Application of Spatial Verification Methods for Ensemble Rainfall Forecasts over India

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Acknowledgements: WMO Joint Working Group Forecast Verification Research (JWGFVR)
E. Ebert (BOM) and Barbara Brown

Outline

- *Why Spatial Vx??*
  - *Spatial vx Approaches*
  - *Need for Object/Features based Verification*
- *Contiguous Rain Area (CRA) verification*
  - *CRA Decomposition*
  - *CRA Verification over India*
- *CRA Verification for Ensemble Rainfall Forecasts*
  - *Case of Extremely Heavy Rainfall (21cm/day) over Mumbai*
  - *Verification for 4cm CRA Objects*
  - *Verification for Highest Rainfall amounts in 4cm CRA*
  - *Verification of attributes (area, volume etc)*
- *Summary*

Why Spatial Vx??

- Weather variables are often predicted as fields defined over a spatial domain.
- Spatial fields are characterized by a coherent spatial structure and often by the presence of features, such as precipitation features.
- Standard verification methods based on a point by point comparison (e.g.Mean Squared Error, MSE) often do not account for the intrinsic spatial correlation existing within these fields.
- The results from such standard verification methods are often difficult to interpret in meaningful physical terms.

Special Issue of

Meteorological Applications
on
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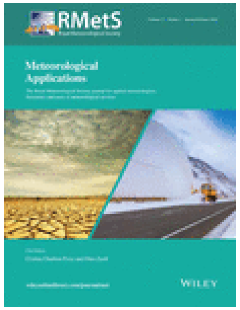

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Why Spatial Vx??

- **Some new approaches that specifically address the verification of forecasts defined over spatial domains have been developed in the last decade.**
- **These approaches account for –**
  - **the spatial nature of forecast fields, and aim to provide feedback on the physical nature of the forecast error**
  - **adding new and complementary information to the traditional categorical and continuous verification methods.**

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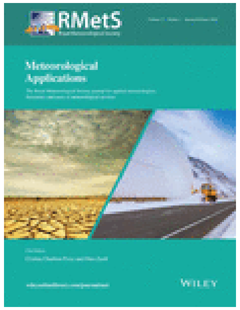
[Volume 15, Issue 1]()



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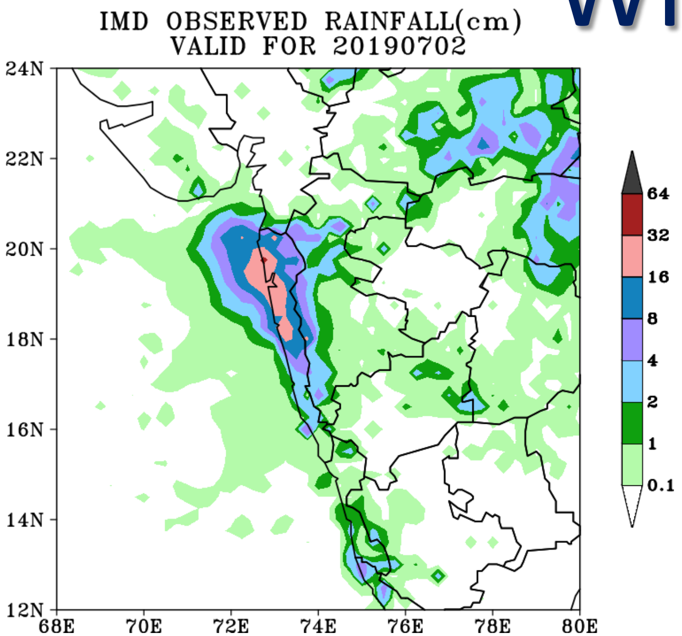
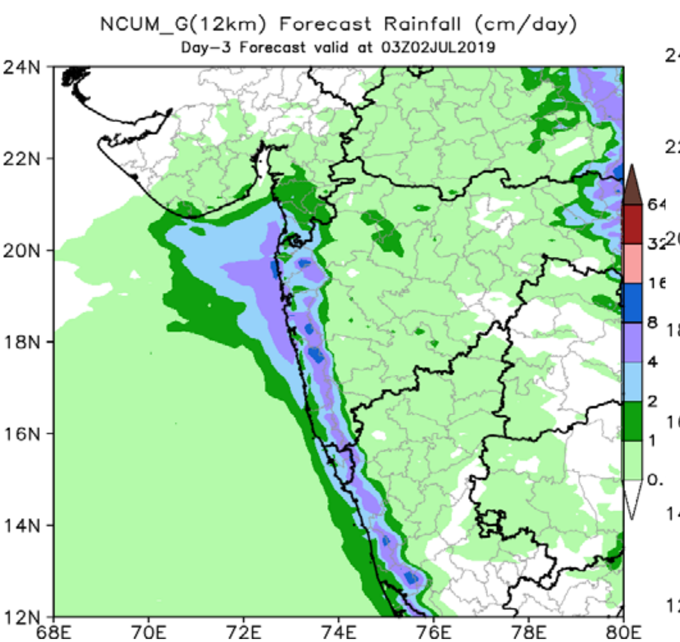
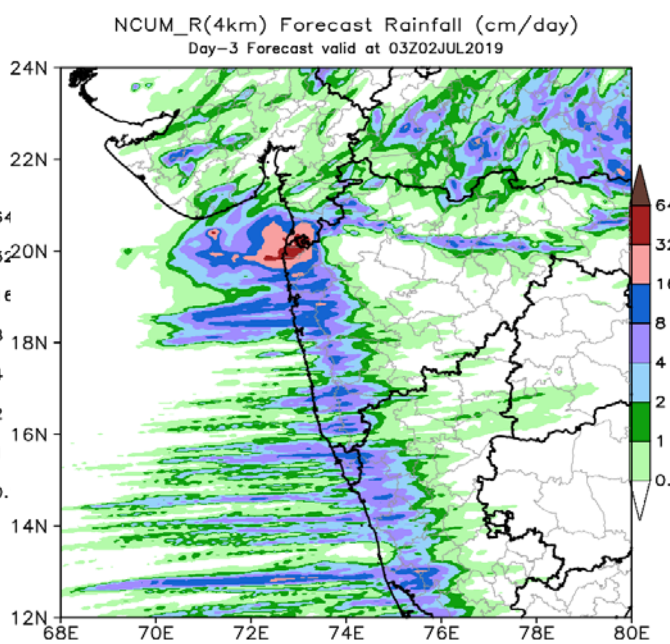
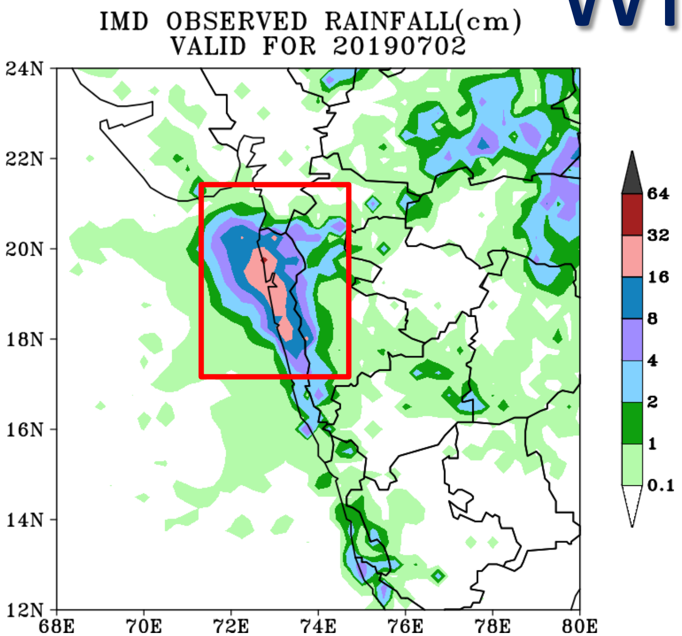
Why Spatial Vx??



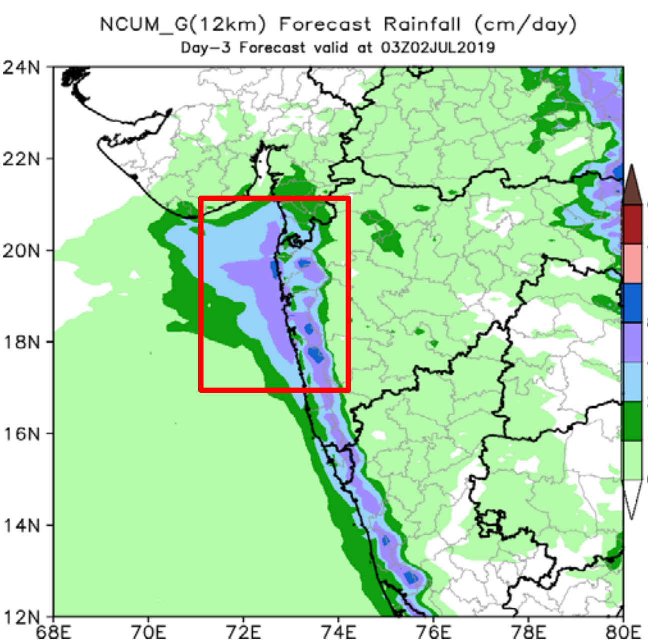


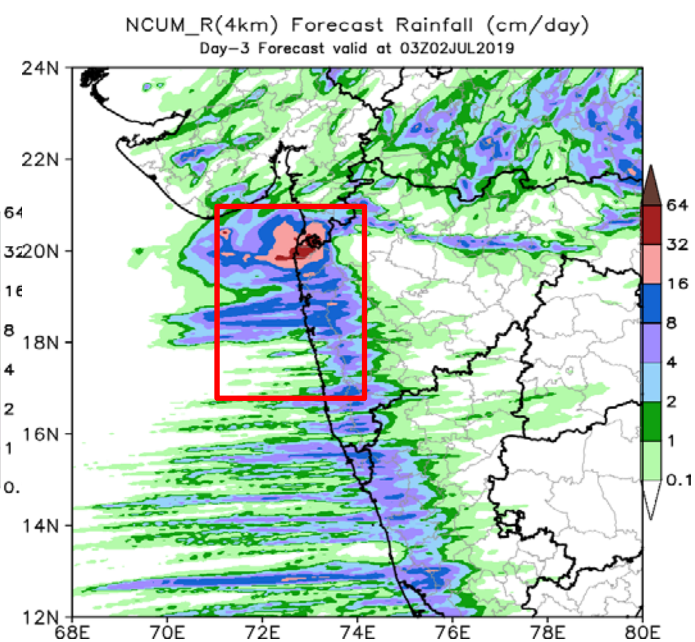


Why Spatial Vx??



	Mean	Max	RMSE	CC
Obs	54	274		
NCUM_G	28	101	76	0.13
NCUM_R	57	293	142	-0.13

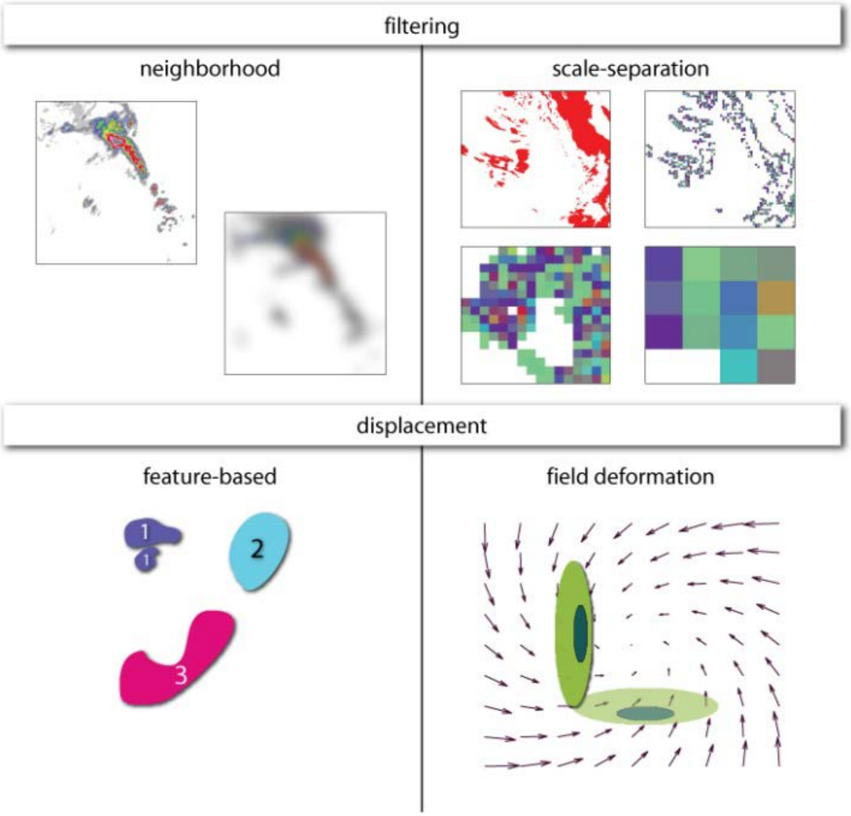




Traditional verification:
Smooth forecasts show higher score

Spatial Verification Approaches

- **Neighborhood**
  - Successive smoothing of forecasts/obs
- **Object- and feature-based**
  - Evaluate attributes of identifiable features
- **Scale separation**
  - Measure scale-dependent error
- **Field deformation**
  - Measure distortion and displacement (phase error) for whole field



http://www.ral.ucar.edu/projects/icp/

Spatial Verification Approaches

Attribute	Traditional	Feature based	Neighborhood	Scale separation	Field Decomposition
Verification at different scales	Indirectly	Indirectly	Yes	Yes	No
Location errors	No	Yes	Indirectly	Indirectly	Yes
Intensity Errors	Yes	Yes	Yes	Yes	Yes
Structure Errors	No	Yes	No	No	Yes
Hits/Misses etc	Yes	Yes	Yes	Indirectly	Yes

Object/feature-based Verification

- Object-based verification is especially relevant in the context of –
  - Verification of higher-resolution forecasts
  - Verification of phenomena that are highly localized and episodic (rainfall, icing, turbulence, etc.)
- Evaluate attributes of identifiable object/features

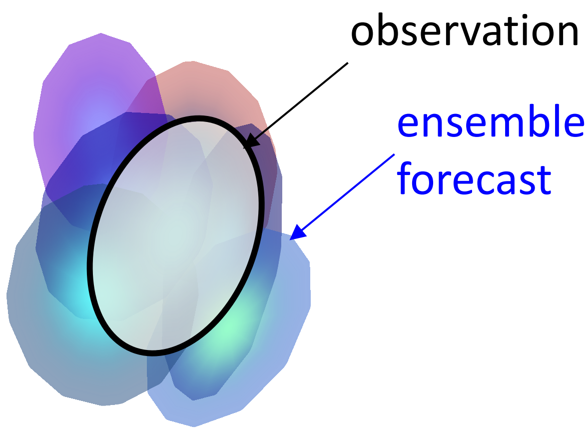
https://doi.org/10.1175/MWR3145.1

Verifying features in ensembles

Significant weather events can be viewed as 2D "objects"

- **tropical cyclones, heavy rain events, low pressure area**
- **objects can be defined by an intensity threshold**

What might the ensemble forecast look like?



Strategies for verifying ensemble predictions of objects

1. **Verify objects**
2. **Verify "ensemble mean": generated from average object properties**

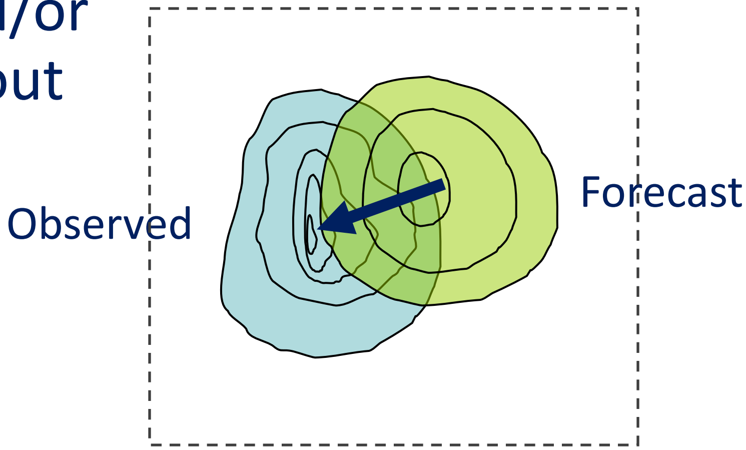
Object/feature-based Verification

- **CRA**: Contiguous Rain Area (Ebert, Gallus, McBride)

- **MODE**: Method for Object-based Diagnostic Evaluation (Davis, Brown, Bullock)

Contiguous Rain Area (CRA) verification
Ebert and McBride (J. Hydrology, 2000)

- Find Contiguous Rain Areas (CRA) in the fields to be verified
  - Take union of forecast and observations
  - Use minimum number of points and/or total volume of parameter to filter out insignificant CRAs



- Define a rectangular search box around CRA to look for best match between forecast and observations
- Displacement determined by shifting forecast within the box until MSE is minimized or correlation coefficient is maximized

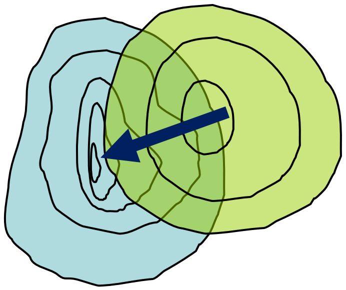
CRA error decomposition

Total mean squared error (MSE)

$$MSE_{total} = MSE_{displacement} + MSE_{volume} + MSE_{pattern}$$

The *displacement error* is the difference between the mean square error before and after translation

$$MSE_{displacement} = MSE_{total} - MSE_{shifted}$$



The *volume error* is the bias in mean intensity

$$MSE_{volume} = (\overline{F} - \overline{X})^2$$

where $\overline{F}$ and $\overline{X}$ are the mean forecast and observed values after shifting.

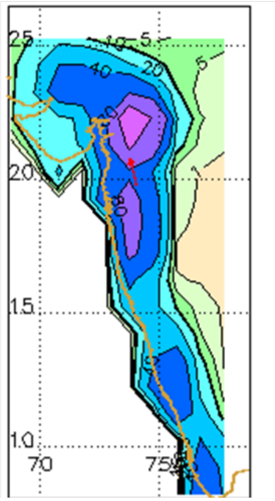
The *pattern error*, computed as a residual, accounts for differences in the fine structure,

$$MSE_{pattern} = MSE_{shifted} - MSE_{volume}$$

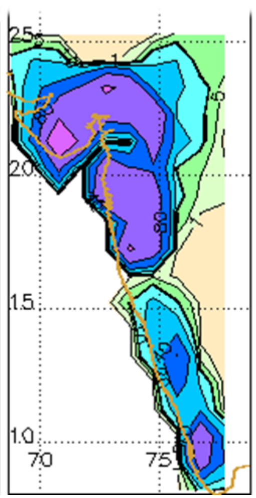
Ebert and McBride (J. Hydrology, 2000)

CRA Verification over India

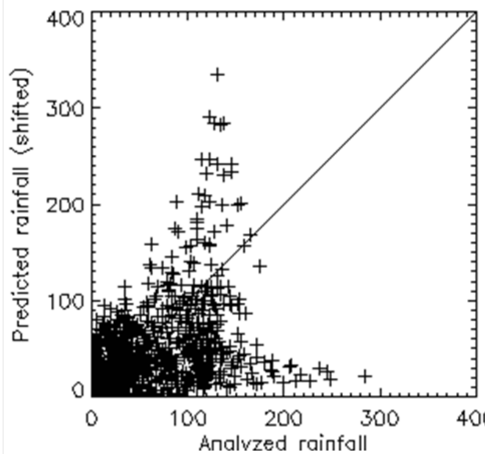
UM Day-1 FCST
valid for 20070703



Observed rainfall 20070703



CRA 20070703



UM Day-1 fcst 20070703 n=1109

(8.50°,69.00°) to (26.00°,78.50°)
Verif. grid=0.250° CRA threshold=10.0 mm/d

	Analysed	Forecast
# gridpoints ≥10 mm/d	932	815
Average rainrate (mm/d)	54.18	40.96
Maximum rain (mm/d)	284.66	335.12
Rain volume (km³)	44.18	33.41

Displacement (E,N) = [0.25°,−1.00°]

	Original	Shifted
RMS error (mm/d)	54.49	51.35
Correlation coefficient	0.373	0.431

Error Decomposition:

Displacement error	8.5%
Volume error	7.5%
Pattern error	84.0%

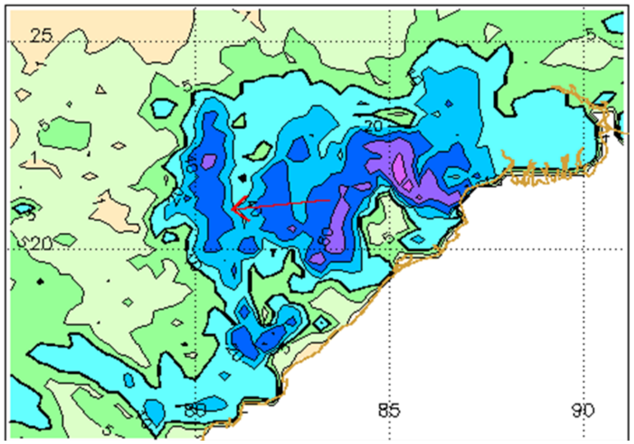
CRA Method measures displacements and estimates errors due to -
-displacement
-pattern
-volume

Displacement 0.25°E and 1°S

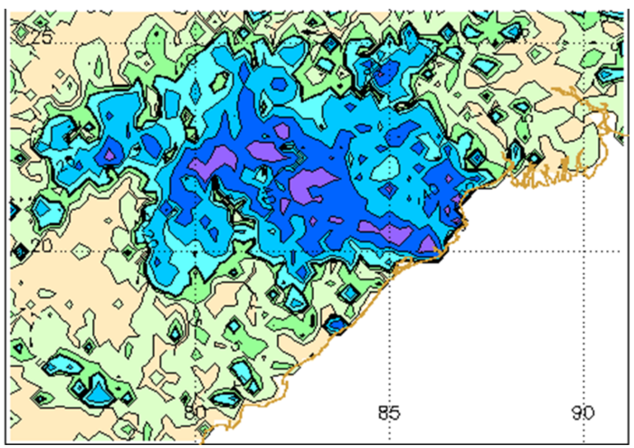
1. What is the location error of the forecast?
2. How do the forecast and observed rain areas compare? Average values? Maximum values?
3. How do the displacement, volume, and pattern errors contribute to the total error?

CRA Verification over India

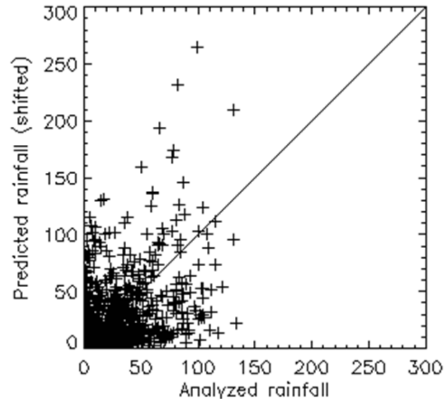
NCUM-G Day-1 valid on 02Jul 2019



Observed rainfall on 02Jul 2019



Obs Vs Day-1 : 02Jul 2019



Day-1 valid on 02Jul 2019 n=1278

(15.75°,75.50°) to (25.50°,90.75°)

Verif. grid=0.250° CRA threshold=10.0 mm/d

	Analysed	Forecast
# gridpoints ≥10 mm/d	730	796
Average rainrate (mm/d)	22.20	24.02
Maximum rain (mm/d)	133.25	264.58
Rain volume (km³)	20.44	22.12

Displacement (E,N) = [2.50°,0.25°]

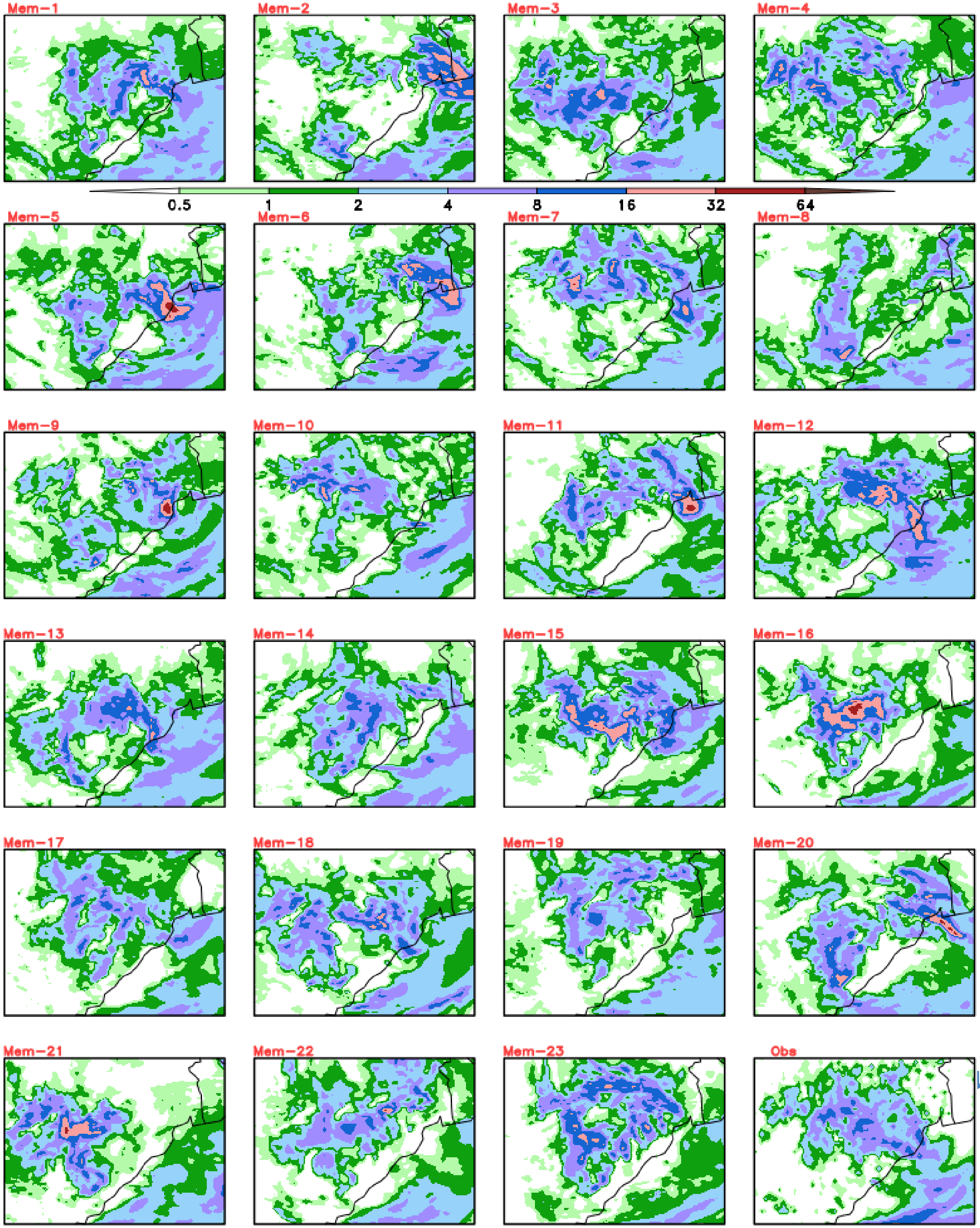
	Original	Shifted
RMS error (mm/d)	30.33	28.66
Correlation coefficient	0.282	0.384

Error Decomposition:

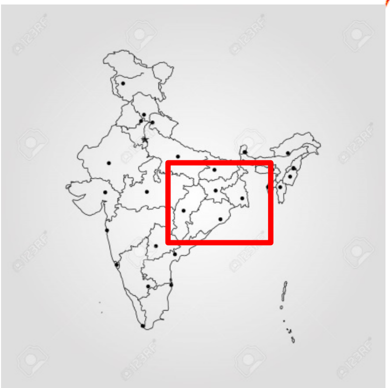
Displacement error	14.2%
Volume error	0.1%
Pattern error	85.7%

CRA Method measures displacements and estimates errors due to -
- **-displacement**
- **-pattern**
- **-volume**

1. **What is the location error of the forecast?** Displacement 2.5°E and 0.25°N
2. **How do the forecast and observed rain areas compare? Average values? Maximum values?**
3. **How do the displacement, volume, and pattern errors contribute to the total error?**



CRA Verification for Ensemble Rainfall Forecasts



2nd Jul 2019

NEPS Day-1 Forecasts

12km grid resolution

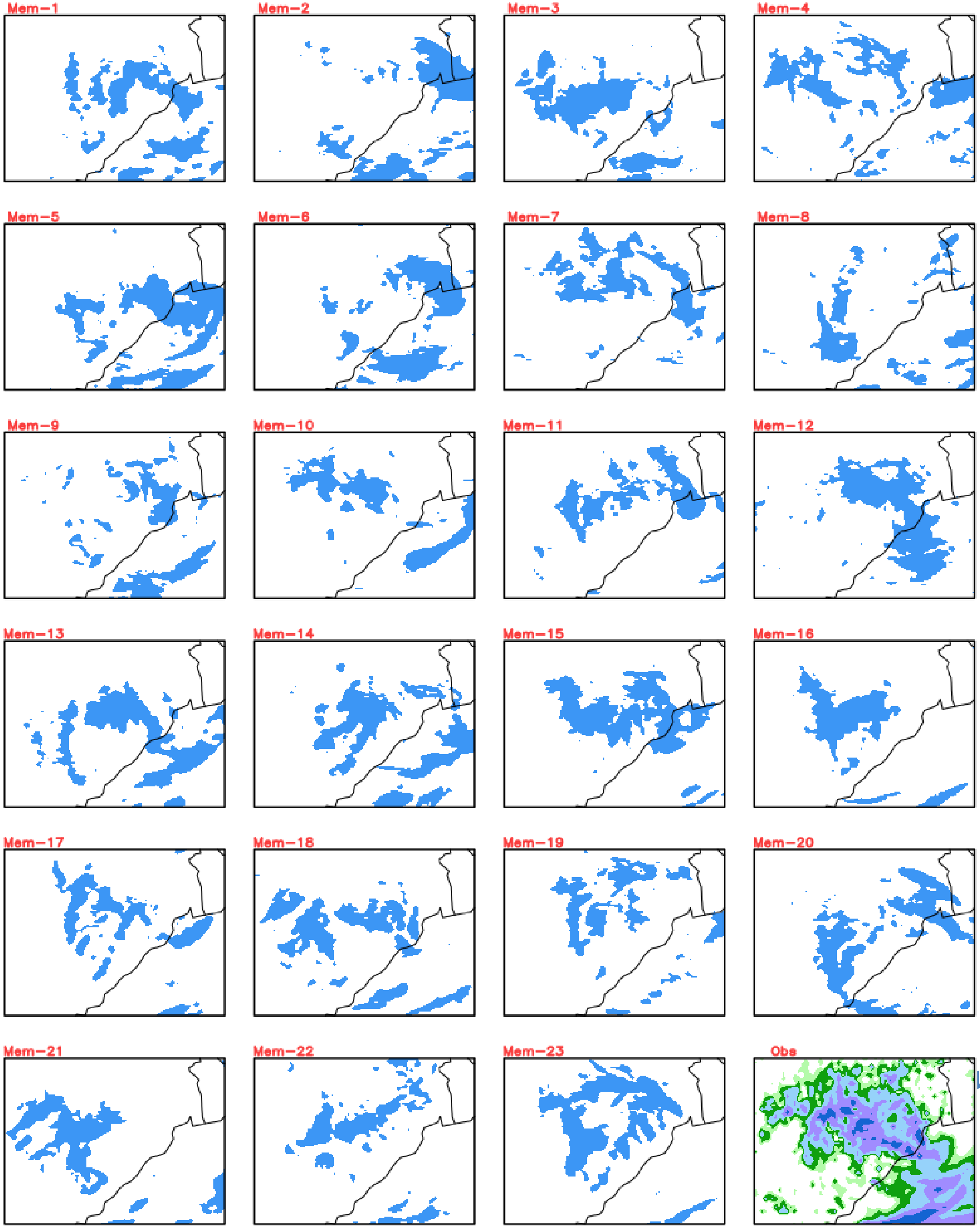
22-member + control

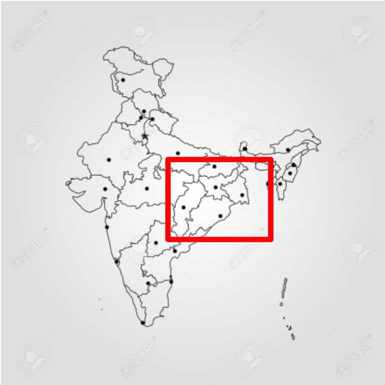
Observed rainfall exceeds-

-4cm/day over large area and

- 8cm/day over isolated locations

CRA Verification for Ensemble Rainfall Forecasts





2nd Jul 2019

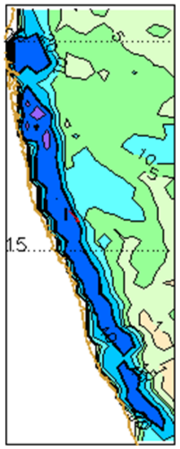
NEPS Day-1 Forecasts
12km grid resolution
22-member + control

Area in blue : 4cm CRA
Rainfall > 4cm/day

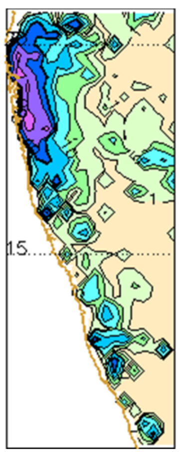
Observed rainfall exceeds-
-4cm/day over large area and
- 8cm/day over isolated locations

CRA Verification over India

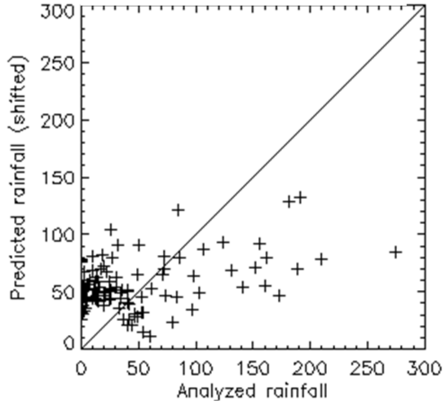
NCUM-G Day-1 valid on 2nd Jul 2019



Observed Rainfall on 2nd Jul 2019



Obs Vs Day-1: 2nd Jul 2019



Day-1 valid on 2nd Jul 2019 n=120

(10.75°,73.00°) to (20.50°,76.75°)

Verif. grid=0.250° CRA threshold=40.0 mm/d

	Analysed	Forecast
# gridpoints ≥40 mm/d	44	79
Average rainrate (mm/d)	41.92	54.94
Maximum rain (mm/d)	274.61	132.10
Rain volume (km³)	3.73	4.89

Displacement (E,N) = [−0.25°,0.25°]

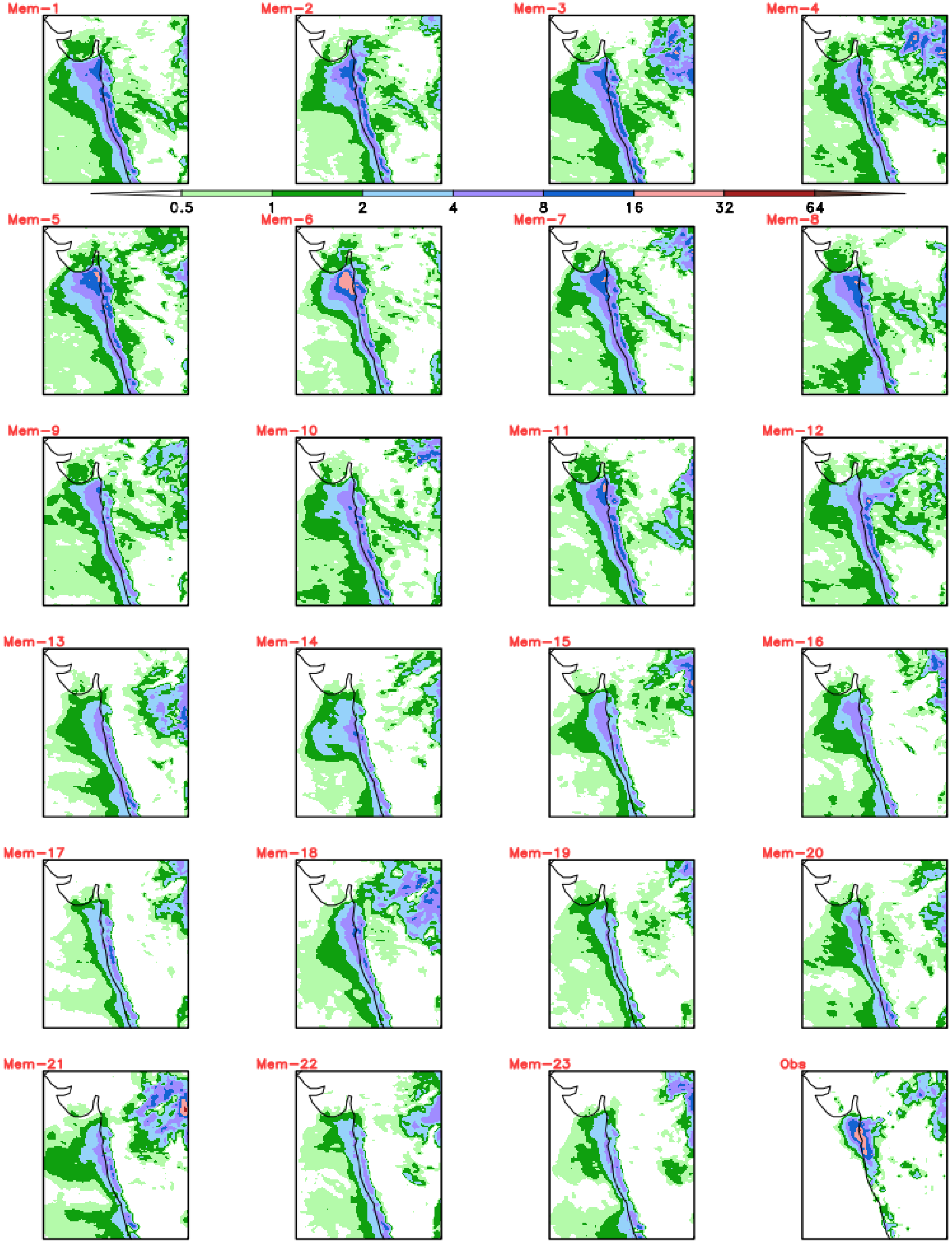
	Original	Shifted
RMS error (mm/d)	53.84	51.25
Correlation coefficient	0.213	0.391

Error Decomposition:

Displacement error	14.3%
Volume error	0.9%
Pattern error	84.8%

CRA Method measures displacements and estimates errors due to -
-displacement
-pattern
-volume

1. What is the location error of the forecast?
2. How do the forecast and observed rain areas compare? Average values? Maximum values?
3. How do the displacement, volume, and pattern errors contribute to the total error?



CRA Verification for Ensemble Rainfall Forecasts

CRA Method measures displacements and estimates errors due to -

-displacement

-pattern

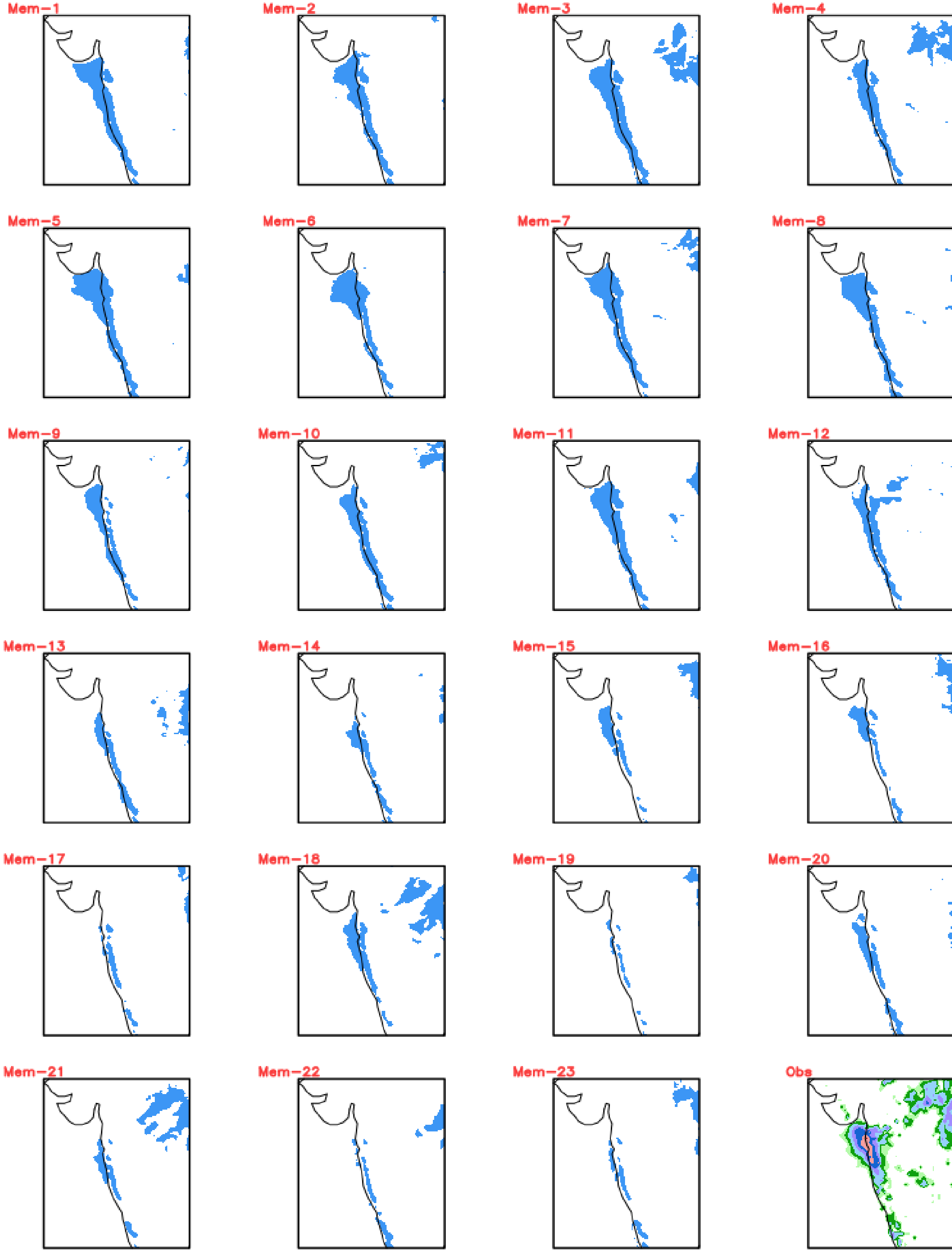
-volume

Observed rainfall exceeds-

-4cm/day over large area and

- 8cm/day over isolated locations

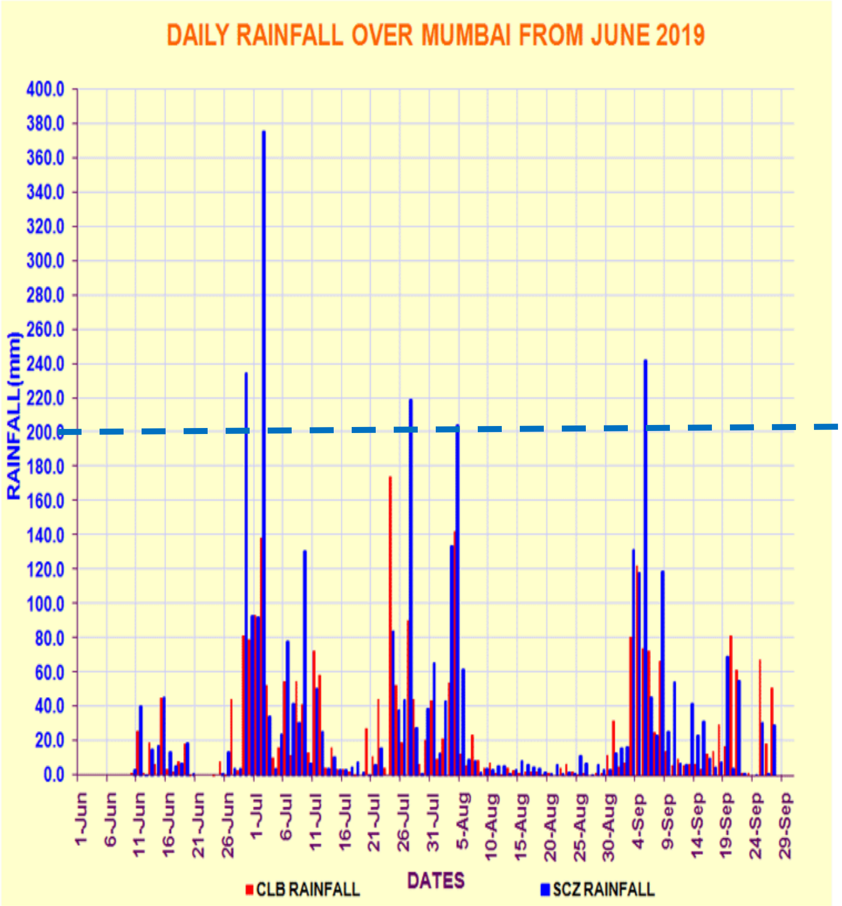
CRA Verification for Ensemble Rainfall Forecasts



2nd Jul 2019
NEPS Day-1 Forecasts
12km grid resolution
22-member + control

Area in blue: 4cm CRA
Rainfall > 4cm/day

Observed rainfall exceeds-
-4cm/day over large area and
- 8cm/day over isolated locations



- **Rainfall exceeding 21cm/day (EHR)**
- **JJAS 2019: 5 cases of "EHR"**
  - **29th Jun2019: 23 cm**
  - **02nd Jul 2019: 37 cm**
  - **27th Jul 2019: 22 cm**
  - **04th Aug 2019: 20 cm**
  - **05th Sep 2019: 24cm**

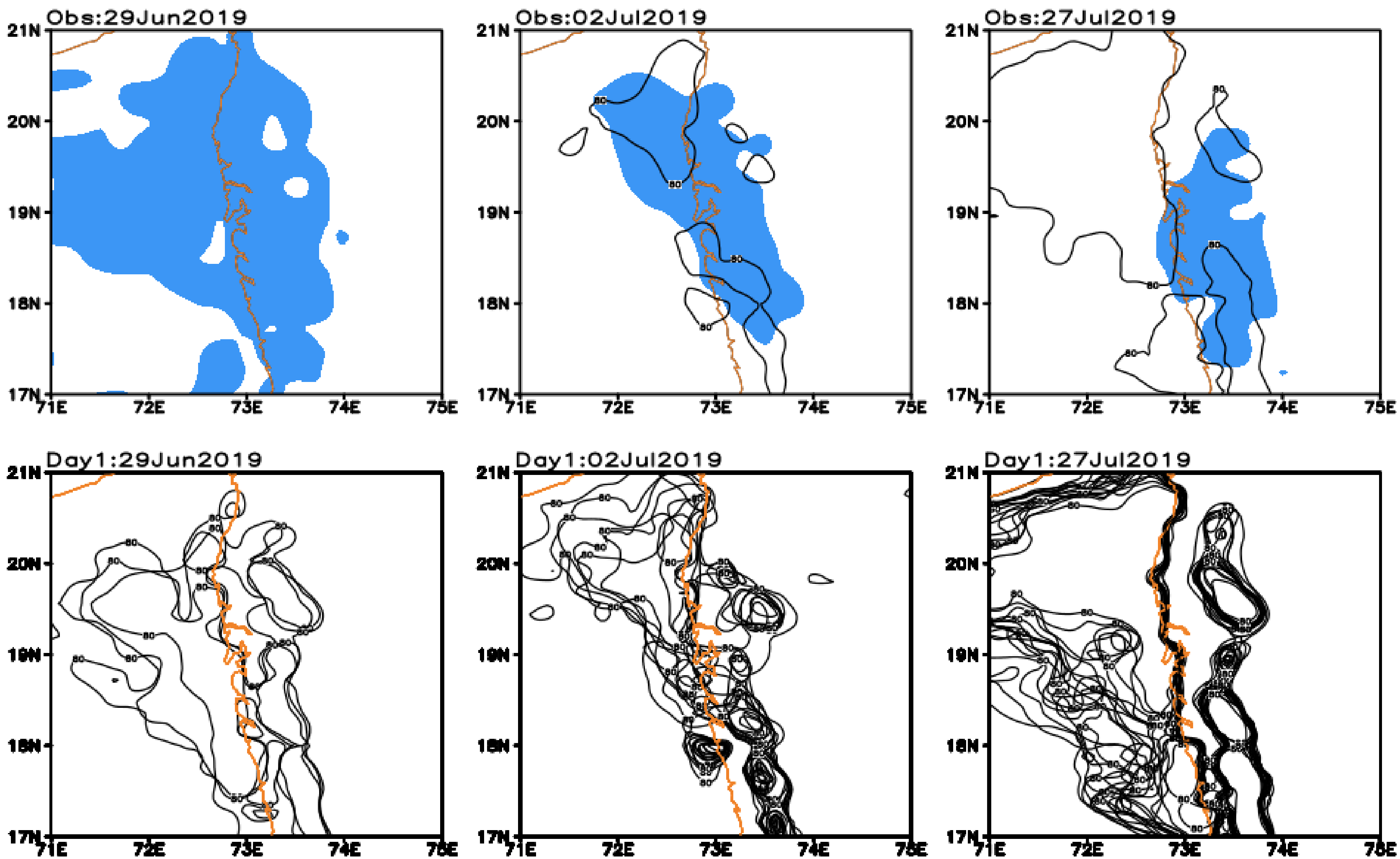
As per the IMD revised terminologies –

-Heavy Rain (HR) (7-11 cm/day)
-Very Heavy Rain (VHR) (12-20 cm/day)
-Extremely Heavy Rain (HER) (>21cm/day).

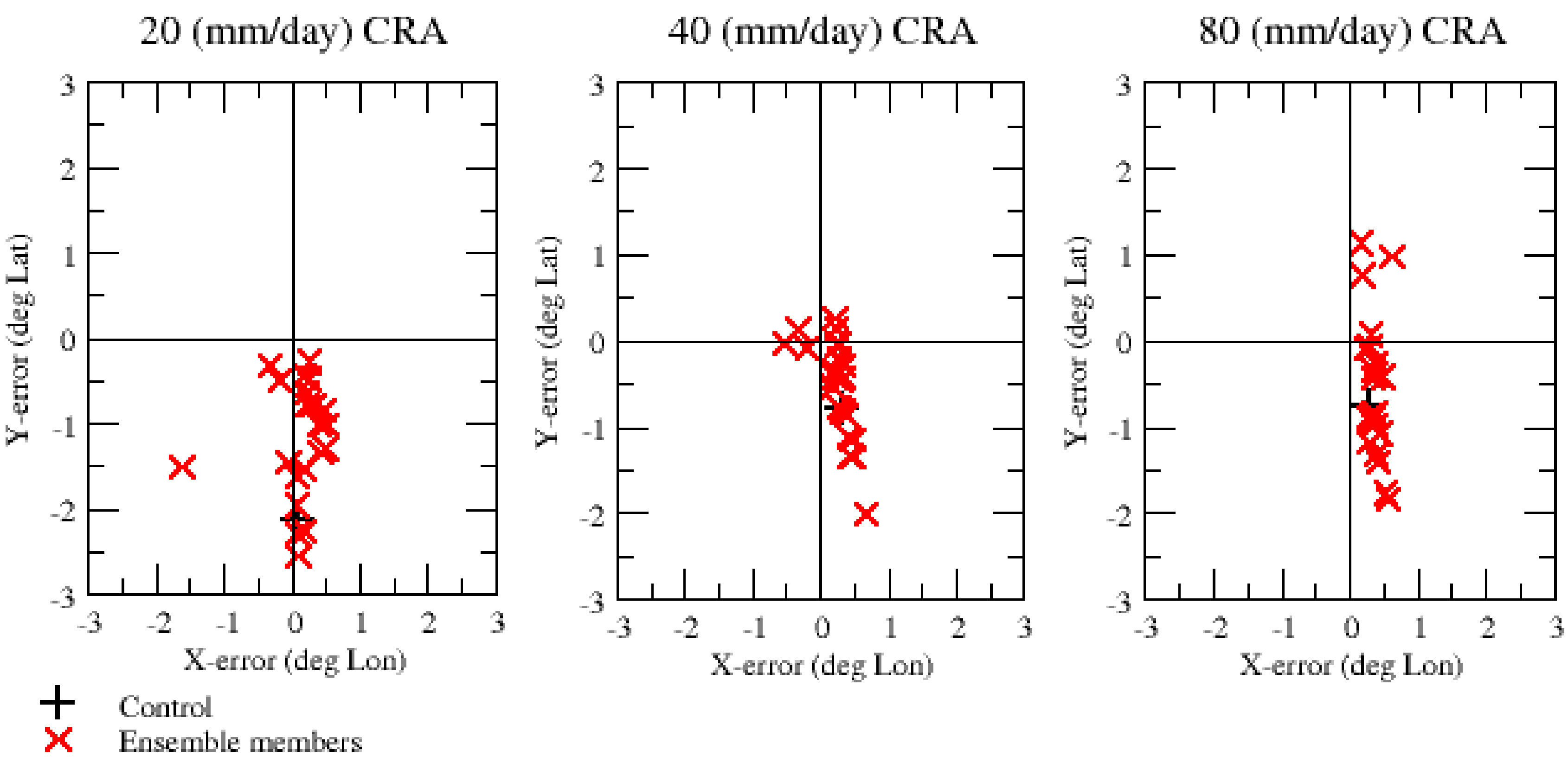
During JJAS 2019, Santacruz reported

-Heavy Rain (HR) (19)
-Very Heavy Rain (VHR) (10)
-Extremely Heavy Rain (HER) (5)

Observed Rainfall 40mm/day CRA (Blue) shaded
Day1: Ensemble members with Rainfall >40mm/day (contours)



CRA : Displacement in Day-1



Forecast objects shifted

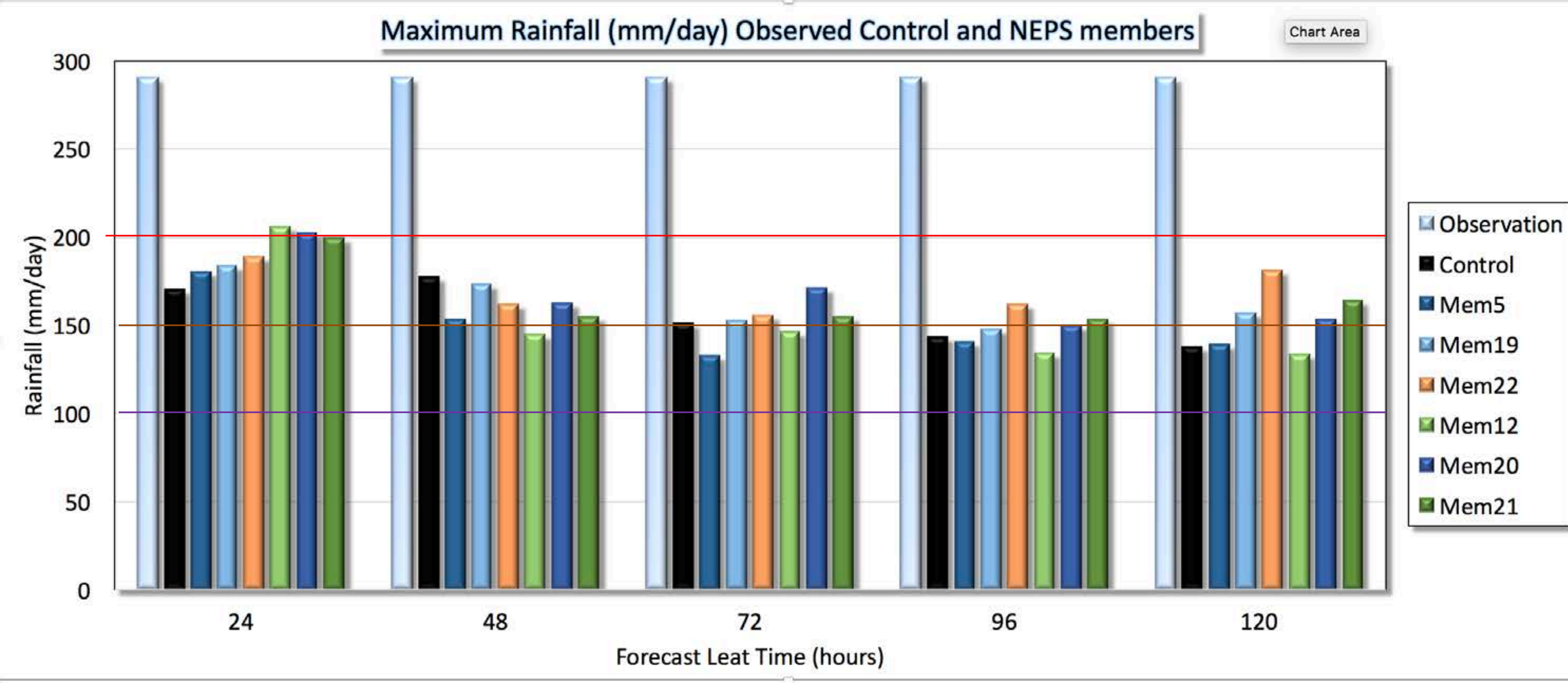
20 mm/day CRA : (0.25° - 2°S) Southward bias

40 mm/day CRA : (0.25 °N -2°S) Southward bias

80 mm/day CRA : (1°N- 2°S)

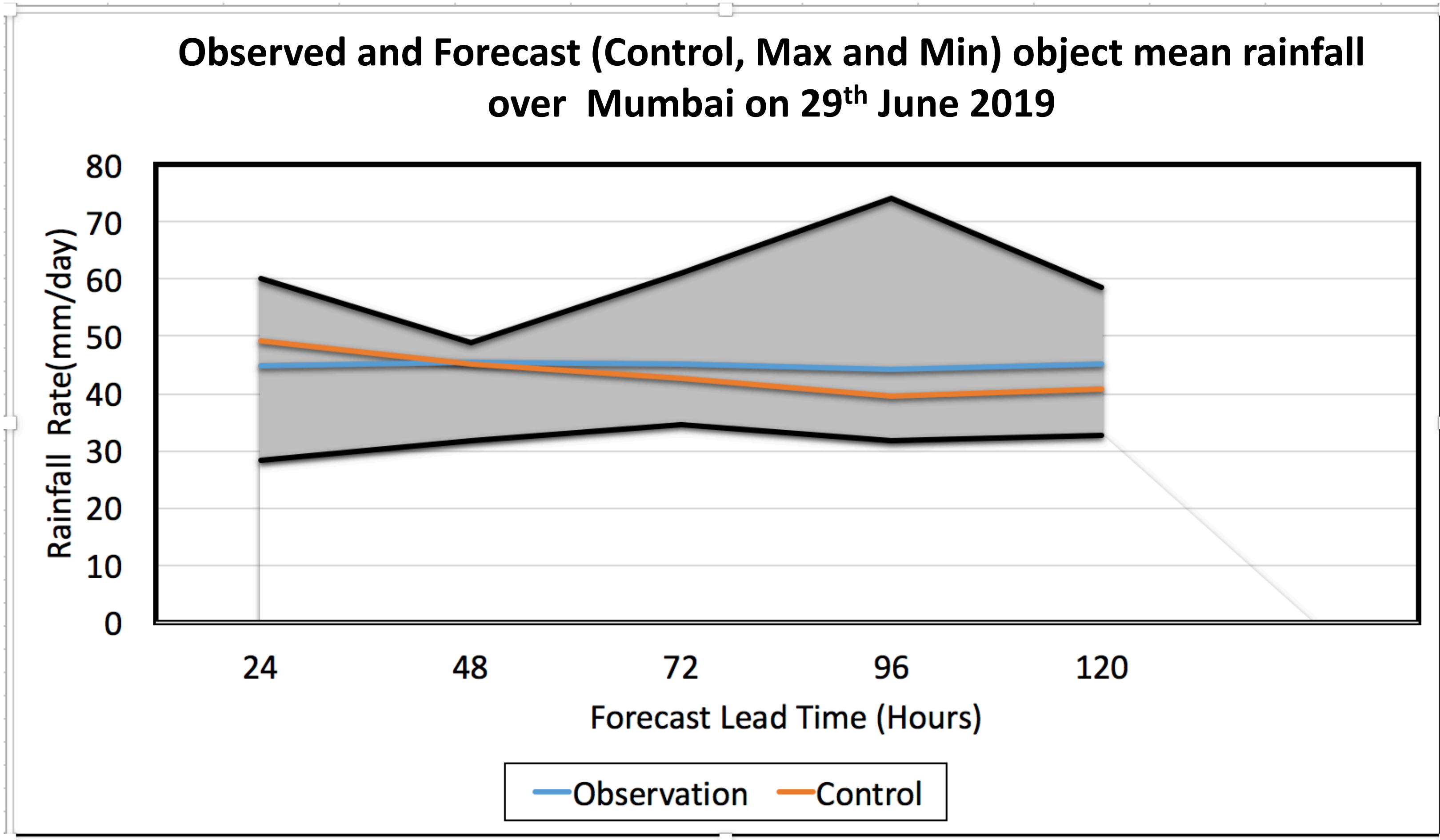
Use of Feature Based Ensemble Forecasting

- Use CRA method to obtain maximum Rainfall within the 40mm Object).
- For Heavy Rainfall case over Maharashtra during JJAS 2019.



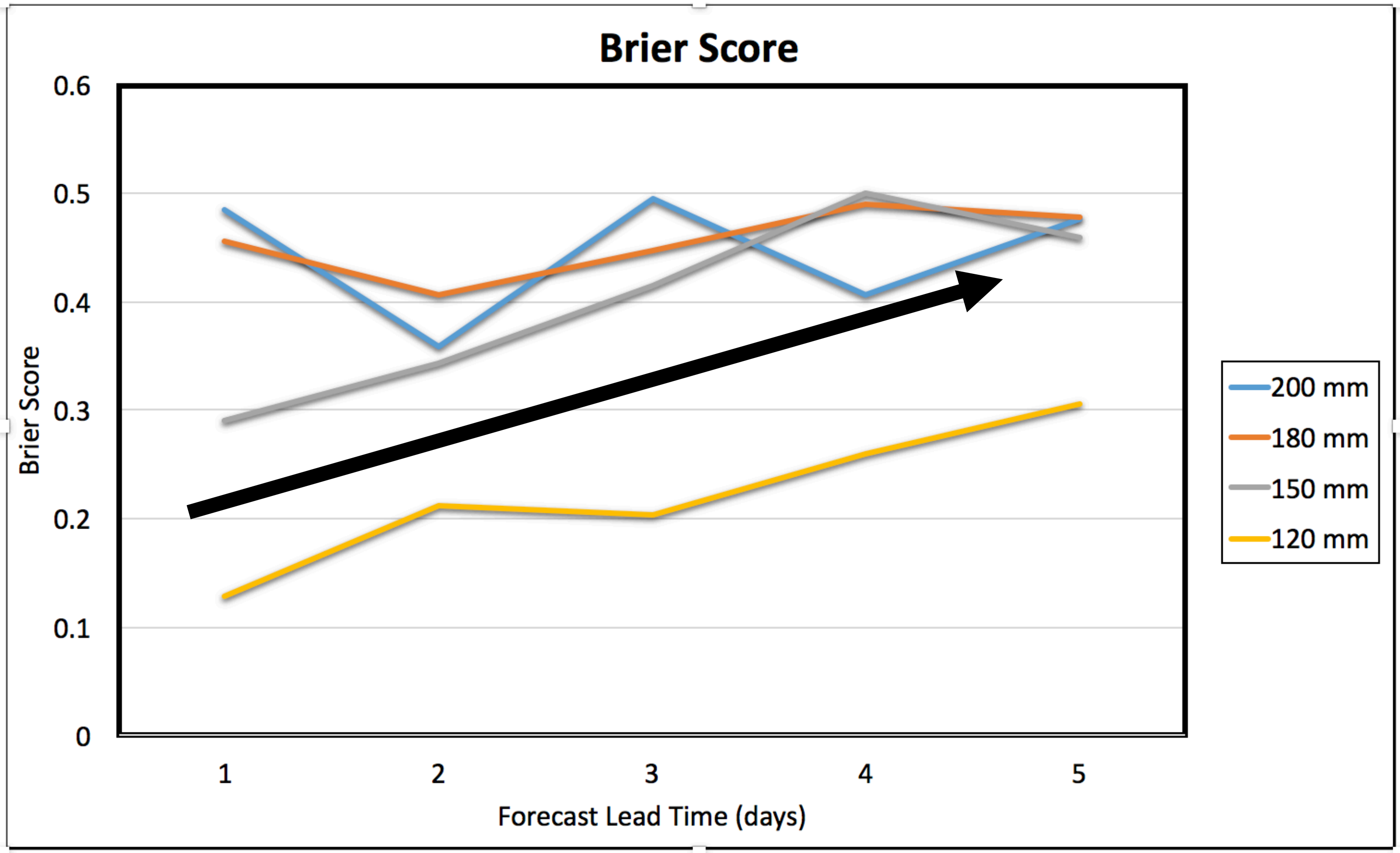
- Observed Rainfall For all Lead Times is Higher than 250 mm/day
- Control Member (deterministic) shows rainfall Less than 180 mm/day for all lead times
- Several EPS members show better forecast than Control.

Rain Rate CRA Method



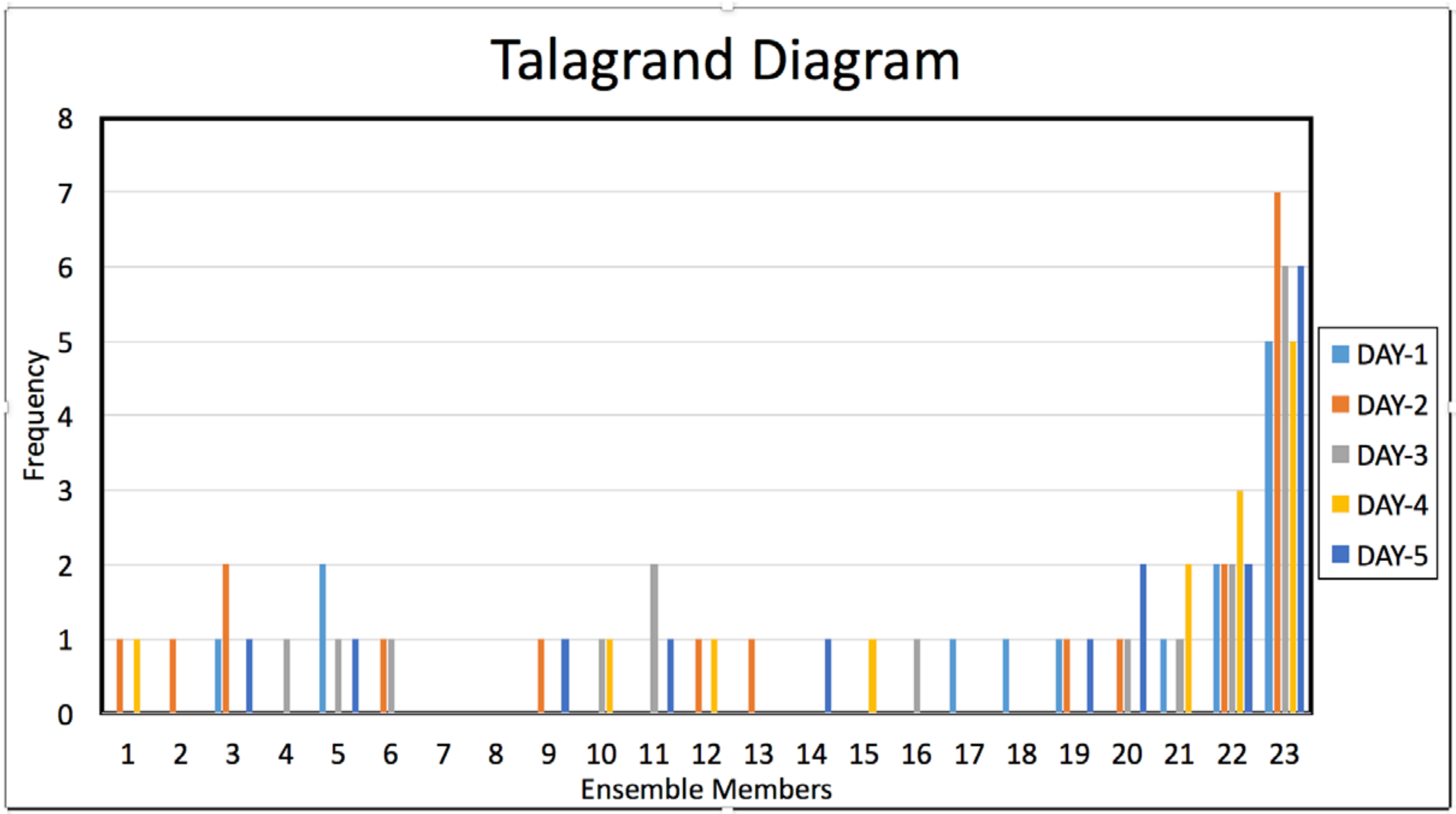
The Observed Rain Rate lies within the Maximum and Minimum Forecast Rain Rate

Verification of Maximum Rainfall in CRA over Mumbai



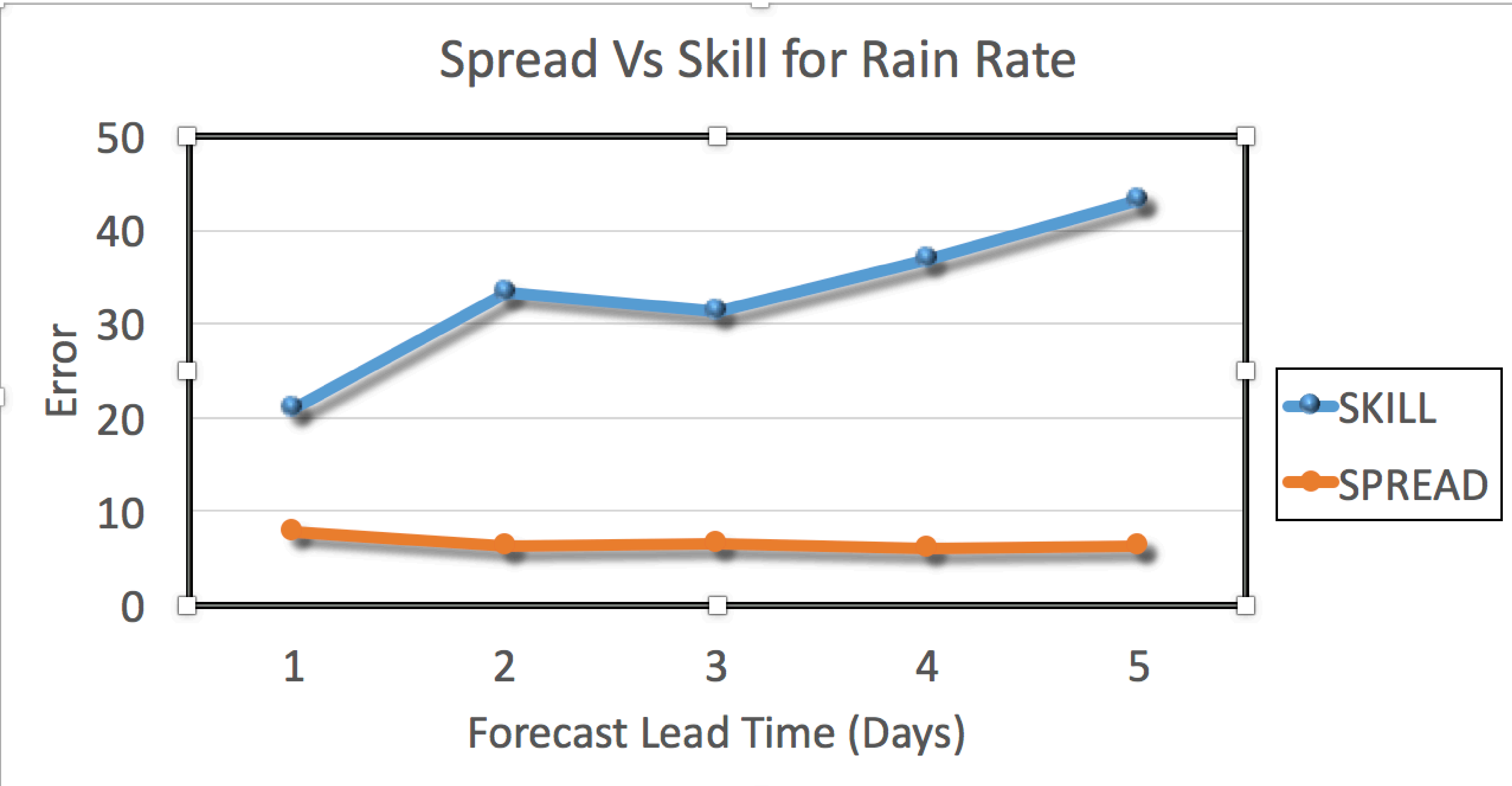
- Brier Score (Forecast Probability – Observed Frequency) Should be small
- BS is calculated for Maximum Observed and Forecast Rainfall within a CRA of threshold 40 mm/day Rainfall
- BS is increasing with increase in Lead Time and Rainfall Threshold

Talagrand Diagram/Rank Histogram for Maximum Rainfall



- **The above plot shows that the Talagrand diagram is skewed to the right implying that the EPS is underforecasting most of the time.**

Spread Vs Skill for Rain Rate



- **The Spread is much Lower as compared to the RMSE in the mean**
- **The ensemble is under-dispersed**
- **This is also clear from the Rank Histogram**

Summary

- ***CRA Verification for Ensemble Rainfall Forecasts during JJAS 2019***
  - ***Case of Extremely Heavy Rainfall (21cm/day) over Mumbai***
  - ***Verification for 4cm CRA Objects***
    - ***Displacement of 20, 40 and 80 mm/day CRA Objects suggest 2° southward bias***
    - ***Members indicating northward and southward distribution in location errors.***
  - ***Verification for Highest Rainfall amounts in 4cm CRA***
    - ***Six of 23 members predicted rainfall > 10 cm/day at all lead times (>26% pqpf)***
  - ***Verification of attributes (area, volume etc)***
    - ***Peak intensity: BS lowest for 12 cm/day rainfall forecast (0.2-0.3 in Day-1 to Day-5)***
    - ***Poor skill for higher thresholds (BS and ROC)***
    - ***Forecasts show underdispersion for 40cm/day CRA***
    - ***Rank Histogram: Skewed to the right***
    - ***RMSE vs Spread for Mean Rain intensity : Spread is too low***
    - ***BS for Area and Volume verification show degradation at similar rate***

TABLE 1. List of individual methods considered in this paper, and the ICP, along with their abbreviations used here. References listed are not comprehensive; see the text and the references for further representative works.

Abbreviation	Description	Method type	Reference(s)
BCETS	Bias-corrected ETS	Traditional	Mesinger (2008)
CA	Cluster analysis	Features based*	Marzban and Sandgathe (2006, 2008)
Composite	Composite method	Features based*	Nachamkin (2005, 2009)
CRA	Contiguous rain area	Features based	Ebert and McBride (2000); Ebert and Gallus (2009)
DIST	Distributional method	Neighborhood	Marsigli et al. (2006)
FQI	Forecast quality index	Field deformation*	Venugopal et al. (2005)
FQM–DAS	Forecast quality measure–displacement amplitude score	Field deformation	Keil and Craig (2007, 2009)
FSS	Fractions skill score	Neighborhood	Roberts (2005); Roberts and Lean (2008); Mittermaier and Roberts (2009)
IS	Intensity scale	Scale separation	Casati et al. (2004); Casati (2009)
IW	Image warping	Field deformation	E. Gilleland, J. Lindström, and F. Lindgren (2009, unpublished manuscript); Lindström et al. (2009)
MODE	Method for Object-based Diagnostic Evaluation	Features based	Davis et al. (2006, 2009)
MSV	Multiscale variability	Scale separation	Zapeda-Arce et al. (2000); Harris et al. (2001); Mittermaier (2006)
Neighborhood	Neighborhood based methods	Neighborhood	Ebert (2008, 2009)
Procrustes	Cell identification and Procrustes shape analysis	Features based	Micheas et al. (2007)
Procrustes2	Multiscale cell identification and Procrustes shape analysis	Scale separation–Features based	Lack et al. (2009)
SAL	Structure, amplitude, and location	Features based	Wernli et al. (2008, 2009)
Traditional	Point-based comparison	Point	Jolliffe and Stephenson (2003)
VGM	Variogram	Scale separation*	Marzban and Sandgathe (2009)

* A method that only loosely belongs to the given method type.

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SPECIAL Spatial Forecast Verification Methods COLLECTION

Intercomparison of Spatial Forecast Verification Methods

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(Manuscript received 3 February 2009, in final form 24 May 2009)

"How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth?"