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# Application of Radar-Raingauge Co-Kriging to Improve QPE and Quality Control of Real-time Rainfall Data

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**Abstract** Quantitative precipitation estimation (QPE) often serves as an important input to hydrological and weather warning operations. Automatic raingauge (RG) data are not only fundamental in QPE but also act as the ground truth in warning operation and forecast validation. Quality control (QC) is required before the data can be used quantitatively due to systematic and random errors. Extremely large random errors and unreasonably small/zero values can hamper effective monitoring of heavy rain. Yet, both are difficult to be detected correctly. A recently proposed QC procedure based on localized radar-raingauge co-Kriging QPE and RG-QPE residuals was enhanced and described in this paper. Improved QPE performance in Hong Kong, a coastal city surrounded by waters and lacking raingauges on three sides, were demonstrated through selected cases and controlled tests.

**Key words** precipitation estimation; co-Kriging; raingauge; quality control; Hong Kong

## INTRODUCTION

In Hong Kong, QPE serves as an important input to hydrological and weather warning operations, e.g. the landslip warning, rainstorm warning and flood alert based on the past 21-hour, 23-hour and 1-hour rainfall analyses. It also provides the initial field for a rainfall nowcasting system. RG data are not only fundamental in QPE but also act as the ground truth in rainstorm warning operation and rainfall forecast validation. QC is required before automatic raingauge data, e.g. typical tipping-bucket RG, can be used quantitatively due to various types of systematic and random errors, caused by various factors including wind, wetting, evaporation, splashing, calibration, finite sampling, mechanical failure, funnel blockage, signal transmission interference, power failure, etc (Habib, 2001). Among the random errors, those arising from contamination during data transmission through radio telemetry systems and blockage of the raingauge itself by external obstructions, like insects or fouling by birds, are crucial in heavy rain monitoring and assessment. While telemetry errors usually contaminate a single observation with an extreme value, a blocked gauge will return zero or unreasonably small values that fall well within the climatological range and are therefore difficult to detect. A simple QC procedure based on radar-raingauge co-Kriging QPE and RG-QPE residuals was recently proposed by Yeung *et al*. (2010) to address the issues. An enhanced version will be described in this paper. With proper treatment of the spatial structure in raingauge data and the use of radar reflectivity to fill up the gauge void areas, the co-Kriging scheme improves the QPE over Hong Kong, a place that is surrounded by waters and lacking raingauges on three sides. Performance will be demonstrated through selected rainstorm cases and controlled tests. Potential application and constraints in real-time environments will also be discussed.

## DATA SETS

The data sets used in this study include raingauge and radar reflectivity data, covering the period March 2009 – February 2010. During the data acquisition period, there were a maximum of 157 tipping-bucket type raingauges available in Hong Kong, covering a total land area of about 1,100 $km^2$. The gauge distribution is uneven with an average separation about 2.6 km. The basic rainfall measurement is a 5-minute accumulation updated every 5 minutes starting at the 00-minute of the hour. The time latency is about 5 minutes and the minimum rainfall amount to tip is 0.5 mm. In operation, the latest twelve 5-minute rainfall reports from a raingauge are added together to estimate the running 60-minute rainfall accumulation at that station. The reflectivity data came from a mosaic of two S-band Doppler weather radars in Hong Kong which is updated every 6 minutes. The reflectivity signals were subjected to basic quality control to remove clutter. The reflectivity data used for co-Kriging were sampled at a constant altitude of 2 km, converted to rainfall rate using the Z-R relation of $Z = 118R^{1.52}$ (derived based on rainfall data from a total of 90 rainy days in 2009) and to a Cartesian field with 1 km resolution. A 1-out-of-5 data thinning procedure was applied to the gridded reflectivity data so as to speed up the co-Kriging analysis during the generation of RG-QPE residuals. The trade-off is the reduction of effective resolution to about 5.3 km. In the generation of gridded co-Kriging QPE, however, the full set of the reflectivity data was used.

## METHODOLOGY

Co-Kriging techniques are very popular for spatial analysis in the world of geostatistics. For basic formulations of the problem, preparation of variograms and the general solutions to the co-Kriging equations, interested readers are referred to the reference books by Wackernagel (1998) or Webster & Oliver (2001), as well as journal papers by Goovaerts (1998) and Phillips *et al.* (1997). For applications to QPE, reference could be made to Creutin *et al.* (1988), Schuumans *et al.* (2007) and Velasco-Forero *et al.* (2009). In Yeung *et al.* (2010), the ordinary co-Kriging technique was explored for optimal combined analysis of raingauge measurements and reflectivity derived rainfall. The co-Kriging QPE was further applied to raingauge data QC. The key characteristics of such QPE and QC schemes include: (a) *localized* — analysis effectively confined within 50 km for computational efficiency; (b) *high spatially consistency and resolution* — due to the use of co-Kriging technique and space-filling reflectivity data; (c) *un-biased* — local mean QPE converged towards raingauge average with reflectivity treated as subsidiary data; (d) *computationally stable* — use of average variograms instead of real-time variograms which could be ill-defined due to insufficient data samples; and (e) *simple* QC procedure — based mainly on threshold checking. Improvements in the present version of the co-Kriging and QC schemes since Yeung *et al.* (2010) include: (i) use of a "climatological" Z-R relationship (see last section) instead of the "stratiform" Z-R relation $Z = 200R^{1.6}$; (ii) a revised set of QC criteria for 5-minute accumulation available in Hong Kong; and (iii) introduction of QC criteria for 60-minute accumulation. In this paper, results and discussions will be focused on the 60-minute rainfall. Fig. 1 shows the corresponding average variograms and cross-variogram obtained with the 2009-2010 data sets. The functional form and fitted parameters of the theoretical variograms/cross-variogram used for all subsequent co-Kriging and Kriging analyses are annotated on the same figure.

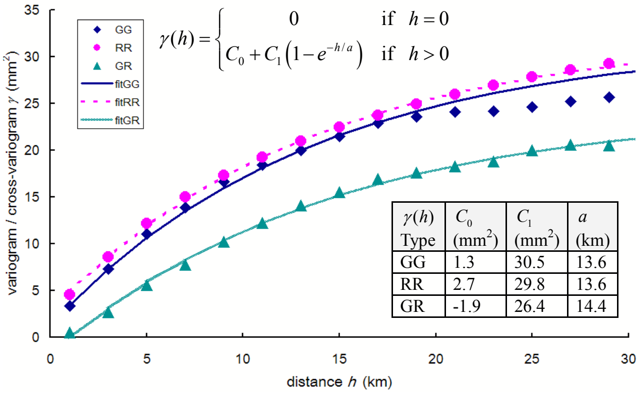


**Fig. 1** The average variogram/cross-variogram of 60-min rainfall for Hong Kong. The legend labels "GG", "RR" and "GR" refer to gauge-gauge variogram, radar-radar variogram and gauge-radar cross-variogram respectively. The respective theoretical variograms/cross-variogram $\gamma(h)$ are shown as solid/dashed curves with fitted parameters for nugget ( $C_0$ ), sill ( $C_1$ ) and range ( $a$ ) summarized in the table.

## PROBABILITY DISTRIBUTIONS FOR RG-QPE RESIDUALS

The raingauge QC algorithm requires the probability distribution of the gauge-radar residuals. Three kinds of residuals, namely linear, logarithmic and standardized, are defined respectively as follows:

$$D = G - K \tag{1}$$

$$\xi = 10\log\left(G/K\right) = 10\log G - 10\log K \tag{2}$$

$$\delta = \left|G - K\right| / \sigma \tag{3}$$

Where $D$ is in units of millimetres (mm), $\xi$ is in decibels (dB) and $\delta$ is dimensionless. $G$

denotes the accumulation amount reported by a raingauge, $K$ is the corresponding co-Kriging estimate that is obtained with the raingauge data under examination excluded in deriving the QPE and $\sigma$ its estimation error. An offset of 0.08 mm was added when either G or K was zero so as to make $\xi$ well defined for all possible $G$ and $K$ values.

(a) (b)

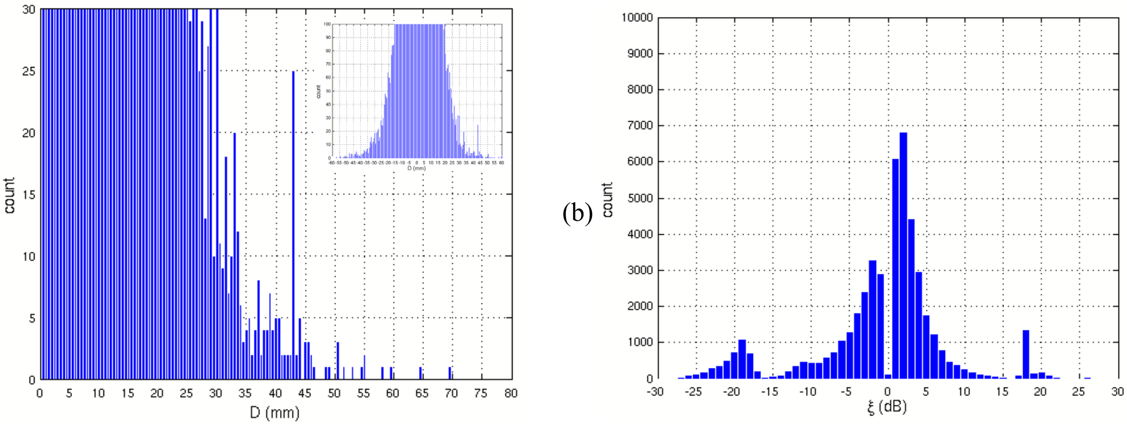


**Fig. 2** Frequency distributions of the 60-minute RG-QPE residuals during the period March 2009–February 2010: (a) magnified view of the positive tail of the entire distribution (see inset) of linear residuals; (b) logarithmic residual distribution reduced with $\delta \le 2$ data samples discarded.

Fig. 2(a) shows the distribution of $D$. The small peaks and outliers shown up in the positive tail were taken to signify abnormally large raingauge values (such as those due to telemetry errors) as compared to their reference QPE. As the current data set only covers one year, a conservative strategy was considered more appropriate and $D > 42$ was selected to identify spuriously large raingauge values (around 50 out of a total of 1.6 million samples).

False zeroes or unreasonably small raingauge data are rather subtle as they are typically buried well within the broad central peak of the distributions of $D$. Following Yeung *et al.* (2010), the condition $\delta \le 2$ was adopted to throw away the uninteresting samples, i.e. those with a small $|D|$ as well as those bearing a relatively large estimation error. Fig. 2(b) shows the resulting distribution of $\xi$ with anomalous peaks in the tails. The peak around –19 dB signifies some unreasonably large negative residuals ($G$ significantly smaller than $K$) which are attributable to false zeroes or unreasonably small gauge values. There is also an anomalous peak around +18 dB, hinting for some raingauge data that are inconsistently larger than surrounding rainfall information. A known example of such curious raingauge reports occurred on 9 September 2010 following the strike by a rainstorm with very intense ground lightning activity. Some faulty stations kept reporting 5 mm of 5-minute accumulations for a prolonged period even after the rainstorm had departed and other normal raingauges ceased to report any rainfall. Whether the positive anomalous peak could be another useful QC criterion would be examined and discussed in later sections.

## APPLICATIONS

### Raingauge Data QC

Following Yeung *et al.* (2010) and based on the results in the last section, a simple QC procedure for 60-minute rainfall accumulation reported by automatic raingauges is proposed as follows:

(i) perform pre-QC screening to retain only those data lower than a threshold value $G^c$;

(ii) perform spatial consistency check on data retained in step (i) —
- calculate a reference QPE using localized radar-raingauge co-Kriging with the raingauge data under examination excluded;
- calculate the RG-QPE residuals (linear, logarithmic and standardized); and
- check against the corresponding threshold values ($D^c$, $\xi^c$ and $\delta^c$ respectively);

(iii) assign QC flags “P” (for pass) or “R” (for reject) according to the following criteria —
- if $D > D^c = 42$ mm, flag “R”;

- else if $\delta > \delta^{c} = 2$ and $\xi < \xi^{c-} = -19$ dB, flag "R";
- [Optional] else if $\delta > \delta^{c}$ and $\xi > \xi^{c+} = 18$ dB, flag "R";
  (superscripts "–" and "+" here refers to peaks in the negative and positive tails respectively);
- otherwise, flag "P".

The pre-QC screening in step (i) is necessary to avoid unphysically large rainfall data from contaminating the co-Kriging QPE. $G^{c}$ was set to be the same as the maximum instantaneous rainfall rate of 513 mm/h registered in Hong Kong in 1971. The other threshold values given in step (iii), namely $D^{c} = 42$ mm, $\delta^{c} = 2$, $\xi^{c-} = -19$ dB and $\xi^{c+} = 18$ dB, were deduced from the distribution of the gauge-radar residuals as explained in the preceding section. Note that the choices for $\xi^{c-}$ and $\xi^{c+}$ were relatively insensitive to the value of $\delta^{c}$. Higher values may also be used at the expense of lower error detection rate.

## Gridded Rainfall Analysis

In gridded analysis, the same co-Kriging scheme was applied except for: (i) grid box centres (with about 1.5-km spacing) as analysis points; (ii) inclusion of raingauges co-located with analysis points; and (iii) use of QC passed raingauge data only. Fig. 3 shows an example of an intense rainband on 7 June 2008 approaching Hong Kong from the west.

(a) (b) (c) (d)

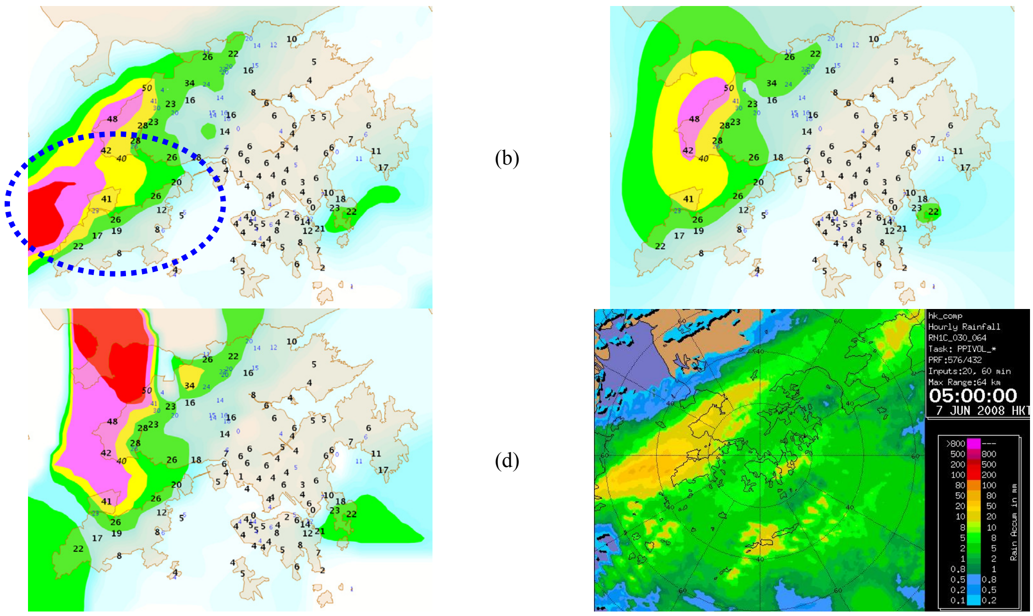


**Fig. 3** Rainfall analyses prepared by four QPE schemes: (a) co-Kriging; (b) Kriging; (c) Barnes and (d) radar rainfall estimation. In (a)-(c), the numbers are raingauge values and the green, yellow, pink and red colour filled contours refer to analyzed rainfall in the ranges of 20–30, 30–40, 40–50 and 50–70 mm. In (d), the greenish and yellowish colours refer to rainfall in the 0.8–10 mm and 10–80 mm ranges respectively.

The isohyet maps (a)–(d) compare respectively the four types of QPE by co-Kriging, Kriging (raingauge only), Barnes (raingauge only) and radar rainfall (reflectivity only) schemes. At the time of analysis, the rainband started to affect the coastal areas posing a real challenge to the raingauge-only analysis schemes as there were no direct rainfall information available over the waters and raingauges are relatively sparse over Lantau Island (the largest island in the southwest corner of the map inside the dashed ellipse). With the subsidiary rainfall information derived from reflectivity, co-Kriging QPE correctly analyzed the rainfall distribution by putting the area with the heaviest rain (the red zone) to the west of Lantau. This is important for the accurate assessment on the likelihood of rainstorm flooding and landslides. Both types of hazards occurred in the subsequent few hours, paralyzing the main traffic to the Hong Kong International Airport at Chek Lap Kok (the landmass adjacent to the north coast of Lantau) and causing a number of serious landslides and significant damage on the Lantau Island.

## PERFORMANCE ASSESSMENT

### Co-Kriging QPE for QC

Due to the exclusion of observation data at the analysis point, the residuals $D$ could be used for cross validation purposes. Discounting unphysically large residuals, which are likely to be raingauge errors, the root mean square (RMS) error of the 60-minute co-Kriging QPE over the whole data period was estimated to be about 1.0 mm with a vanishing mean error of 0.01 mm. The RMSE and mean error statistics were calculated as a function of rain depth and are shown in Fig. 4. While the QPE remained unbiased up to about 60 mm, it tends to underestimate beyond that depth. The RMS error grew almost linearly as the QPE increases.

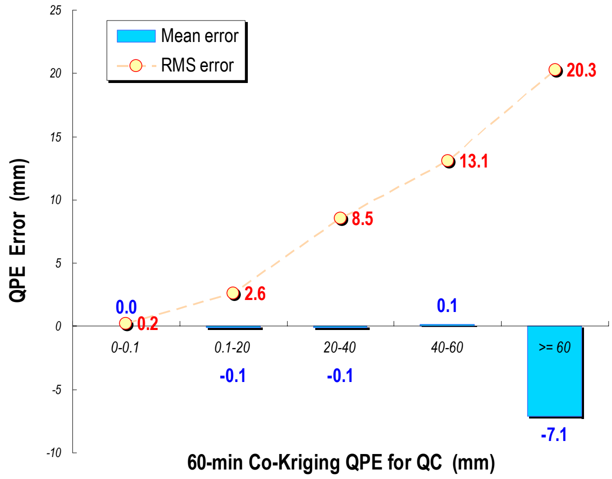


**Fig. 4** Error analysis of co-Kriging QPE for QC.

### Raingauge Data QC

The effectiveness of the proposed QC procedure was assessed through a rainfall event which occurred from 3 a.m. to 2 p.m. local time on 10 June 2010. There were a total of 20,289 raingauge reports of 60-minute rainfall available for testing. Besides the proposed objective QC procedure, subjective inspection by the authors was also performed for cross validation. Three additional controlled tests using bogus data by setting $G \geq 10$ reports to zero, and zero reports to 10 mm and 47 mm were also conducted to respectively simulate clogged raingauges, inconsistently large raingauge reports and data contamination during transmission through the telemetry systems.

**Table 1** Test results for 60-minute raingauge rainfall data QC.

| R/G reports | QC method | Tests with different raingauge amounts, $G$ (mm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | $G = 0.0$ | $G \geq 0.5$ | all $G$ | bogus 0 ($G \geq 10$) | bogus 10 ($G = 0$) | bogus 47 ($G = 0$) |
| Subtotal | - | 1,967 | 18,322 | 20,289 | 2,873 | 1,653 | 1,653 |
| Rejected | co-Kriging | 57 | 0 | 57 | 2,797 | 913 | 1,652 |
| | human | 57 | 0 | 57 | 2,873 | 1,653 | 1,653 |
| Ratio of correct rejections w.r.t. subtotal | | - | - | - | 97.4 % | 55.2 % | 99.9 % |

Except for the test on inconsistently large raingauge reports, the proposed QC procedure was considered satisfactory as summarized in Table 1. The detection rate for a false observation of 10 mm is just 55%, and it is not possible to detect such errors reliably during convective rainfall events. Despite the high detection rate (99.9%) for abnormally large raingauge reports, it must be remarked that the there exists a significant negative bias for the QPE in the case of extreme rainfall so that a raingauge report with residual exceeding the QC threshold $D^c = 42$ may well be a valid data if it occurs during an extreme rainfall event.

### Verification of Gridded QPE

The cross validation results presented above are relevant to raingauge locations only. The accuracy of QPE away from raingauges is even more crucial. To assess this, we carried out a verification exercise based on five rainstorm cases in 2010. The maximum 60-minute rainfall recorded by raingauge ranged between 78.0 and 131.0 mm. For each case, the 4-hour period with the heaviest rain was selected and a total of 245 gridded rainfall analyses were obtained and submitted to the following verification exercise designed to simulate gauge sparse situations. To derive the gridded QPE, only one third of the gauges were used. The other two thirds were reserved as verification points. The four nearest gridded QPE values were bilinearly interpolated to the verification points for calculating errors against that raingauge data (QC passed). Table 2 summarizes the verification results and compares the different QPE techniques. As indicated by the mean errors, all QPEs were underestimating the actual rainfall in a similar way. The RMS errors indicated that co-Kriging or Kriging QPEs were in general more accurate than the Barnes QPE in gauge sparse situations.

**Table 2** Gridded QPE errors (in mm) in gauge sparse situations during five rainstorm cases in 2010.

| Date | Mean error | | | RMS error | | |
|---|---|---|---|---|---|---|
| (2010) | *B* | *K* | *cK* | *B* | *K* | *cK* |
| 22 Jul | -1.02 | -1.43 | -0.95 | 9.54 | 9.06 | 8.86 |
| 28 Jul | -1.37 | -1.89 | -1.90 | 10.30 | 9.55 | 7.29 |
| 5 Aug | -0.94 | -1.08 | -1.01 | 6.55 | 6.06 | 6.43 |
| 10 Sep | -1.08 | -1.35 | -0.31 | 10.77 | 9.75 | 7.57 |
| 21 Sep | -0.51 | -0.90 | -1.45 | 6.22 | 5.86 | 6.70 |
| *Mean* | *-0.99* | *-1.34* | *-1.13* | *8.90* | *8.25* | *7.42* |

*B*, *K* and *cK* denote respectively the Barnes, Kriging and co-Kriging QPE techniques.

## CONCLUDING REMARKS

Enhanced co-Kriging QPE and QC schemes were developed and the performance was assessed through cross-validation, QC tests and verification with selected rainfall events. The results showed that the QC scheme performed satisfactorily with high error detection rate in general. However, it was found to be difficult to detect spurious gauge observations reliably in extreme rainfall events and when the errors were of a similar magnitude to the rain rates. As for the gridded analysis, co-Kriging QPE was shown to be generally more accurate than both the Kriging technique and Barnes method (the operational scheme in the Hong Kong Observatory) in gauge sparse situations. For the size of Hong Kong (about 1,100 km$^2$), the current co-Kriging QPE and QC algorithms can be completed within a 5-minute cycle on a commodity PC system and are therefore suitable for real-time operation.

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