A convection permitting model: IITM HGFM to improve High Impact weather prediction

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[4]UVIC, Canada

Outline of the talk

- The backdrop: Increasing trend of extreme rainfall events
- The extreme events over Kerala August 2018 & 2019 and its forecast (Deterministic vs Ensemble: GFS vs GEFS)
- Approaches to improve the dynamical model (GFS)
- Development of IITM HGFM (Tco 6.5km resolution)
- Summary

What did we hear so far on Dynamical model since day 1 of STIPMEX

KM scale model

Stochastic Approaches

EPS: Ensemble Prediction System

Vertical Resolution

Hybrid NWP+AI

Increasing Trend of Extreme Rain Events Over India in a Warming Environment

Goswami et al. 2006

Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data

Rajeevan et al. 2008

A threefold rise in widespread extreme rain events over central India

Roxy et al. 2017

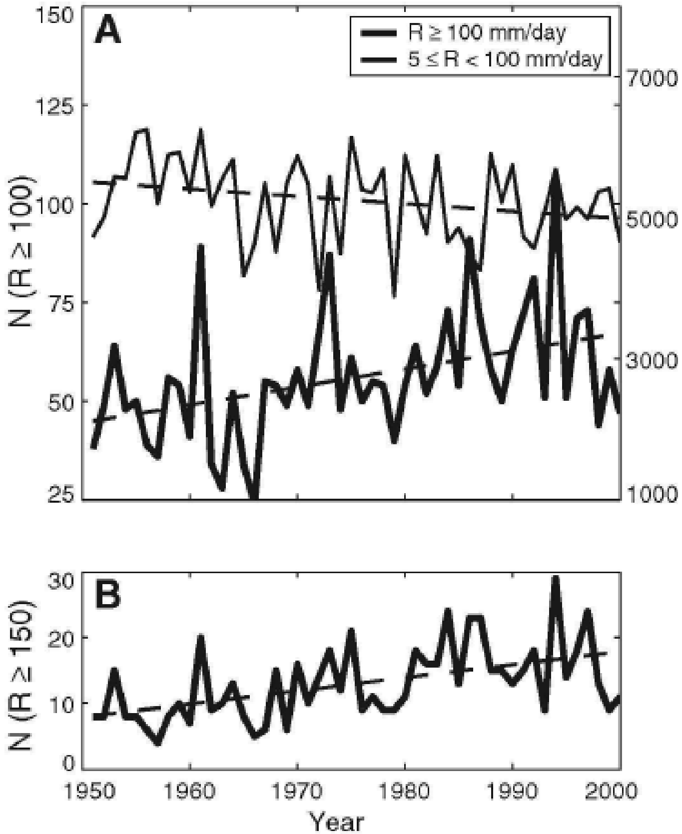
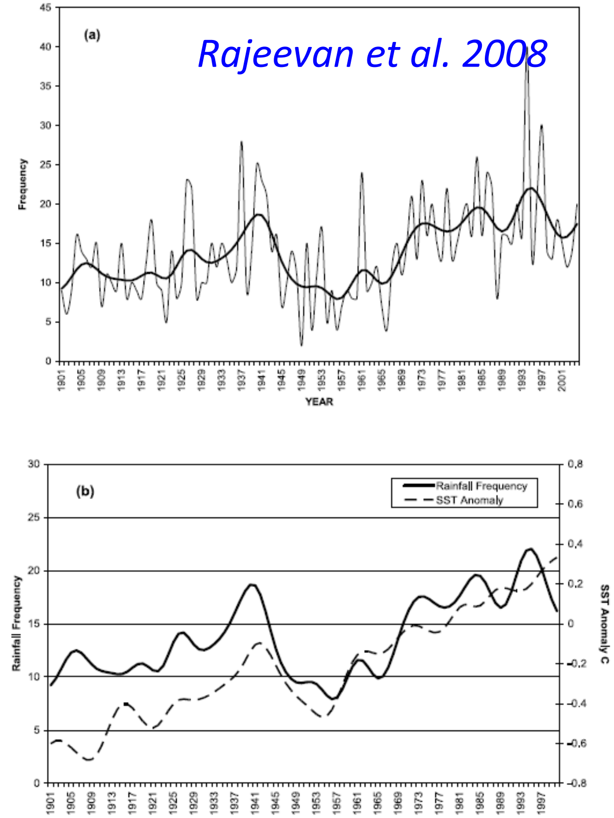


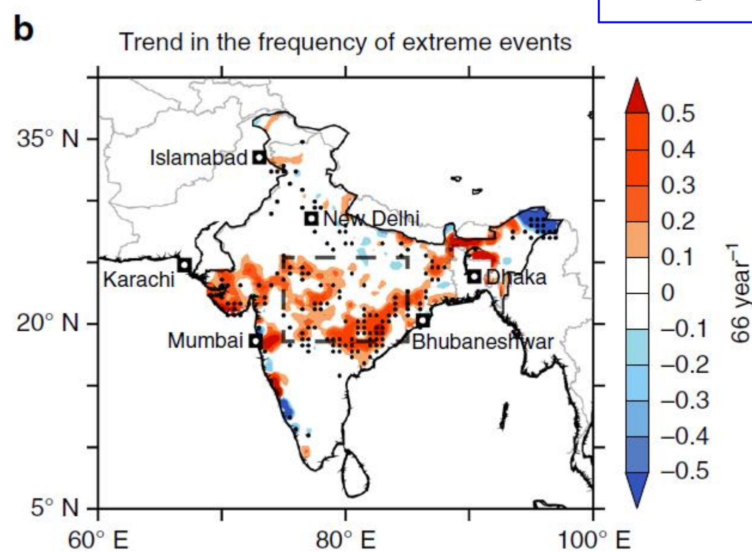
Fig. 3. Temporal variation (1951 to 2000) in the number (*N*) of (**A**) heavy (*R* ≥ 100 mm/day, bold line) and moderate (5 ≤ *R* < 100 mm/day, thin line) daily rain events and (**B**) very heavy events (*R* ≥ 150 mm/day) during the summer monsoon season over CI. The statistical significance of the trends (dashed lines) was calculated as in Fig. 2.

Goswami et al. 2006



Rajeevan et al. 2008

(a) Temporal variation of frequency of very heavy rainfall events (R 150 mm/day) over central India (thin solid line) and its smoothed variation (thick solid line) for the period 1901–2004. (b) Smoothed variation of frequency of very heavy rainfall events over central India and SST anomalies over the Equatorial Indian Ocean. The smoothing has been done to remove the sub-decadal fluctuations using a 13-point filter [IPCC, 2007].



Roxy et al. 2017

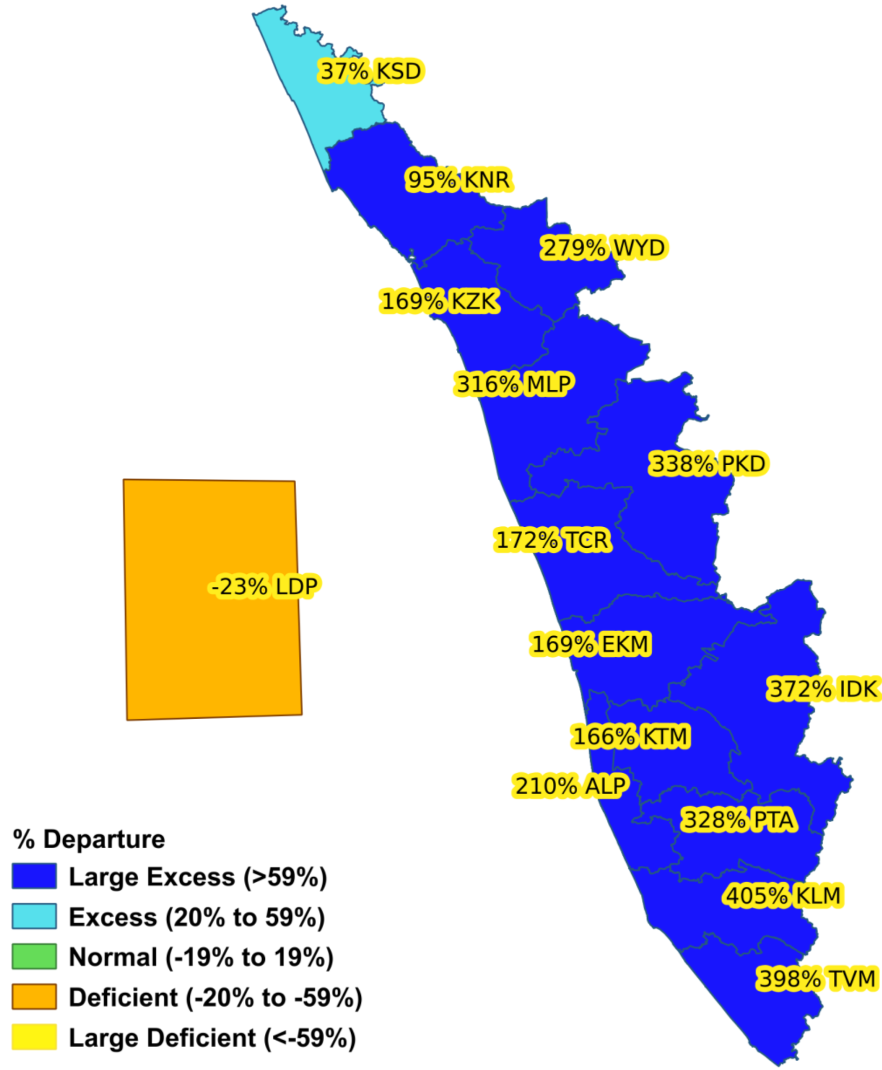
THE KERALA DELUGE AUGUST 2018

Ref: CWC Report, Sept, 2018

RAINFALL % DEPARTURES FROM THE LONG PERIOD AVERAGES FOR DISTRICTS IN KERALA.

Period 06.08.18 to 19.08.18
Actual: 704 mm
Normal: 209 mm
Dep From Normal: 236%

KSD - KASARAGOD
KNR - KANNUR
WYD - WAYANAD
KZK - KOZHIKODE
MLP - MALAPPURAM
PKD - PALAKKAD
TCR - THRISSUR
EKM - ERNAKULAM
IDK - IDUKKI
KTM - KOTTAYAM
ALP - ALAPPUZHA
PTA - PATHANAMTHITTA
KLM - KOLLAM
TVM - THIRUVANANTHAPURAM
LDP - LAKSHADWEEP

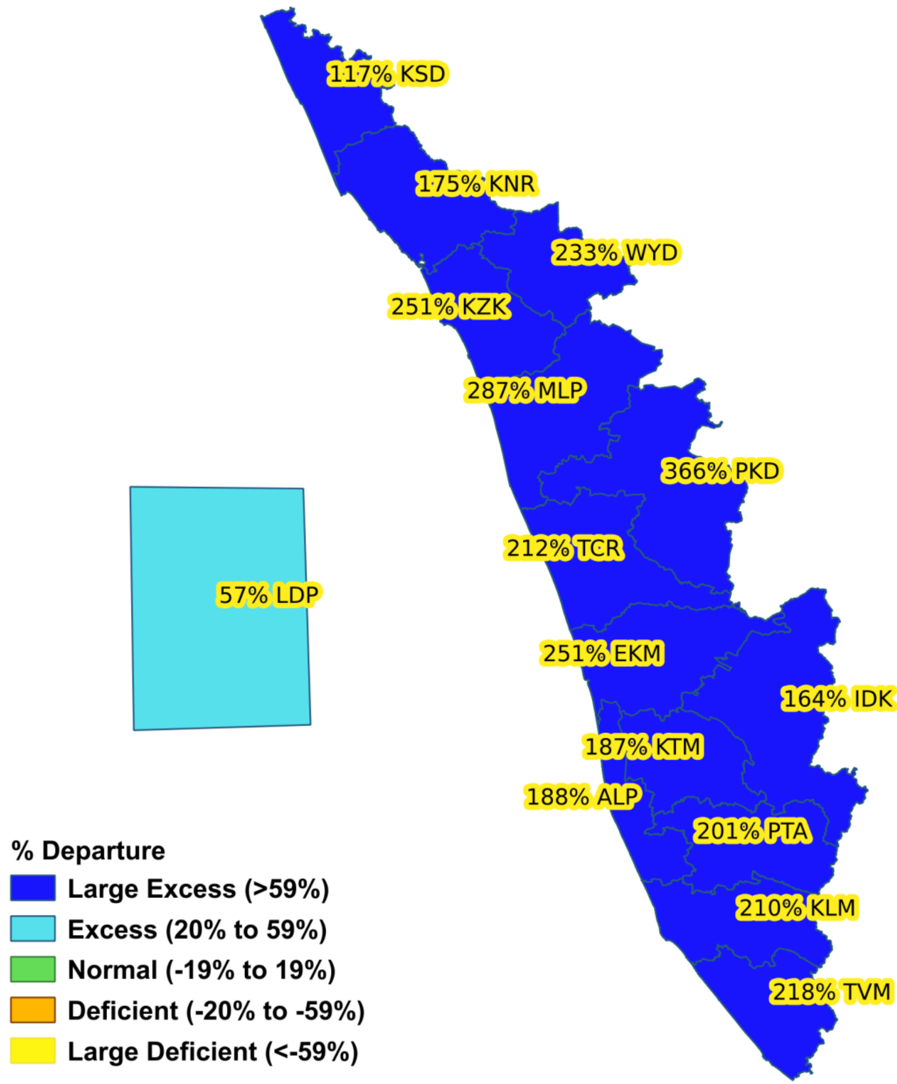


Mukhopadhyay et al. 2021, WAF

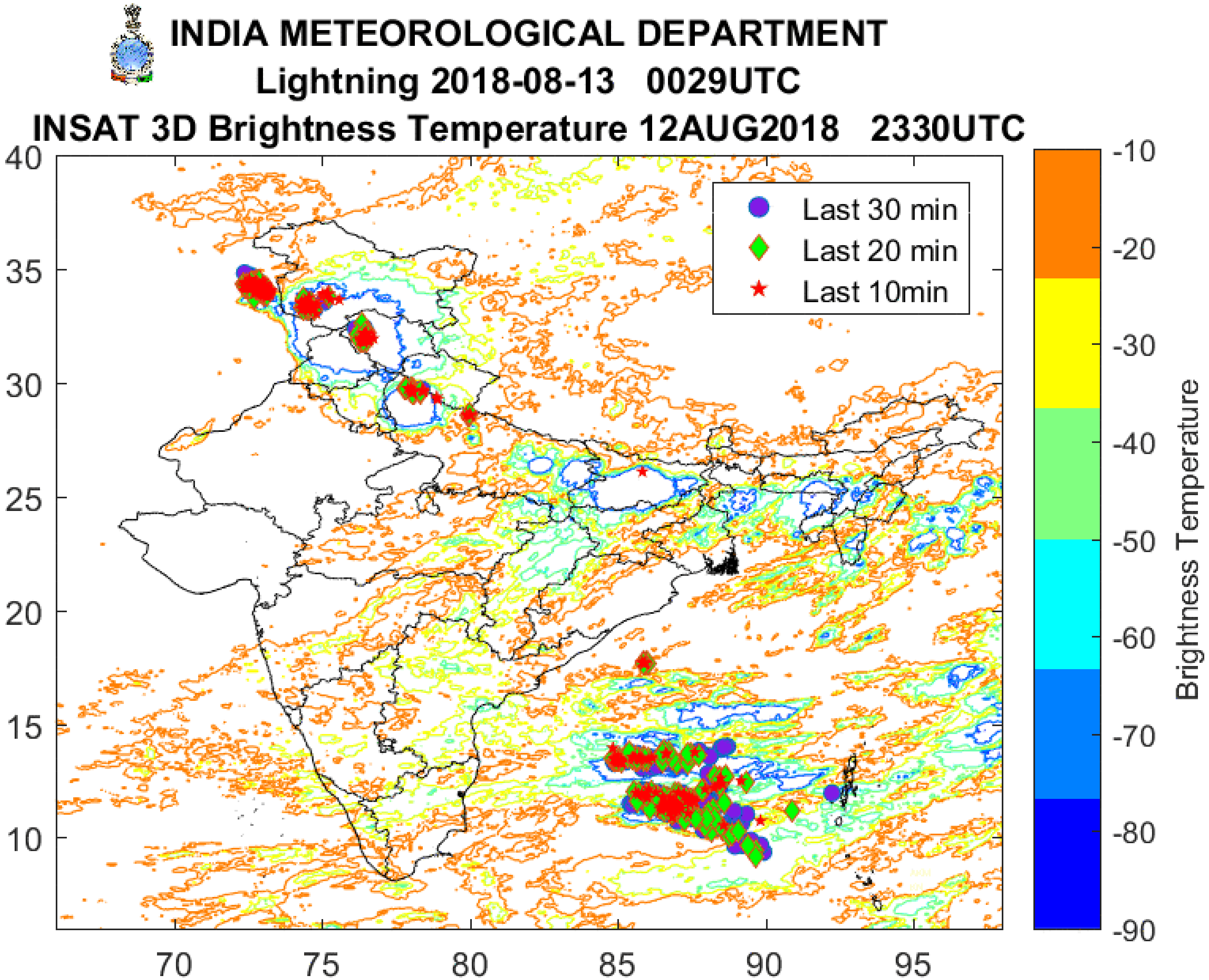
RAINFALL % DEPARTURES FROM THE LONG PERIOD AVERAGES FOR DISTRICTS IN KERALA.

Period 06.08.19 to 19.08.19
Actual: 668 mm
Normal: 209 mm
Dep From Normal: 219%

KSD - KASARAGOD
KNR - KANNUR
WYD - WAYANAD
KZK - KOZHIKODE
MLP - MALAPPURAM
PKD - PALAKKAD
TCR - THRISSUR
EKM - ERNAKULAM
IDK - IDUKKI
KTM - KOTTAYAM
ALP - ALAPPUZHA
PTA - PATHANAMTHITTA
KLM - KOLLAM
TVM - THIRUVANANTHAPURAM
LDP - LAKSHADWEEP

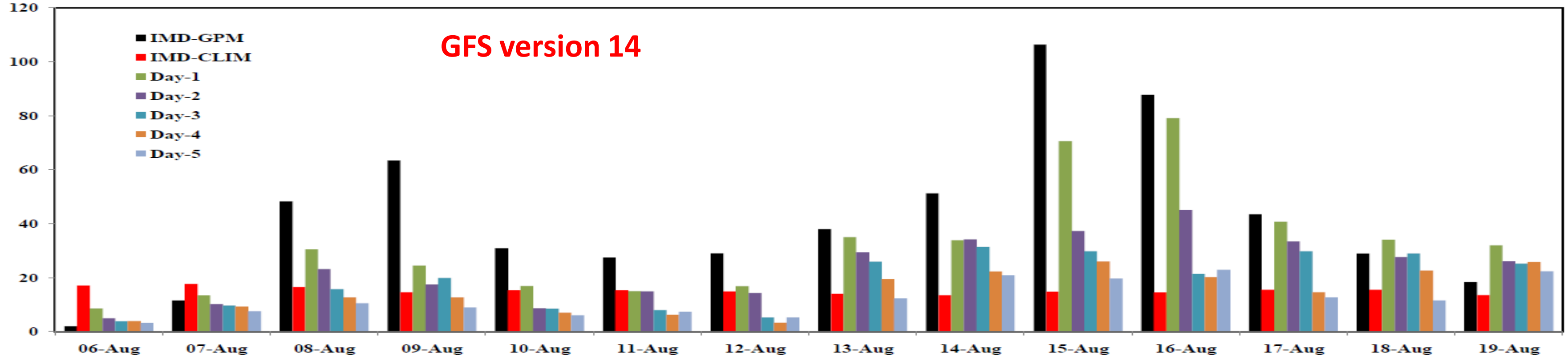


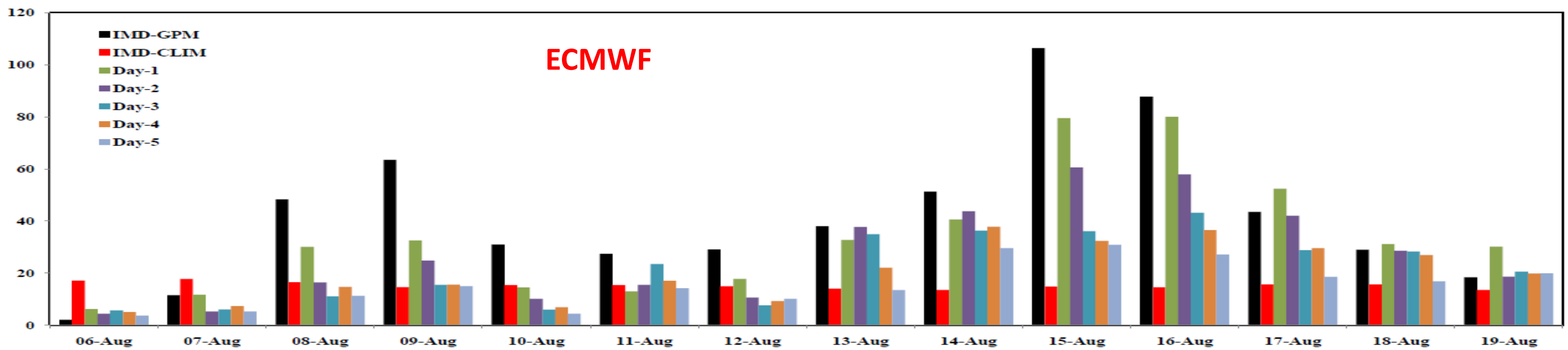
	06.08.2018 to 19.08.2018				06.08.2019 to 19.08.2019			
	Climatological Mean (mm)	Climatological SD(mm)	Actual Mean(mm)	Actual SD(mm)	Climatological Mean(mm)	Climatological SD(mm)	Actual Mean(mm)	Actual SD(mm)
Kerala	14.95	1.12	50.29	41.67	14.95	1.12	47.74	44.43
Alappuzha	11.21	1.38	34.76	31.25	11.21	1.38	32.33	28.48
Ernakulam	14.25	1.61	38.31	46.78	14.25	1.61	50.08	46.25
Idukki	19.94	1.99	94.09	74.47	19.94	1.99	52.65	54.22
Kannur	19.39	1.74	37.97	32.16	19.39	1.74	53.49	49.30
Kasaragod	23.52	2.87	32.24	22.22	23.52	2.87	51.26	46.18
Kollam	8.22	1.11	41.58	37.59	8.22	1.11	25.56	24.07
Kottayam	13.19	2.08	35.16	29.82	13.19	2.08	37.91	31.36
Kozhikode	18.73	2.74	50.48	54.31	18.73	2.74	65.79	72.00
Malappuram	13.97	1.33	58.21	52.12	13.97	1.33	54.12	59.49
Palakkad	12.00	1.11	52.61	50.82	12.00	1.11	55.99	76.67
Pathanamthitta	11.10	1.20	47.59	42.21	11.10	1.20	33.42	32.62
Thiruvananthapuram	4.62	0.86	23.02	26.50	4.62	0.86	14.71	18.46
Thrissur	16.88	2.13	45.92	64.83	16.88	2.13	52.78	49.50
Wayanad	19.97	3.47	64.78	49.89	19.97	3.47	66.64	78.95
Lakshadweep	6.69	1.12	5.15	5.74	6.69	1.12	10.52	14.15

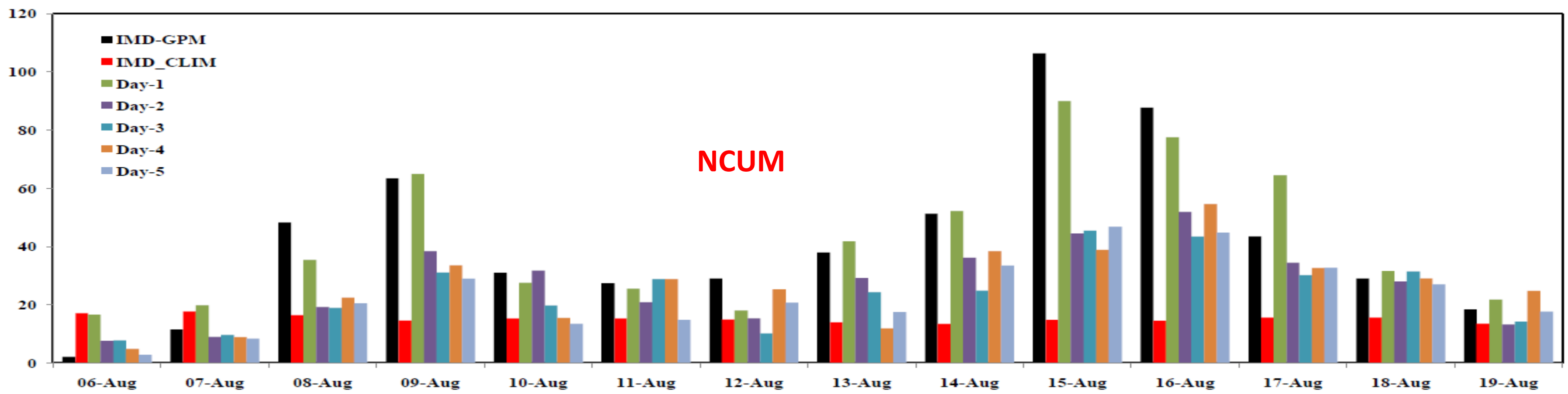


The merged lightening & satellite cloud top temperature operational product is a joint collaboration of IMD, IITM & IAF

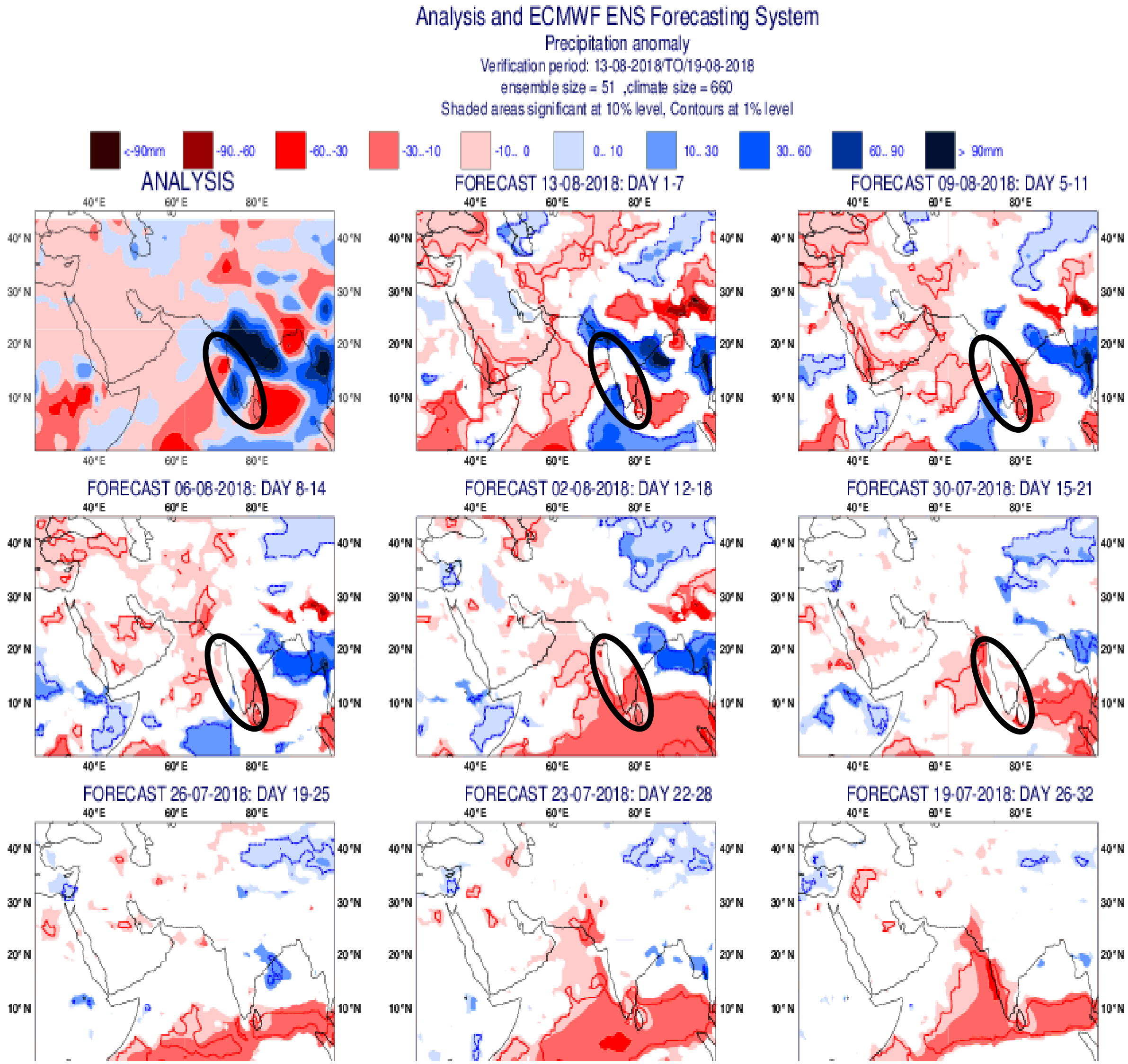
Rainfall (mm/day) time series over Kerala during 06-19Aug, 2018



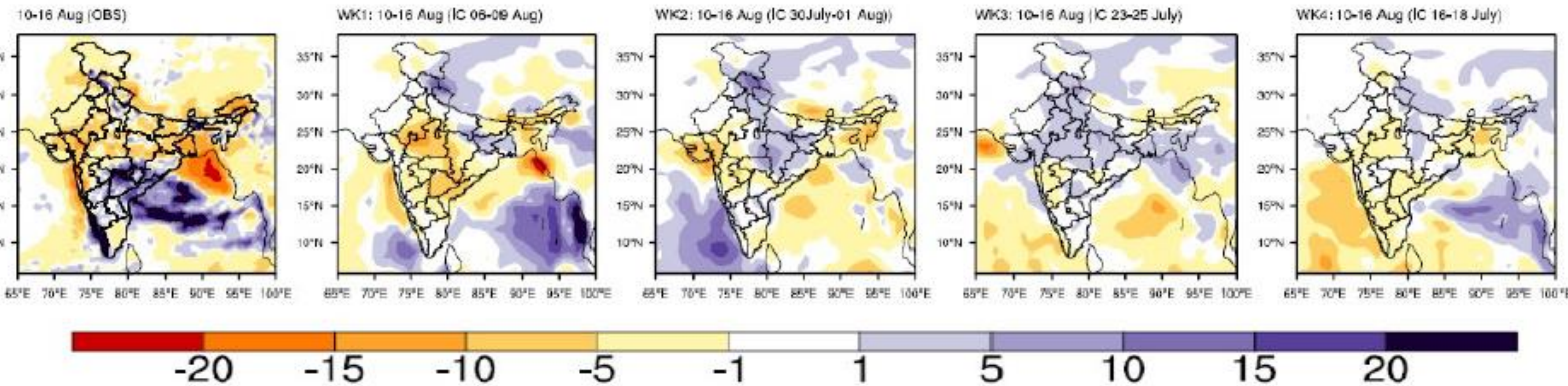




ENS weekly TP fc over India for 20180813-0819



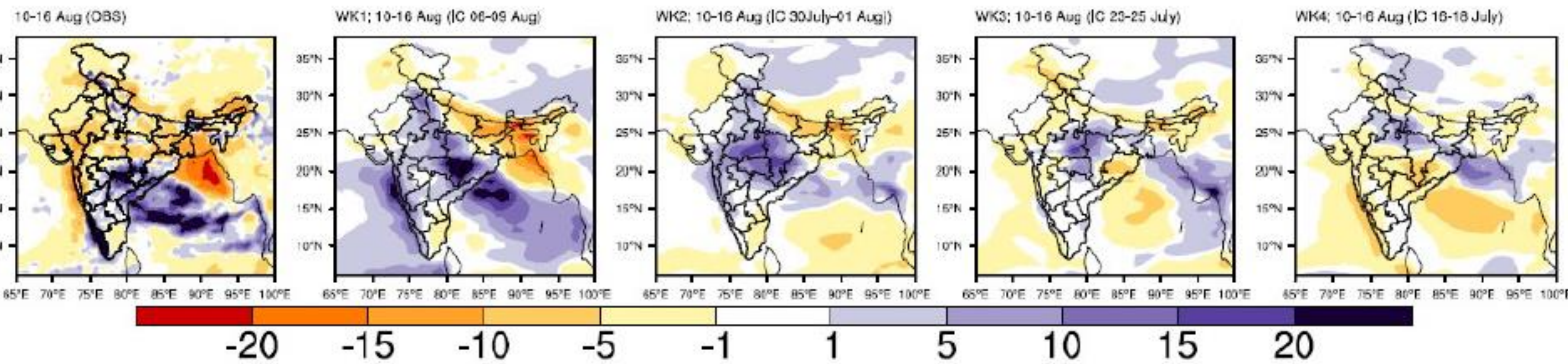
Slide borrowed from Roberto Buizza, ECMWF



Valid period 10-16 Aug 2018

Above Plot: Rainfall anom from NCEP CFS (T126) ~ 100 km

Bottom Plot: rainfall anom from NCMRWF Coupled model ~ 60 km



The Ensemble Approach

Flowchart of GEFS

The Global (Ensemble) Forecast Model

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 240 hrs (10 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

Flowchart of deterministic GFS

GDAS
EnKF – GSI Hybrid Data Assimilation System

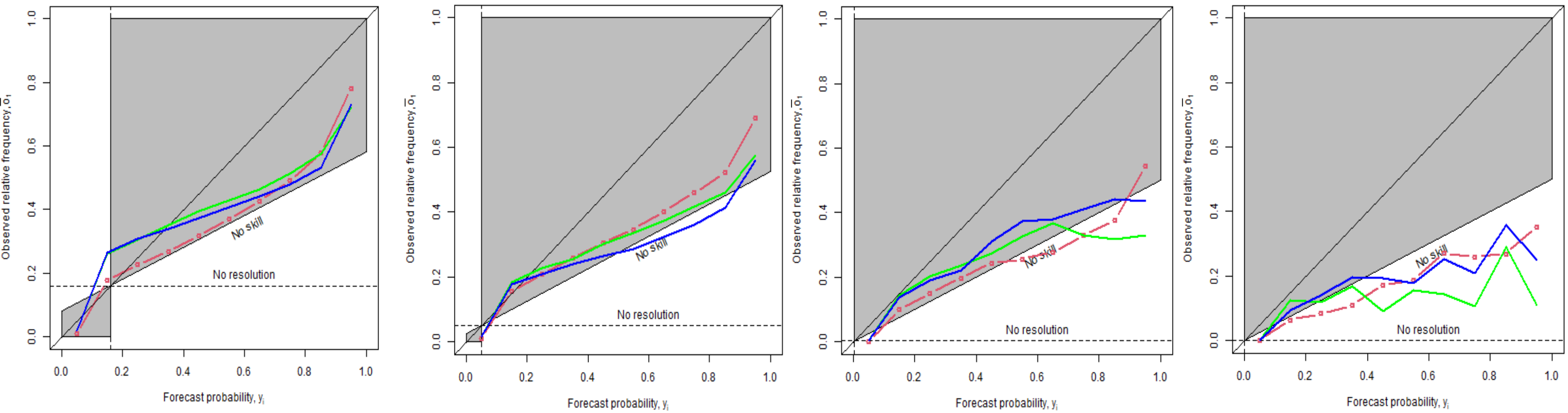
↓ Analysis(Control)

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

↓

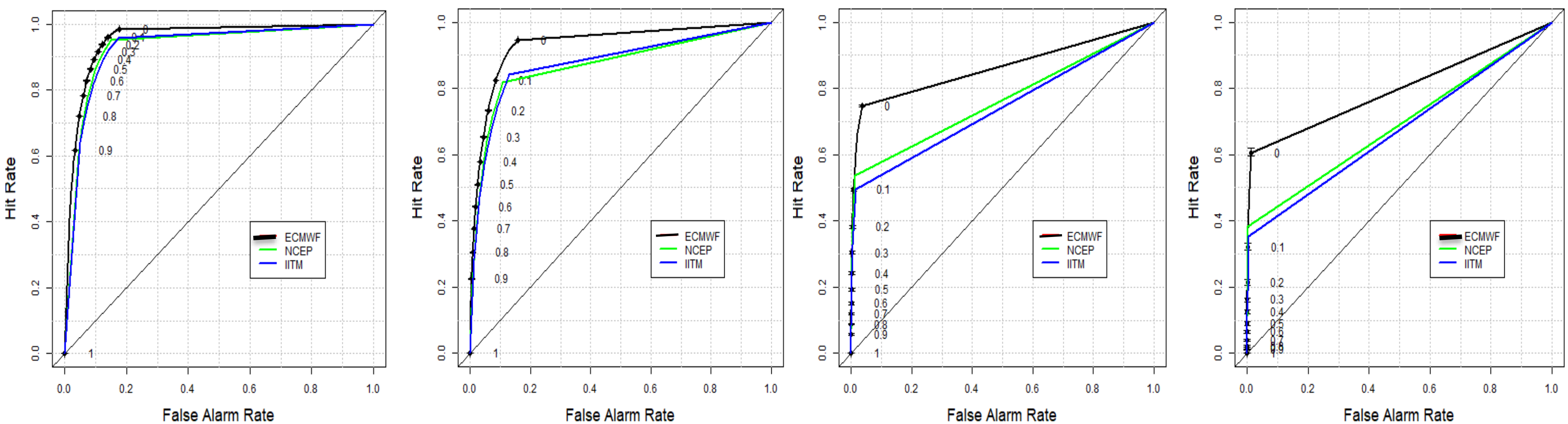
POST PROCESSING
240hr (10 days) forecast
Resolution: Regular grid and Gaussian grid at different resolutions
0.125°x0.125°

Verification EPS



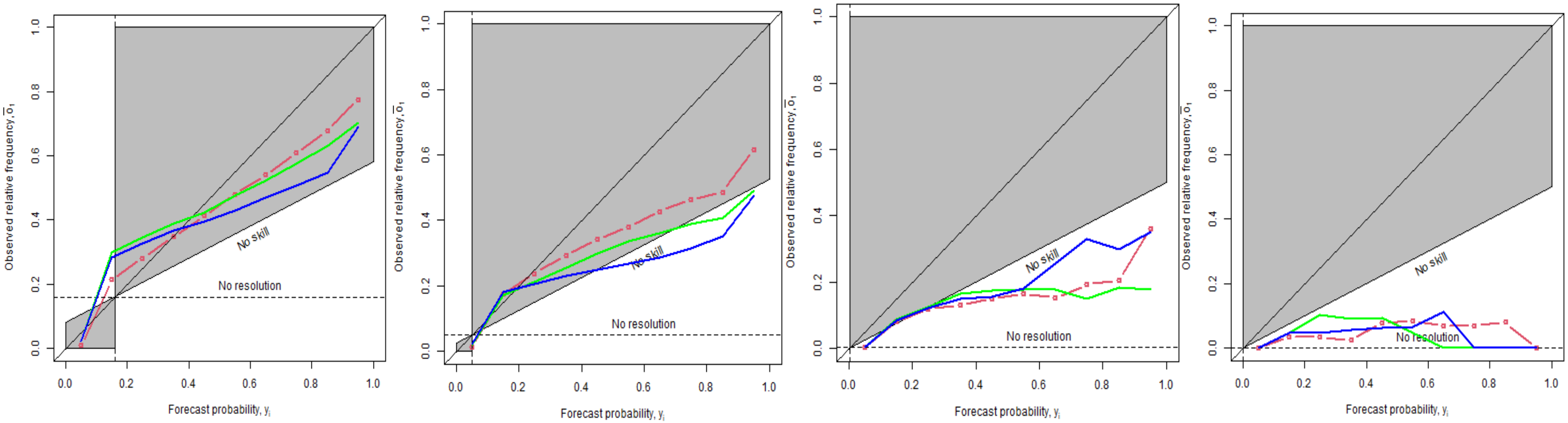
Reliability Diagram for **day 1** rainfall forecast from IITM (blue), NCEP (green) and ECMWF (red)

ROC curve for **day 1** rainfall forecast from IITM (blue), NCEP (green) and ECMWF (black)



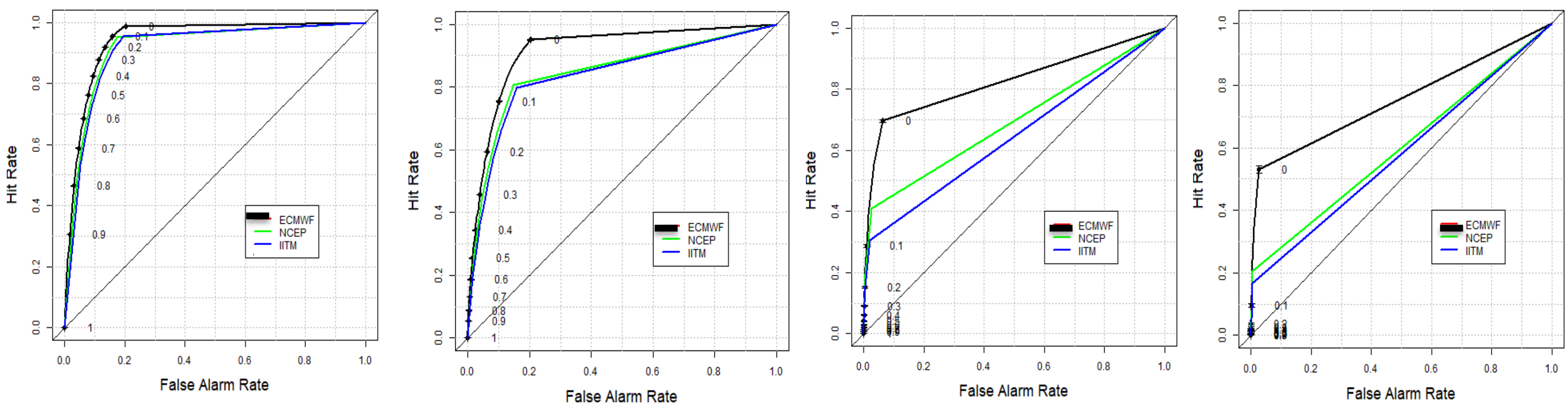
> 2.5 mm/day **> 15.6 mm/day** **> 65.5 mm/day** **> 115 mm/day**

Verification day 5

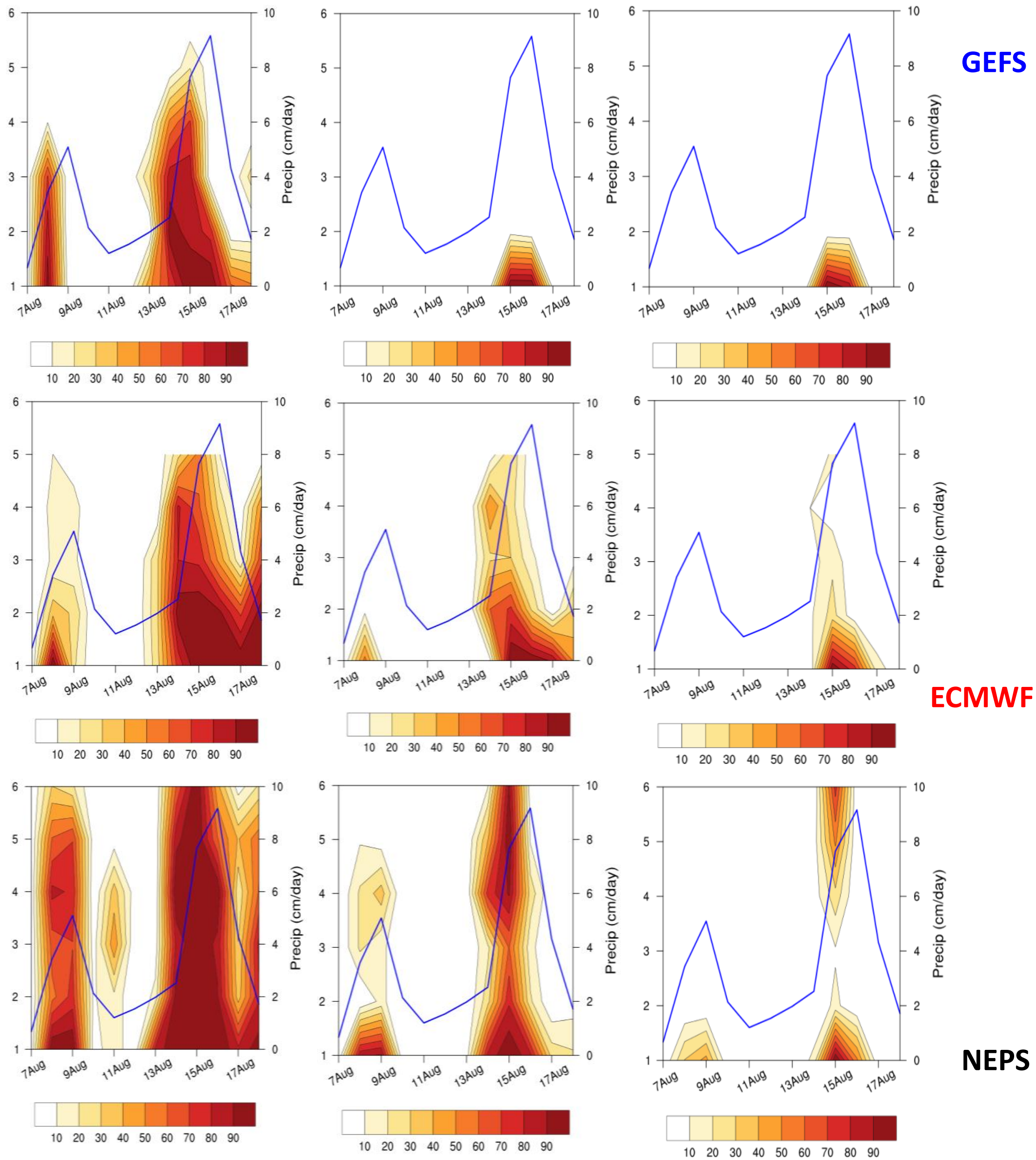


Reliability Diagram for **day 5** rainfall forecast from IITM (blue), NCEP (green) and ECMWF (red)

ROC curve for **day 5** rainfall forecast from IITM (green), NCEP (red) and ECMWF (black)

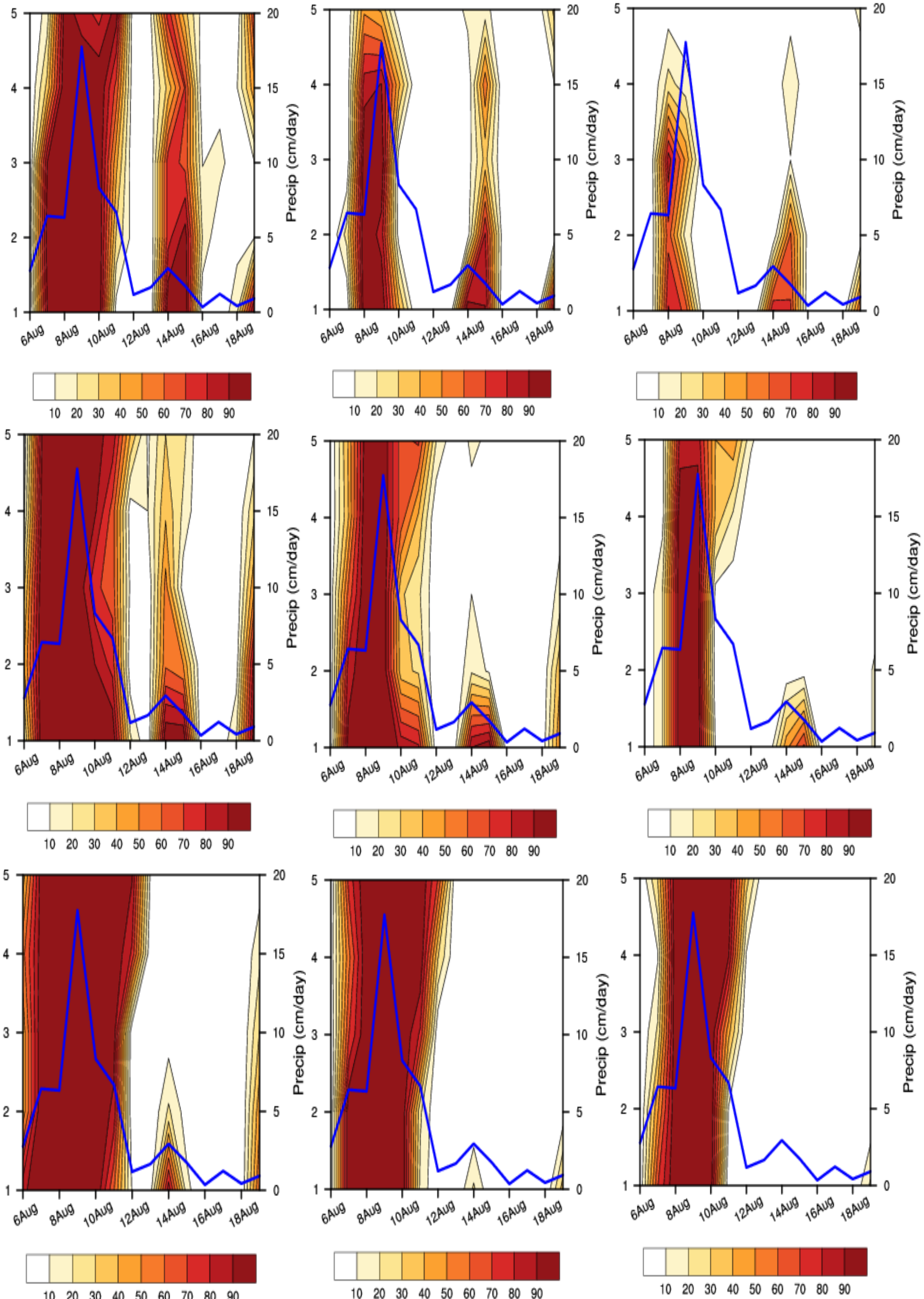


> 2.5 mm/day | **> 15.6 mm/day** | **> 65.5 mm/day** | **> 115 mm/day**



August 2018

Forecast lead time diagram of the probability (%) from (a)–(c) GEFS, (d)–(f) ECMWF, and (g)–(i) NCUM forecasts for the daily accumulated rain over Kerala (9.58–11.58N, 768–77.58E) exceeding the observed daily climatology (left) plus one standard deviation (SD), (center) two SD, and (right) three SD. The thick blue line represents the IMD-GPM rainfall (cm day^{-1}) averaged for the same region for the period 6–19 Aug 2018. The shading represents probability.



GEFS

6-19 August 2019

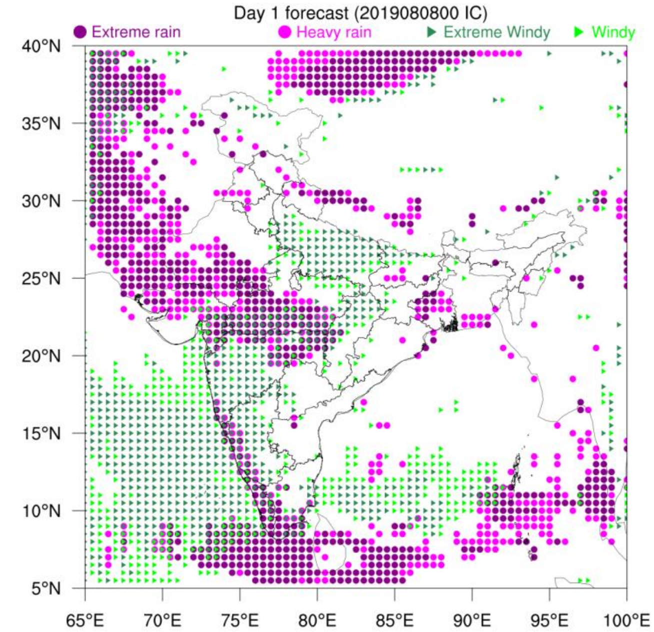
1st column (Climatology+1SD)

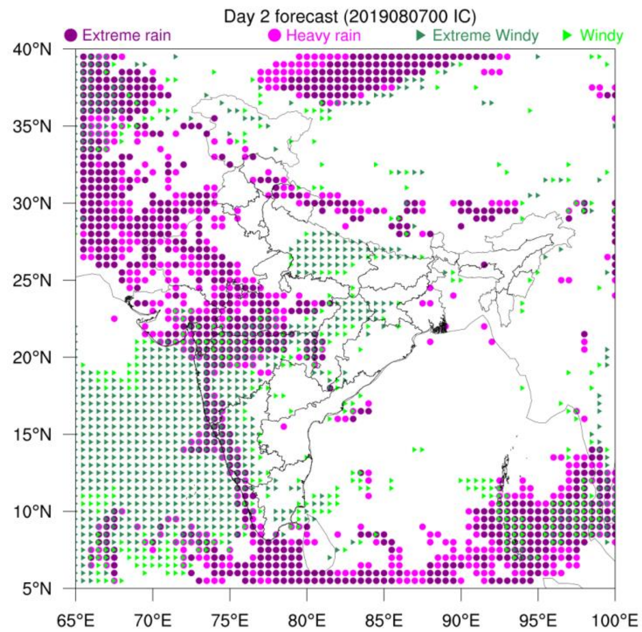
2nd column (Climatology+2SD)

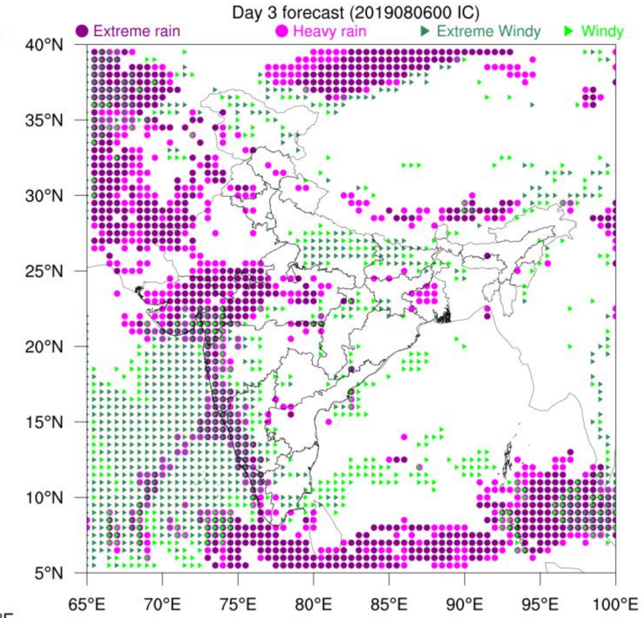
3rd column (Climatology+3SD)

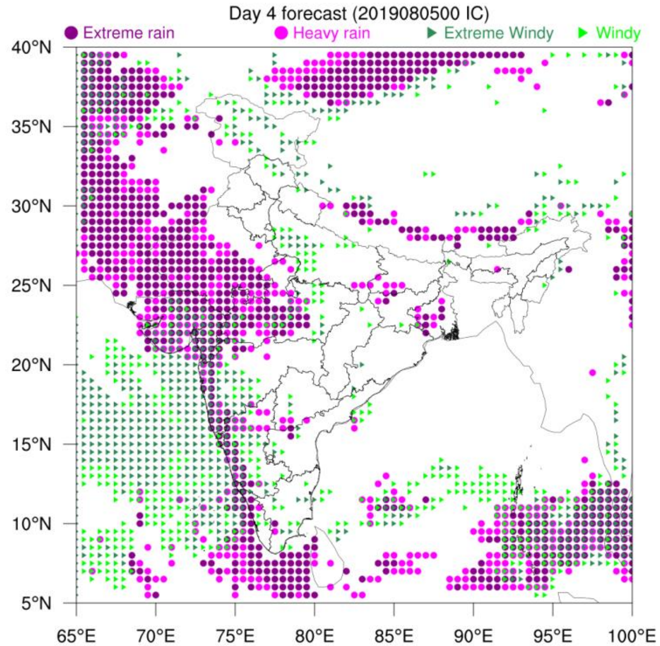
ECMWF

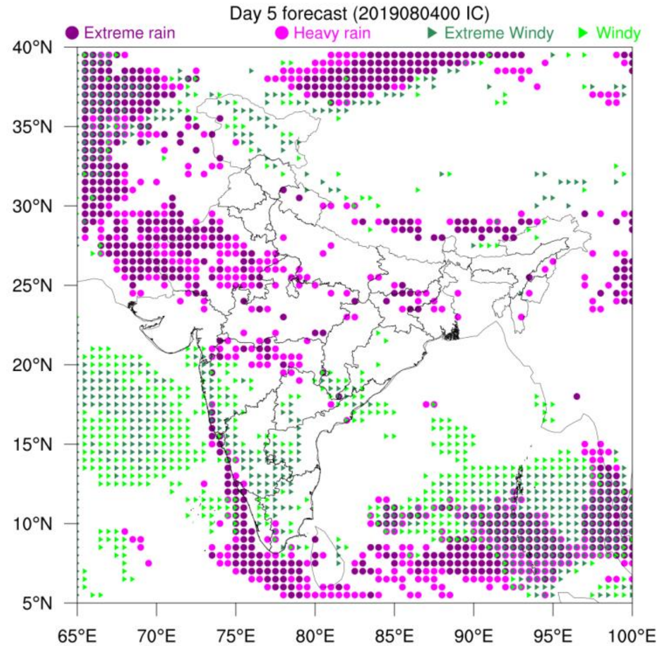
NEPS



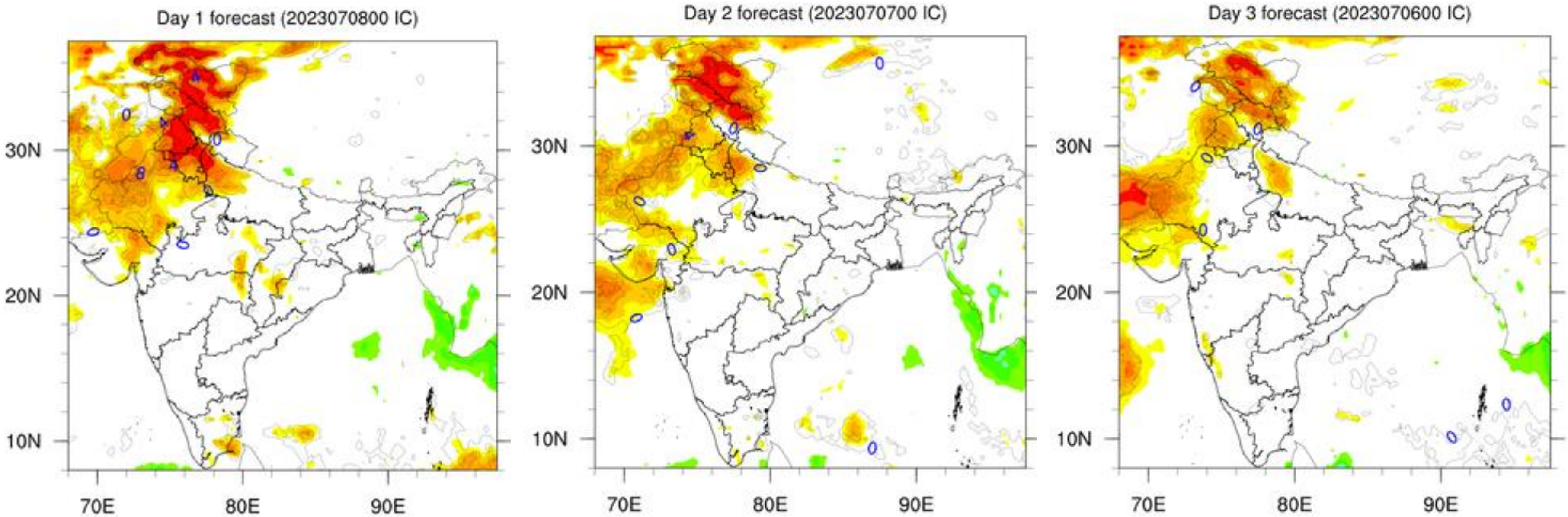




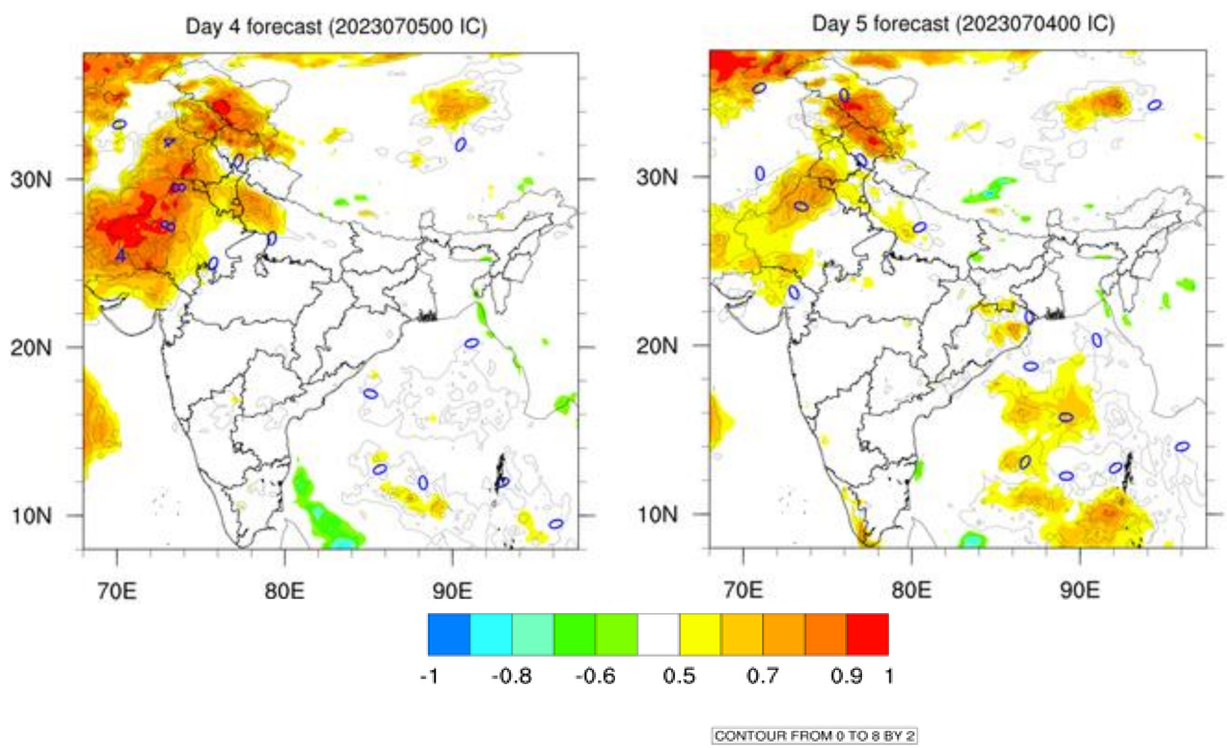




Day 1 to Day 5 forecast valid for 2019080900

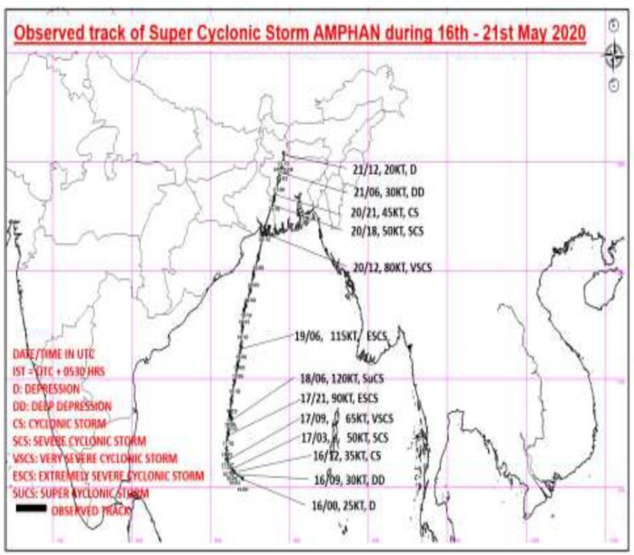


Day 1 to 5 EFI and SOT valid for the 9 July 2023 event

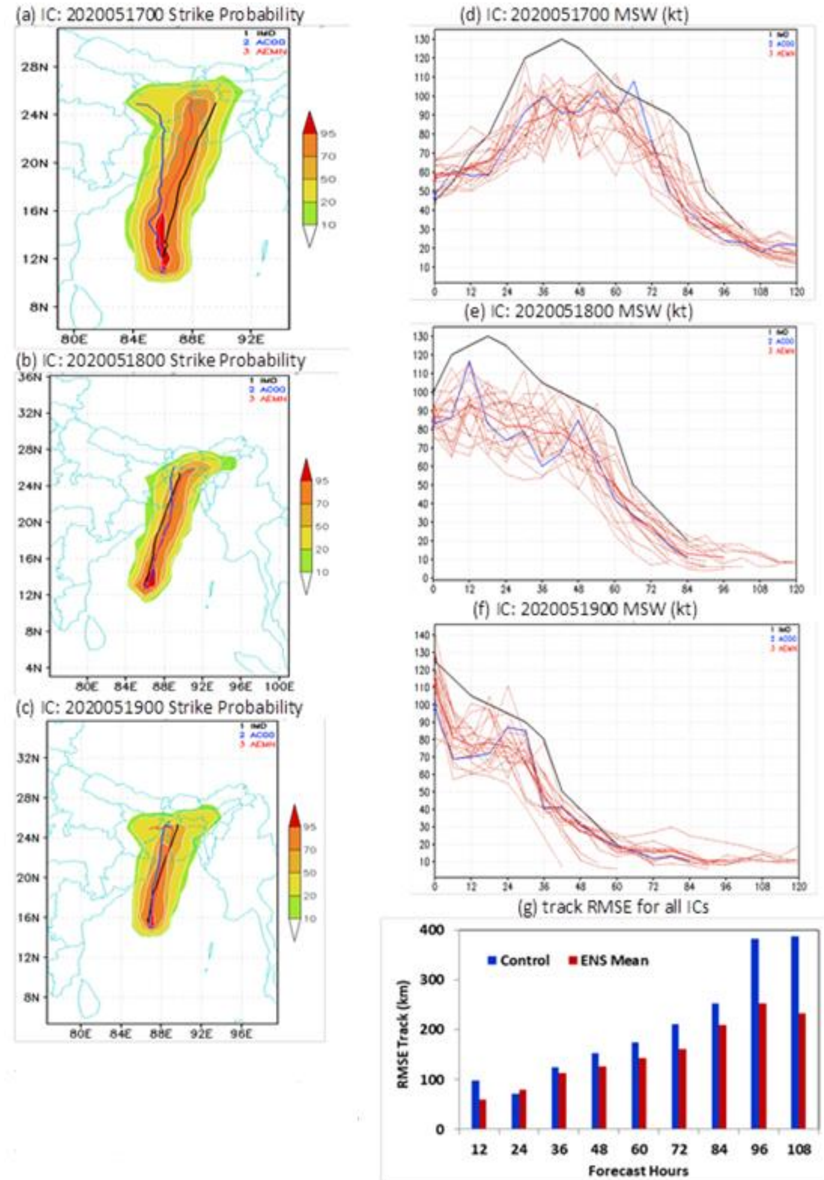


The Super Cyclonic Storm (SuCS) "AMPHAN"

- The system intensified into Cyclonic Storm "AMPHAN" over southeast BoB in the evening (1200 UTC) of 16th May, 2020.
- It became a Super Cyclonic Storm (SuCS) around noon (0600 UTC) of 18th May, 2020 then weakened into an ESCS over westcentral BoB around noon (0600 UTC) of 19th May.
- Thereafter, it crossed West Bengal – Bangladesh coasts as a VSCS, across Sundarbans during 1000-1200 UTC of 20th May, with maximum sustained wind speed of 155 – 165 kmph gusting to 185 kmph. *Source: IMD*



Observed Track



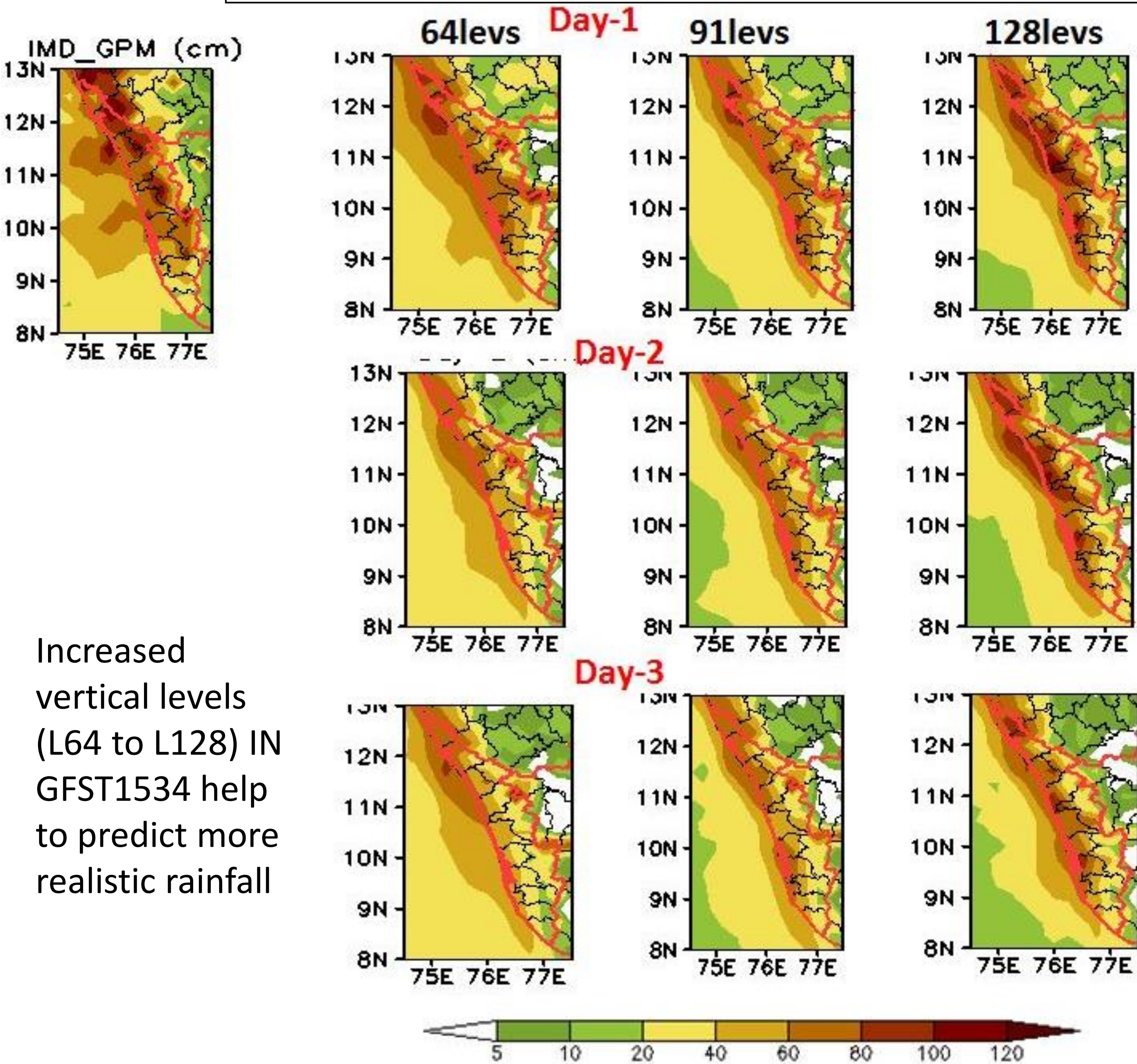
(a-c)Strike probability from GEFS, (d-f) Maximum sustained winds, (g) Track error

Deshpande et al. 2021

New Approaches

Accumulated rainfall (cm) 1-20th August 2019

GFS T1534



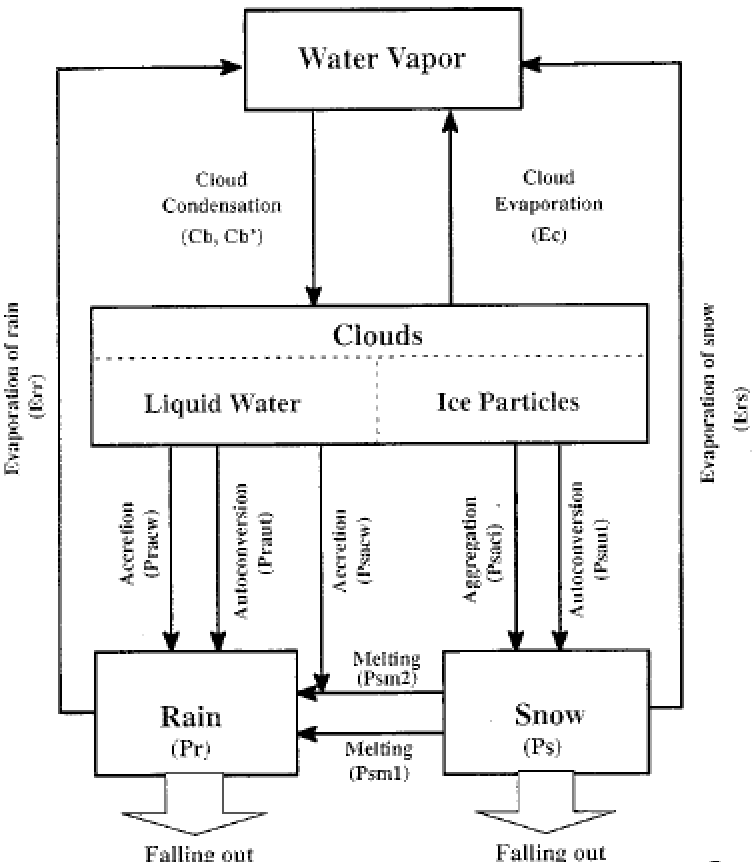
Increased vertical levels (L64 to L128) IN GFST1534 help to predict more realistic rainfall

CFS/GFS Vertical levels
CFST62L64
CFST82L64
CFST126L64
GFST254L64
CFST382L64
GFST574L64
GFST1534L64

GFST1534L128 (31 levels within 800hPa)

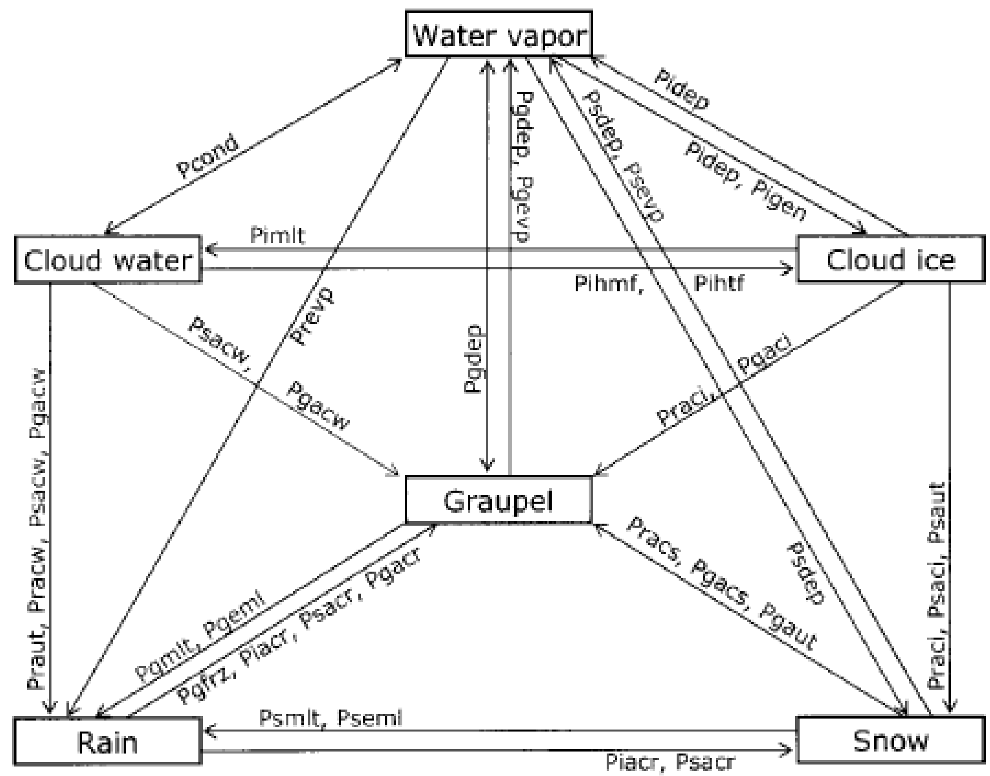
Zhao & Carr 1997

Default CFS Microphysics



Hong & Lim 2006

WSM6

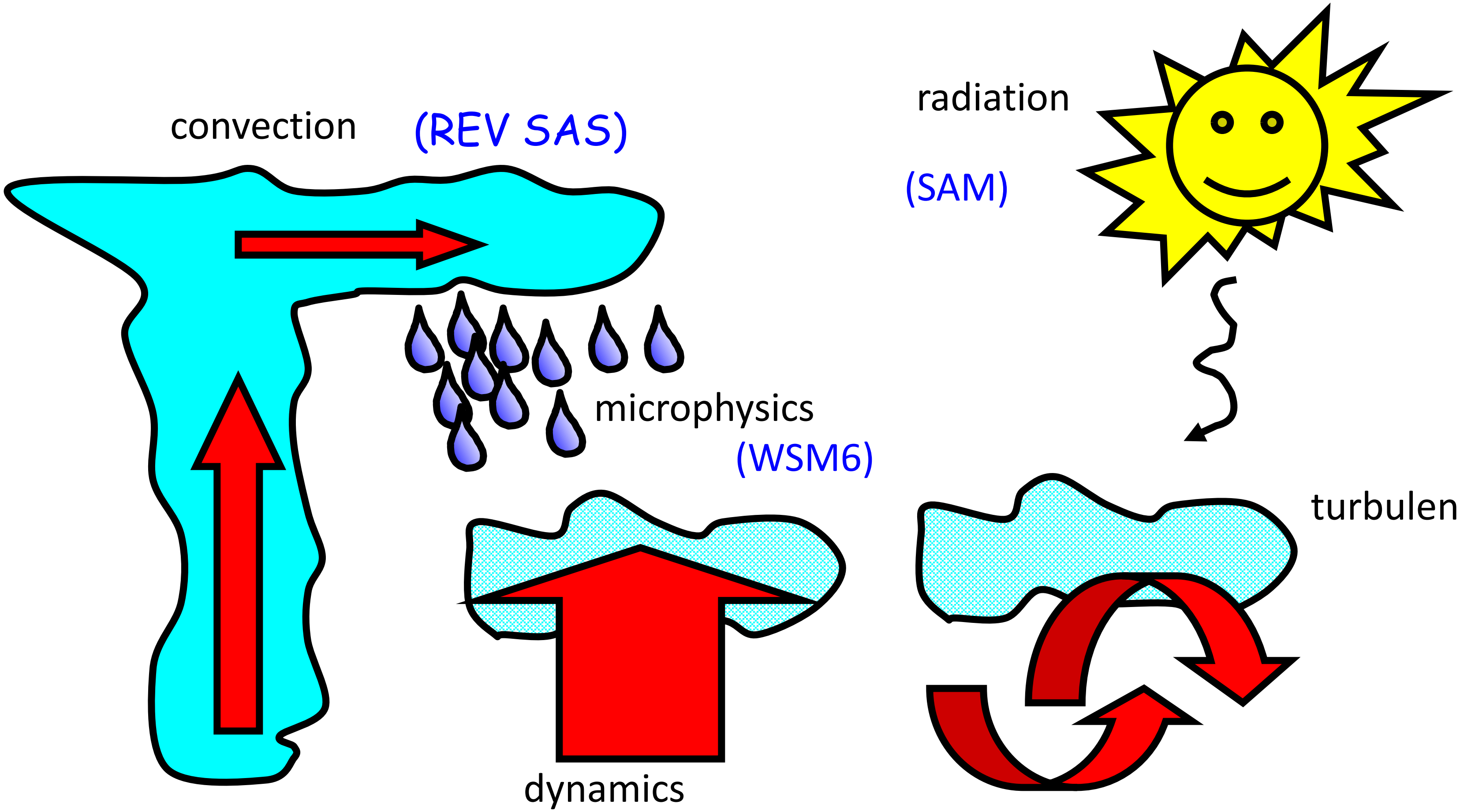


Tendencies

$$\frac{\partial}{\partial t}(n) = \mathrm{ADV}(n) + \mathrm{TURB}(n) + \mathrm{SEDIM}(n) + \mathrm{SOURCE}(n)$$

where n = *[n_r, n_i, n_s, n_{clw}, n_g, n_v] represents the concentration of rain, ice* crystals, snow, graupel, cloud water, water vap.

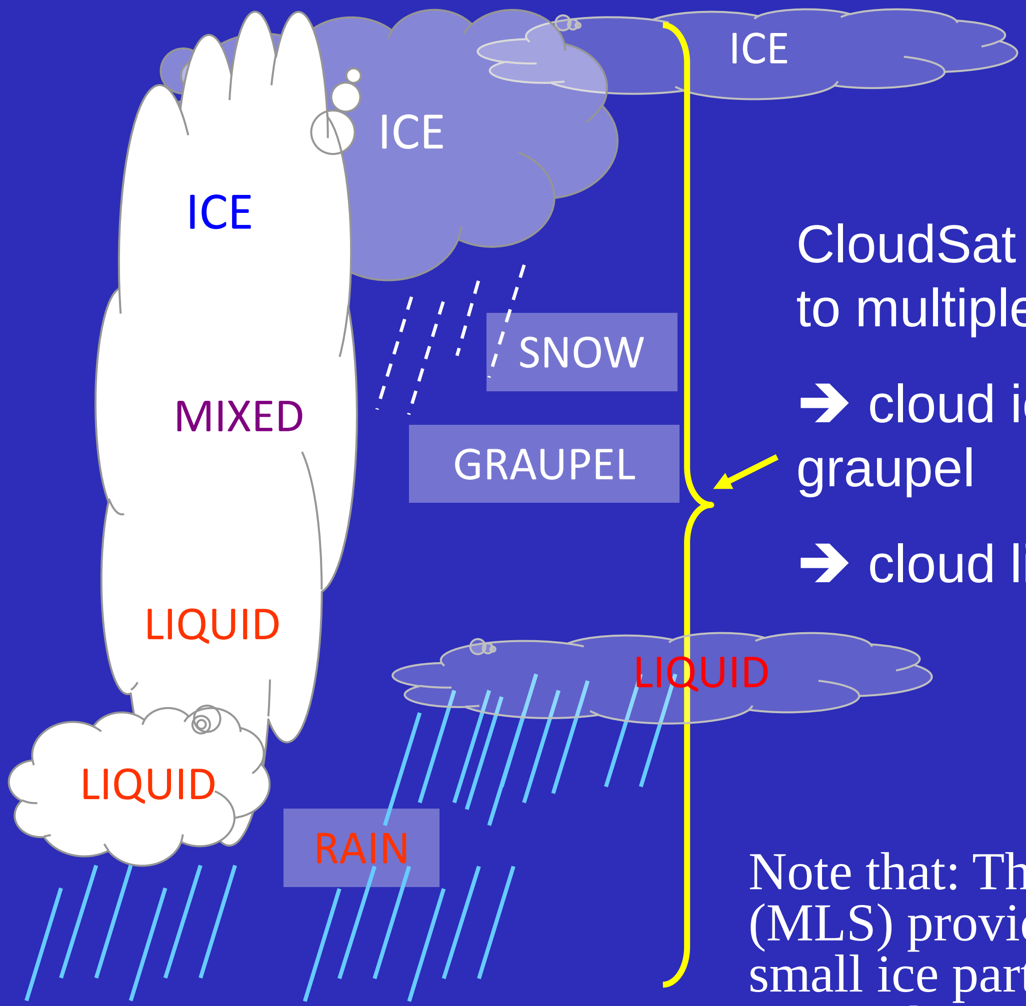
Revised Cloud-Convective-Radiation in CFSv2 T126



Clouds are the result of complex interactions between a large number of processes

SAM: System of Atmospheric Model

CloudSat IWC/LWC Retrieval



CloudSat measurements are sensitive to multiple particle types:

➔ cloud ice (~small particle), snow, graupel

➔ cloud liquid (~small particle), rain

Note that: The Micro Wave Limb Sounder (MLS) provides IWC estimates described as small ice particles at levels in the upper-troposphere

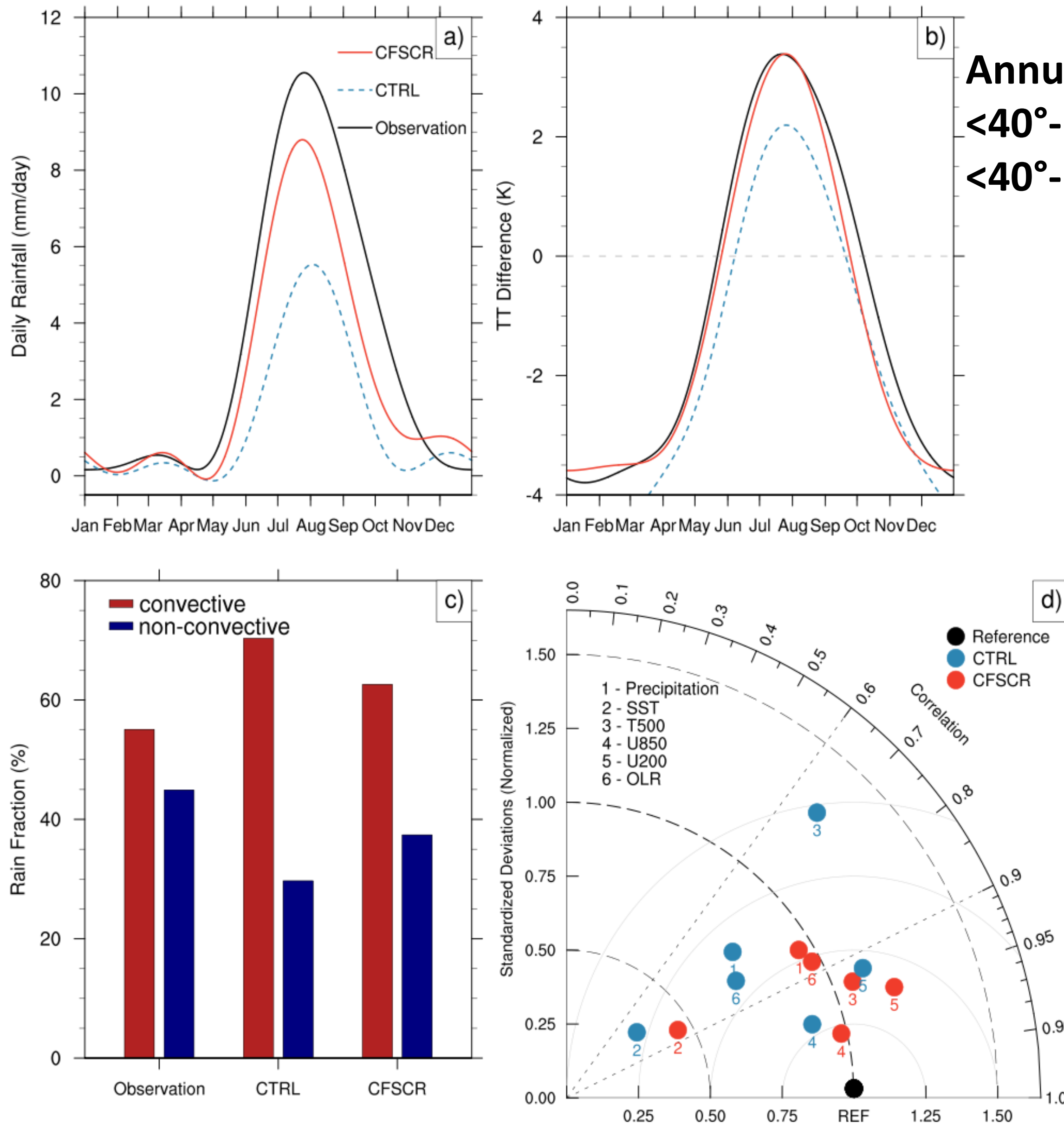
Slide Courtesy: Frank Li, JPL

Revised convection, modified microphysics and radiation is able to improve the mean state and Intraseasonal variability of CFSv2T126

Annual Rainfall Cycle
<73°-85°E,15°-25°N>

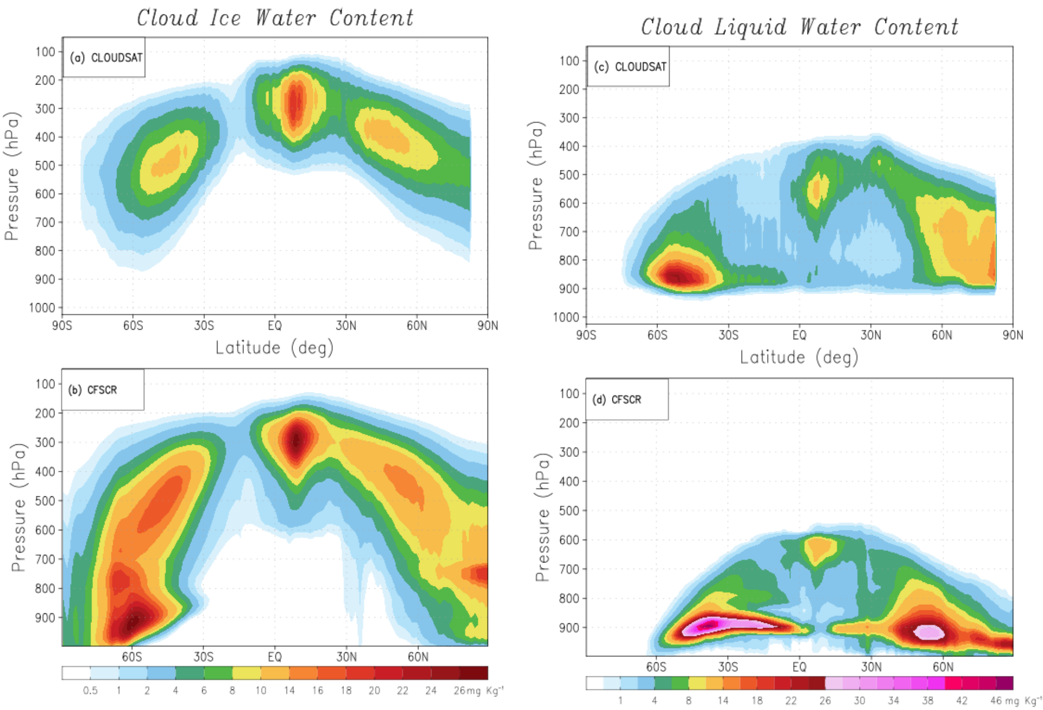
Annual TT Difference
<40°-100°E,5°-35°N> - <40°-100°E,15°S-5°N>

<40°-120°E, 15°S-30°N>

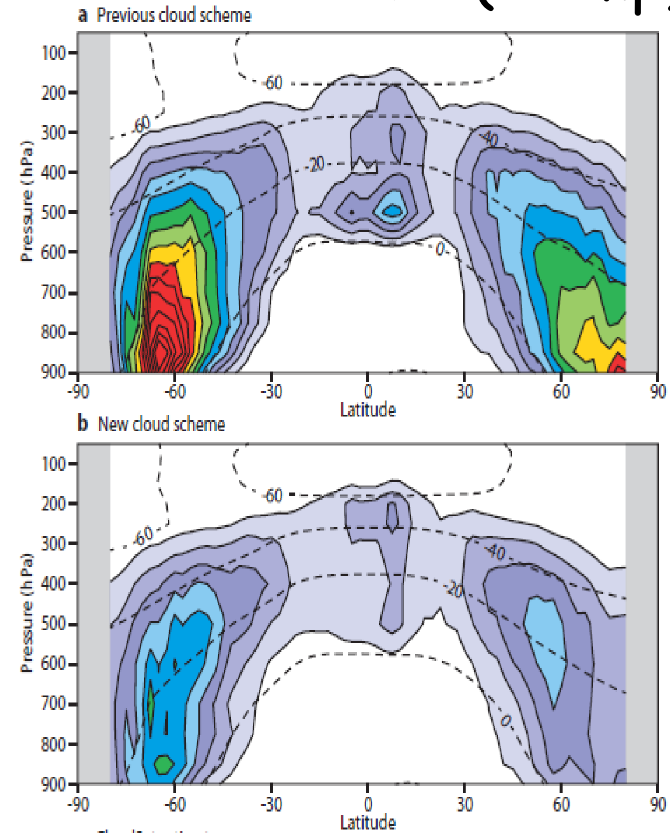


Abhik et al, JAMES 2017

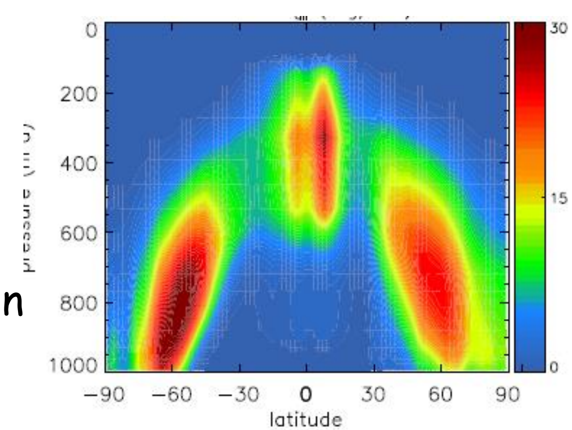
ECMWF IFS cloud ice Betchold+Bulk (comp)



Abhik et al. 2017, JAMES

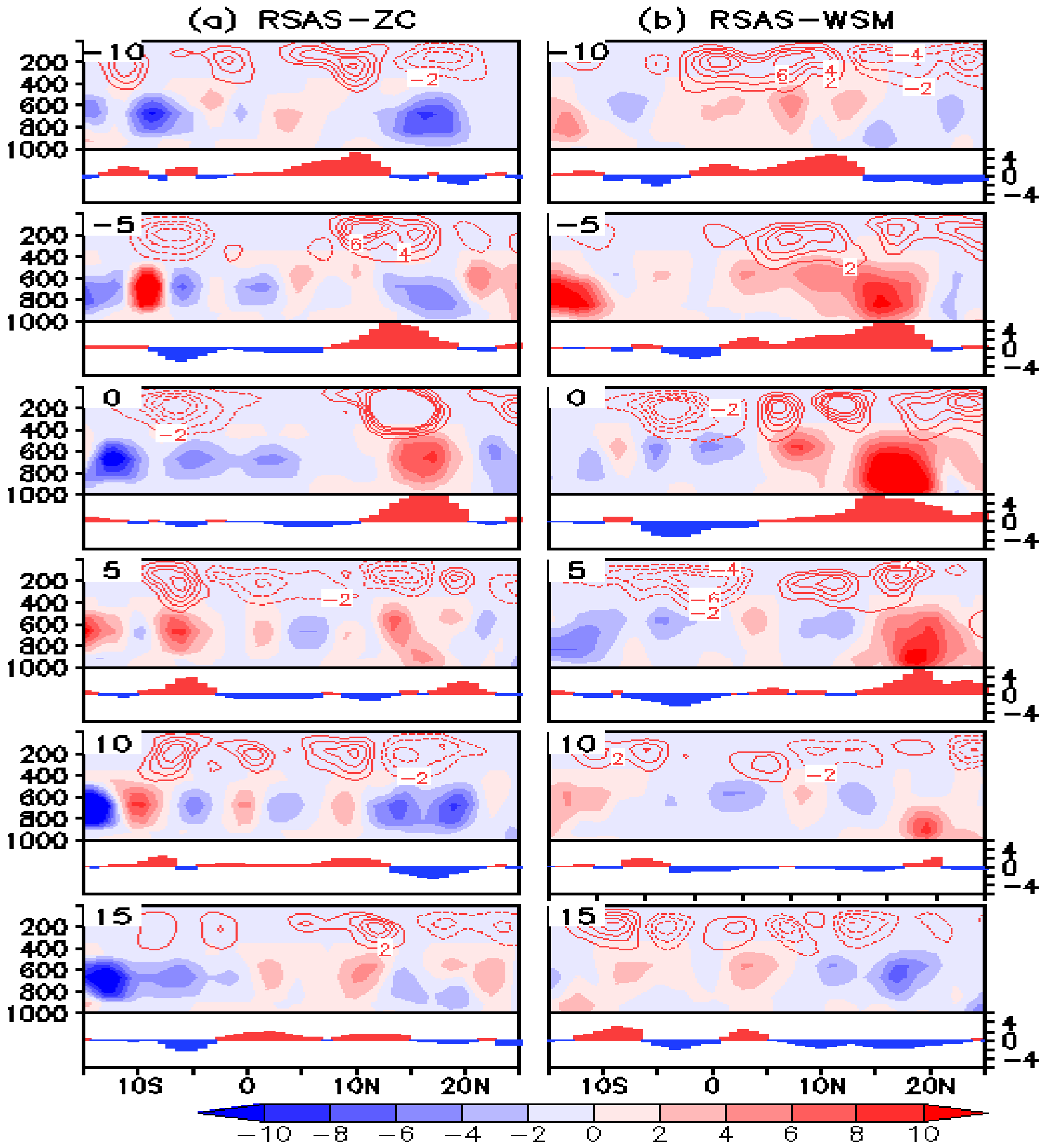


GFDL AM3+Morrisson



Zonally averaged annual mean vertical distribution of cloud ice water content (mg kg^{-1}) obtained from (a) CFSCR; and cloud liquid water content (mg kg^{-1}) from (b) CFSCR model.

CFSCR: Modified CFSv2 with revised Cloud Microphysics, Convection and radiation



Lag composite of CLW (shaded) and CLI (red contour, solid (+ve) and dashed (-ve)) during strong event averaged over 70E-90E, corresponding rainfall anomalies plotted in the bottom in each plot.

Ganai et al. 2019, Clim. Dyn.
https://doi.org/10.1007/s00382-019-04657-9

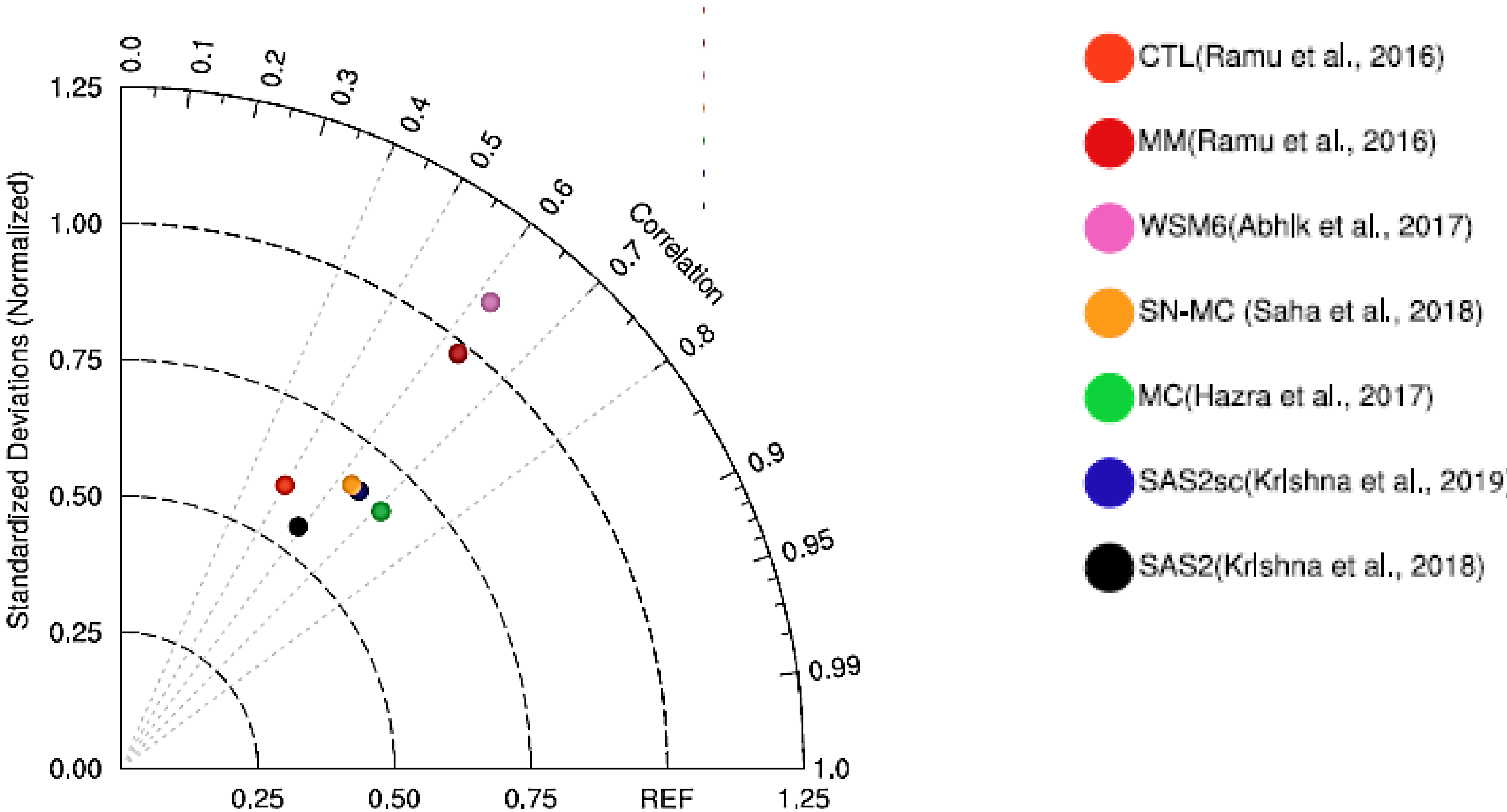


FIG. 6. Taylor diagram showing the skill of ISMR prediction using reforecasts from the control run (CTL) and the developmental activities under MM, namely, the revised microphysics (WSM6) along with revised convection (SAS2) and a modified radiation scheme, new cloud physics parameterization (MC), the new snow model (SN) and MC together (SN-MC), the revised convection parameterization scheme (SAS2), and SAS2 with a revised shallow convection scheme (SAS2sc). The improvement in skill over the CTL run is notable in the experiments. The period of the hindcast is 1981–2010.

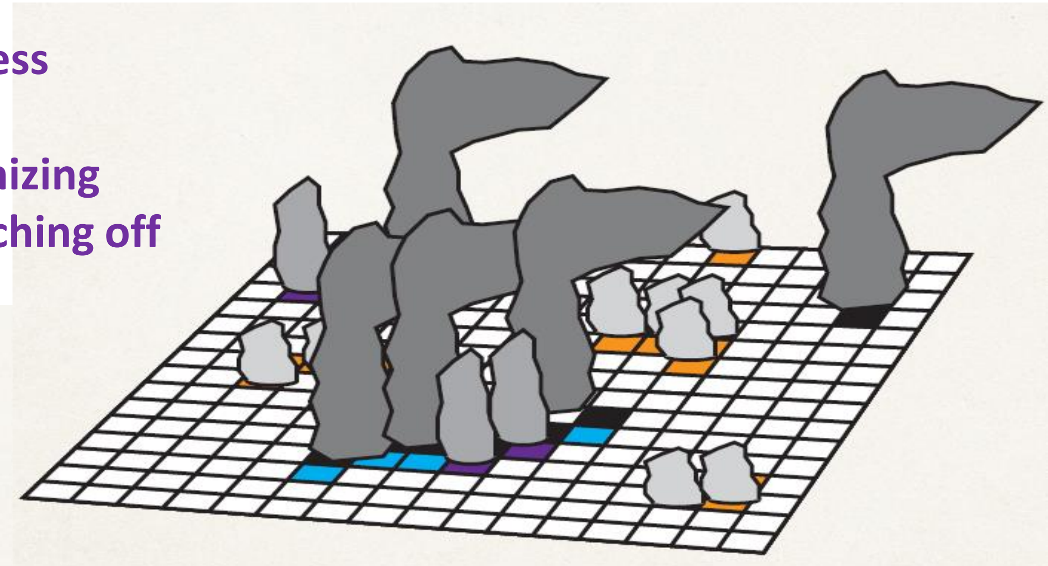
Rao et al. 2019, BAMS

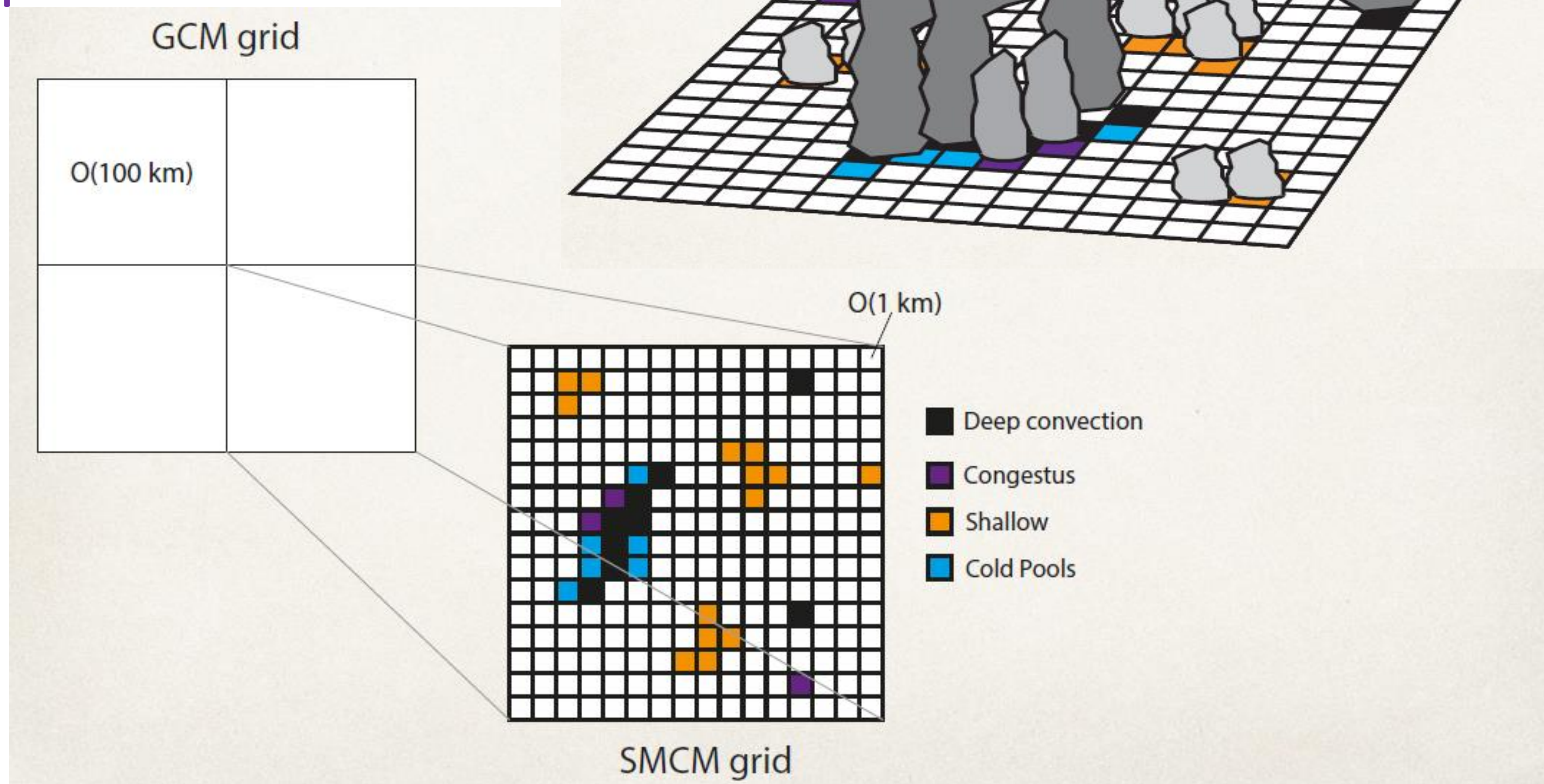
Stochastic modelling in Climate Forecast System (CFSsmcm)

Convective tendencies are explicitly simulated in each GCM grid column which replaces the traditional cumulus parameterization of the GCM.

A Framework for the implementation of the Stochastic model in CFS

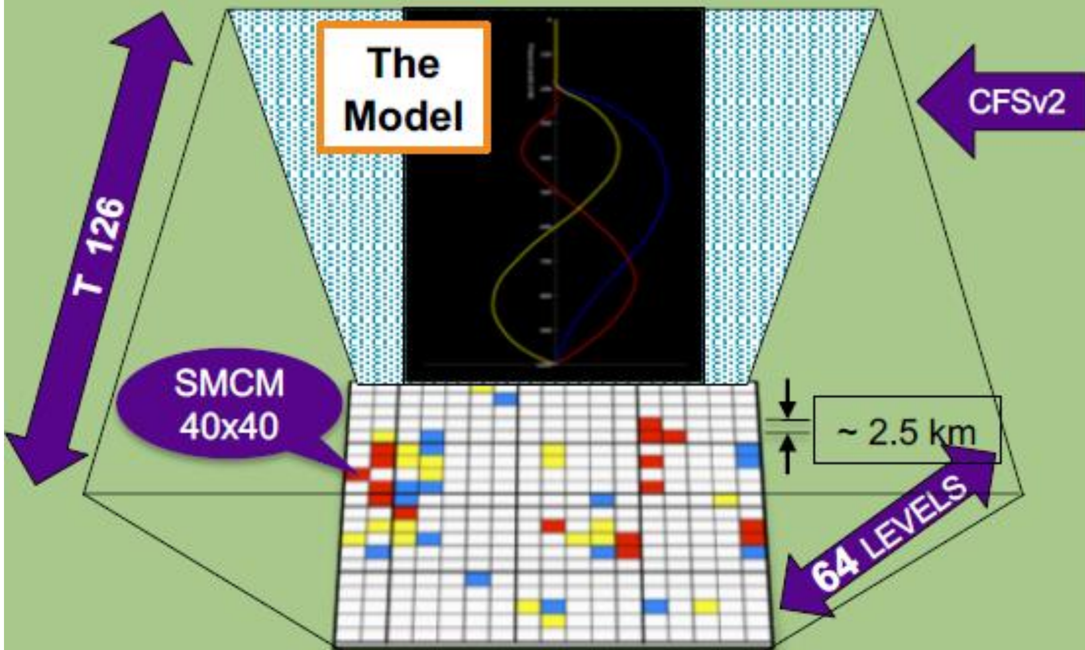
- Stochastic nature in the convective process
- Existence of different clouds
- Distinguishing different clouds and organizing
- Resolution awareness and dynamic switching off in convection





Roy et al. 2021, AGU ESS
Goswami B. B. et al. 2017, JAS;
Goswami B. B. etal., 2017, JAS
Goswami B. B etal., 2017, GRL

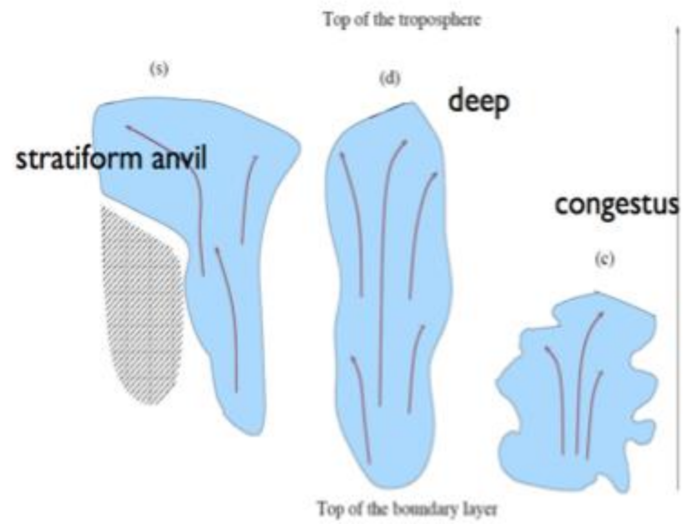
Stochastic multi-cloud model (SMCM)



$$Q_{tot}(z) = H_d\,\phi_d(z) + H_c\,\phi_c(z) + H_s\,\phi_s(z)$$

$$Single\ site\ transition = f(CAPE, LCAPE, MTD, CIN, W)$$

Main cloud types of tropical weather



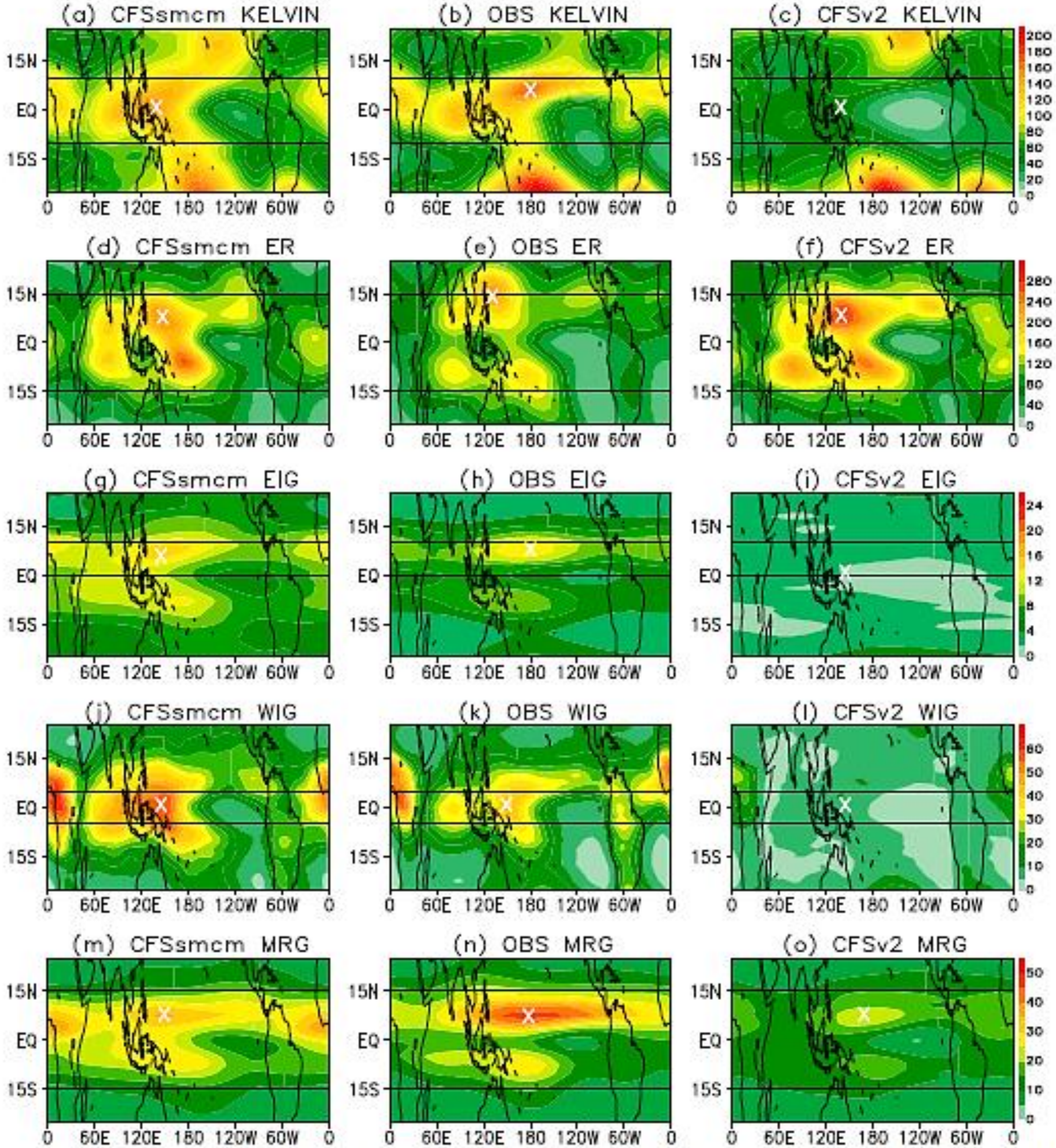


FIG. 7. Daily variance of different equatorial waves for OLR $[(W\ m^{-2})^2]$ anomalies filtered respectively for the different waves. (left) CFSsmcm simulation, (center) observations, and (right) CFSv2. The black lines in each panel show the zonal belt used for averaging the anomalies to plot Fig. 8. The white cross marks identify the location at which the respective indices are considered for the different equatorial waves used in the analyses in plotting Figs. 8–10.

B. B. Goswami et al. JAS, 2017

Update in Dynamic Core: Spectral Cubic Octahedral grid

Conventional Spectral grid:
- **Not scalable**
- **I/O**
- **Artificial diffusion damping**
- **Negative tracer**

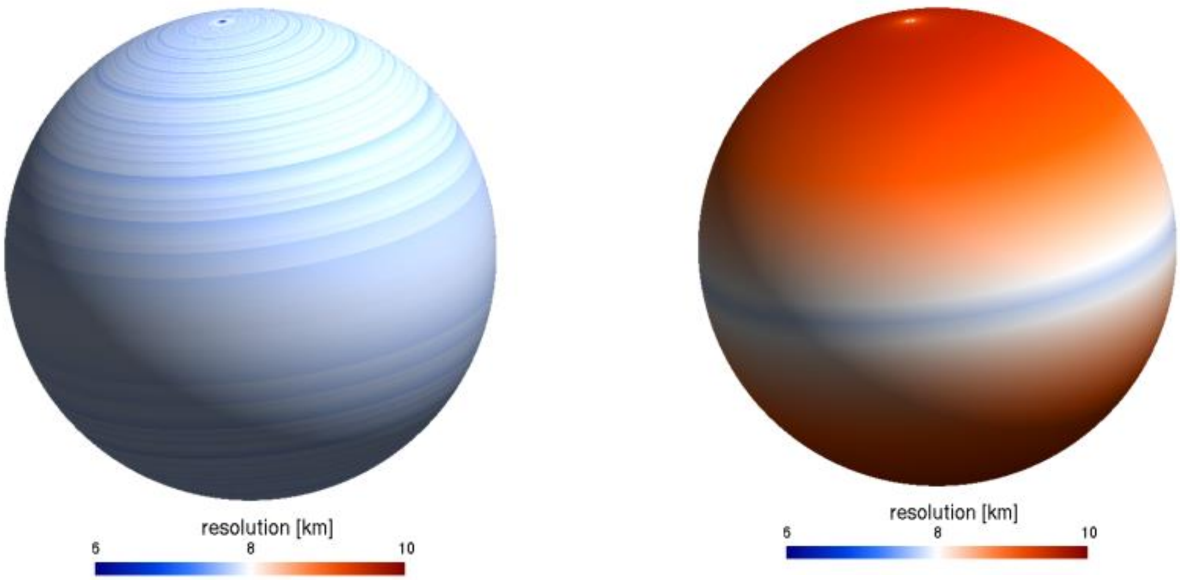
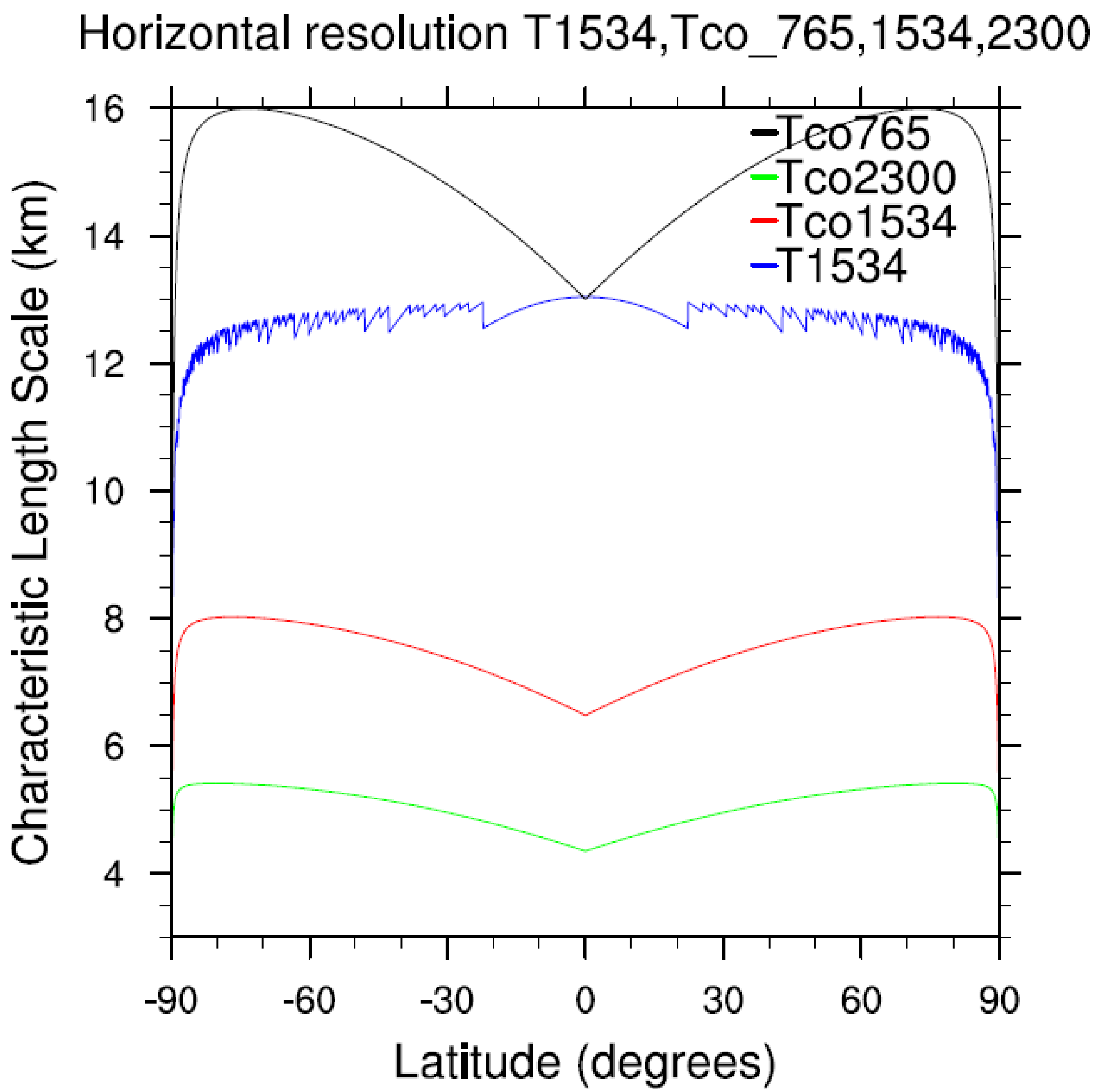


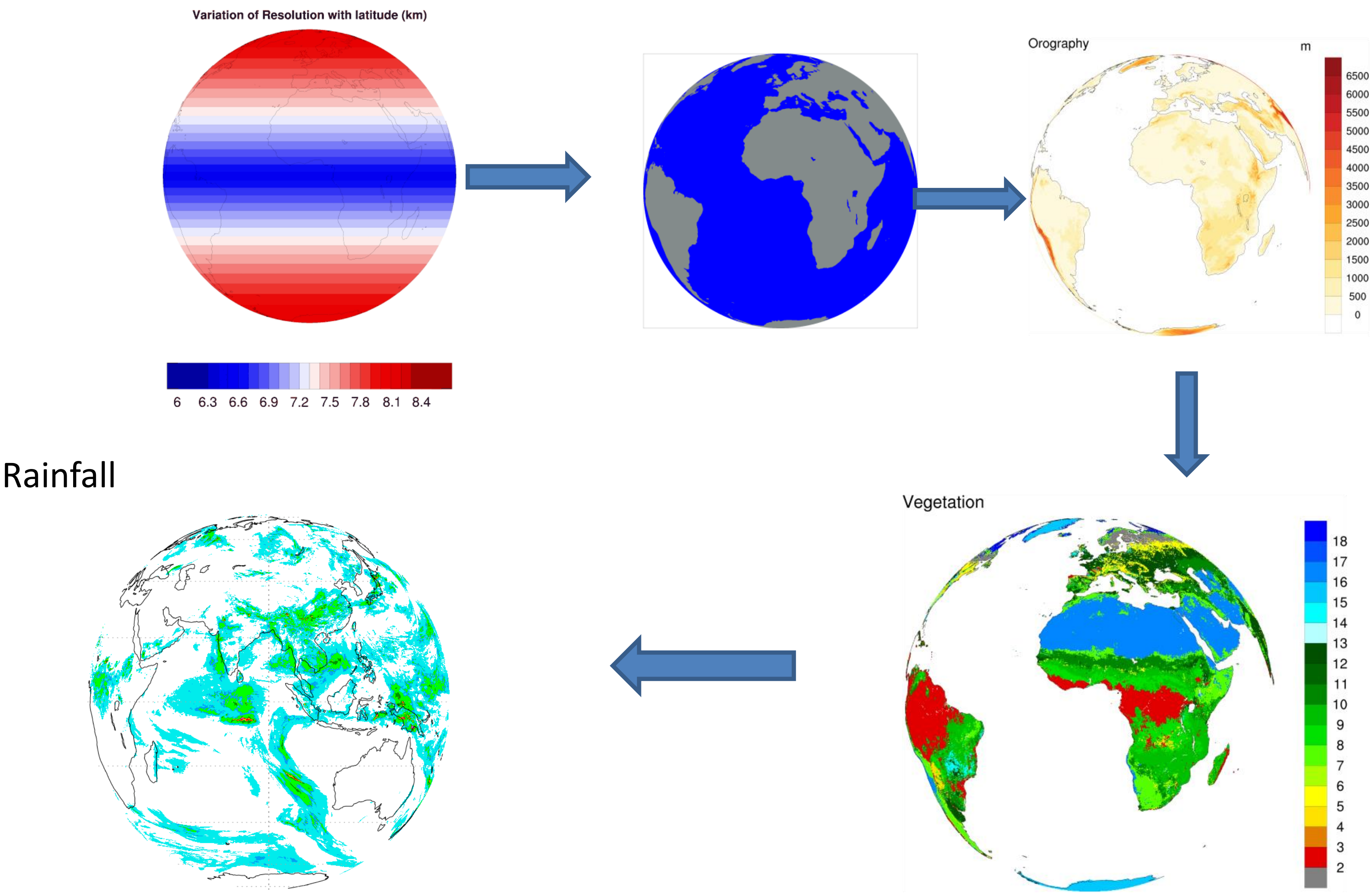
Figure (adopted from ECMWF News Letter 146) demonstrates that the octahedral mesh (right) has a locally more uniform dual-mesh resolution than the mesh (left).

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).

A new Global Model developed at IITM, Pune (HGFM)

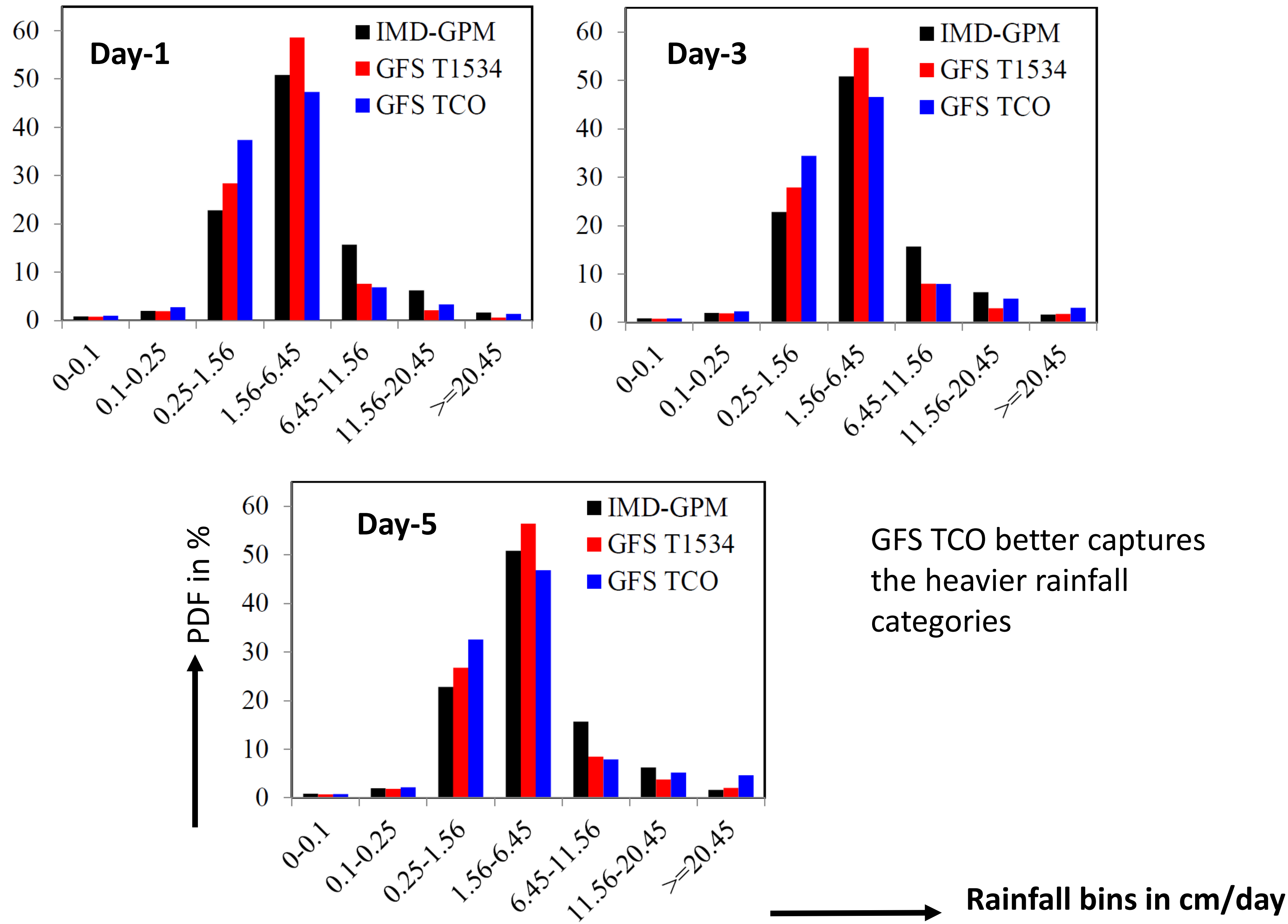


Sequence of IITM HGFM Development



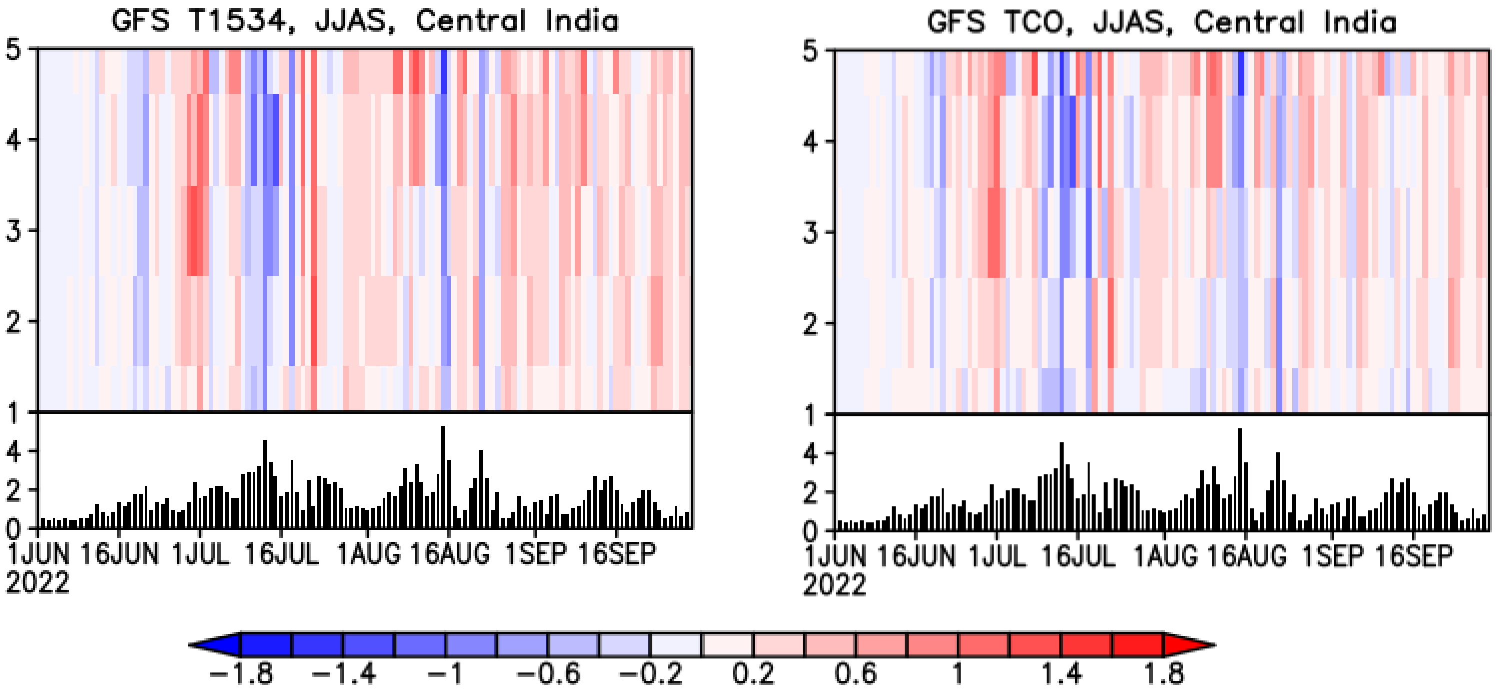
[Link for a film on the development of the model https://youtu.be/dxacESa28bY](https://youtu.be/dxacESa28bY)

JJAS rainfall PDF over continental India during 2022



GFS TCO better captures the heavier rainfall categories

Chiclet diagram of daily precipitation bias (cm day^{-1}) for GFS T1534 and GFS TCO during JJAS 2022

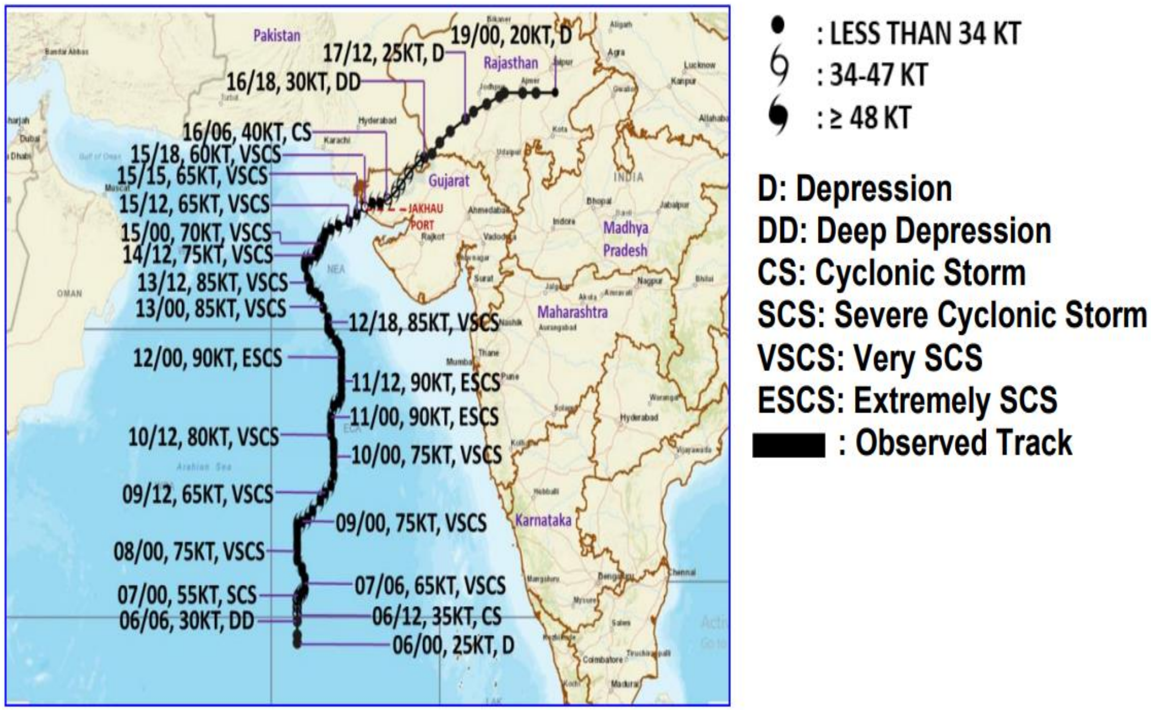


With respect to observation as a function of the verification date (x axis) and lead time (y axis)

Time series of daily mean precipitation (cm day^{-1}) is plotted in the lower panel in each plot

ESCS Biparjoy 06-19June 2023

A depression is formed over Arabian Sea on 00Z 06 June 2023. It further intensified into cyclone Biparjoy within 12hrs of formation of Depression and into VSCS within 18hrs of formation of cyclonic storm. It intensified further to ESCS and maintained intensity as VSCS and ESCS throughout its life period over ocean. It crossed Saurashtra and Kutch and adjoining Pakistan coasts between Mandvi (Gujrat) and Karachi (Pakistan) close to Jakhau port (Gujarat) near 23.28^0N/68.56^0E between 17-18Z 15June 2023. It attained its maximum intensity in terms of maximum sustained wind speed of 90kts and minimum central sea level pressure as 958hPa.

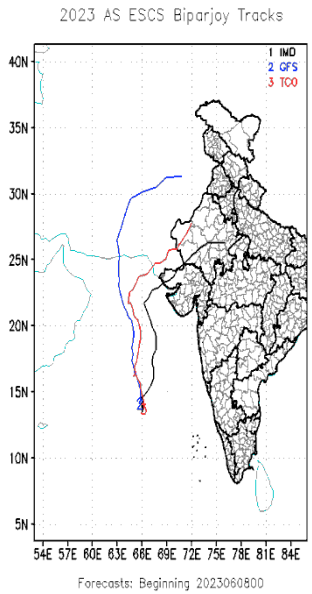


Observed track of extremely severe cyclonic storm 'BIPARJOY" over the AS during 6th-19th June, 2023

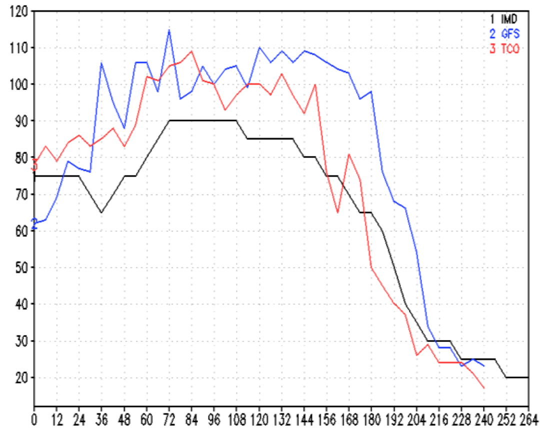
GFST1534 and TCO

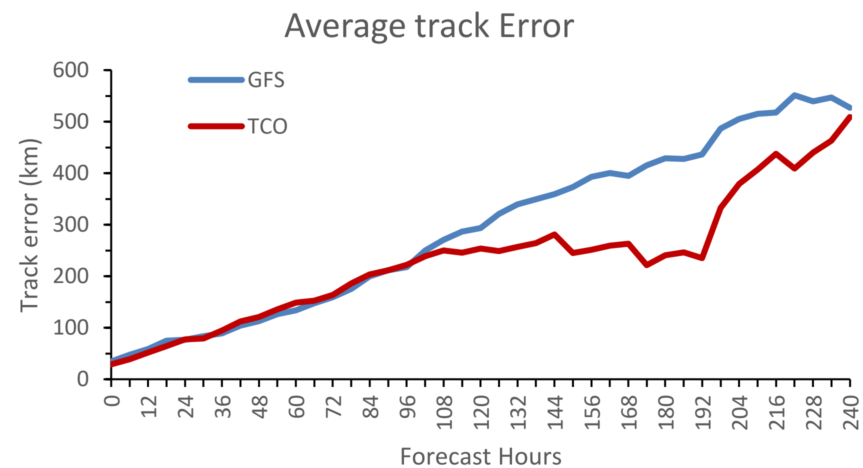
IC: 00Z 08June 2023

GFS T1534 operational is mentioned as GFS
GFS T1534 with TCO grid is mentioned as TCO

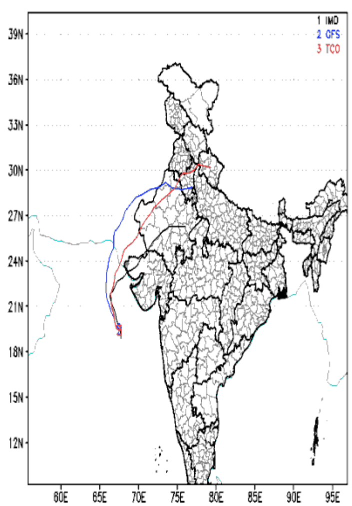


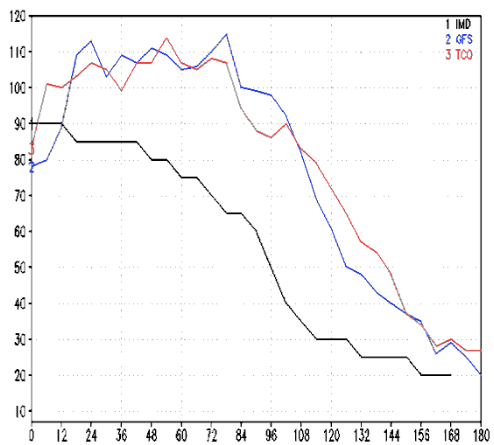
Intensity (kts)





IC: 00Z 12June 2023

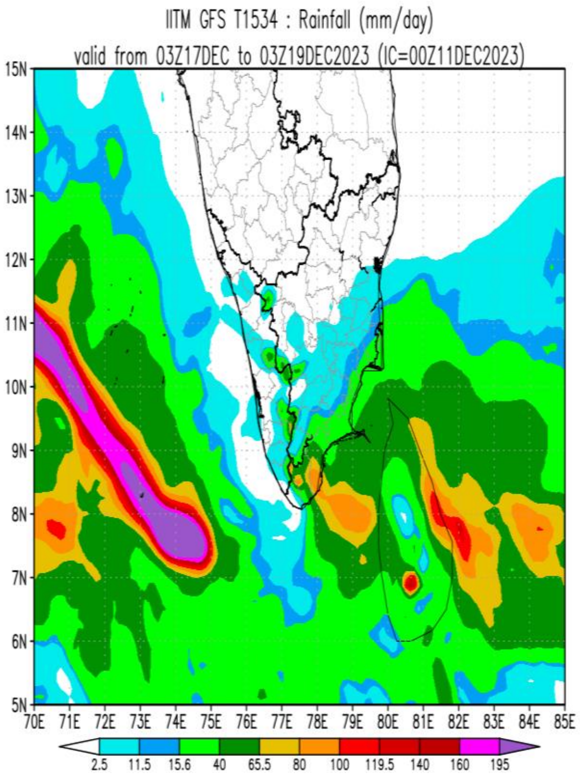




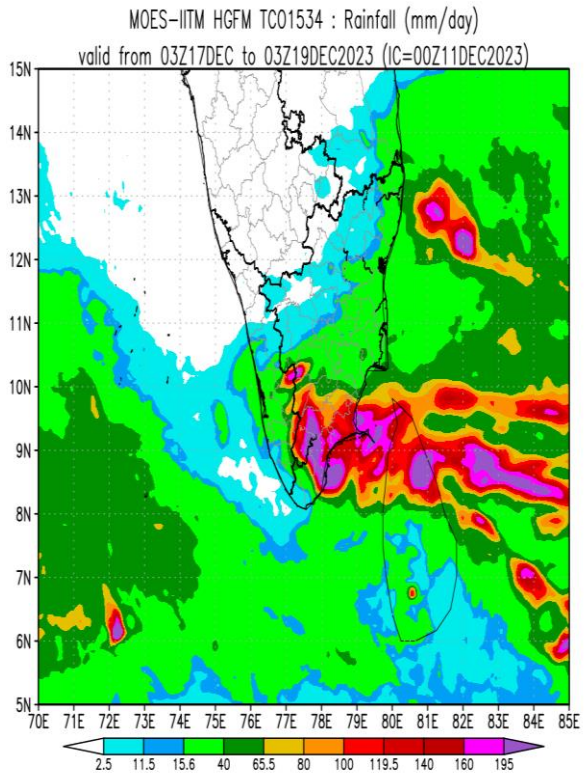
LANDFALL ERRORS		GFS	TCO	GFS	TCO
Lead Hours	IC	positions error (km_		Time Errors(hr)	
228hr	2023060600	298	**57**	0	-30
204hr	2023060700	No landfall			
180hr	2023060800	616	**201**	0	0
156hr	2023060900	349	**197**	12	12
132hr	2023061000	428	**197**	12	6
108hr	2023061100	197	**7**	6	-18
84hr	2023061200	279	**123**	12	12
60hr	2023061300	197	**163**	6	6
36hr	2023061400	89	**86**	0	0
12hr	2023061500	57	**53**	0	0

2days accumulated rainfall (mm/day) from 03Z17 Dec to 03Z19 Dec 2023

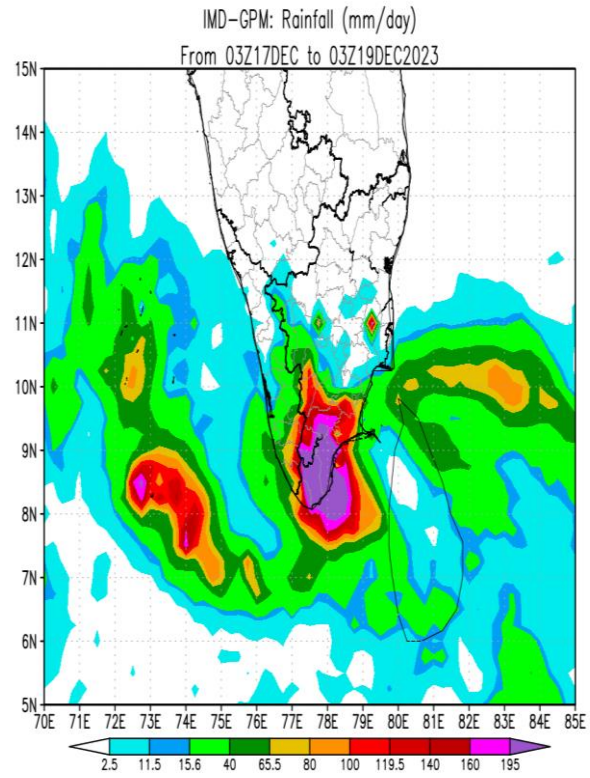
GFS_T1534



TCO_1534

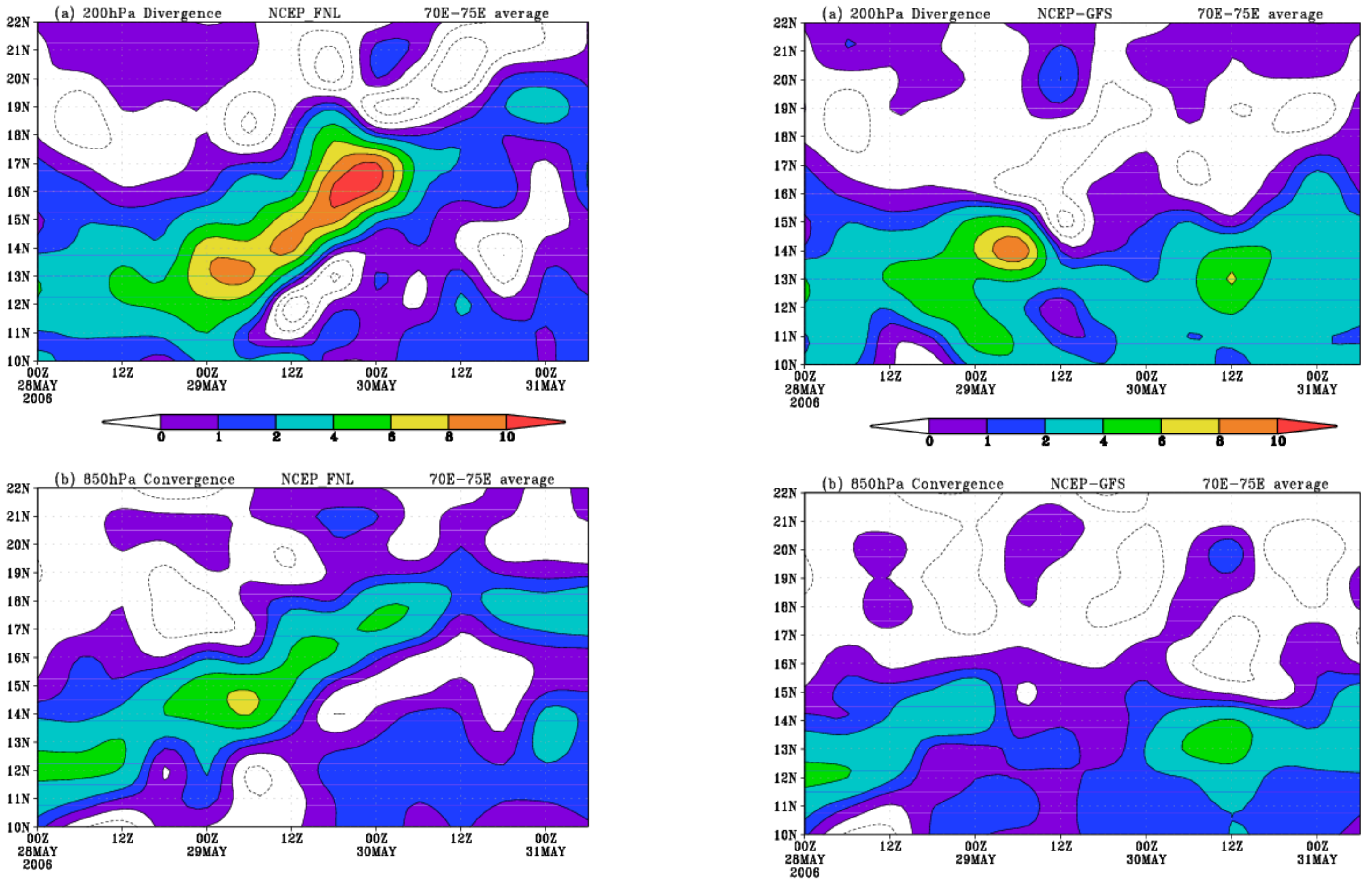


IMD_GPM



The spatial and temporal structure of the sub daily movement of convergence zones associated with onset of monsoon 2006 is revealed based on the higher resolution NCEP GFS analyses and forecasts (28-31 May 2006)

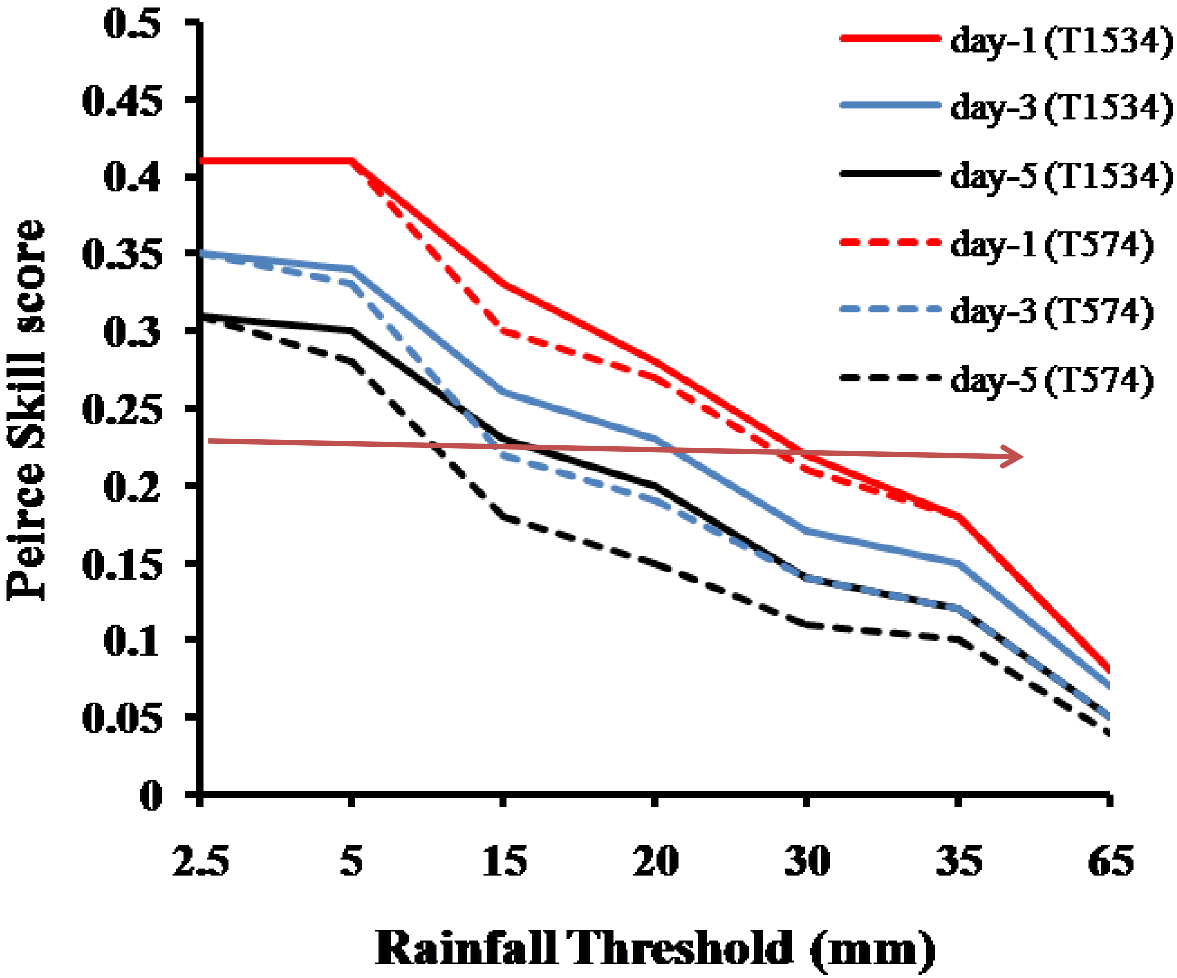
ANALYSES FORECASTS



Poor representation of vertical advection of zonal wind in the middle atmosphere leads to misrepresentation of convective processes and thus deteriorates the forecast beyond 24 hour

Taraphdar et al. 2009

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

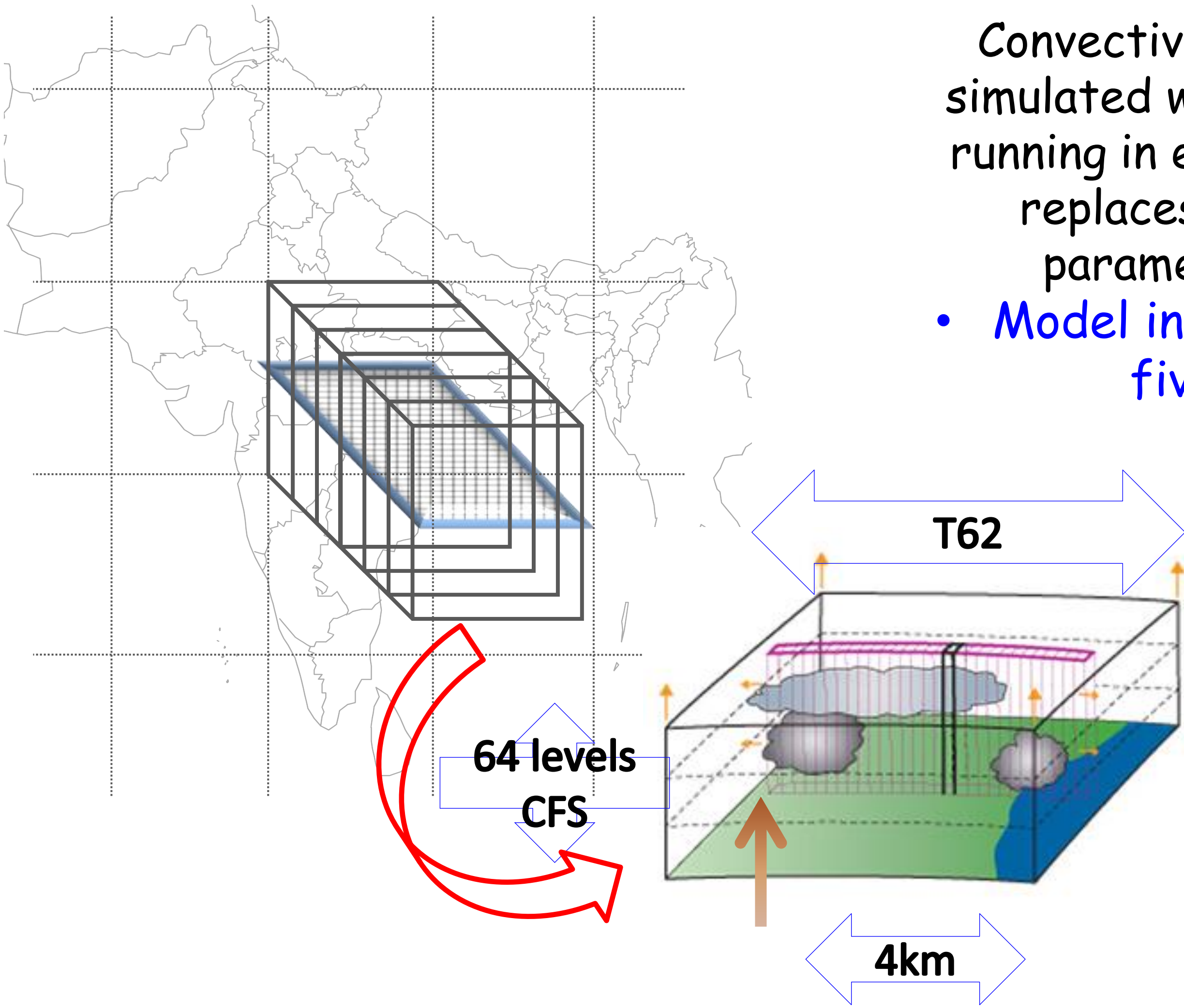


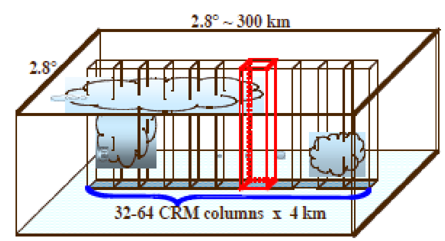
Rao et al. 2019

Superparameterized CFSv2-T62 **(SPCFS) Analyses of 6.5 year free run**

Convective tendencies are explicitly simulated with a **C**loud **R**esolving **M**odel running in each GCM grid column which replaces the traditional cumulus parameterization of the GCM.

- Model integrated for 6.5 years and five years are analyzed



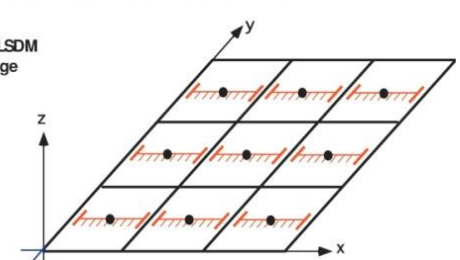


Cloud-Resolving Convection Parameterization or Super-Parameterization

Grabowski (2001), Khairoutdinov and Randall (2001)

Application of
a 2D CSRM within each column of a large-scale dynamical model (LSDM)
with periodic lateral boundary conditions

At the ● points, the LSDM and the domain-average of the CSRM interact.

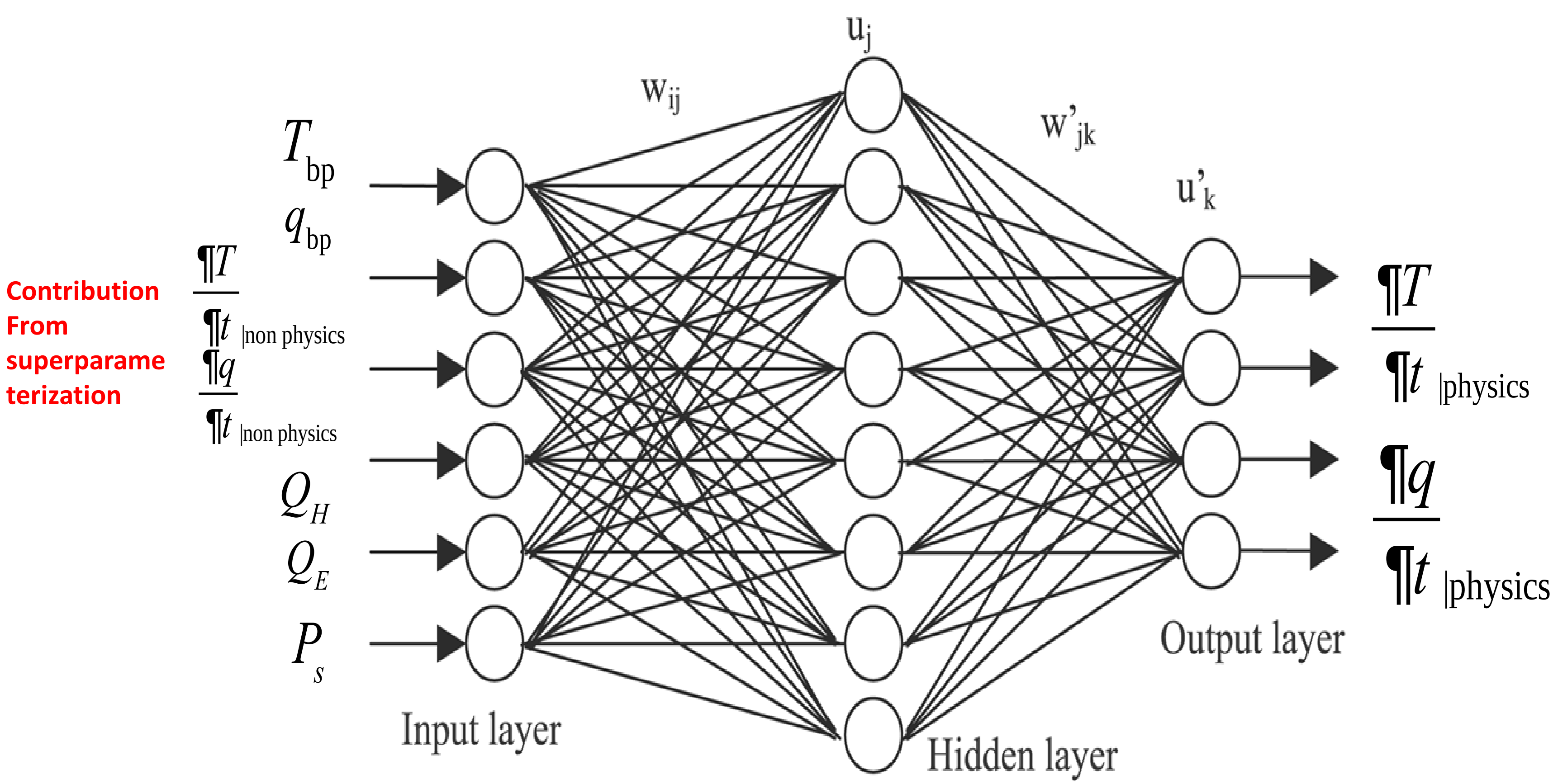


Concept and viewgraph from Akio Arakawa

Bidyut B. Goswami, R. P. M. Krishna, P. Mukhopadhyay, Marat Khairoutdinov, and B. N. Goswami, 2015: Simulation of the Indian Summer Monsoon in the Superparameterized Climate Forecast System Version 2: Preliminary Results. J. Climate, 28, 8988–9012

AI/ML in Weather Forecasting

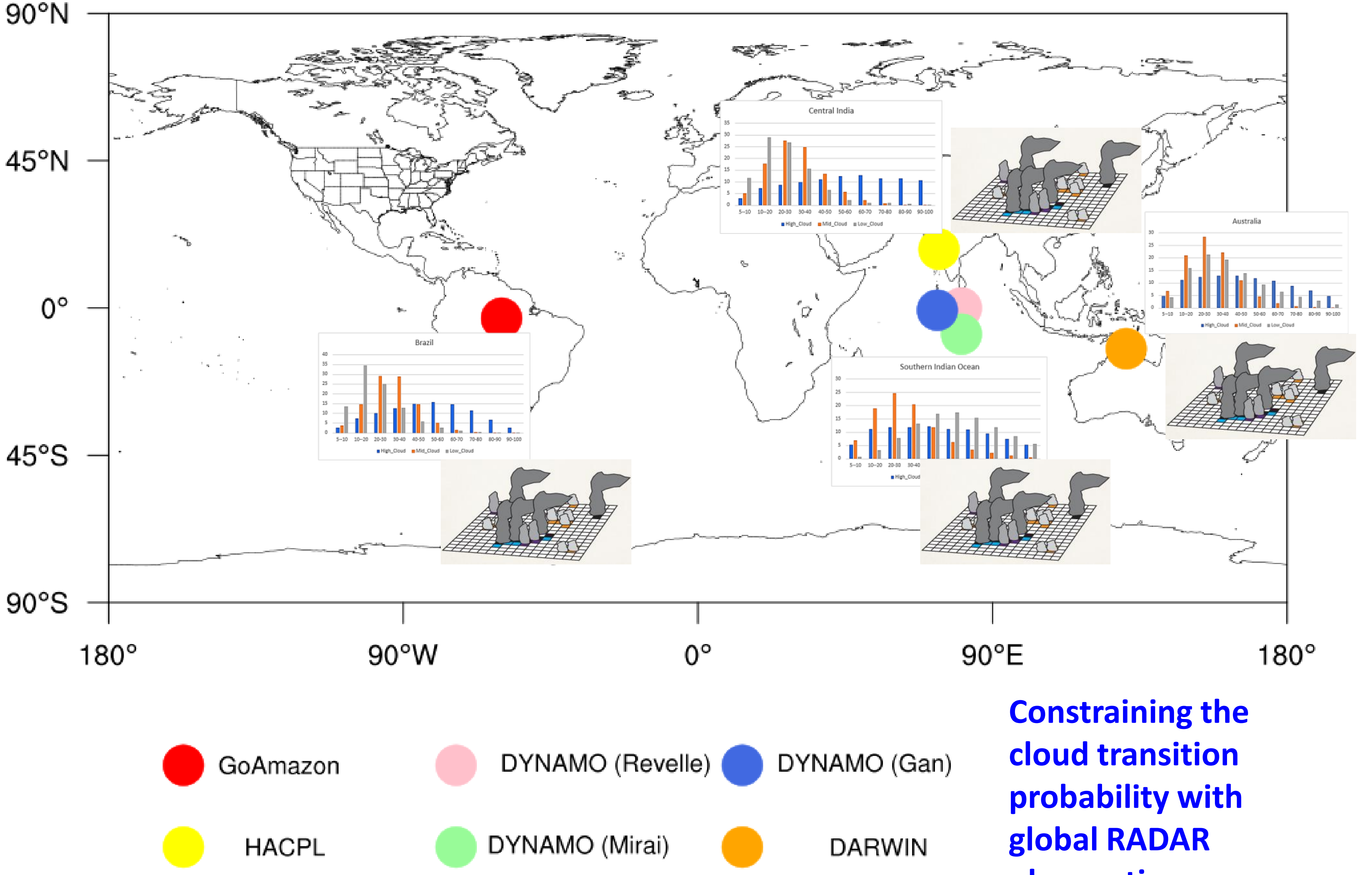
Presentation of a feed forward neural network architecture and the inputs used as well as the predicted tendencies



The deep layers will be trained from the cloud resolving model tendencies embedded in CFS (i. e. from Sp-CFS)

The trained tendencies will be given to CFS grid and the conventional cumulus parameterization will be switched off.

Radar Locations for estimations of cloud fractions



Constraining the cloud transition probability with global RADAR observations

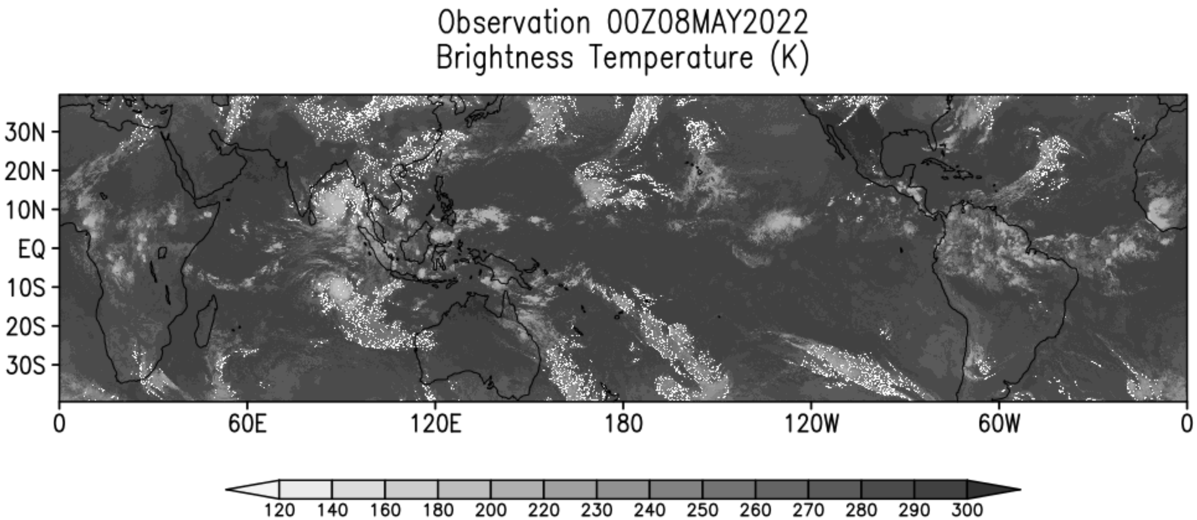
Summary and Conclusion

- For extreme events/high impact weather events Ensemble forecast provides longer lead which is useful for disaster managers/forecasters

- However, the GEFS forecast is under-dispersive (not shown), which needs further model improvement

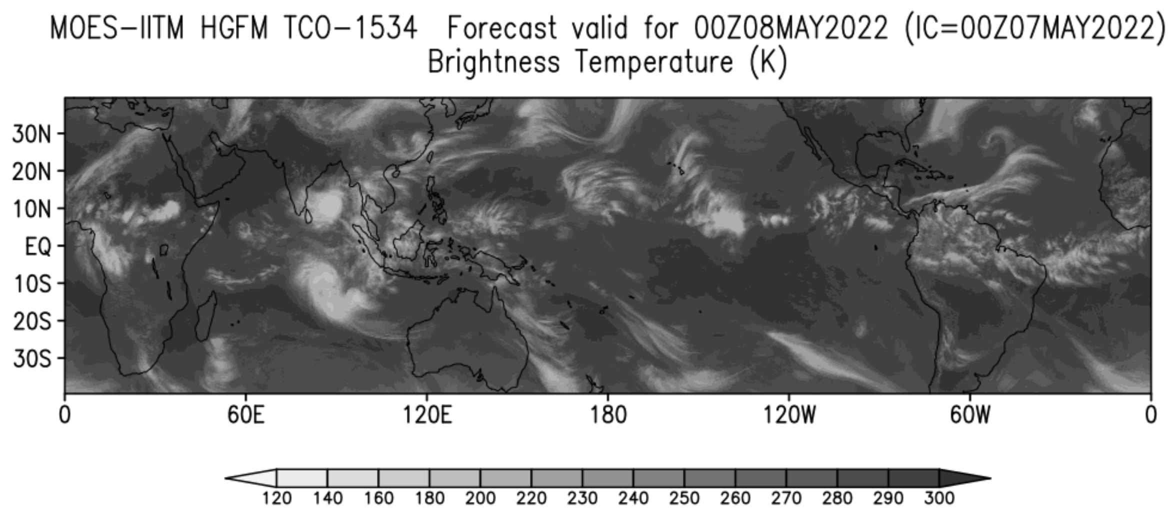
- Stochastic parameterization helps improving tropical variability.
- Realistic microphysics help improving the stratiform and convective proportion in the model
- Vertical resolution helps improving heavy rainfall forecast

- Tco (6km) global model shows higher skill in longer lead for Heavy rain forecasts and tropical cyclone forecasts and mostly resolves the spurious orographic rainfall and Gibbs wave issues (not shown) providing efficient computer time.
- Further Improvement may be achieved through NWP (SP-GFS) and AI combined forecast system.



TC ASANI

Thank You !



Following Lopez et al. 2020, BAMS