Lessons learnt from weather scale forecast to improve fidelity of S2S

Partha Mukhopadhyay,
(mpartha@tropmet.res.in)

R. Phani Murali krishna, Siddharth Kumar, Malay Ganai, Snehlata Tirkey, Medha Deshpande, R. Prajeesh, Tanmoy Goswami, Sahadat Sarkar, Radhika Kanase, Kumar Roy

Indian Institute of Tropical Meteorology, Pune
(email:mpartha@tropmet.res.in)

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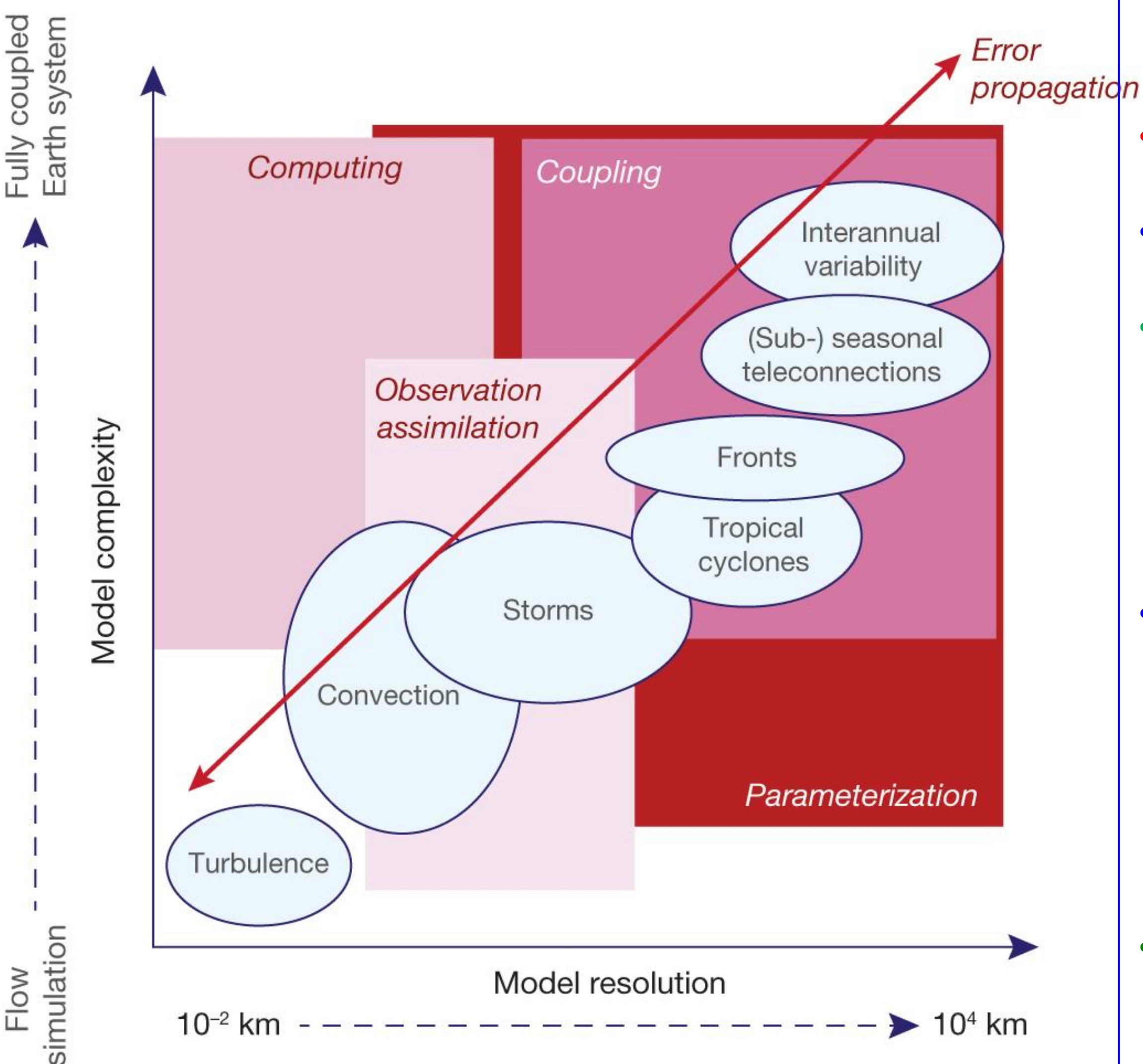
"Future directions of Sub-seasonal to Seasonal Prediction over South Asia",
29-31 March 2021, ITM, Pune

Outline of the talk

- Introduction
- Deterministic GFS vs GEFS
- Under-dispersive nature of forecast
- Possible future pathways to overcome the issues
- Conclusion

Key challenge areas for NWP in the future



- Advances in forecast skill will come from scientific and technological innovation in computing
- The representation of physical processes in parameterizations,
- Coupling of Earth-system components,
- The use of observations with advanced data assimilation algorithms, and the consistent description of uncertainties through ensemble methods and how they interact across scales.
- The ellipses show key phenomena relevant for NWP as a function of scales between 10^{-2} and 10^{4} km resolved in numerical models and the modelled complexity of processes characterizing the small-scale flow up to the fully coupled Earth system.
- The boxes represent scale-complexity regions where the most significant challenges for future predictive skill improvement exist.
- The arrow highlights the importance of error propagation across resolution range and Earth-system components.

nature

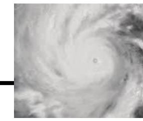
The quiet revolution of numerical weather prediction

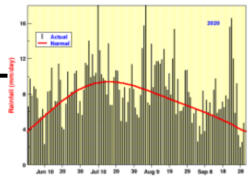
P Bauer *et al.* *Nature* **525**, 47-55 (2015) doi:10.1038/nature14956

Models for earth system relevant processes at IITM

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

TS





Cumulus clouds

Renewable

TCs, MDs

LES Model, DNS

Cloud System Resolving Model (CSRM)

WRF

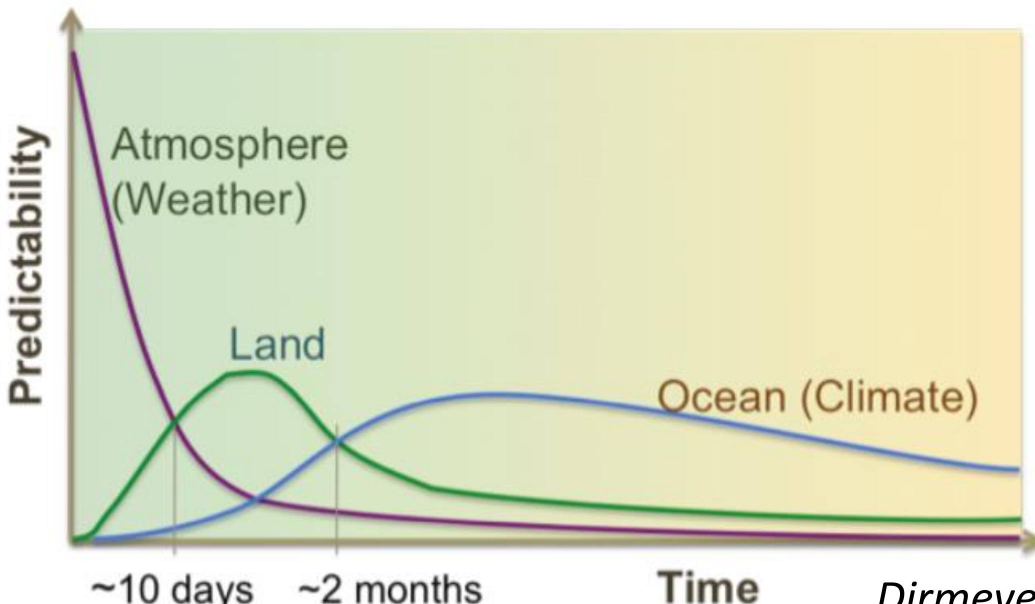
GFS/GEFS GFS/CFS CFS

T1534. 21EM T126/T382 T382

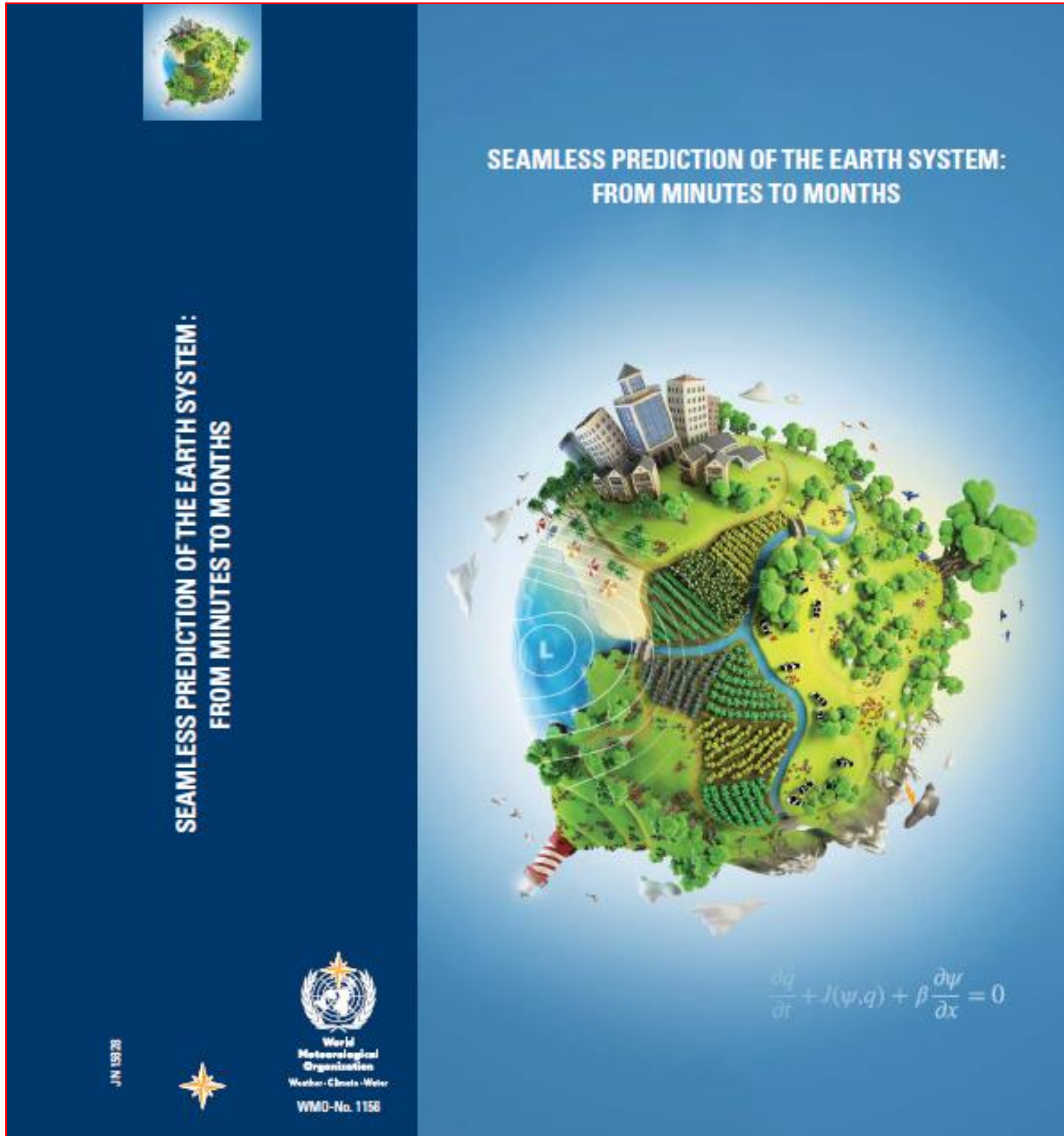
Subgrid

Numerical Weather Prediction (NWP) Model

Global Climate Model



Dirmeyer et al. 2015


SEAMLESS PREDICTION OF THE EARTH SYSTEM:
FROM MINUTES TO MONTHS
$\frac{\partial q}{\partial t} + J(\psi,q) + \beta \frac{\partial \psi}{\partial x} = 0$
SEAMLESS PREDICTION OF THE EARTH SYSTEM:
FROM MINUTES TO MONTHS
World Meteorological Organization
Weather · Climate · Water
WMO-No. 1156

WMO 2015

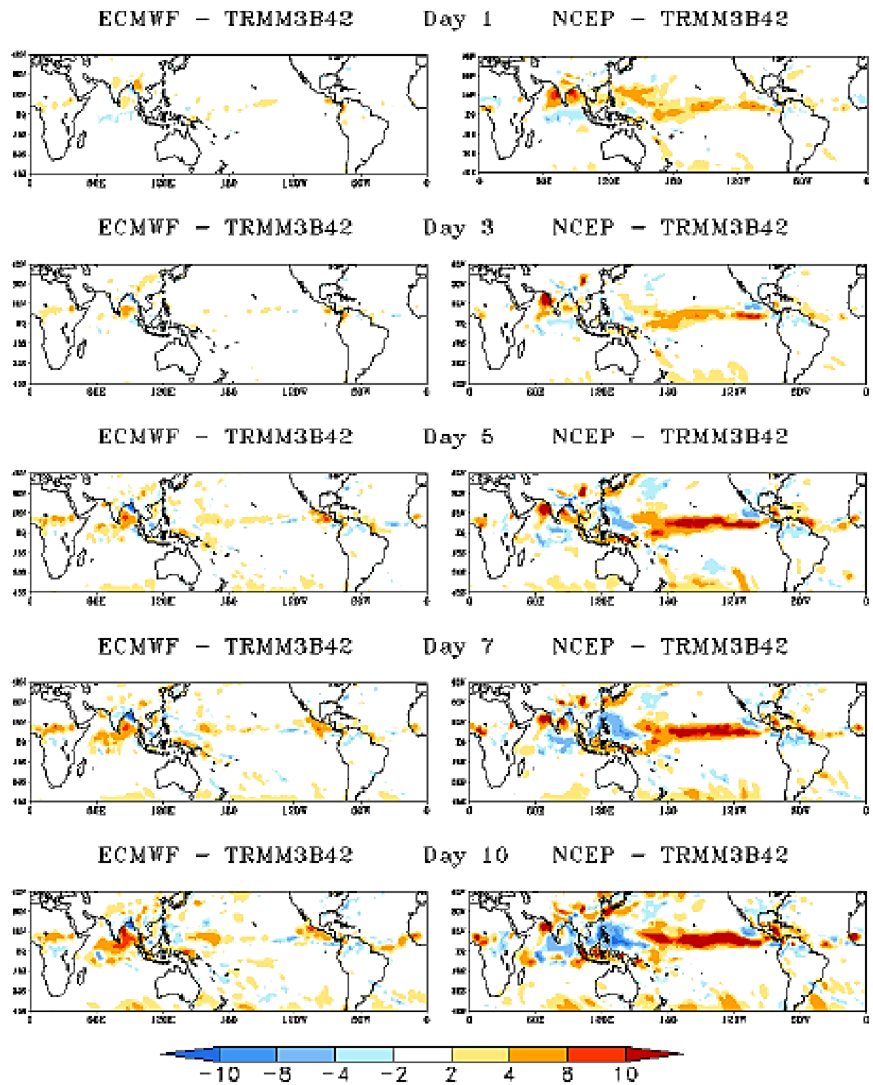


Figure 4: Difference of JJA (2007 - 2009) average lead time (Day1, Day3, Day5, Day7 and Day10) large scale precipitation forecast for ECMWF EPS and NCEP EPS from observation (TRMM3B42).

Taraphdar et al. 2016

Flowchart of GEFS (Ensemble)

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 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

Flowchart of GFS (Deterministic)

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)

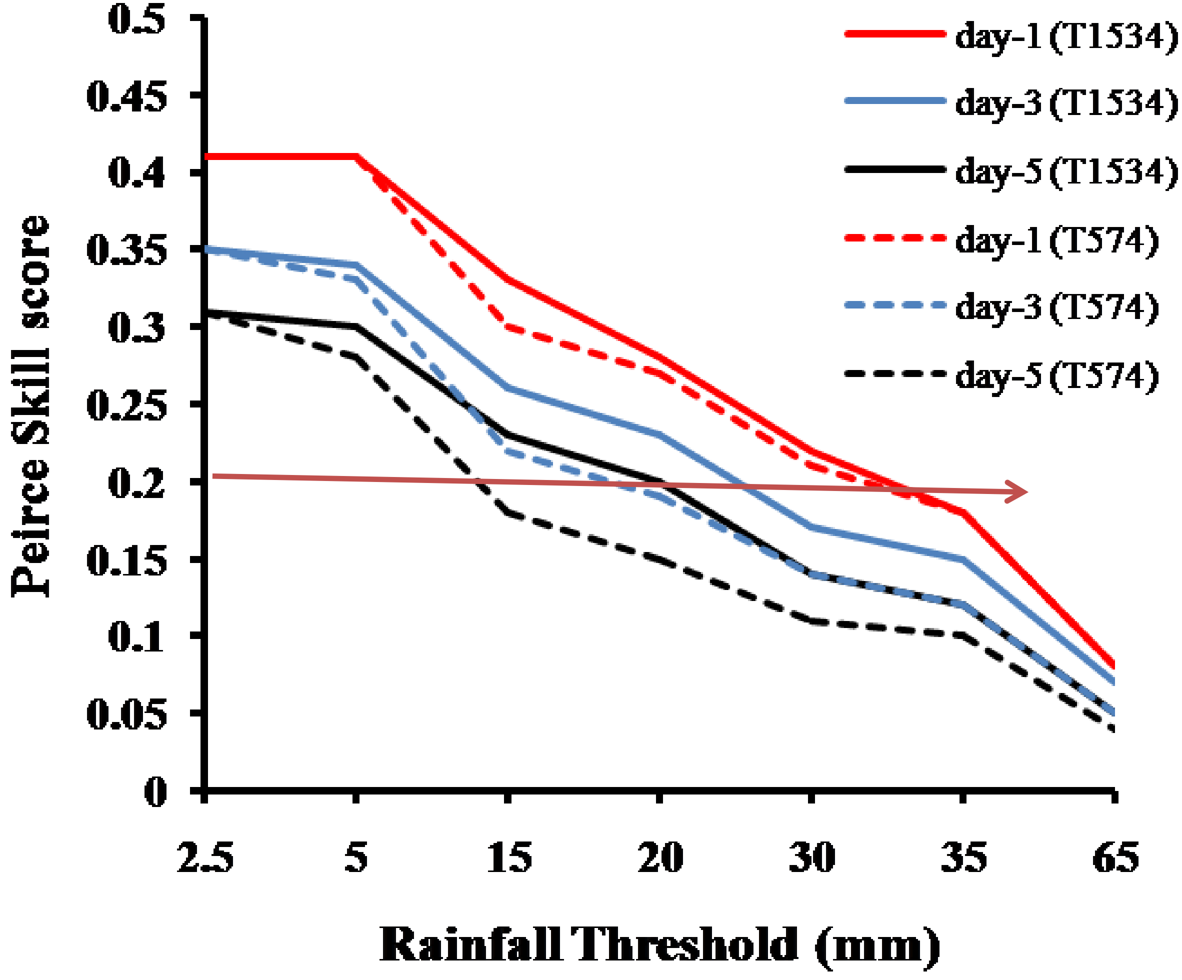
POST PROCESSING

240hr (10 days) forecast

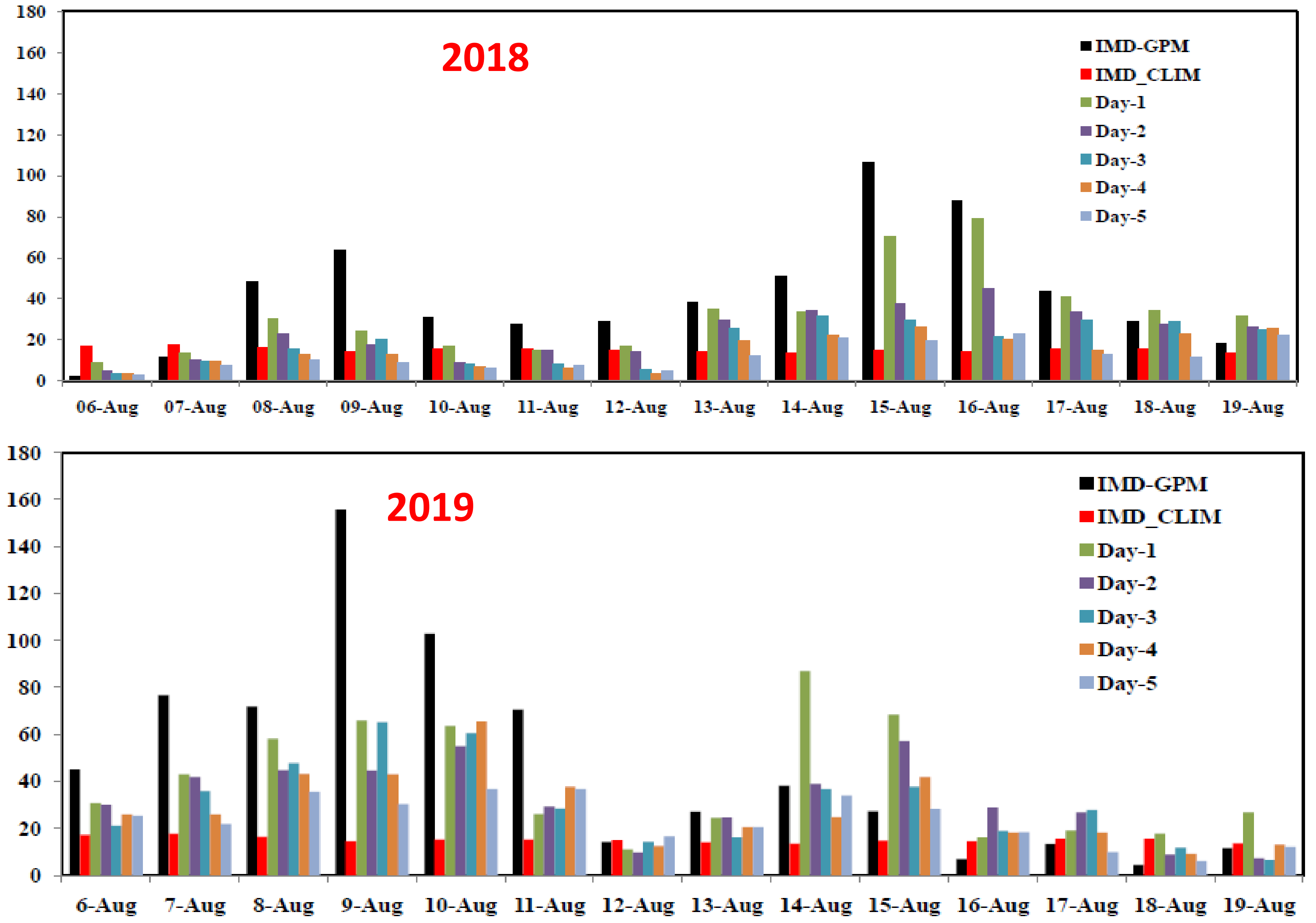
Resolution: Regular grid and Gaussian grid at different resolutions

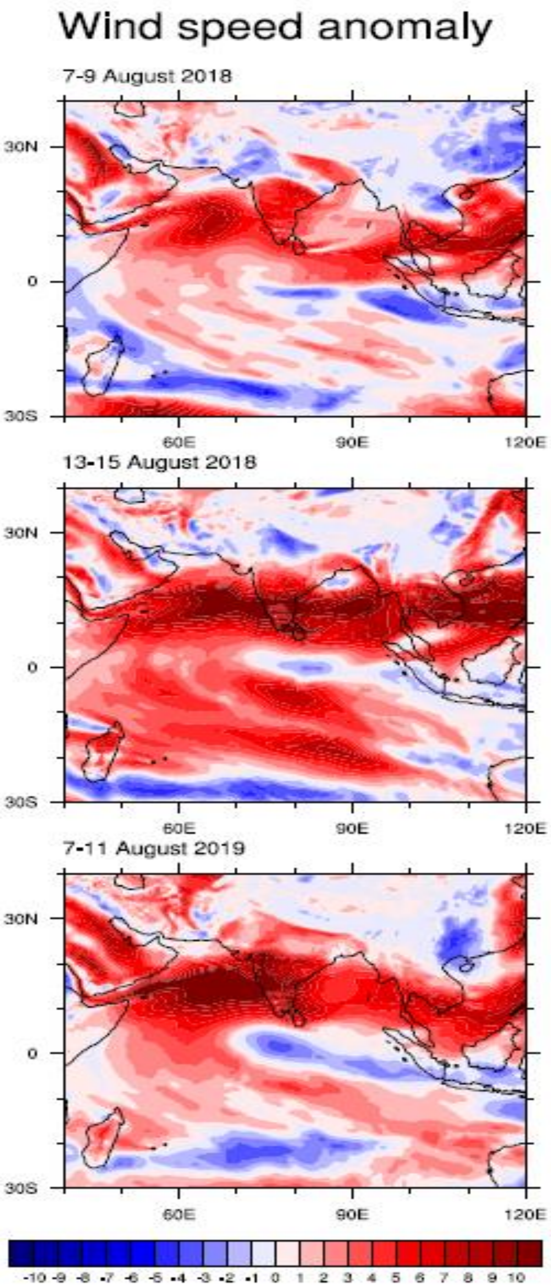
0.125°x0.125°

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

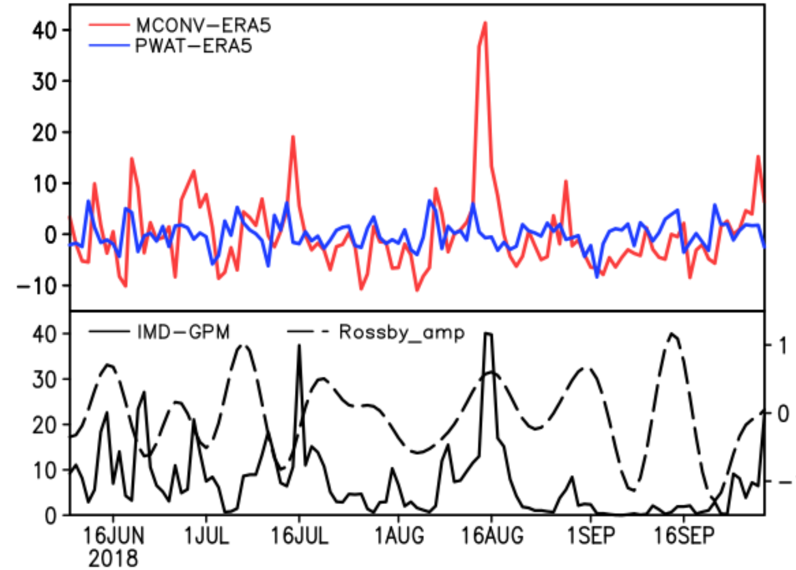


Rainfall (mm/day) time series over Kerala during 06-19Aug from GFS T1534





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

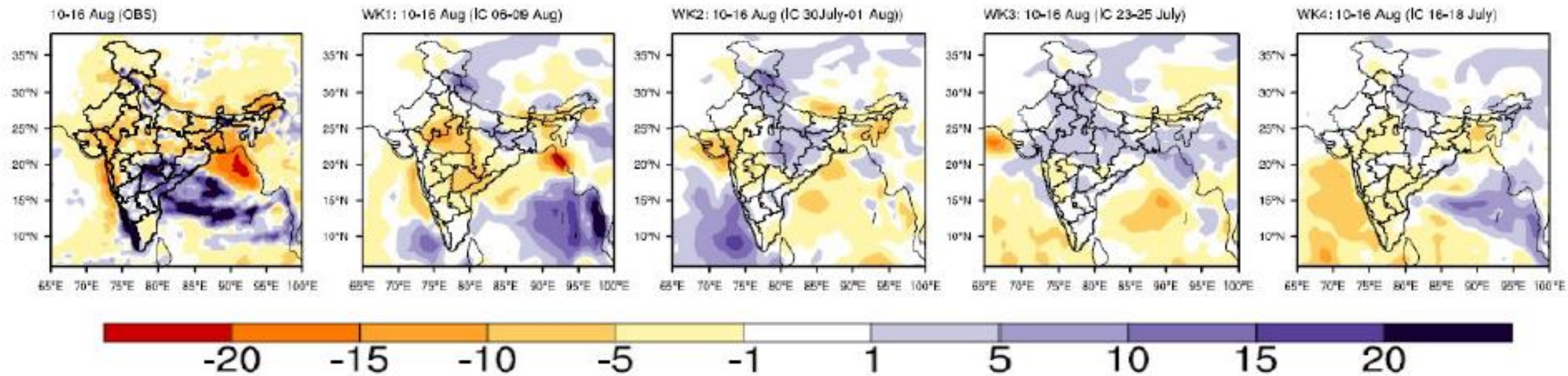
Following Yanai et al. (1973), the traditional WVB equation may be expressed in the following form:

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

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.

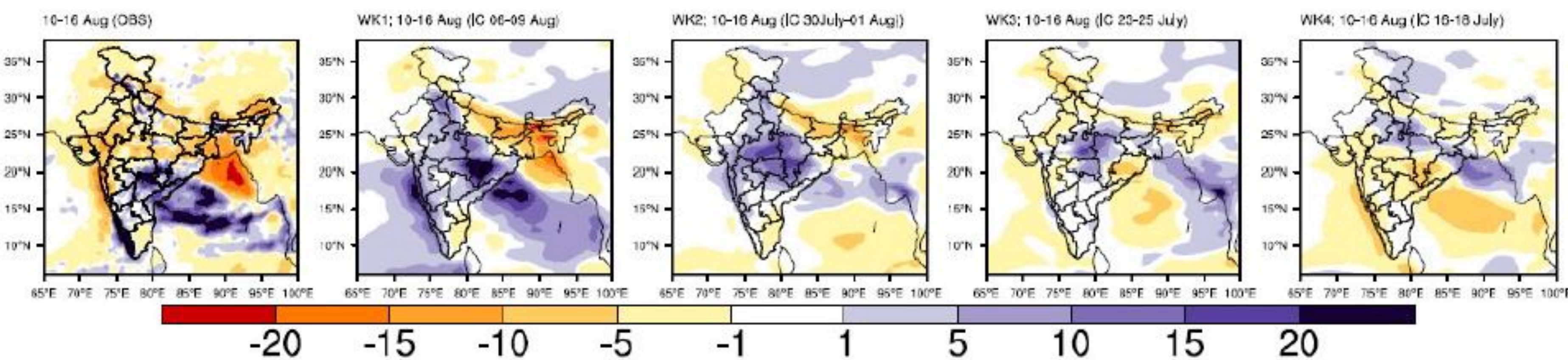
Weekly forecast



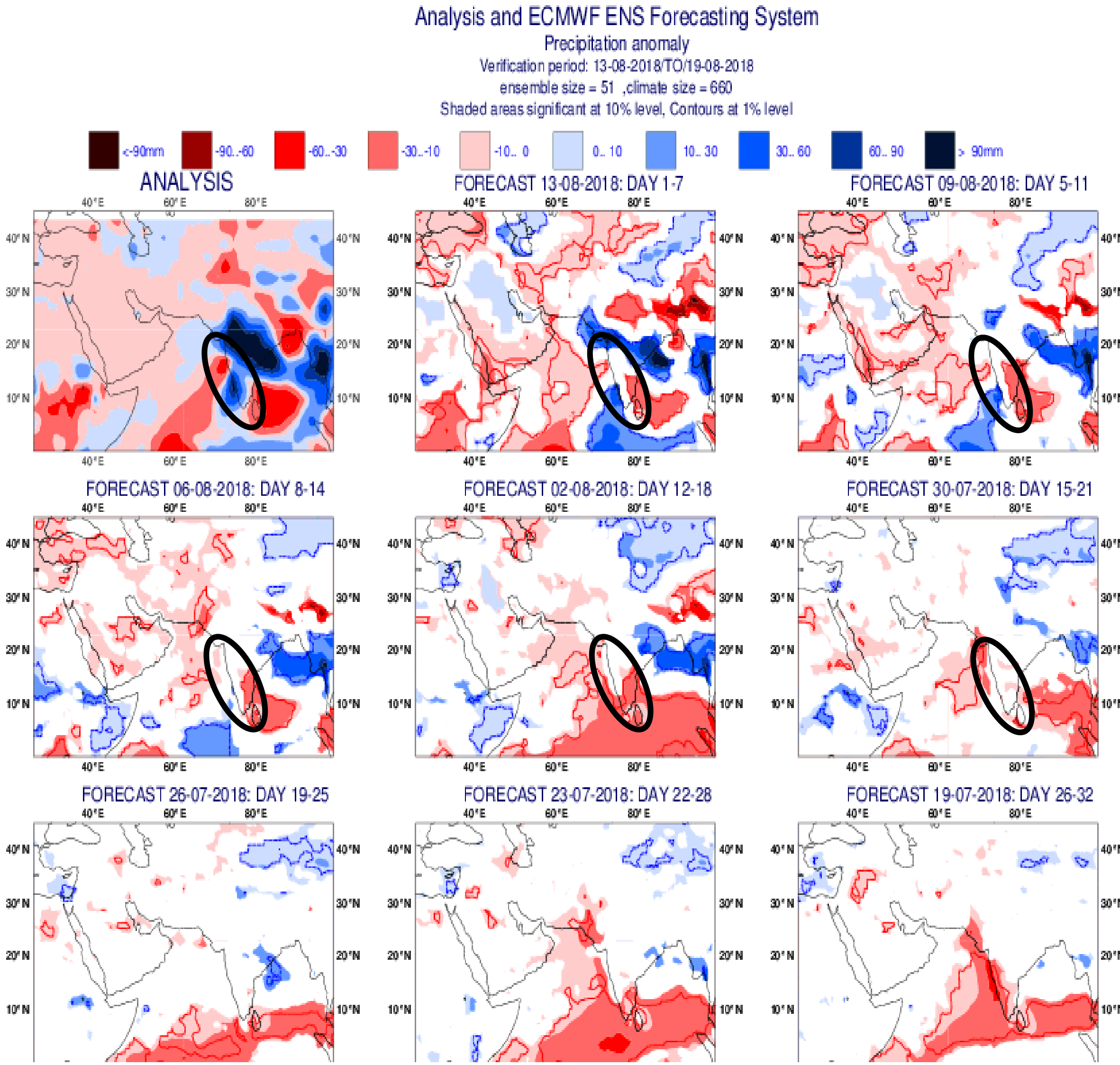
Valid period 10-16 Aug 2018

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

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



ENS weekly TP fc over India for 20180813-0819



ECMWF

Slide borrowed from Roberto Buizza, ECMWF

GEFS

IFS

NCUM

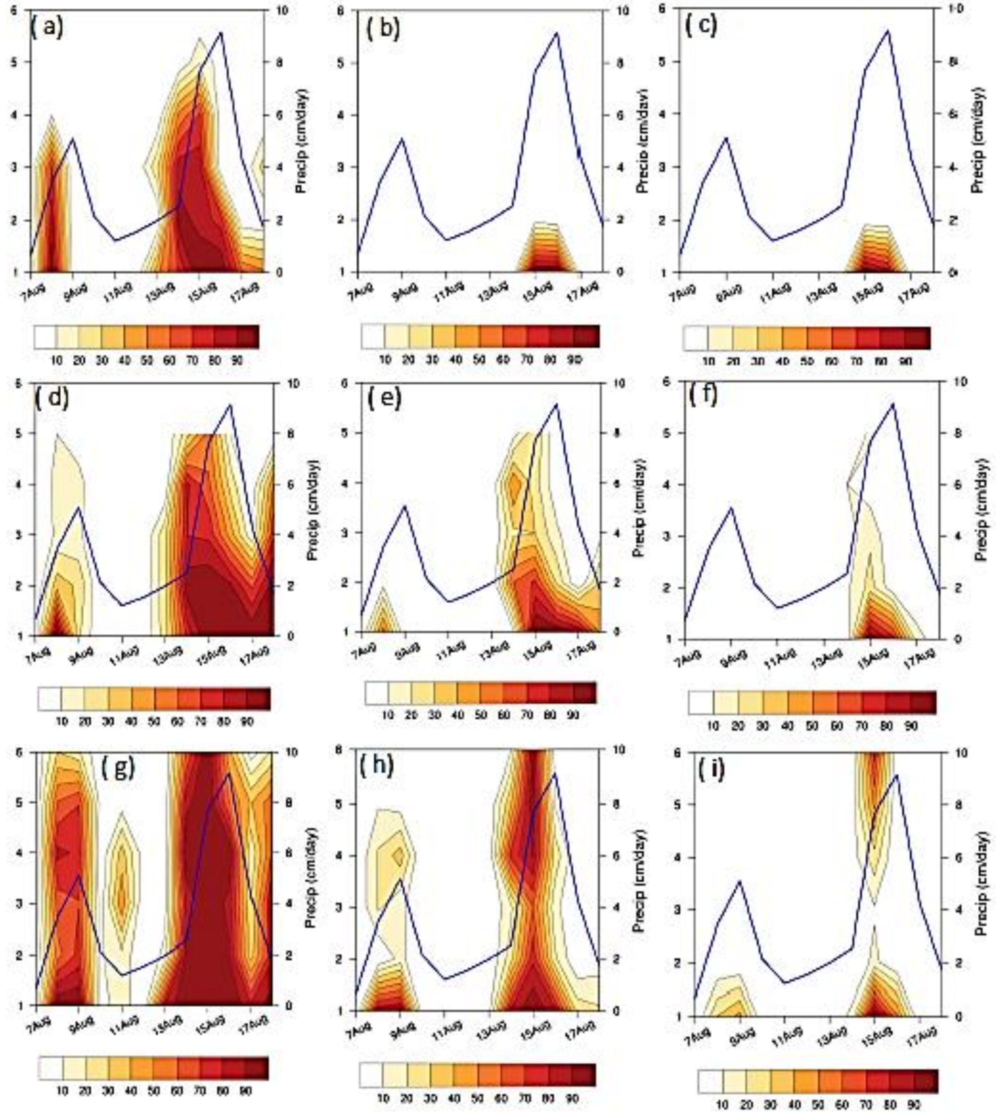
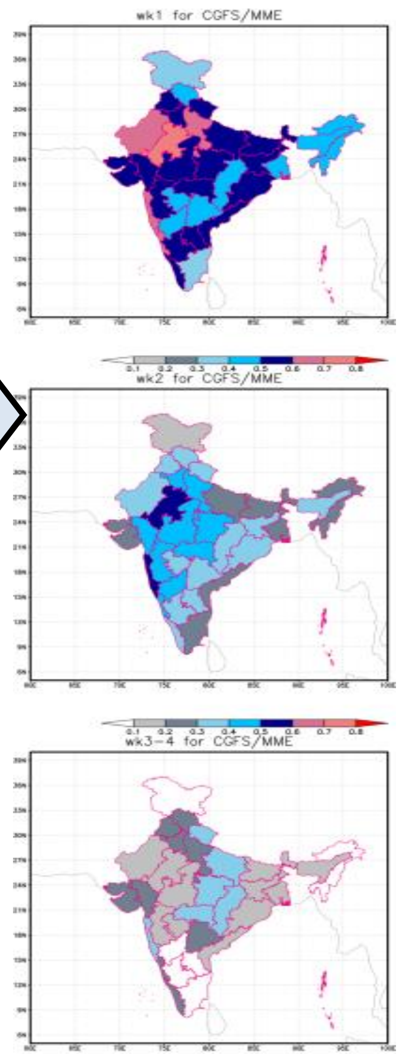


Figure 12. Forecast lead time diagram of the probability that the GEFS forecast (top row), ECMWF (middle row) and NCUM (bottom row) for the daily accumulated rain over Kerala (9.5-11.5°N, 76-77.5°E) exceeding the observed daily climatology plus 1 standard deviation (first column), 2SD (middle column) and 3SD (third column). The blue line represents the IMD-GPM rainfall (cm/day) averaged for the same region.

Summer Monsoon Rainfall Prediction Skill

Anomaly Correlation

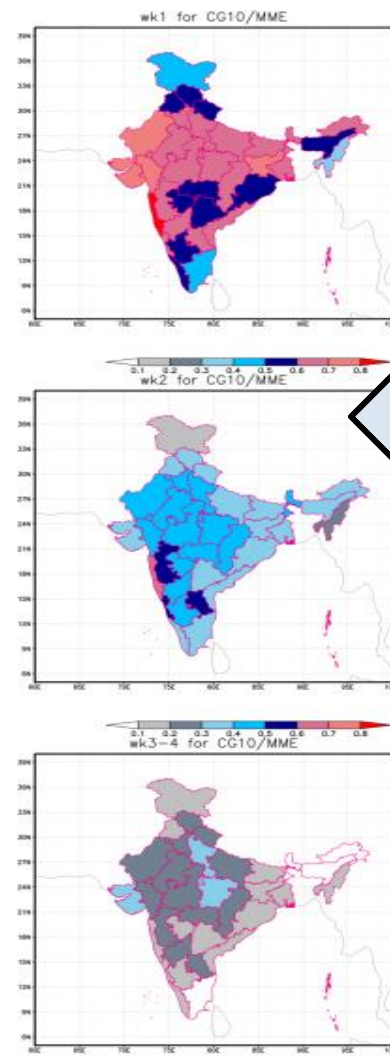
ERPv1



Wk 1

Wk 2

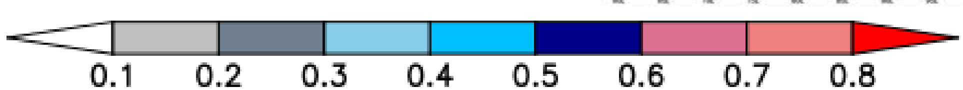
Wk 3- 4



MPMME

Skill is not improving in 3-4 week

From Dr. Sahai et al.

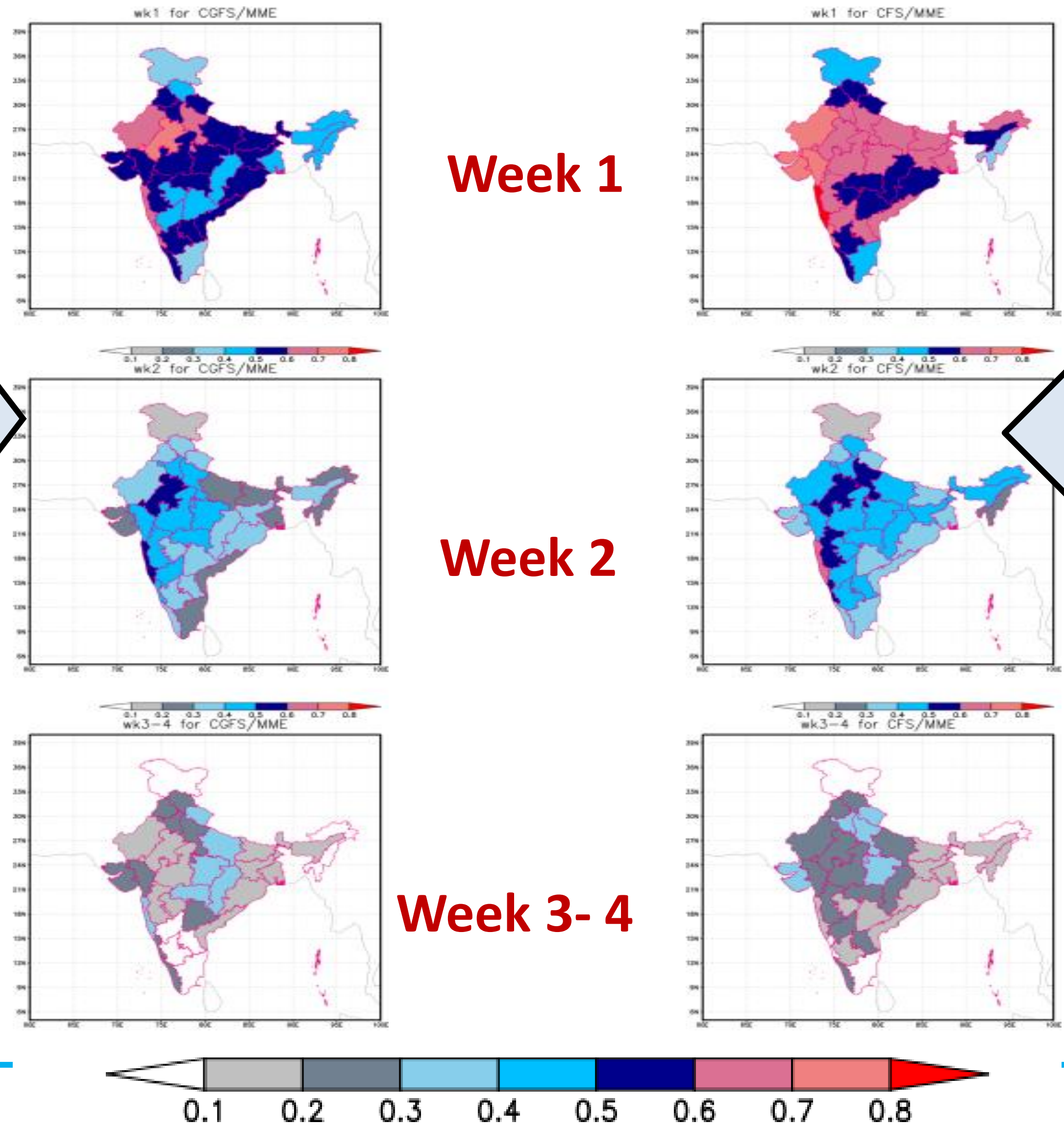


Summer Monsoon Rainfall Prediction Skill

Anomaly Correlation

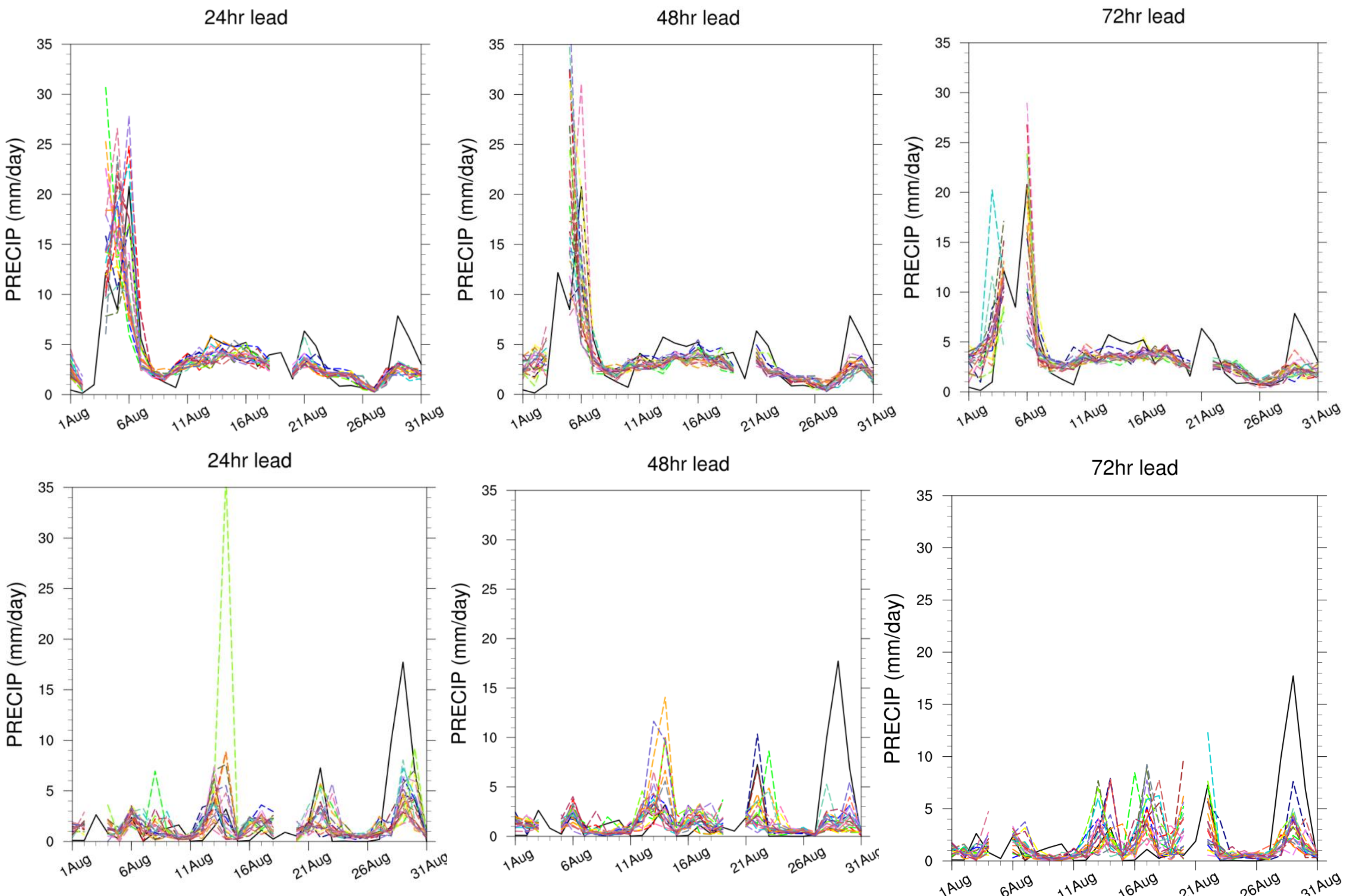
ERPv1

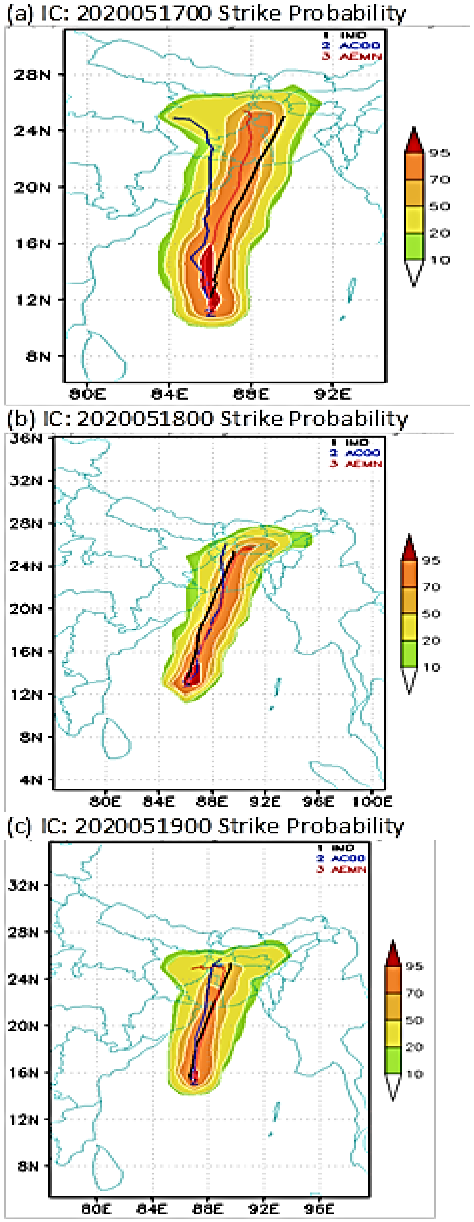
CFS (MPMME)



From Dr. Sahai et al.

Time series of rainfall from all ensemble members for Mumbai (1st row) and Bhopal region (2nd row) for the month of August 2020





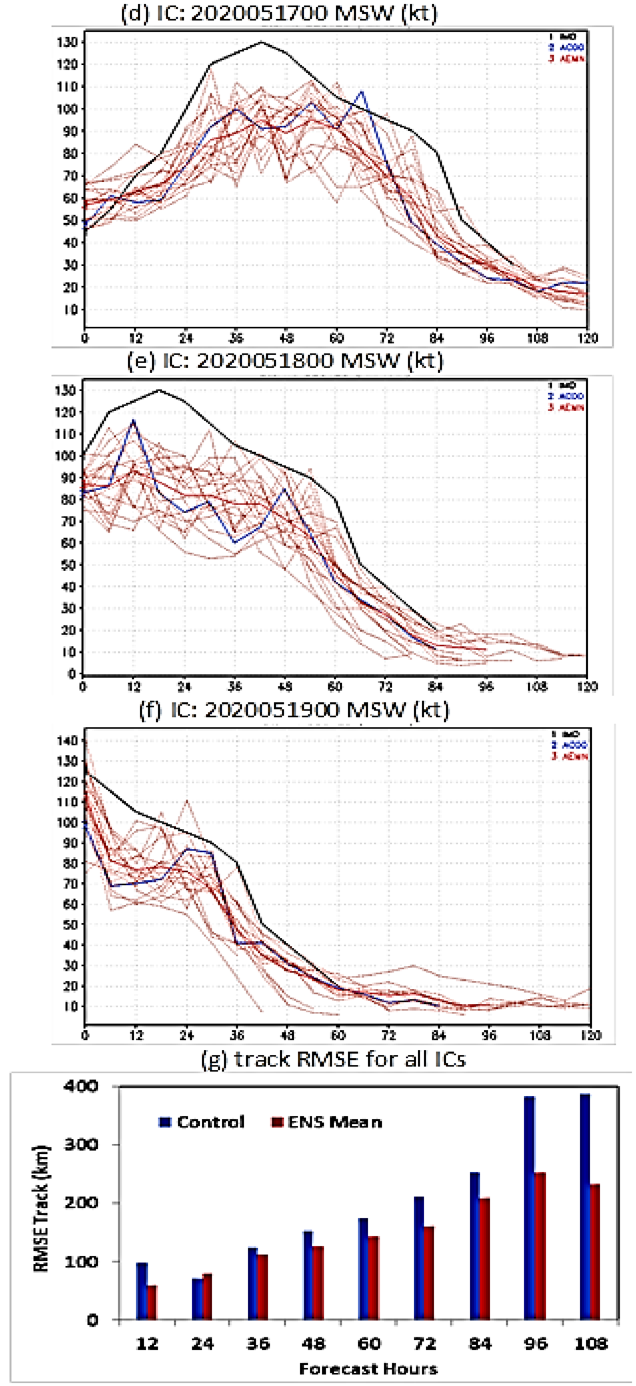
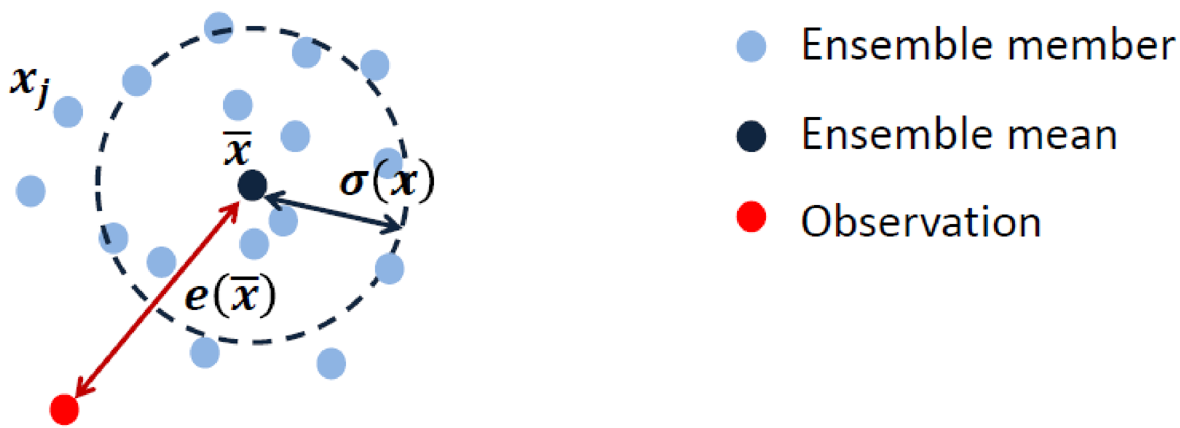


Figure 8: TC AMPHAN (a-c) strike probability, (d-f) Maximum Sustained Wind and Verification of the forecast of (g) track from all the ICs during the lifespan of the AMPHAN.

Ensemble reliability

- In an **under**-dispersive ensemble,

$$e(\bar{x}) \gg \sigma(x)$$



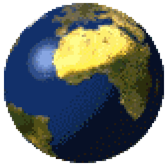
The small spread implies low uncertainty and hence, small errors:

an "over-confident forecast"

What happens when the ensemble includes no representation of model uncertainty?

Slide adopted from: Sarah-Jane Lock, ECMWF

Model Configuration

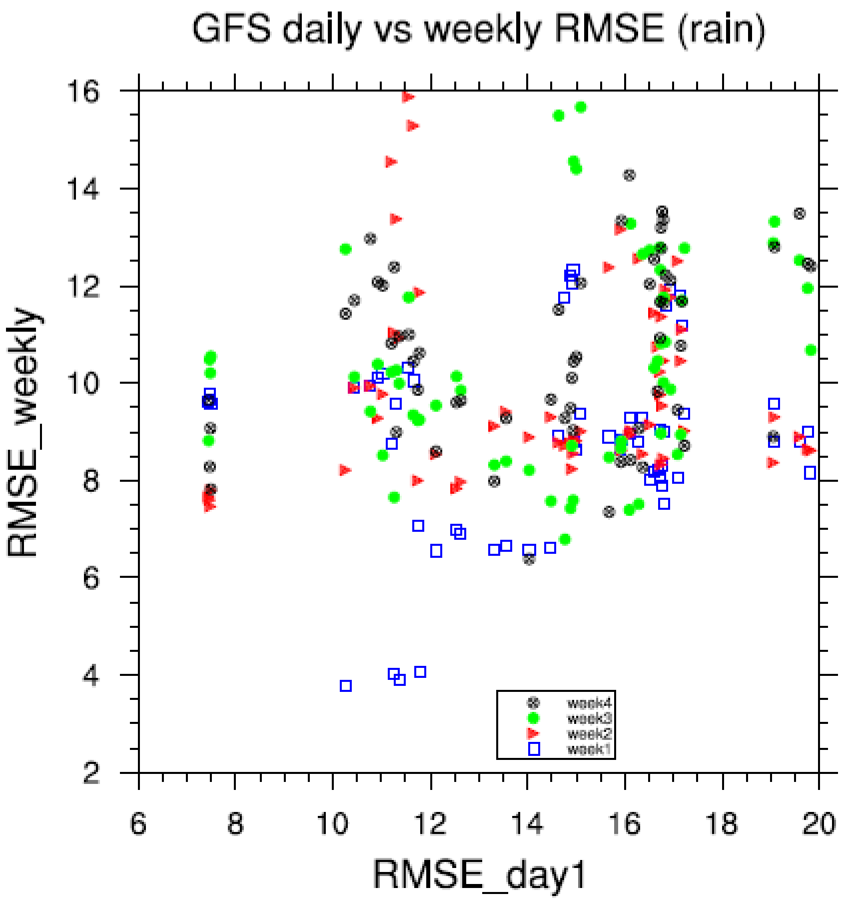


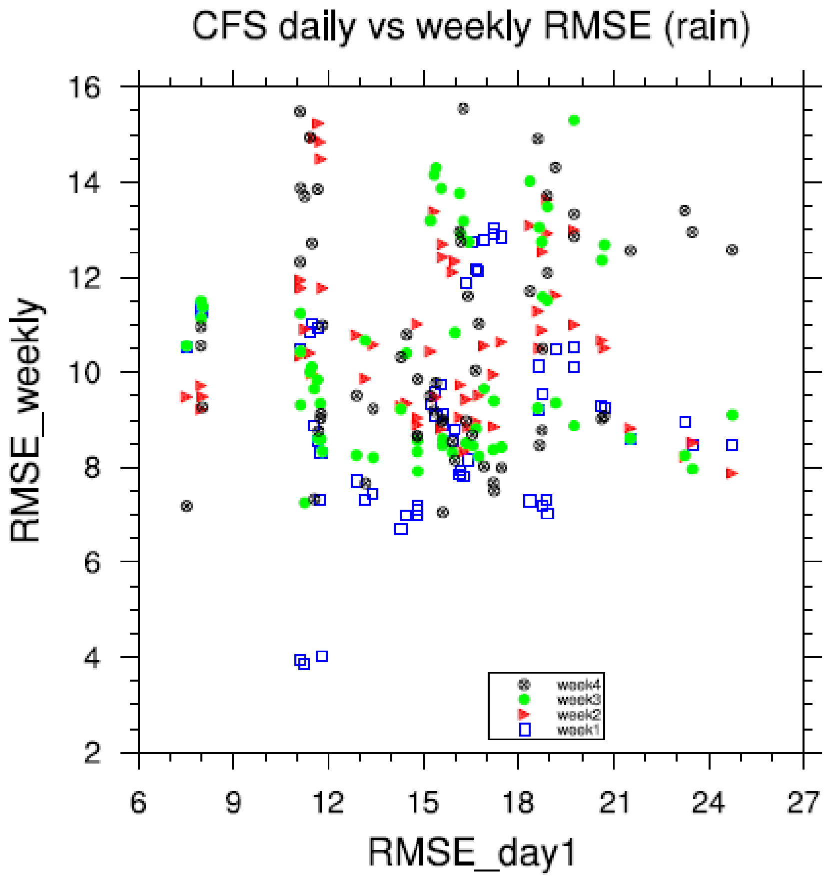
MonsoonMission-IMD GFS Model (T382) (Euler-Lagrangian) : 4 Weeks
MonsoonMission-IMD CFS Model (T382) (Euler-Lagrangian) : 4 Weeks
MonsoonMission-IMD GFS Model (T574) (Semi-Lagrangian) : 10 days

All models are run with

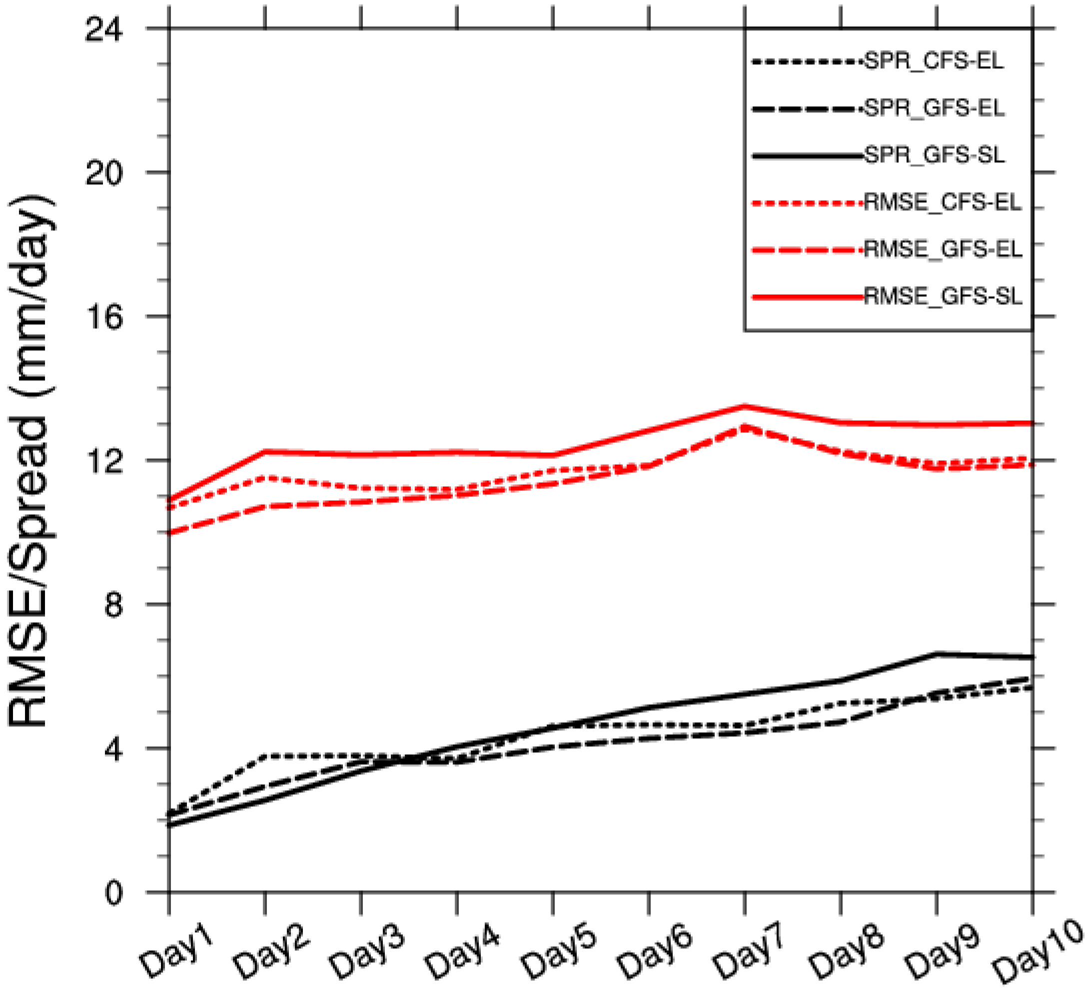
1) same horizontal resolution
2) Same IC's
3) June-July-August 2020 (Every Wednesday)
4) Minimum of 4 Ensembles each IC.

RMSE Daily vs Weekly

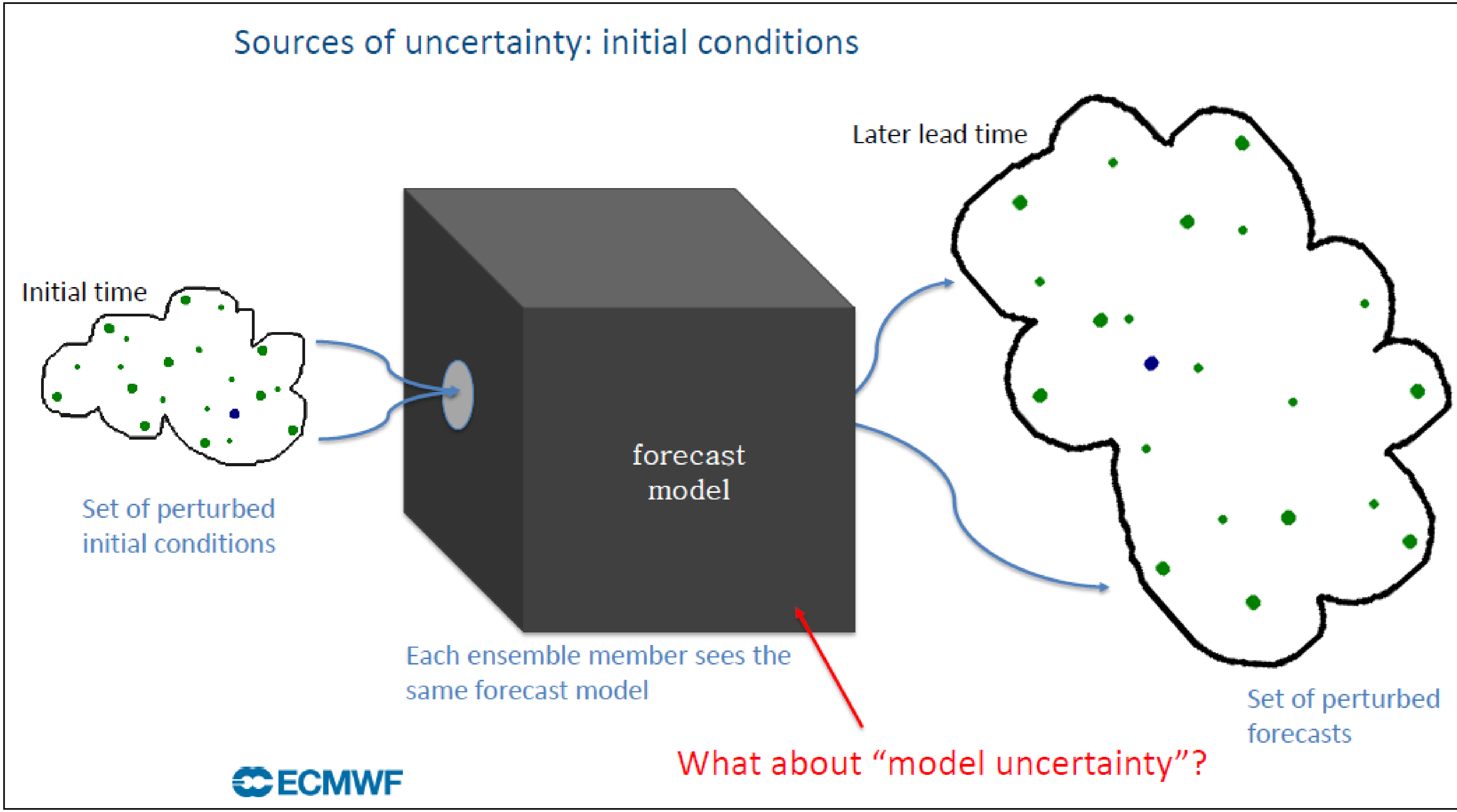




Over 10-40N, 60-90E

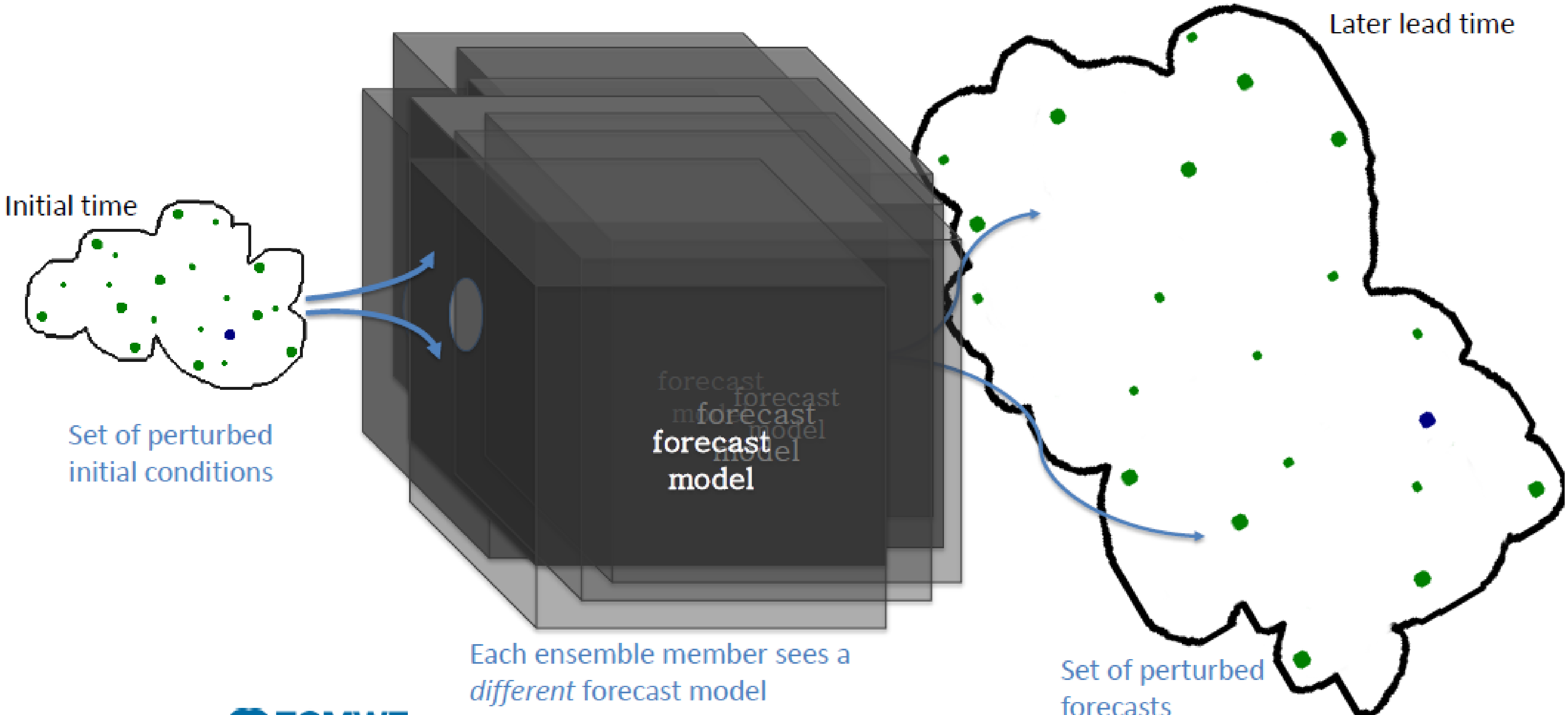


RMSE and Spread for rainfall over 10-40N, 60-90E



Slide: Sarah-Jane Lock, ECMWF

Sources of uncertainty: accounting for model uncertainty



ECMWF

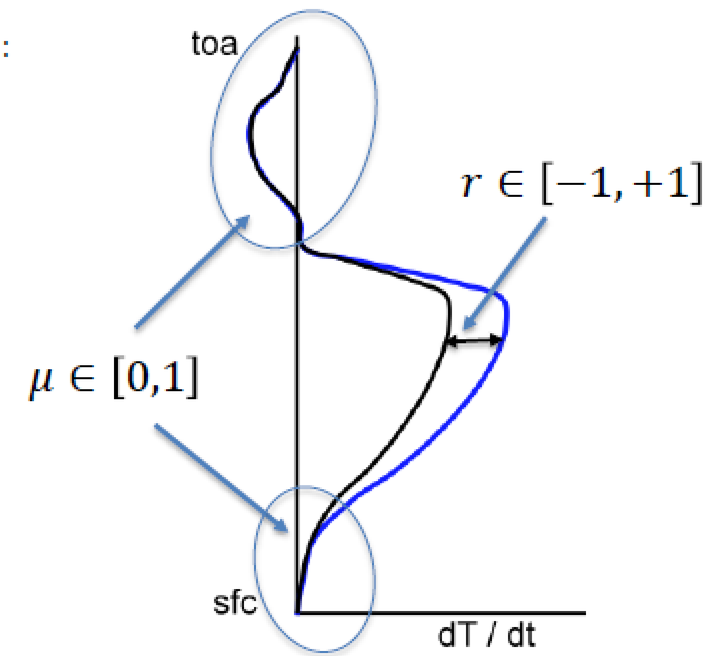
Slide: Sarah-Jane Lock

Stochastically Perturbed Parametrisation Tendencies (SPPT) scheme

- Initially implemented in IFS, 1998 (**Buizza et al., 1999**); revised in 2009:
- Simulates model uncertainty due to physics parameterisations by
  - taking the net tendencies from the physics parametrisations:

$$\boldsymbol{X} = [X_U, X_V, X_T, X_Q]$$

coming from { *radiation*, *gravity wave drag*, *vertical mixing*, *convection*, *cloud physics* } schemes



  - and perturbing with multiplicative noise $r \in [-1,+1]$ as:

$$\boldsymbol{X}' = (1 + \mu r)\boldsymbol{X}$$

where $\mu \in [0,1]$ tapers the perturbations to zero near the surface & in the stratosphere.

Shutts et al. (2011, ECMWF Newsletter); Palmer et al., (2009, ECMWF Tech. Memo.)

Slide: Sarah-Jane Lock, ECMWF

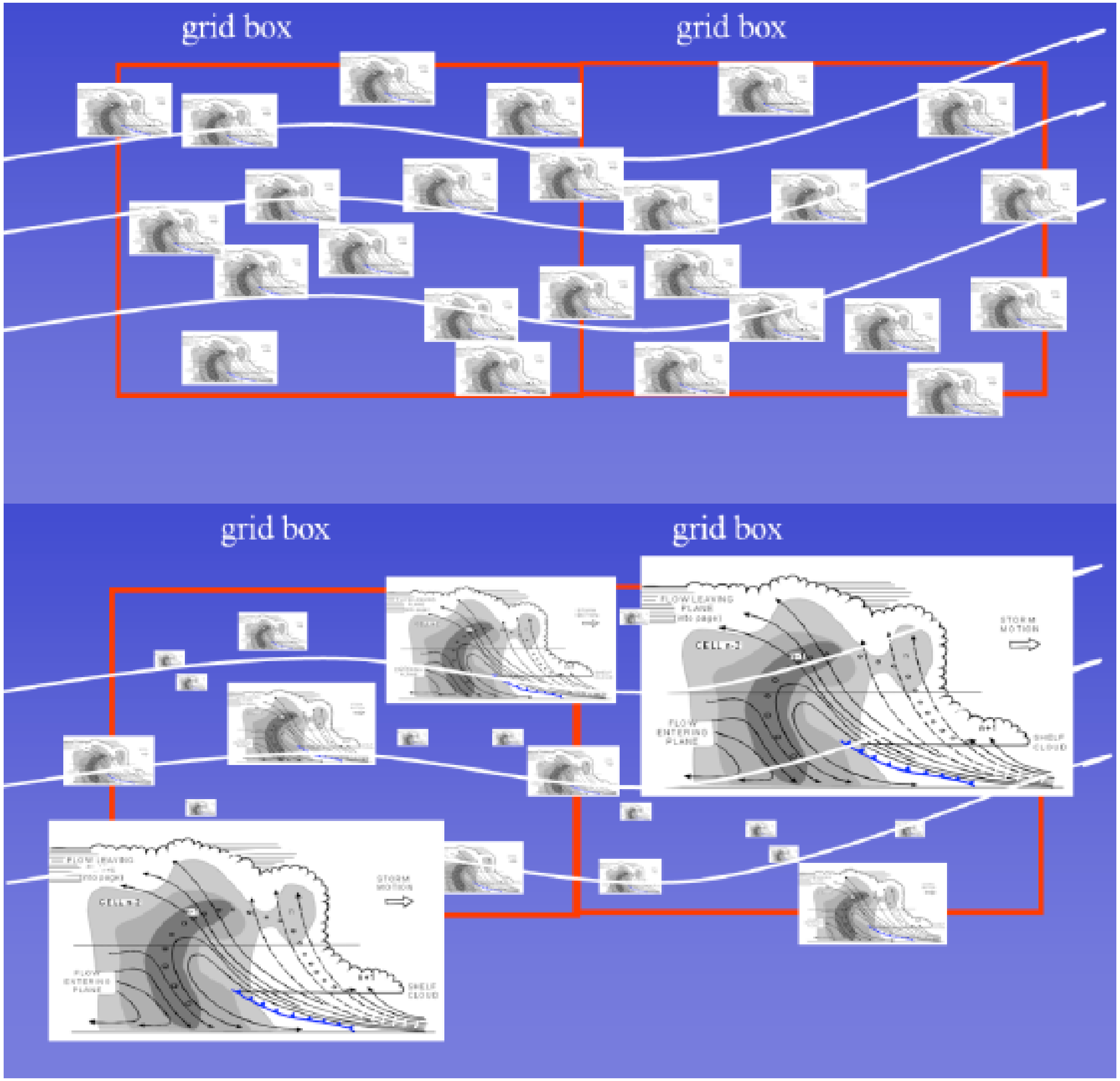
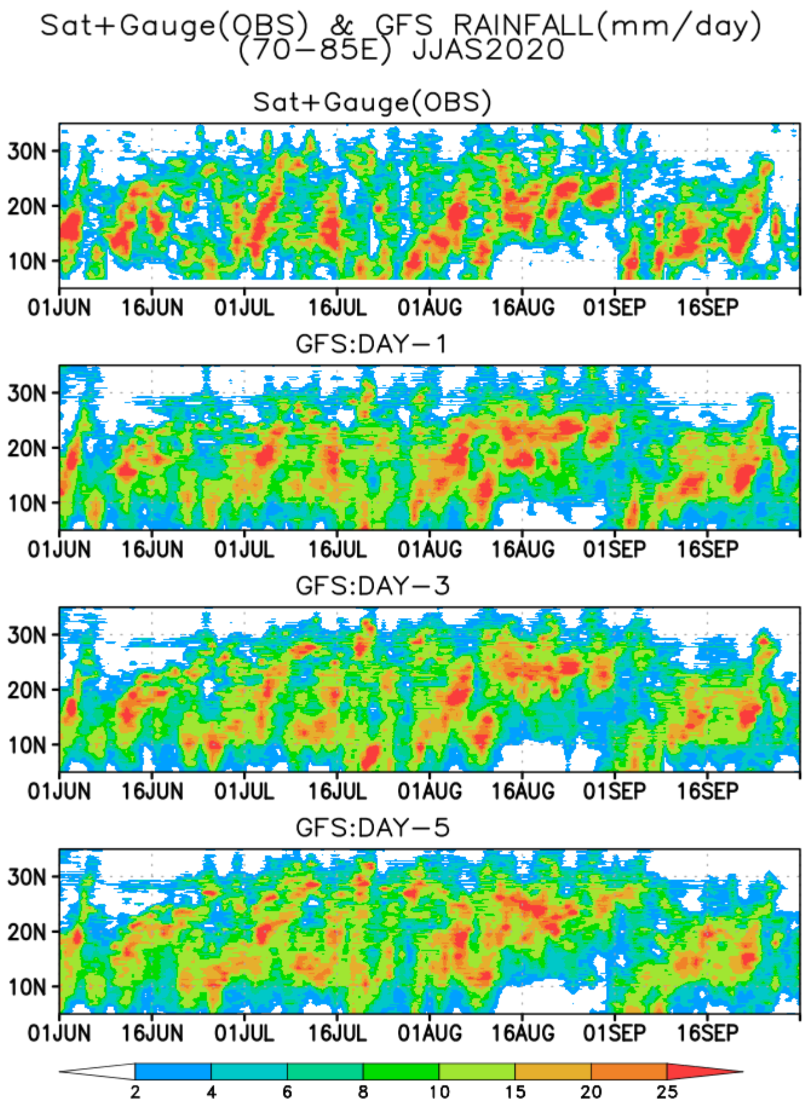
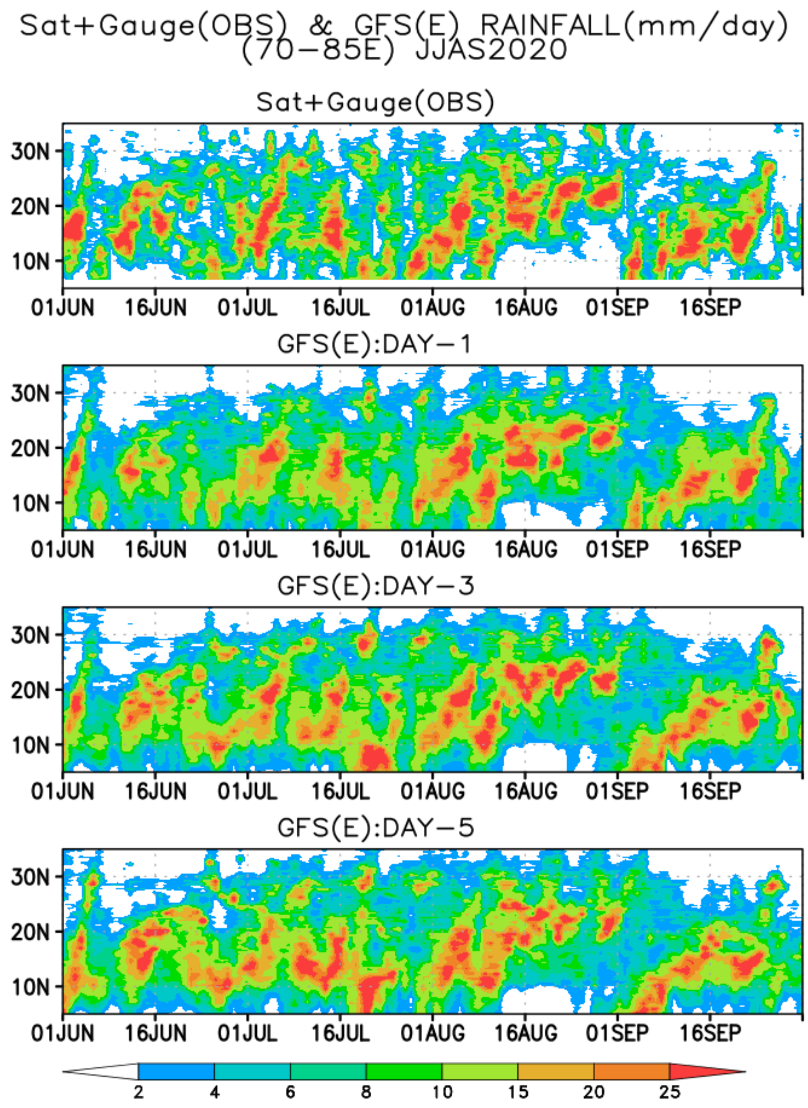


Figure 1. a) Schematic showing clear scale separation between resolved flow and sub grid-scale convection.
b) schematic of a more realistic situation where there is no scale separation.

Source: courtesy of Tim Palmer, Oxford University


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)
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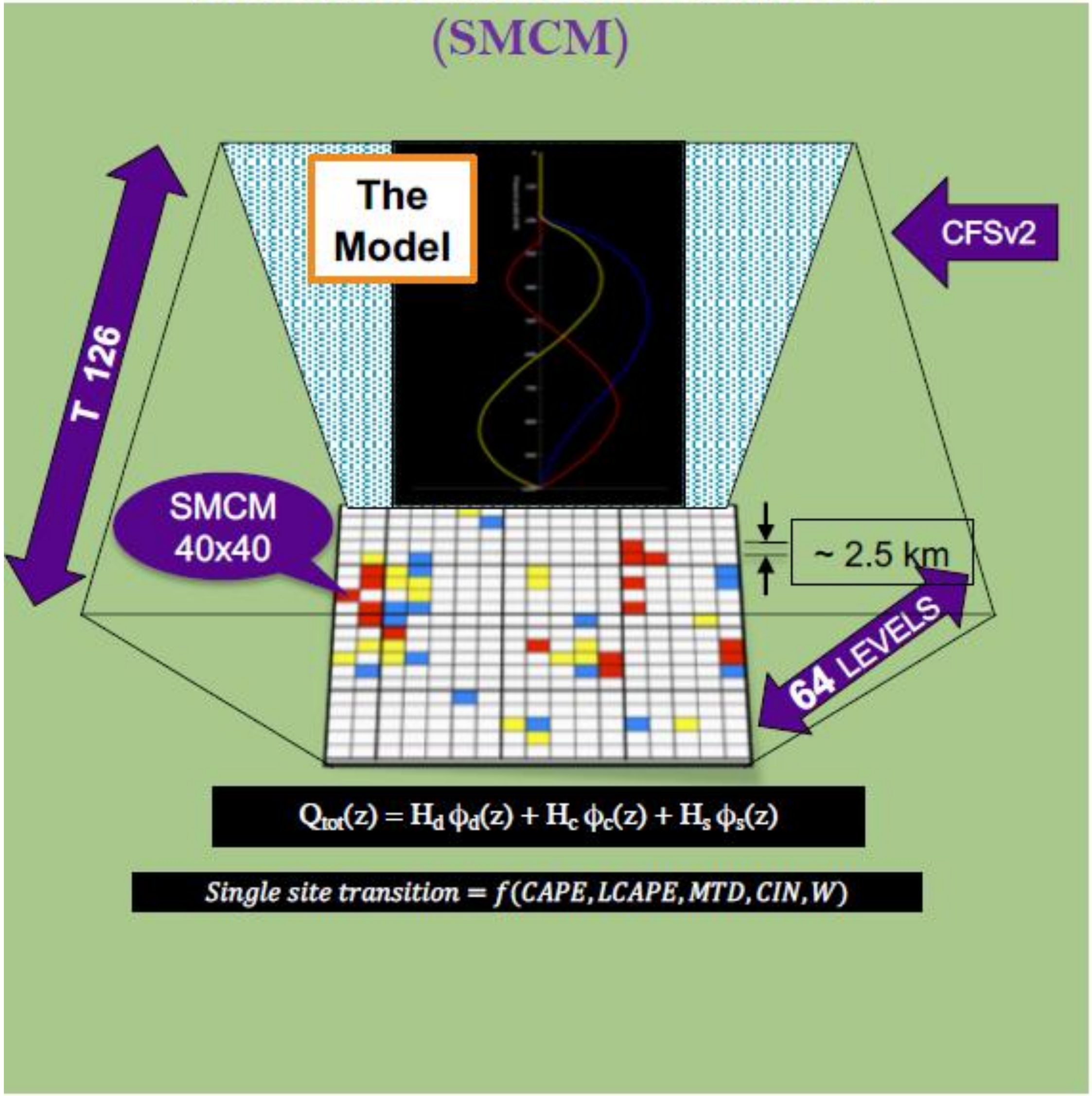
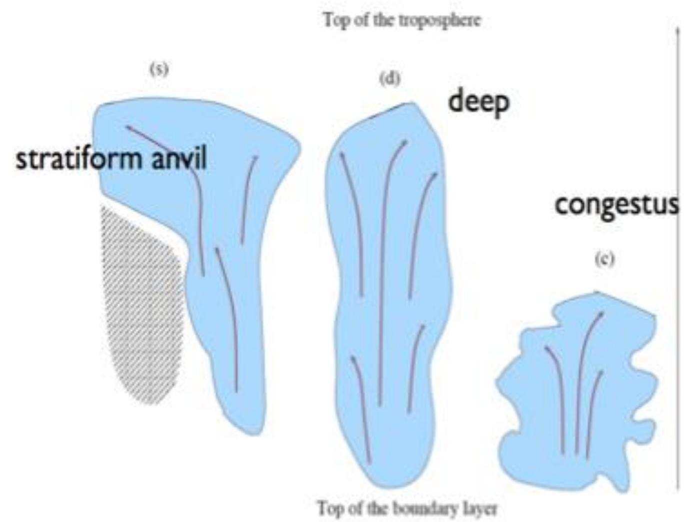
GFS(E):DAY–3
GFS(E):DAY–5
30N
20N
10N
01JUN 16JUN 01JUL 16JUL 01AUG 16AUG 01SEP 16SEP
2 4 6 8 10 15 20 25

Stochastic multi-cloud model (SMCM)

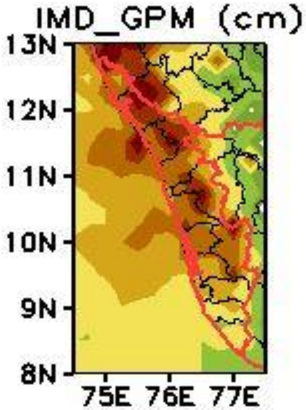


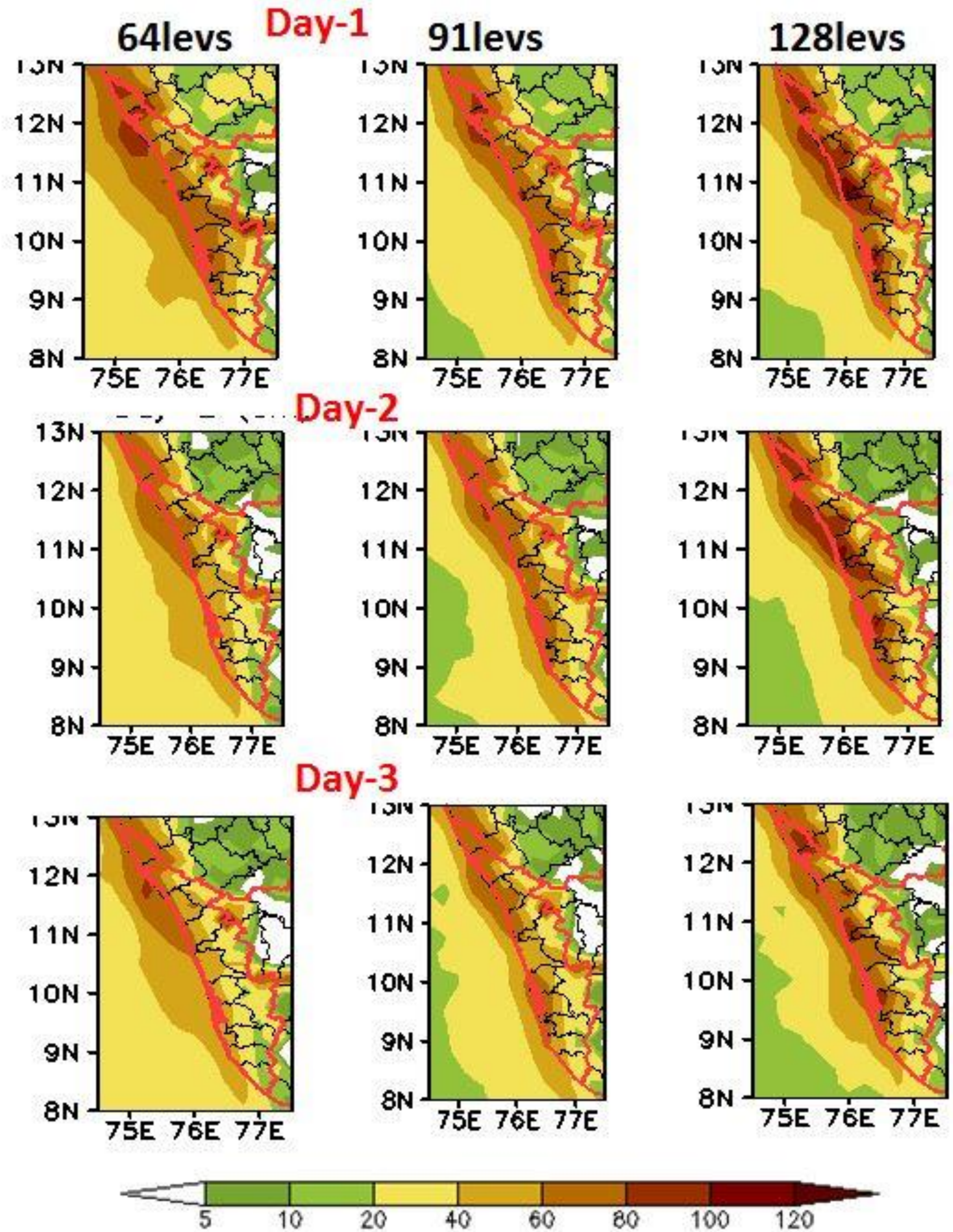
Main cloud types of tropical weather



B. B. Goswami et al. 2017, JAS
B. B. Goswami et al., 2017 JAMES
B. B. Goswami, 2017, GRL

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





GFS T1534

Enhanced Vertical Res.

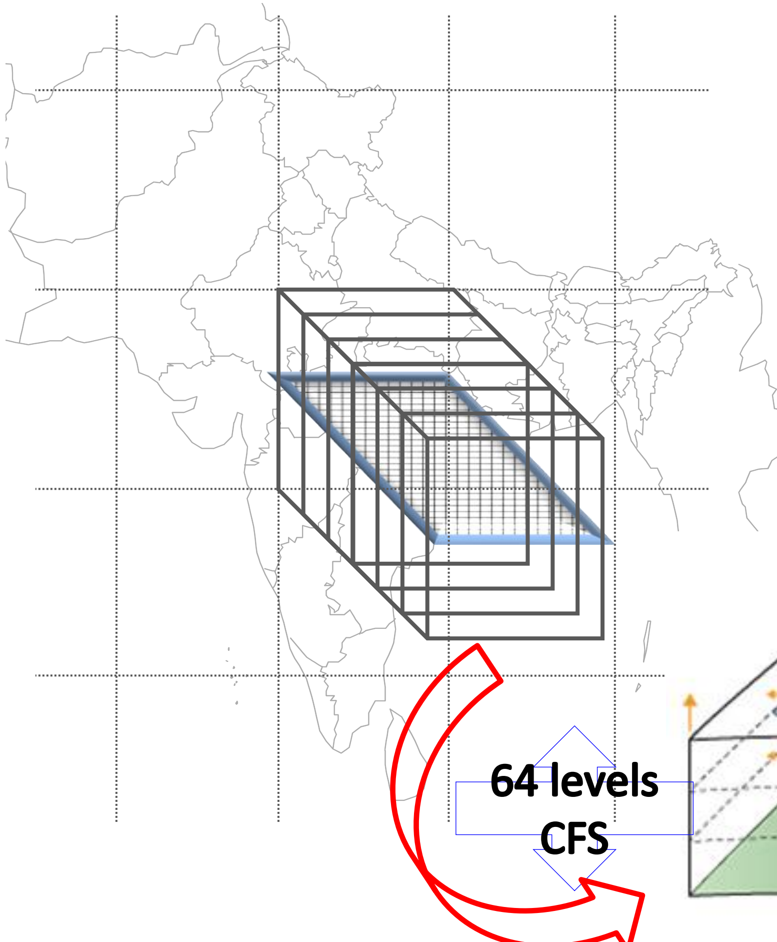
Scale Aware Stochastic Physics

Ensemble/Probabilistic approach

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

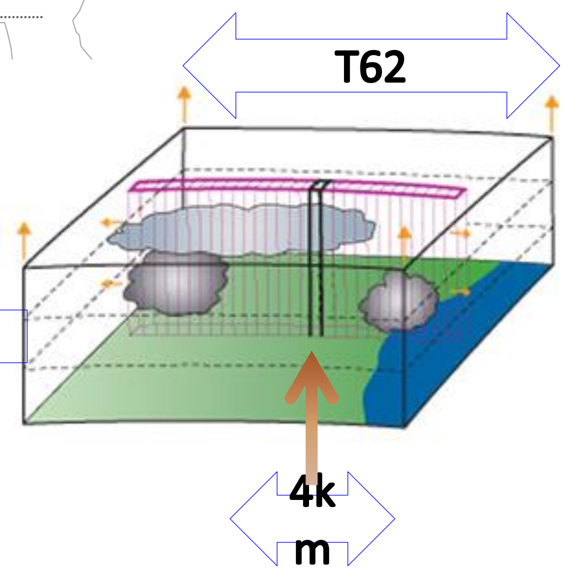
GFST1534L128 (31 levels within 800hPa)

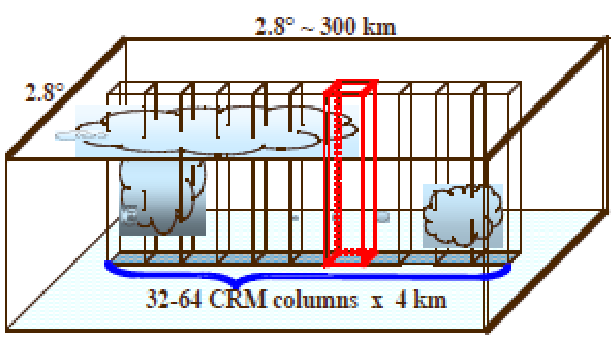
Superparameterized CFSv2-T62 **(SPCFS) Analyses of 6.5 year free run**

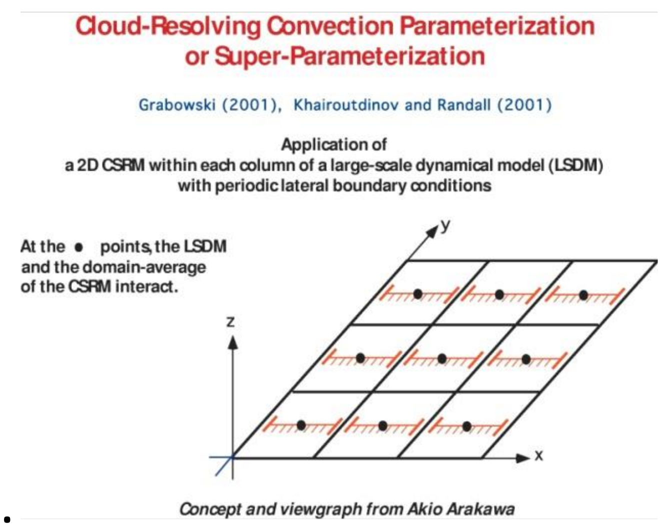


Convective tendencies are explicitly simulated with a **C**loud **R**esolving **M**odel running in each GCM grid column which replaces the traditional cumulus parameterization of the GCM.

- Model integrated for 6.5 years and five years are analyzed



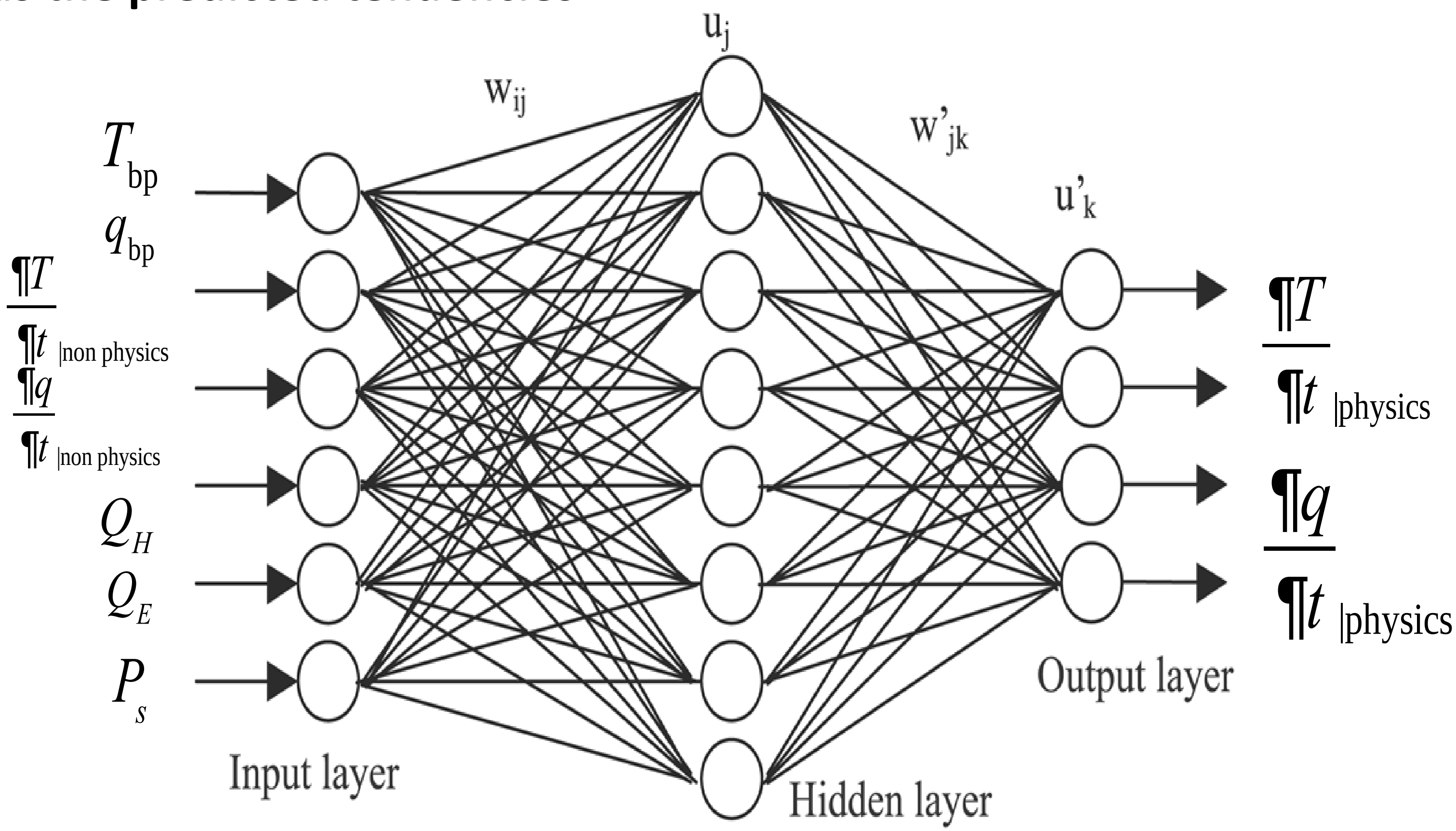




B. B. Goswami et al. 2015, J. Cli.

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

From the CRMs of SP

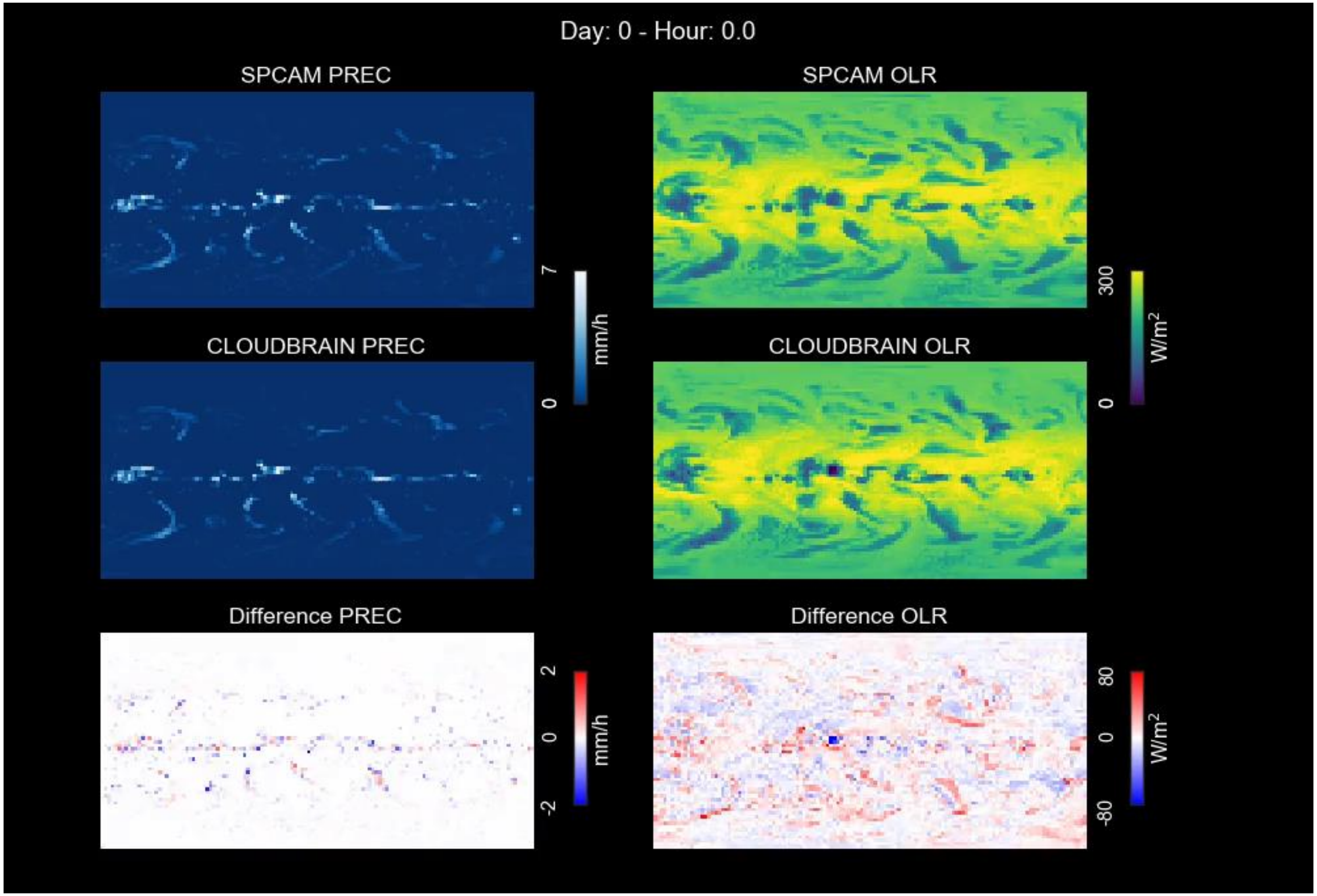


High-resolution (SP) constraints

machine learning from high-resolution cloud-resolving models

HiRes model

Machine learning model

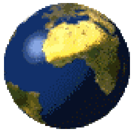


Precipitation

Radiation

Gentine et al. 2018

Summary



- The ensemble forecast based on GFS at 12km show good skill in predicting extreme/high impact weather events. Though the forecast is under-dispersive.

- The daily scale error growth from Ics and Physics modulates the weekly growth of error

- Models show tendency to shift to a drier regime.

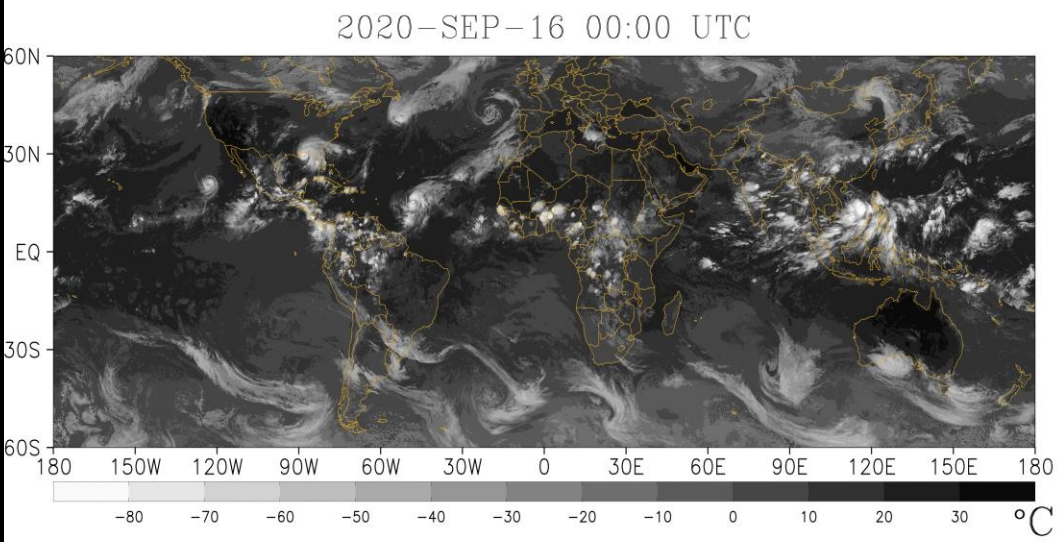
=====================================

- Improving the resolution of GFS from 12km to ~5km using Tco Dycore and vertical from L64 to L128 shows promise to provide improved prediction of extremes in general and orographic rainfall of western Ghats in particular.

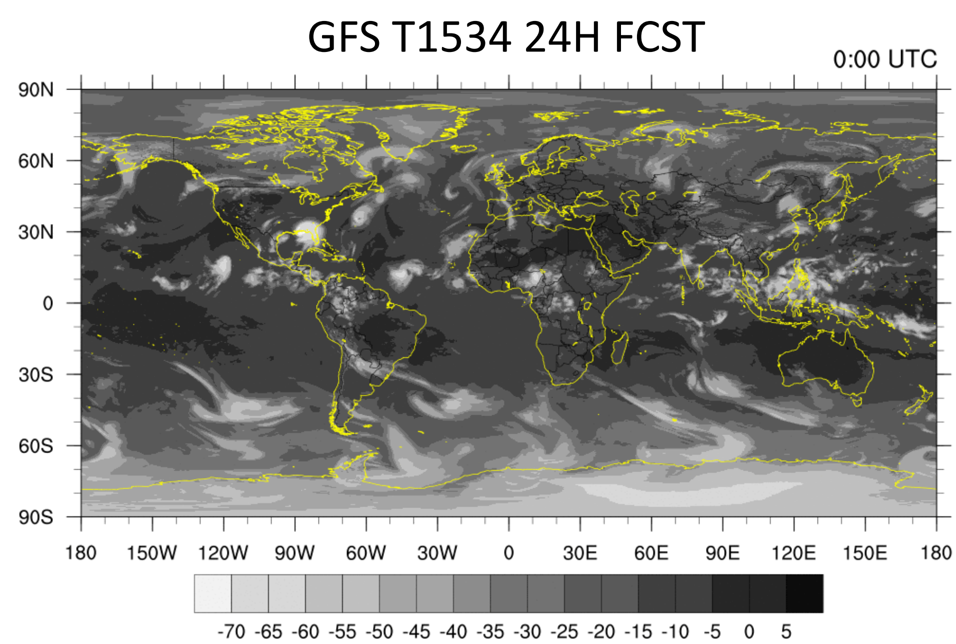
- <u>SPPT and Stochastic Multi cloud parameterization could be helpful to improve the spread and RMSE.</u>

- <u>AI/ML could help to breakthrough the cloud/convection uncertainty deadlock.</u>

- GEFS forecast data is available in TIGGE archive of ECMWF since July 2020 (https://apps.ecmwf.int/datasets/history/tigge-prod/)



Satellite Obs. Brightness temperature



Thank You

Following Lopez et al. 2020, BAMS