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.
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.
Why Spatial Vx??
Why Spatial Vx??

Traditional verification: Smooth forecasts show higher score

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Max</th>
<th>RMSE</th>
<th>CC</th>
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<tr>
<td>Obs</td>
<td>54</td>
<td>274</td>
<td></td>
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<td>NCUM_G</td>
<td>28</td>
<td>101</td>
<td>76</td>
<td>0.13</td>
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<td>NCUM_R</td>
<td>57</td>
<td>293</td>
<td>142</td>
<td>-0.13</td>
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</table>

Mean Max RMSE CC

Obs 54 274
NCUM_G 28 101 76 0.13
NCUM_R 57 293 142 -0.13
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

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Traditional</th>
<th>Feature based</th>
<th>Neighborhood</th>
<th>Scale separation</th>
<th>Field Decomposition</th>
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<tbody>
<tr>
<td>Verification at different scales</td>
<td>Indirectly</td>
<td>Indirectly</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Location errors</td>
<td>No</td>
<td>Yes</td>
<td>Indirectly</td>
<td>Indirectly</td>
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<tr>
<td>Intensity Errors</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Structure Errors</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Hits/Misses etc</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Indirectly</td>
<td>Yes</td>
</tr>
</tbody>
</table>
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 areas
- 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)

\[ \text{MSE}_{\text{total}} = \text{MSE}_{\text{displacement}} + \text{MSE}_{\text{volume}} + \text{MSE}_{\text{pattern}} \]

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

\[ \text{MSE}_{\text{displacement}} = \text{MSE}_{\text{total}} - \text{MSE}_{\text{shifted}} \]

The volume error is the bias in mean intensity

\[ \text{MSE}_{\text{volume}} = (\overline{F} - \overline{X})^2 \]

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,

\[ \text{MSE}_{\text{pattern}} = \text{MSE}_{\text{shifted}} - \text{MSE}_{\text{volume}} \]

Ebert and McBride (J. Hydrology, 2000)
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

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

Displacement 0.25°E and 1°S
CRA Verification over India

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
2nd Jul 2019
NEPS Day-1 Forecasts
12km grid resolution
22-member + control
Area in blue: 4cm CRA
Rainfall > 4cm/day

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CRA Verification for Ensemble Rainfall Forecasts
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)

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

Observed and Forecast (Control, Max and Min) object mean rainfall over Mumbai on 29th June 2019

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
The above plot shows that the Talagrand diagram is skewed to the right implying that the EPS is underforecasting most of the time.
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>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Method type</th>
<th>Reference(s)</th>
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<tbody>
<tr>
<td>BCETS</td>
<td>Bias-corrected ETS</td>
<td>Traditional</td>
<td>Mesinger (2008)</td>
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<tr>
<td>CA</td>
<td>Cluster analysis</td>
<td>Features based*</td>
<td>Marzban and Sandgateh (2006, 2008)</td>
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<tr>
<td>Composite</td>
<td>Composite method</td>
<td>Features based*</td>
<td>Nachamkin (2005, 2009)</td>
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<td>CRA</td>
<td>Contiguous rain area</td>
<td>Features based</td>
<td>Ebert and McBride (2000); Ebert and Gallus (2009)</td>
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<td>DIST</td>
<td>Distributional method</td>
<td>Neighborhood</td>
<td>Marsigli et al. (2006)</td>
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<td>FQI</td>
<td>Forecast quality index</td>
<td>Field deformation*</td>
<td>Venugopal et al. (2005)</td>
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<td>FSS</td>
<td>Fractions skill score</td>
<td>Neighborhood</td>
<td>Roberts (2005); Roberts and Lean (2008); Mittermaier and Roberts (2009)</td>
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<td>IS</td>
<td>Intensity scale</td>
<td>Scale separation</td>
<td>Casati et al. (2004); Casati (2009)</td>
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<td>IW</td>
<td>Image warping</td>
<td>Field deformation</td>
<td>E. Gilleland, J. Lindström, and F. Lindgren (2009, unpublished manuscript); Lindström et al. (2009)</td>
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<td>MODE</td>
<td>Method for Object-based Diagnostic</td>
<td>Features based</td>
<td>Davis et al. (2006, 2009)</td>
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<td>MSV</td>
<td>Multiscale variability</td>
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<td>Zapeda-Arce et al. (2000); Harris et al. (2001); Mittermaier (2006)</td>
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<td>Neighborhood</td>
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<td>Micheas et al. (2007)</td>
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<td>Jolliffe and Stephenson (2003)</td>
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<td>VGM</td>
<td>Variogram</td>
<td>Scale separation*</td>
<td>Marzban and Sandgateh (2009)</td>
</tr>
</tbody>
</table>

* A method that only loosely belongs to the given method type.
“How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth?”

Thanks!