L64

CFST126L64

GFST254L64

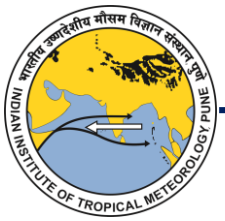
CFST382L64

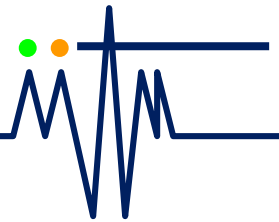
GFST574L64

GFST1534L64

GFST1534L128 (31 levels within 800hPa)

New Approach of Dycore in GFS





Update in Dynamic Core: Spectral Cubic Octahedral grid

Conventional Spectral grid:

- **Not scalable**
- **I/O**
- **Artificial diffusion damping**
- **Negative tracer**

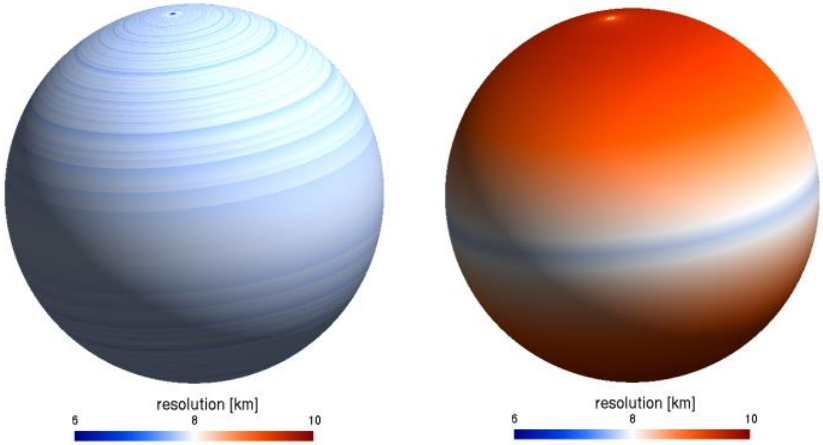
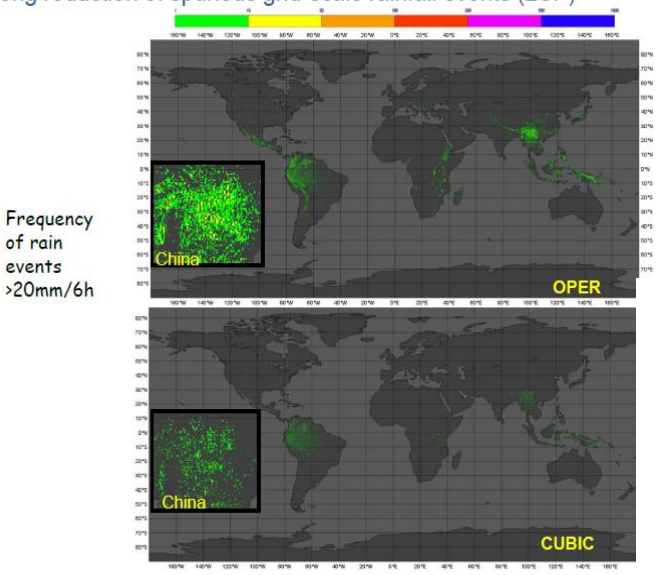
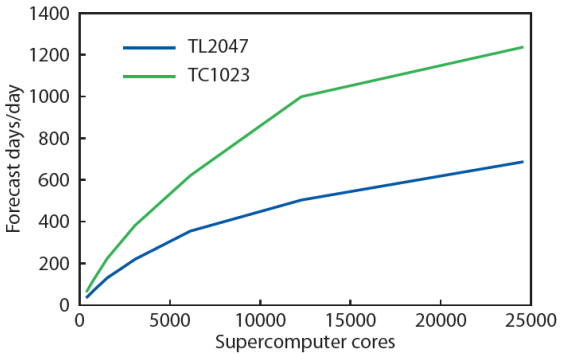


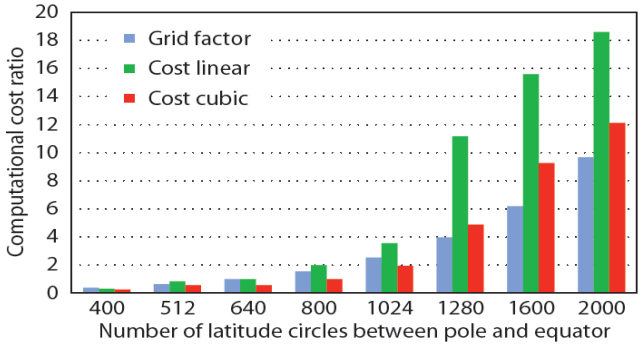
Figure (adopted from ECMWF News Letter 146) demonstrates that the octahedral mesh (right) has a locally more uniform dual-mesh resolution than the mesh (left).

Improvements: ….

Strong reduction of spurious grid-scale rainfall events (LSP)



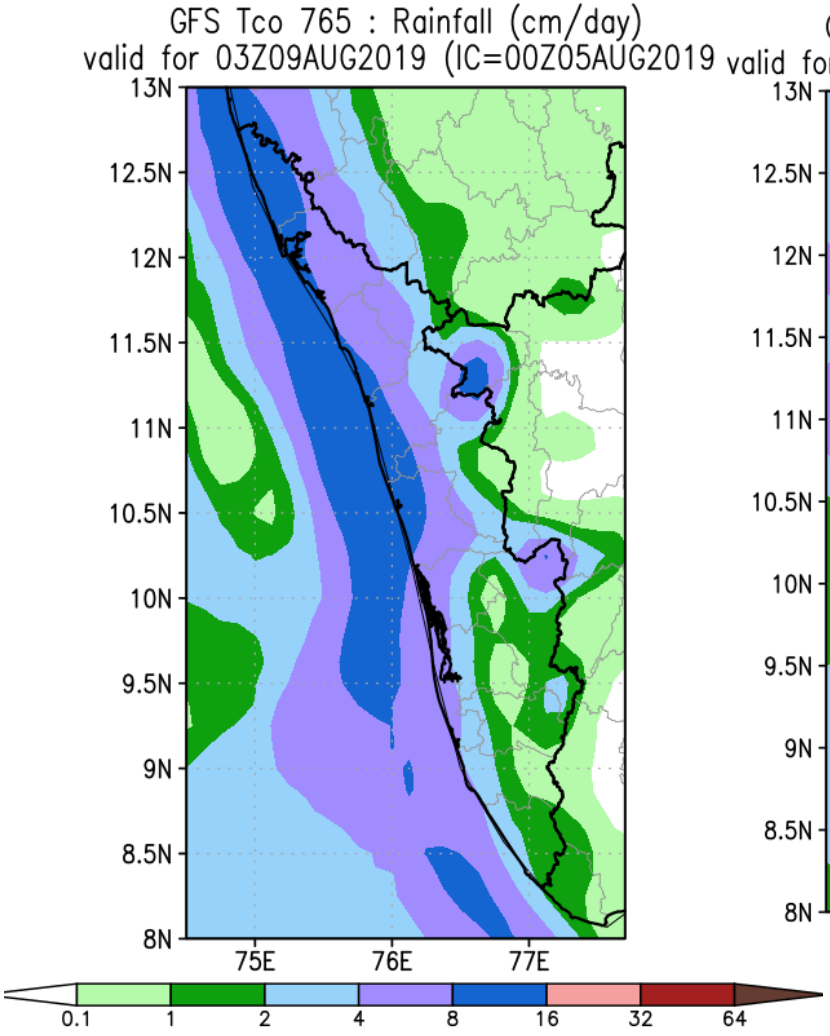




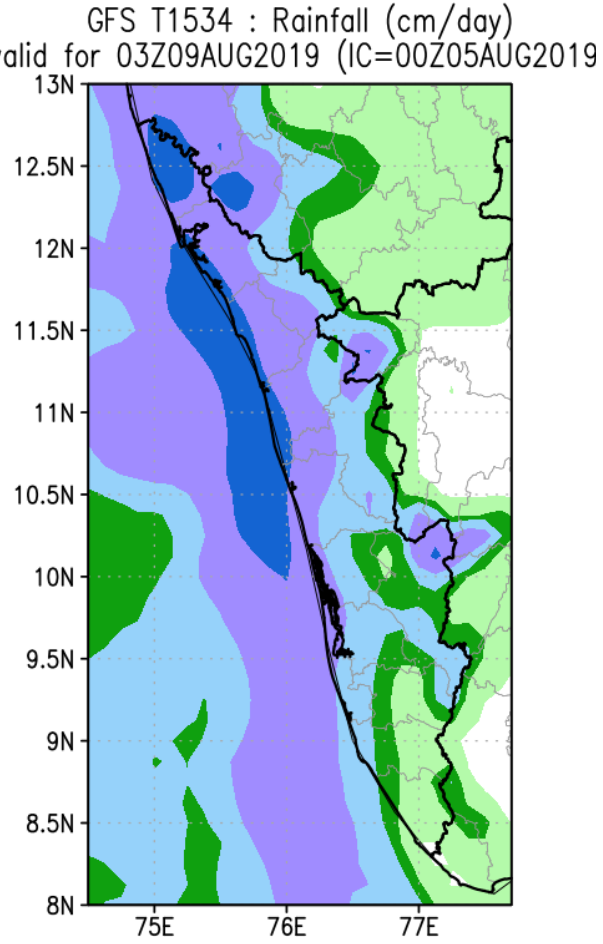
Numerical simulation of an idelaised baroclinic instability, conducted using IFS model on both the mesh showed the octahedral grid results in higher accuracy and substantially reduced unphysical flow distortions accuracy mainly as the approach depends on the underlying mesh which defines the shape of the elementary volumes around which the computations are made (ECMWF New Letter, No. 146, 2015).

96 hour forecast

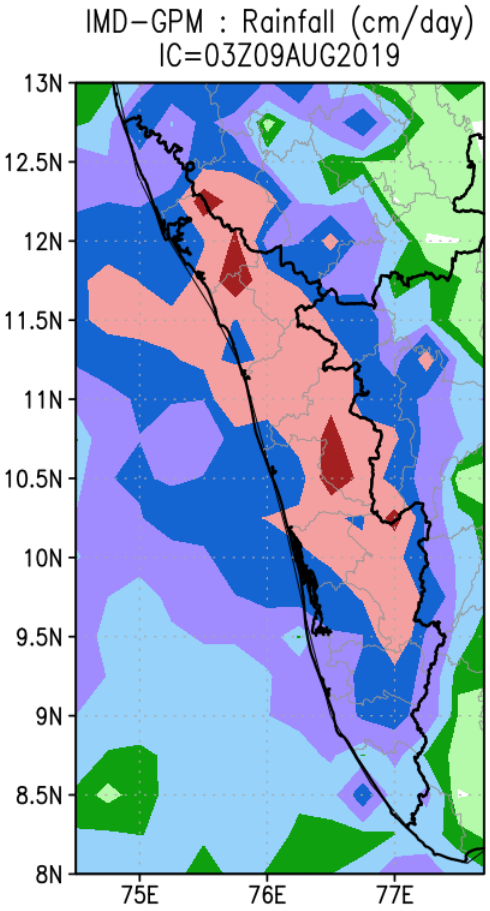
OBS



Tco765



T1534

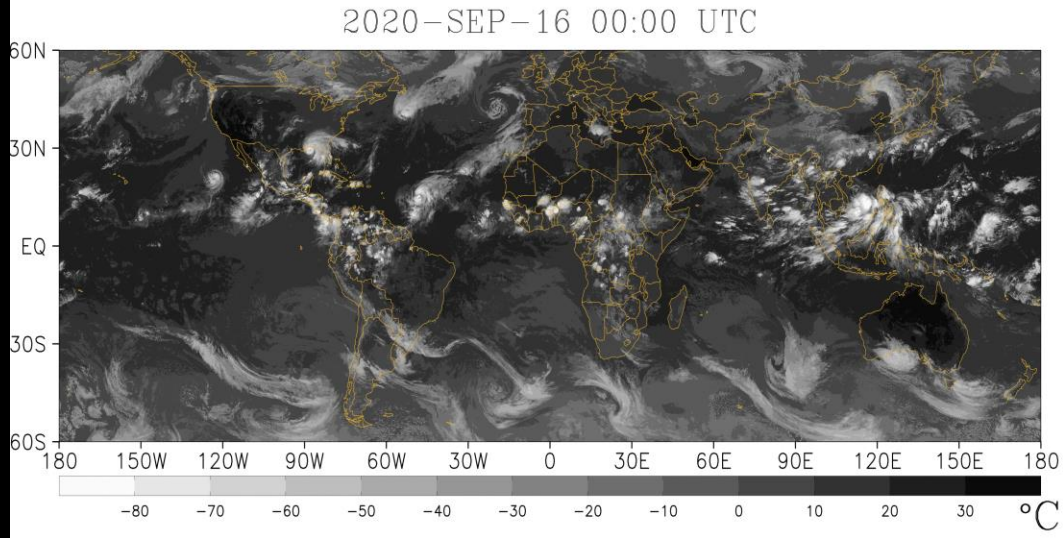


Summary

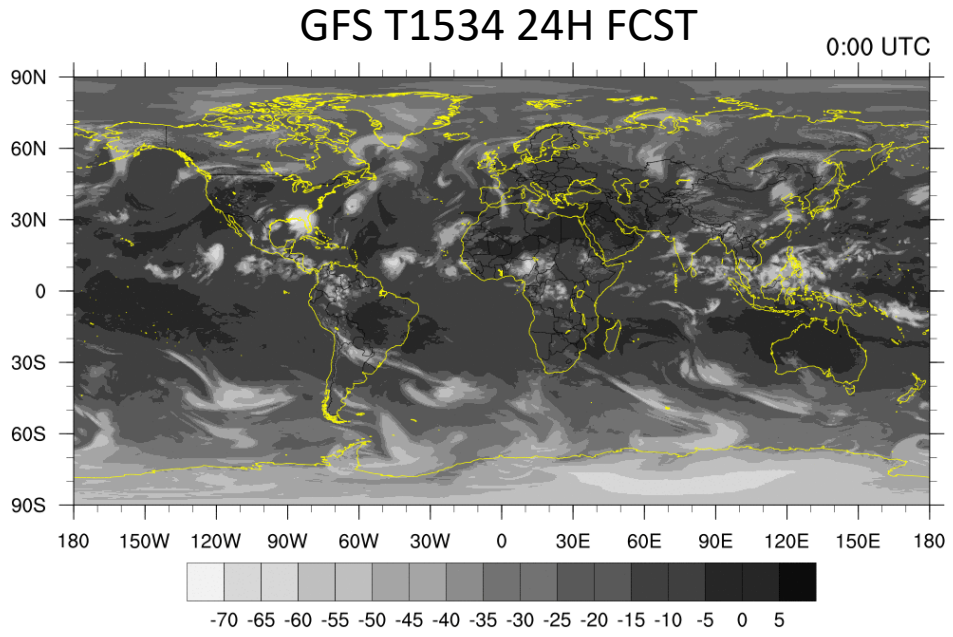
- The way forward is the probabilistic forecast of extremes
- Ensemble prediction system based on GEFS is able to provide better forecast for extreme events/high impact events with longer lead time.
- Ensemble prediction provides better skill for high impact weather in longer lead.
- The heavy rain of Kerala of 2018 and 2019 appear to be influenced by westward propagating Rossby wave phase and large scale moisture convergence resulting extremely heavy rain.

- Models show fidelity in capturing the Rossby wave propagation but limited fidelity in moisture convergence.

- Percentile based forecast provide better forecast guidance with longer lead time
- Tco shows promise in improving the rainfall forecast over western Ghat. Tco based GFS is under development



Satellite Obs. Brightness temperature



Following Lopez et al. 2020, BAMS