Overview of QPE/QPF techniques and hydrological applications

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Talk Structure

- **Lecture A1**: QPE techniques and development
  - Real-time radar rainfall estimates
  - Case studies

- **Lecture A2**: QPF techniques and development
  - QPF techniques (Radar-based nowcasting)
  - Operation and research development systems
  - QPF accuracy assessment
  - Case study: Bangkok rainfall forecasting system

- **Lecture A3**: Hydrological Applications
  - Cases studies
Real-time Radar Rainfall Estimation – An Overview
Why do we need weather radar?

• Measure rainfall continuously covering large area

• Provide fine spatial and temporal resolution

• Can be used to project the storm trajectory, i.e., provide a short-term storm forecast
Basic concept of measuring rainfall using radars

\[ p = \frac{C \cdot K \cdot Z}{r^2} \]

where: \( A, b \) – radar parameters; \( Z \) – reflectivity;

\( R \) - rainfall

\[ z = A R^b \]
Volume scan data

Range from radar (km)

Height above ground (km)
Simplified scheme of radar processing

Measurement of rain drops

Radar image in polar coordinates - continuous values

Radar products, e.g. in cartesian coordinates - values in 256 classes
Polar and cartesian coordinates

Due to the radar measurement in polar coordinates, the data near to the radar are denser than far from the radar. When transforming polar data to a cartesian square grid close to the radar, several polar square grid pixels, close to the radar, are used. The spatial resolution of the square grid data is less than that of the originally measured polar data. Far from the radar, one polar pixel may be the original for several cartesian grid pixels. Here, the density of the data is less and therefore measurement errors have a higher impact on the cartesian data.
PPI reflectivity map is extracted from the raw reflectivity data from the beam at a particular elevation angle.
CAPPI

Constant Altitude Plan Precipitation Indicator (CAPPI)
Problems and Limitations

- Are parameters measurable?
- Are parameters stable?
- Does reliability stay constant with distance away from the radar?
- What about obstructions (buildings, mountains)?
- What about multiple raindrops and rain-clouds in the path of the beam?
- What about the effect of the earth’s curvature?
- What about differences in rain profile on ground versus high elevations?

\[ Z = AR^b \]

where

- \( A,b \) – radar parameters
- \( Z \) – reflectivity
- \( R \) - rainfall
Problems of using weather radar?

1. Reflectivity measurement error
   - ground clutter
   - attenuation
   - vertical reflectivity profile
   - beam geometry

2. Reflectivity-rainfall rate conversion error

3. Residual errors when compared with rain gauges
Some difficulties …

- Ground-clutter, bright-band, hail, attenuation, range dependent bias – not so difficult to remove as they can be noticed easily.
Some difficulties … Distance vs height of radar beam
Some difficulties …

- Increasing uncertainty in measured reflectivity as a function of range

![Cumulative Distribution Function (CDF) graph](image)
Some difficulties … Range dependent errors
Some difficulties … Range dependent errors

\[ \sigma_{GR}^2 = 0.1320 \]

\[ \sigma_{GR}^2 = 0.0003 \left( R_0 - 70 \right) + 0.1320 \]

\[ \sigma_{GR_i}^2 = \frac{1}{N} \sum_{i=1}^{N} \left\{ \left[ \log R_G(i) - \log R_R(i) \right]^2 \right\} \mid R_G(i) > r \]

Anagnostou et al. (1999)
Some difficulties … Attenuation example

Rainfield without attenuation
(up to 6 classes)

Marienfeld

Rainfield attenuated

Radar Flechtdorf

Radar Essen

Einfalt (2004)
Some difficulties ... Bright-band

Fabry et al. (1994)
Some difficulties... Effect of storm types on Z-R relation

\[ Z = \int_{0}^{\alpha} N_o e^{-\Lambda D} D^6 dD \]

\[ R = \int_{0}^{\alpha} N_o e^{-\Lambda D} \frac{4}{3} \pi \left( \frac{D}{2} \right)^3 \nu(D) dD \]

**Convective**

- \( Z = 35 \text{ dBZ} \)
- \( R = 7 \text{ mm/h} \)

**Stratiform**

- \( Z = 35 \text{ dBZ} \)
- \( R = 10 \text{ mm/h} \)
Z-R relationship for each rain-cloud

- Parameters ‘a’ and ‘b’ varies on rain drop size distribution.

- Cumulus
- Cumulonimbus
- Nimbostratus
Z-R relationship of each type of rain-cloud (Calibration)

Chumchean et al. (2009)
Z-R relationship of each type of rain-cloud

• Rainy season

Cumulus
\[ Z = 29R^{1.5} \]
\[ Z = 30 \text{ dBZ} \]
\[ R = 10.58 \text{ mm/h} \]

Cumulonimbus
\[ Z = 55R^{1.5} \]
\[ Z = 30 \text{ dBZ} \]
\[ R = 6.90 \text{ mm/h} \]

Nimbostratus
\[ Z = 208R^{1.5} \]
\[ Z = 30 \text{ dBZ} \]
\[ R = 2.85 \text{ mm/h} \]

• Summer

Cumulus
\[ Z = 38R^{1.5} \]
\[ Z = 30 \text{ dBZ} \]
\[ R = 8.93 \text{ mm/h} \]

Cumulonimbus
\[ Z = 90R^{1.5} \]
\[ Z = 30 \text{ dBZ} \]
\[ R = 4.99 \text{ mm/h} \]

Chumchean et al. (2009)
Some difficulties …

- Variations in Z~R relationships for different storm types

![Graph showing variations in reflectivity for convective and stratiform types of storms.](image)
Some difficulties …

- Residual errors – results in a “mean-field-bias”
- Exhibits persistence from one time-step to the next
- Very important in real-time estimation
- Difficult to remove using physical relations
Philosophy

“Estimated radar rainfall must first be corrected for reflectivity measurement errors and $Z-R$ conversion errors based on the physical methods, and then a statistical method will be used to remove the average difference (mean field bias) between radar estimates at the rain gauge locations and the corresponding gauge rainfall amounts”.
Real-time radar rainfall estimation method

**Reflectivity measurements**
- Record reflectivity field in 3D polar coordinate at operational temporal resolution
- Exclude reflectivity that are greater or lower than the maximum/minimum reflectivity thresholds
- Conversion to CAPPI Cartesian coordinate at altitude below bright-band level
- Remove the effect of ground and sea clutter
- Scaling correction

**Z-R conversion**
- Instantaneous storm classification
- Instantaneous convective/stratiform reflectivity
- Z-R conversion \( Z = A R^b \)
- Instantaneous convective/stratiform radar rainfall
- Account for the storm movement within an hour
- Accumulate into hourly radar rainfall
- Initial hourly radar rainfall estimates

**Rain gauge adjustment**
- Estimate hourly gauge-radar bias adjustment factor (AF) based on Kalman filtering approach proposed by (Chumchean et al., 2003) [under review]

**Final hourly radar rainfall**
\[ AF \times \text{initial radar rainfall estimates} \]

Chumchean et al. (2006)
Real-time radar rainfall estimation

Scaling correction
(to remove range-dependent bias)

Storm classification
(to remove bias in Z~R relation due to the dominant storm type)

Correction of residual mean-field bias
Data

- C-band Kurnell radar
- 10-minute, 1km\(^2\) resolution
- Analysis period November 2000 to April 2001
- 254 hourly rain gauges (SWC, SCA, BoM)
Correction of range dependent bias due to radar beam geometry
Application of scaling in measured reflectivity

Assume simple scaling holds for measured reflectivity

$$Z_D^{\text{dist}} = \left(\frac{d}{D}\right)^{-\eta} Z_d$$
The proposed scale transformation formula is:

\[ Z_{\text{transformed}} \text{ (dBZ)} = \left(\frac{20}{D}\right)^{-0.024} Z_D \text{ (dBZ)} \]
Range-dependent bias correction

Using simple-scaling theory:\[ Z_{\text{transformed}} (\text{dBZ}) = \left( \frac{20}{D} \right)^{-0.024} Z_D(\text{dBZ}) \]
Effectiveness of scale transformation function in correcting range dependent bias in radar rainfall

The graph shows the Gauge-Radar ratio (G/R) against the range interval (km). Two lines are plotted: one for no correction and another for scaling correction.

- No correction line:
  - Slope = 8.9%

- Scaling correction line:
  - Slope = 0.3%

The range intervals are divided into five categories: 0-20, 20-40, 40-60, 60-80, and 80-100 km.
Effect of storm types on radar rainfall Estimates (Z-R conversion error)
Instantaneous pixel classification

- Apply Steiner et al. (1995) storm classification method to use for separation of instantaneous reflectivity of each pixel into convective or stratiform components.

- Revise the classification criteria to be suitable for instantaneous reflectivity of the Kurnell radar.
Parameter for pixel classification
(after Steiner et al., 1995)

- convective centre
- background radius
- convective radius
- minimum convective threshold* 
- maximum stratiform threshold*

* = proposed additional classification parameter
Classification results: calibration

Using modified parameters based on Steiner et al. (1995)

Using modified pixel based classification approach
Classification results: verification

Using modified pixel based classification approach

Using modified Parameters based on Steiner et al. (1995)
Verification using VPR

(a) Stratiform

(b) Convective
Correcting for mean field bias in real-time radar rainfall estimates using **Kalman Filtering techniques**

Rain gauge rainfall \((G) = \text{AF} \times \text{Radar rainfall} \ (R)\)

AF = adjustment factor or mean field bias
Advantage of Kalman filtering technique over the simple G/R

1) It accounts for the “noise” in the measurements when updating the mean bias.

2) It provides an estimate of the error in the computed bias.

3) It combines an estimate of the bias and its error variance made an hour earlier with the current measurements and its estimated measurement error variance to compute an updated bias estimate and new forecast for the next hour.
Residual mean-field bias correction\textsuperscript{1}

- Logarithmic Mean Field Bias ($\beta$)
- Assumed $\beta$ exhibits Markovian dependence (Kalman process model assumed AR1)
- Kalman measurement error model specified as function of range\textsuperscript{2}

\[ \beta_t = \frac{1}{n} \sum_{i=1}^{n} \log_{10} \left( \frac{G_{i,t}}{R_{i,t}} \right) \]

Radar rainfall error variance model

\[ \sigma_{Y_{i,t}}^2 = -0.015 \times \bar{G}_t + 0.14 \quad ; \quad \text{for } r_i \leq 55 \text{ km} \]

\[ \sigma_{Y_{i,t}}^2 = -0.015 \times \bar{G}_t + 0.13 \times \frac{(r_i - 55)}{p} + 0.14 \quad ; \quad \text{for } r_i > 55 \text{ km} \]
Comparison of observed G/R and the Kalman-filter estimated bias (Calibration)

lag 1 correlation coefficient of innovation sequence

= 0.047
Comparison of observed G/R and the Kalman-filter estimated bias (Validation)

lag 1 correlation coefficient of innovation sequence = 0.08
Application

- Stepwise application of error correction strategies
- Base reflectivity data free of effects of ground-clutter, bright-beam, hail
- Total rain gauges - 260
- Cross-validation performed by leaving fraction of rain gauges to evaluate predictive uncertainty
- Performance statistic - Root Mean Square Error (RMSE)
Results

Climatological \( Z-R \) parameters of convective and stratiform rainfall

\[ (Z = AR^{1.5}) \]

<table>
<thead>
<tr>
<th>Calibration strategies</th>
<th>( A ) parameter</th>
<th>No scaling correction</th>
<th>Scaling correction</th>
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<tbody>
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<td>Hourly pixel classification</td>
<td>150</td>
<td>93</td>
<td>172</td>
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</table>
Results

Gauge-based adjustment methods

- ‘GHNBO’ – Base data
- ‘SC’ – Scaling correction
- ‘ZR’ – Storm classification
Results

a) No bias correction

b) Sample G/R

c) Kalman filtering

Number of calibrated gauges
Conclusions

- A stepwise decrease in RMSE with added levels of error correction
- Correcting mean-field bias more important than correcting the other sources of errors
- Storm classification relatively more important than the correction of range dependent bias
- Kalman filtering much better than use of sample G/R correction, particularly when calibration rain gauges are few
Conclusions

- Range dependent bias and storm-classification, though small, are certainly not insignificant

- Complete model (after mean-field bias correction) explains more than 50% variance of gauge rainfall

- This may be the best we will ever have – remember we are comparing 1kmx1km grid averages to rainfall at a point!