Bias Correction for Satellite Precipitation Estimation used by the MRC Mekong Flood Forecasting System

Mission report - March 2010

Author

Dr. W.W. Immerzeel

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FutureWater

Costerweg 1G

6702 AA Wageningen

The Netherlands

+31 (0)317 460050

info@futurewater.nl

www.futurewater.nl

Preface

This consultancy has been undertaken for the MRC RFMMC in March 2010 to develop a bias correction for the satellite rainfall estimation (SRE) used by the MRC Mekong Flood Forecasting System with the ultimate aim to improve the flood forecasts by the FEWS-URBS-ISIS modeling system.

This mission report describes the basics of satellite remote sensing of precipitation and the available operational products, an analysis of the 2008 and 2009 flood seasons, options for and implementation of bias correction algorithms and concludes with a number of key recommendations.

The author would like to thank Dr. Son Lam Hung, Mr. Nicolaas Bakker, Dr. Hatda Pitch An, Dr. Janejira Tospornsampan, Dr. Katry Phung, Mr. Kien Nguyentien, Mr. Boly Chen, Mr. Sambo Pich and Mr. Kunthea Noun for the interesting discussions, guidance and advice necessary for successful completion for this mission. The author is also grateful to Ms. Sotheavy Cheap for making excellent logistical arrangements.

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1 Introduction

1.1 Background

The Regional Flood Management and Mitigation Centre (RFMMC) has been established in Phnom Penh, Cambodia under the umbrella of the Mekong River Commission (MRC). The Centre plays an important role in maintaining the national and regional availability of important flood-related tools, data, skills and knowledge; producing accurate regional forecasts with suitable lead time, and a timely and effective dissemination of it; in providing accurate, well documented and consistent tools for basin-wide flood risks assessment and trans-boundary impact assessment

The main objective of the RFMMC at present is to establish an improved, robust and reliable flood forecasting system for short and especially medium-term forecast periods. This system is identified as the new MRC Mekong Flood Forecasting System (MRC Mekong FFS).

To achieve this, three main issues need to be tackled:

- improved, timely and reliable data availability;
- improved and extended use of rainfall forecasts; and
- an improved flood forecast model.

The Satellite Rainfall Estimate (SRE) is obtained from NOAA and is a grid based product of 24 hour rainfalls derived from satellite estimates of the cloud top temperatures. The data is calibrated by NOAA to a limited number of ground truth observations obtained through the WMO's GTS, this number varied from 5 to 35 stations on any particular day for the entire Asian domain.

As the primary input to the new FFS (based on the Deltares' Flood Early Warning System or Delft-FEWS Platform), the spatial and temporal accuracy of this gridded data is critical to an appreciation of the accuracy of the MRC flood forecasting systems. In addition to the gridded rainfall estimates, daily rainfalls from several locations, concentrated along the mainstream, are also collected and available in the system.

A comparison of the daily SRE data with daily observations from rainfall stations was carried out for the 2008 season (MRC-RFMMC 2009) at selected stations. While it is recognized that this analysis is not comprehensive and a more rigorous approach over several seasons is required, it did provide a preliminary assessment of the accuracy of the SRE. The analysis showed that with regard to rainfall depths, there is no consistency over the region; the SRE can be either under or over estimated the observed rainfall by several orders of magnitude. The results indicate a definite bias in overestimating number of days on which rainfall occurs. The seasonal bias shows quite some spatial variation. As a result, modeled runoff across the basin may be either over or under estimated for a given set of parameters. The implication for overestimating the number of occurrences of rainfall is that the intensity of the input rainfall, however much in error, will be significantly underestimated most days. Given that the generating of peak discharge is largely driven by rainfall intensity, it is likely that the modeled flows (both volume and peak) will be underestimated for a given SRE input.

Estimation of accurate intensity and distribution of high resolution rainfall is still a challenging effort. Rainfall intensity can be captured through different ground and remote sources of observation, such as gauge, radar, and satellite. There is still no source of observation or a technique that can provide the realistic spatial distribution and true intensity of precipitation. In addition to observation error and instrument noise, traditional gauge observations typically have limited spatial coverage.

Reliable direct rainfall information can be obtained, only, from rain gauges but at point scale. Therefore, a more effective observing technique and source is required to cover regions where cannot be covered by rain gauges. Satellites from remote sources are the only observation sources, capable of providing unique information about spatial distribution and intensity of precipitation from regions where are inaccessible by rain gauge techniques. SRE is indirect rainfall retrieval from visible, Infrared (IR), and/or Microwave (MW) based information of cloud properties, with larger uncertainties. Merging multi-sources products is a challenge effort for reducing some of the uncertainties and limitations associated with each source of data.

1.2 Rational and objective of the consultancy

By far the largest source of error in the Mekong system is the inconsistency of accurate precipitation inputs. These errors can accumulate over a season and lead to modeled basin conditions that drift from reality. Previous MRC consultants (Malone, 2009; Smith 2009) recommend the RFMMC should investigates methods to use observations from rain gauge measurements to adjust satellite rainfall estimates (SRE) prior to being input to the forecasting system. Implementing this recommendation would allow significant improvements in accuracy for the MRC Mekong flood forecasts.

Taking into account the required and expected performance of the new MRC Mekong FFS, this consultancy responds to these recommendations and a number of issues are investigated during this assignment:

- The scientific basis for adjusting the bias of NOAA SRE with rain gauge information available for the Mekong Basin, considering its unique properties;
- A proposed operational methodology/tool to implement rain gauge-based bias correction to NOAA SRE into the MRC Flood Forecast operations (by establishing a connection with the Mekong-FEWS);
- Implementation of rain gauge-based bias correction to NOAA SRE into the MRC Mekong FFS (Mekong-FEWS).

1.3 Expected outputs

The following outputs are produced during this assignment:

- A mission report outlining the scientific basis and algorithm for rain gauge-based bias adjustment for SRE in the Mekong River Basin by which the rain gauge-based bias adjustment to SRE is integrated into MRC flood forecasting operations; and

- A methodology/tool (algorithm) for rain gauge-based bias adjustment for SRE in the Mekong River Basin, which is linked to the Mekong-FEWS.
- A presentation during an Internal FMMP Management Meeting, in which the validity and importance of SRE bias adjustment is discussed, and preferably agreed upon.

1.4 Structure of the report

The mission report first describes the algorithm of the NOAA SRE in chapter 2. In chapter 3 an alternative source of satellite rainfall will be discussed that is provided by the Tropical Rainfall Monitoring Mission (TRMM). This is followed by an in-depth analysis of the quality of the SRE during the flood season 2008 and 2009 in chapter 4. In chapter 5 the bias corrections algorithm will be defined and discussed. Finally in chapter 6 conclusions and recommendations will be given based on the preceding analysis.

2 NOAA satellite rainfall estimates

The detection of the spatial-temporal patterns of rainfall with remote sensing technologies has been studied for a long time. There are essentially 4 different technologies available to estimate rainfall remotely:

- Cloud indexing
- Top cloud temperatures
- Microwave emissivity
- Radar reflectivity

There are four types of sensors that measure radiation in different parts of the electromagnetic spectrum (Figure 1) that are commonly used in satellite remote sensing of precipitation:

- Active radars (or microwave) (~cm) are used to determine vertical distribution of precipitation by measuring backscatter. Active radars send out a microwave signal and the backscatter is measured. The backscatter strength is proportional to the rain rates.
- Passive microwave measure emitted radiances from the land surface and atmosphere and these can be related to atmospheric water vapor or cloud liquid water
- Sensors in the visible part of the spectrum (0.4 - 0.7µm) can be used to distinguish clouds
- Sensors in thermal infrared part of the spectrum (10 - 12 µm) are used to determine cloud thermodynamic properties

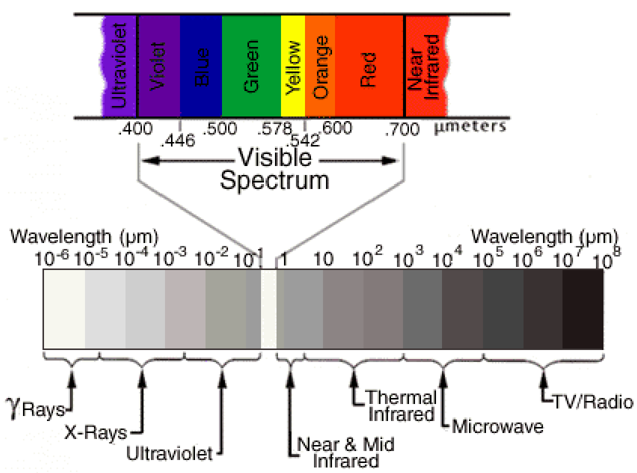

Figure 1 Overview of the electromagnetic spectrum

For the SRE the RFMMC uses the NOAA RFE2.0 algorithm for South-East Asia[1]. RFE 2.0 uses four types of input data, including three satellite sources, to create the satellite rainfall estimates.

Firstly half-hourly GOES Precipitation Index (GPI) rainfall amounts are derived from Meteosat IR cloud top temperatures and input into RFE 2.0. Empirical methods have determined that

[1] http://www.cpc.ncep.noaa.gov/products/fews/SASIA/

cloud top temperatures less than 235K in the tropics are generally expected to produce stratiform rainfall at the rate of 1.5mm/half hour according to the equation below (Arkin and Meisner, 1987). All daily IR segments are combined and total daily GPI rainfall is input into RFE 2.0.

$$GPI = \left(\frac{T < 235}{T}\right)\left(\frac{3mm}{hr}\right)(\# hrs)$$

Secondly satellite estimates are used from the Special Sensor Microwave/Imager (SSM /I), which is onboard of the Defense Meteorological Satellite Program polar satellites tracks. The instrument measures the brightness temperature increases due to the presence of liquid precipitation. Returned scattering patterns are compared against previously derived rainfall amounts, and instantaneous rain rates are determined. The NOAA SSM/I rainfall algorithm is described by (Ferraro et.al., 1995).

Thirdly AMSU-B data are input to RFE 2.0. AMSU-B rain rates are based on a scattering algorithm over land and an emission algorithm over ocean (Zhao et. al., 2000). The rain rate retrieval process used for AMSU-B is very similar to that used with the SSM/I instrument.

The three satellite products are then combined using the following equations

$$S = \sum_{i=1}^{3} W_i S_i$$

$$W_i = \frac{\sigma_i^{-2}}{\sum_{i-1}^{3} \sigma_i^{-2}}$$

Where S is the satellite estimate, W_i is a weighing factor, σ_i is the standard error. The standard error is determined by comparing the individual satellite estimates to the observed gauge data.

The final step of the process merges the satellite-estimated precipitation with GTS rain gauge data to remove as much bias as possible. For a complete explanation of this process reference is made to Xie and Arkin (1996).

The data are available daily at a spatial resolution of 0.1 degree.

3 TRMM rainfall estimates

Another option for operational SRE is the product provided by the Tropical Rainfall Monitoring Mission (TRMM)[1]. Combining visible, infrared, passive microwave and radar is likely the best spectral satellite-based rainfall monitoring system. TRMM consists of a closely knit combination of (i) a passive microwave radiometer TRMM Microwave Imager (TMI), (ii) a precipitation Radar (PR) and (iii) A visible/infrared (VIS/TIR) radiometer. More details on the TRMM sensor specification can be found in Kummerow et al. (1998).

The TRMM satellite is unique as it is the only space born sensor that has active radar. Radar measurements of rainfall are based on the Rayleigh scattering caused by the interaction of rain and the radar signal. Space borne radar measurement of rain intensity is possible with the Precipitation Radar aboard TRMM.

There is a wide variety of TRMM based rainfall products available using different sensor combinations and with different temporal and spatial resolutions. Details of the available data products are provided by Huffman et al. (2007). Using this dataset and a global hydrological model there is an online global flood risk system available[2].

For operational flood forecasts the so called 3B42RT product can be used. This is a three-hourly product at 0.25° resolution available approximately 7 hours after acquisition time. The background and file format of this product is described in:

ftp://trmmopen.gsfc.nasa.gov/pub/merged/3B4XRT_doc.pdf

The data can be downloaded from

ftp://trmmopen.gsfc.nasa.gov/pub/merged/mergeIRMicro/

Historical data from 2008 and 2009 are also provided.

It is highly recommended to assess the potential of TRMM 3B42RT for used in the FEWS-URBS-ISIS modeling system as the algorithm is more advanced because it includes radar; the data are available at higher temporal resolution (3 hours) and are provided 7 hours after acquisition time.

To test this approach a dataset for 2009 with daily (accumulated from the 3-hourly data) TRMM data has been provided to the MRC-RFMMC. Only NOAA SRE data have been used in the bias correction.

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[1] http://trmm.gsfc.nasa.gov/

[2] http://trmm.gsfc.nasa.gov/publications_dir/potential_flood_hydro.html

4 Evaluation of the NOAA-SRE during the flood season in 2008 and 2009

The SRE were compared with rainfall observations (hereafter referred to as OBS) provided by the MRC line agencies through a SMS system. Two different periods were compared:

- 1 April to 31 October 2008
- 14 June 2009 to 31 December 2009

For all analysis only data are used for which rainfall was reported. A first analysis of the OBS showed that there are in principle 143 station that report rainfall (Figure 2). The data show a number of inconsistencies. The most important issue is the fact that several line agencies report No Data when no rainfall occurs. There is however a big difference between no rainfall and No Data and this has a large effect on the bias correction algorithm.

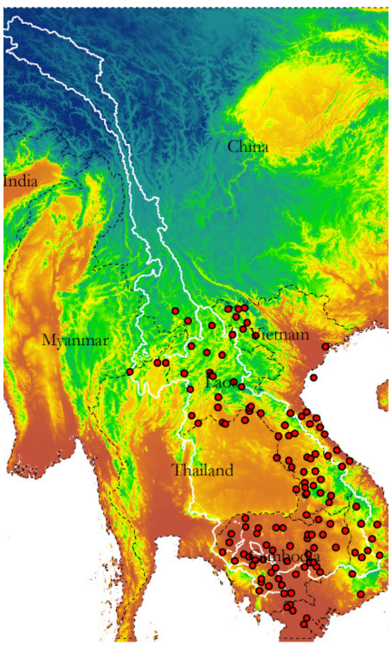


Figure 2 Overview Mekong basin and rainfall stations

In addition the number of stations that report on a daily basis is highly variable in time as is shown in Figure 3. In 2009 the number reporting stations is significantly higher and most stations do not report outside the flood seasons. For other applications (drought monitoring) and continuity it is advisable to strive towards the highest possible amount of reporting station throughout the year.

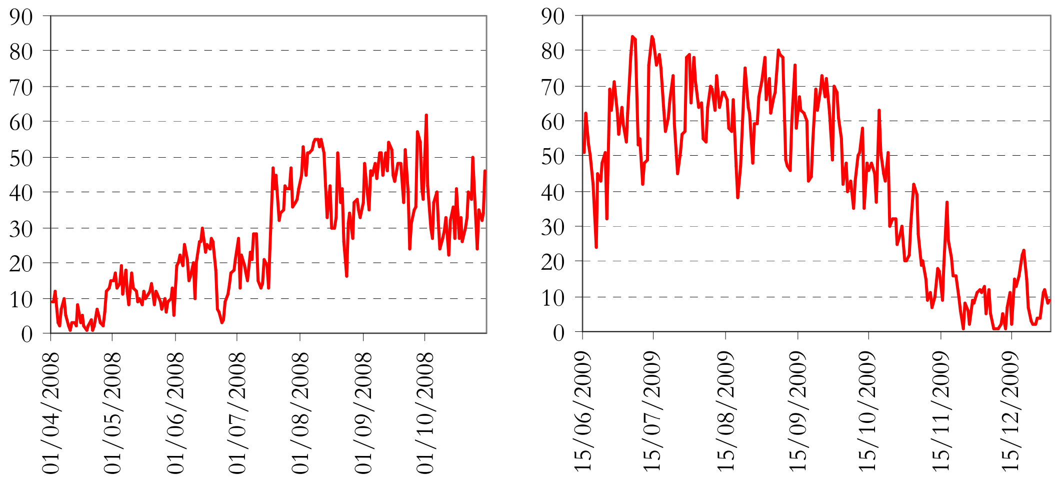


Figure 3 Number reporting stations in 2008 and 2009

Figure 2 also shows that for the northern part of the basin in China no OBS data is available. There are however stations in this region that are part of WMO-GTS system that are publicly available. It would be recommendable to include the WMO-GTS stations in the operational system.

The potential of SRE to detect rainfall was first assessed using contingency tables (Table 1). Only the occurrence of rainfall is analyzed and not the magnitude of rainfall. The frequency of OBS and SRE is recorded for all stations and number of statistics was derived as shown in the table.

- Hits: the event was estimated occur and did occur
- False Alarm: the event was estimated to occur but did not occur
- Misses: the event was not estimate to occur but did occur
- Null: the vent was not estimated to occur and did not occur

The data for 2008 and 2009 are given in Table 2 and Table 3 .

Table 1 Contingency table

		Observed values gauge data		Total
		Yes	No	
Estimated values SRE	Yes	*Hit*	*False Alarm*	*Total*
	No	*Misses*	*Null*	*Total*
Total		*Total*	*Total*	

Table 2 Contingency table for 2008

		Observed values gauge data		Total
		Yes	No	
Estimated values SRE	Yes	*4483*	*328*	*4811*
	No	*664*	*187*	*851*
Total		*5147*	*515*	*5662*

Table 3 Contingency table for 2009

		Observed values gauge data		Total
		Yes	No	
Estimated values SRE	Yes	*4920*	*1369*	*6271*
	No	*1773*	*716*	*2489*
Total		*6675*	*2085*	*8760*

Based on these data a number of different indicators can be determined. The accuracy provides the fraction of estimated values that are correct (*Hits + Null / Total*). In 2008 the accuracy was 0.82 and 2009 0.64. A second measure is the bias score that determines the ratio of the frequency of the estimate events to the frequency of observed events (*Hits + False / Hits + Misses*). In the 2008 the bias score was 0.83 and in 2009 the bias score was 0.94. From this analysis it can be concluded that the SRE captures rainfall with reasonable accuracy and that there is a slight underestimation of the occurrence of rainfall.

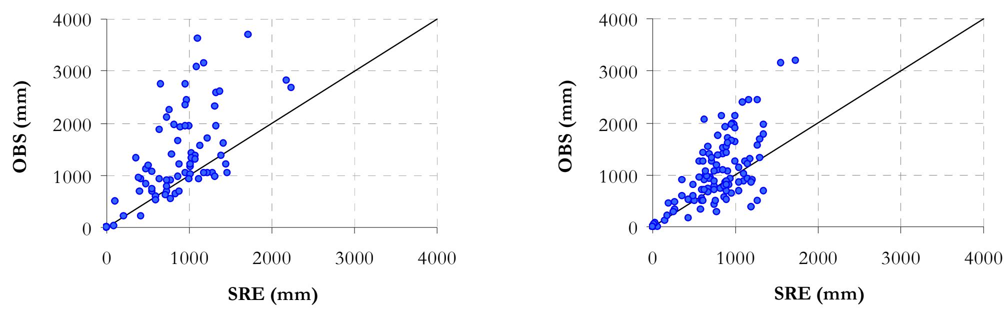


Figure 4 Precipitation sum for all reporting stations for 2008 (left) and for 2009 (right) (only for days when observations are reported). Each dot represents a station.

Figure 4 shows that the correlation between the OBS and SRE for total precipitation for the two years. There is a clear positive correlation (r = 0.84 in 2008 and r = 0.79 in 2009). Hence the spatial patterns provided by the SRE are reliable. However, if the daily rainfall amounts are plotted for a single station the performance is logically decreases (Figure 5, Figure 6)

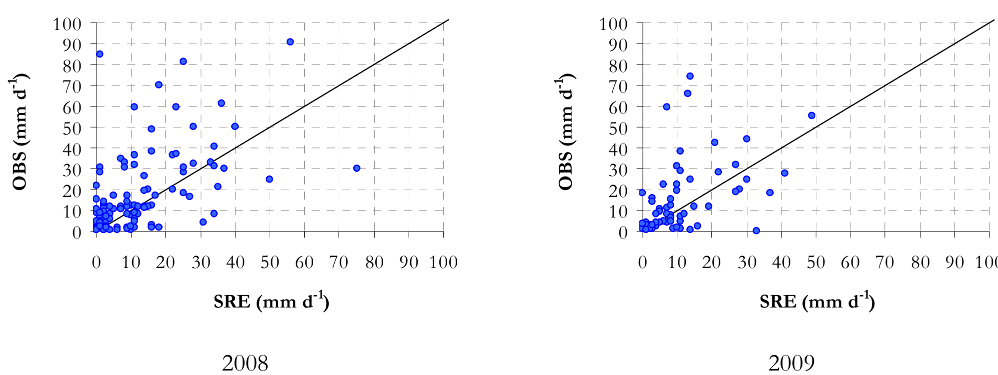


Figure 5 Precipitation sum for Vientiane in 2008 and 2009 (only for days when observations are reported).

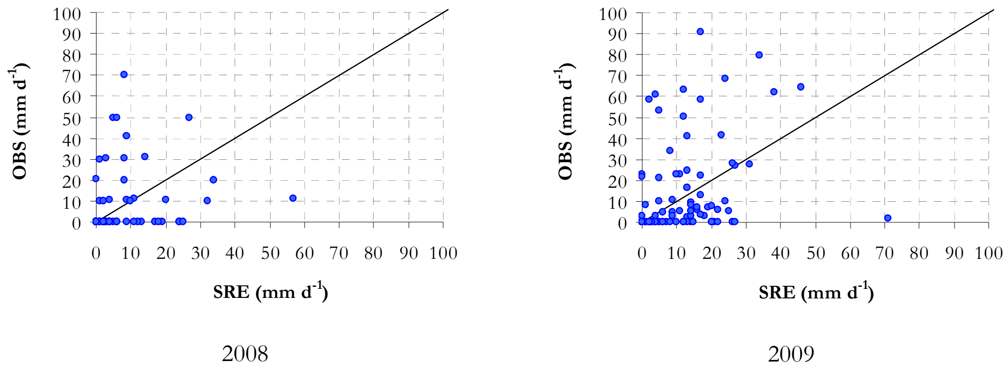


Figure 6 Precipitation sum for Sadan in 2008 and 2009 (only for days when observations are reported).

The figures also show that extreme rainfall events are generally missed by the SRE that there is a consistent underestimation by the SRE. On average considering all station data available the underestimation is 33%. Some care is warranted with this conclusion as there are many stations that do not report if no rain occurs. These stations are ignored in the analysis and therefore the underestimation may be less in reality. A quick test revealed that when the No Data values are changed into 0 the average underestimation is reduced to about 10%.

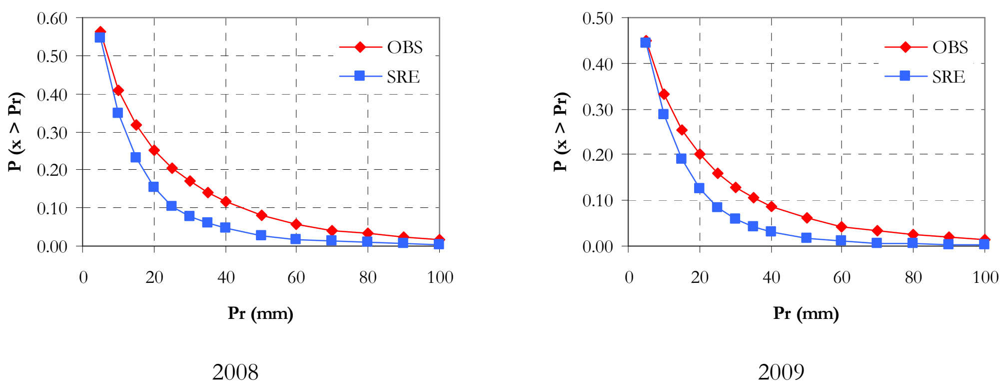


Figure 7 Probability of extreme precipitation for all reporting stations for 2008 and 2009 (only for days when observations are reported)

Figure 7 shows an analysis of the occurrence extreme precipitation for both 2008 and 2009. On the y-axis the chance on a precipitation exceeding a certain amount is shown. The figure clear shows that SRE consistently underestimates extreme precipitation. A plausible explanation is the fact that the SRE depends on the cloud temperature. This method is suited for stratiform precipitation, but is much less reliable for detecting convective precipitation.

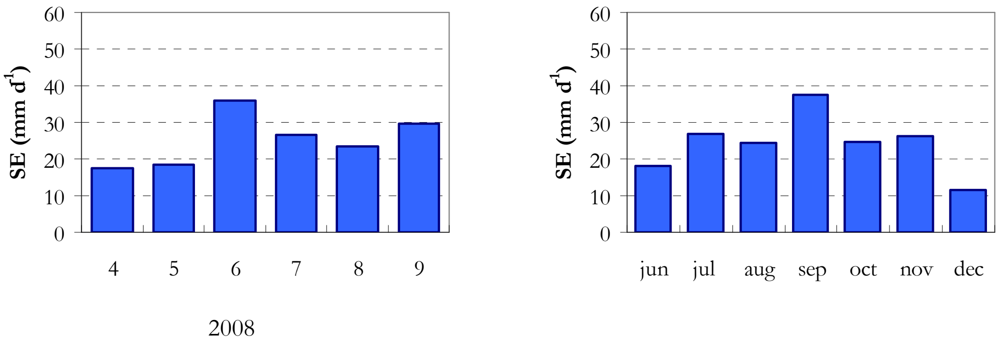


Figure 8 Average monthly standard error in 2008 and 2009 (only for days when observations are reported)

Figure 8 shows the monthly variation in standard error for both years. The standard error generally varies around 20 mm d^{-1}, which is significant. There are variations between months but no clear patterns are detected. It is also interesting to map the standard errors per station (Figure 9).

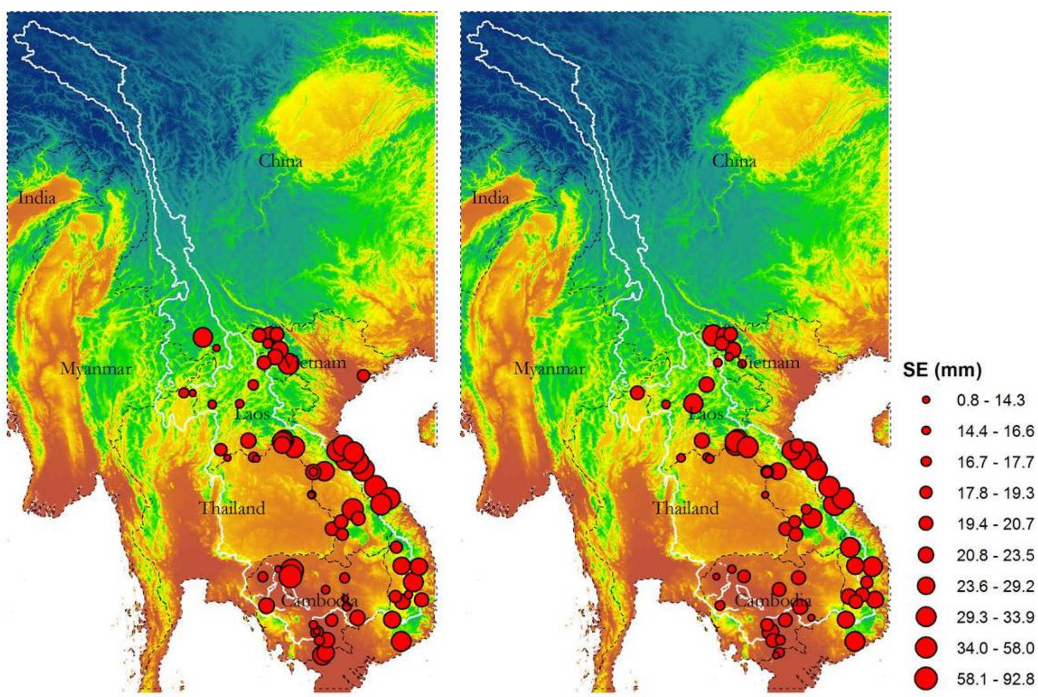


Figure 9 Spatial patterns in standard error

The maps show that there is considerable variation among the stations. If we assume that error in SRE is random then a persistent low or high standard error in both years is an indication of the reliability of the station data.

5 Proposed bias correction algorithm

The bias correction algorithm to needs to fulfill the following criteria:

- The number of reporting stations varies daily and the algorithm needs to cope with this
- The absolute values observed at these stations must be represented in the corrected SRE
- The spatial distribution of the uncorrected SRE needs to be represented in corrected SRE
- For flooding the correct representation of extreme precipitation is extremely important
- The output of the tool needs to be compatible with FEWS

Four different bias correction algorithms were considered. Firstly the mean bias correction was assessed. This method has for example been used by Seo and Briedenbach (1999). This is a straightforward correction methodology that determines the average bias for all stations on a specific day and this mean bias is subsequently used to correct the SRE. Since the bias in the Mekong basin is spatially highly heterogeneous it is deemed unsuitable.

The second approach is the use of a regression equation. Several studies have used this approach successfully to correct monthly TRMM based estimates (Immerzeel, 2009; Cheema and Bastiaanssen, 2010). With this method a regression equation is derived for each station using a historical time series. The coefficients of the regression equation are then spatially interpolated and used to spatially correct the SRE. A prerequisite for this approach is good agreement between OBS and SRE at station level, which is not the case and therefore this approach is also not suitable.

Two other approaches which are likely to yield better results are described in more detail.

5.1 Distribution transformation

This approach has been developed for the statistical downscaling climate model data (Bouwer, 2004). The method determines the statistical distribution of all station data on a particular day and of all SRE data at the same stations. The SRE distribution is then translated to the OBS distribution. Both the difference in mean value and the difference in variation are corrected. First the correction factor for the mean is determined using the following equation

$$\mu_f = \frac{\mu_{OBS}}{\mu_{SRE}}$$

Where μ_f is the correction factor for the mean, μ_{obs} is the average value of OBS for all reporting stations and μ_{SRE} is average SRE for all reporting stations. Secondly the correction factor for the variation is determined by the quotient of the standard deviations.

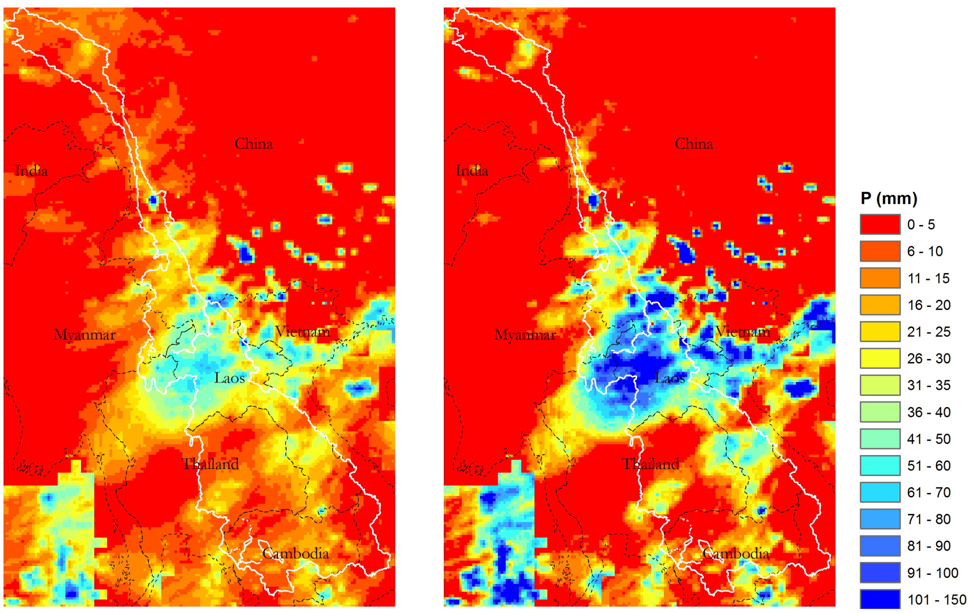
$$\tau_f = \frac{\tau_{OBS}}{\tau_{SRE}}$$

Once the correction factors are knwon they are used to correct all pixels in SRE image using the following equation.

$$SRE_c = (SRE_o - \mu_{SRE}) \cdot \tau_f + \mu_{SRE} \cdot \mu_f$$

Where SRE_c is the corrected SRE and SRE_0 is the uncorrected SRE. If the number of stations available on a particular day is below a user specified threshold then a default correction factor (μ_{fd}) is applied according to the following equation

$$SRE_{cor} = SRE_o \cdot \mu_{fd}$$



Uncorrected Corrected

Figure 10 Example of 5 July 2009. The left map shows the uncorrected SRE and the right map shows the corrected SRE for the entire basin using the distribution approach.

Figure 10 shows an example of the effects of the bias correction on the SRE image of 5 July 2009. In this particular case the μ_f equaled 1.44 and the σ_f equaled 1.67. The images also show that spatial pattern of the uncorrected SRE does not change, but only the magnitude is adapted. Therefore if there are short-term convective rainfall events measured at a particular station, which are not well observed by the SRE, this will still be the case in the corrected product. The distributions are matched but no spatial changes occur. This point is further clarified in Figure 11 where the observed rainfall is interpolated. There is an obvious rain system located over Cambodia but this is not visible in the corrected SRE.

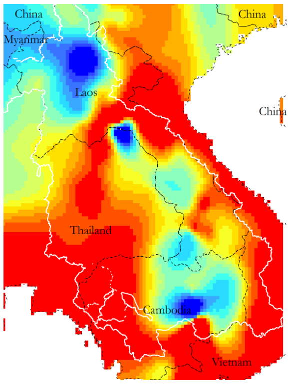
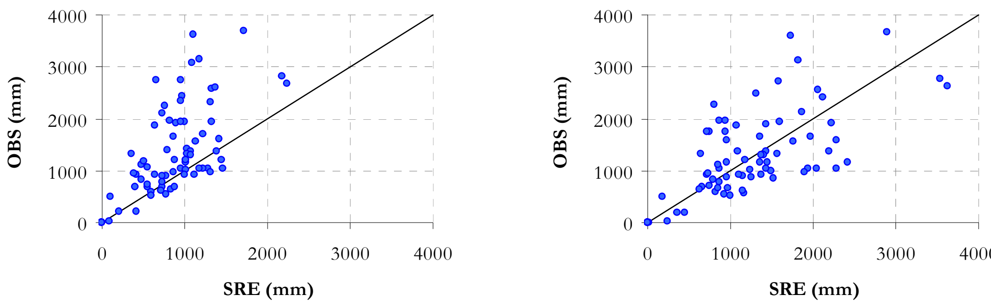


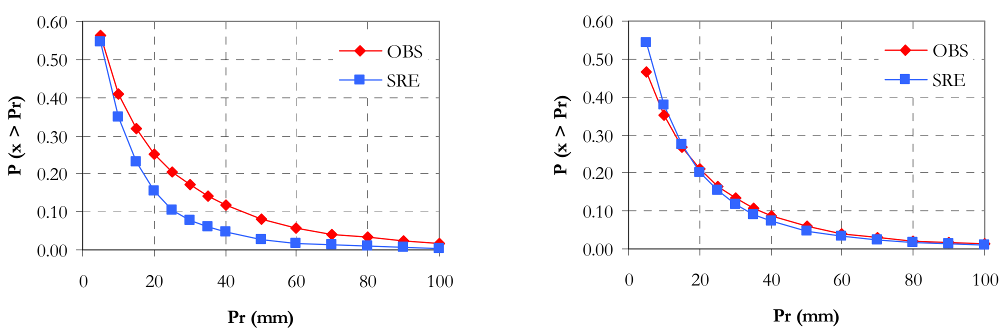
Figure 11 Spatial patterns in observed rainfall on 15 July 2009

Figure 12 shows the improvement in the relation between OBS and SRE for the uncorrected and corrected SRE for the total precipitation sum in 2008. The graph shows a clear improvement and the large negative bias has disappeared. The analysis of the probability of extreme precipitation also shows a very clear improvement and the extreme precipitation is captured well by the corrected SRE.



uncorrected corrected

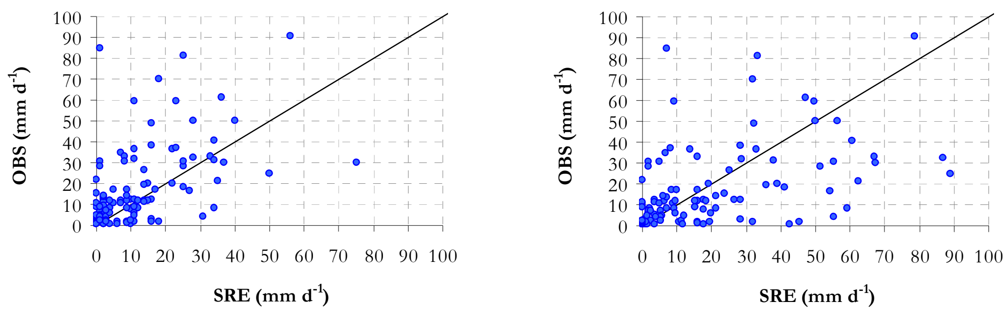
Figure 12 Total precipitation sum for 2008 for the uncorrected and corrected SRE (distribution method)



uncorrected corrected

Figure 13 Probability of extreme precipitation for 2008 for the uncorrected and corrected SRE (distribution method).

Inherent to methodology is that the spatial pattern of the SRE does not change and therefore the correlation for a specific station for daily precipitation does not necessarily improve. This is clearly visible in Figure 14 where the daily scatter plots are shown for Vientiane in 2008.



uncorrected corrected

Figure 14 Daily regression of 2008 rainfall in Vientiane for the uncorrected and corrected SRE (distribution method)

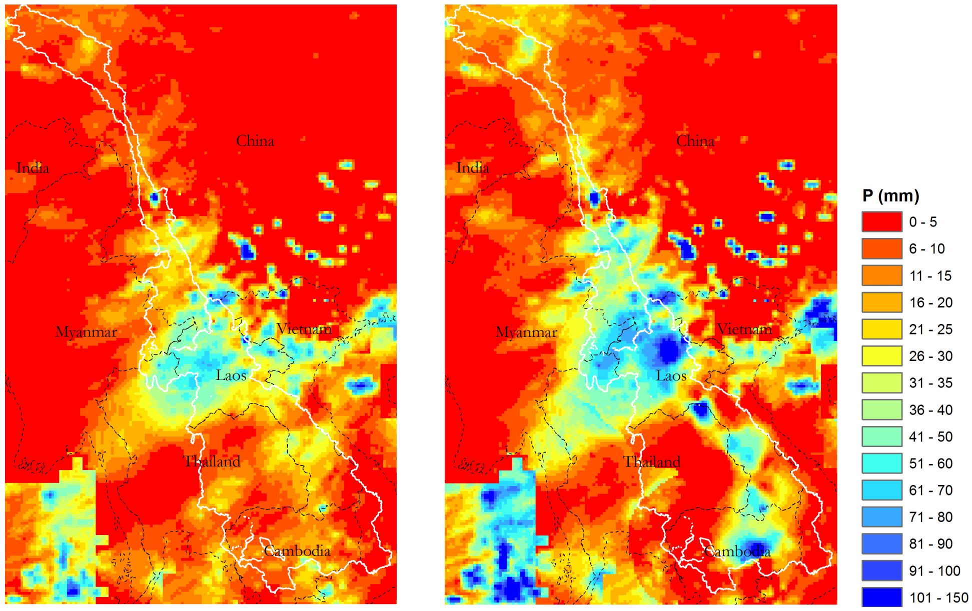
5.2 Spatial bias

The second approach that has been evaluated is the spatial bias method. Applications of this approach are provided by Cheema and Bastiaanssen (2010), Seo and Briedenbach (2002) and Hunink et al. (2009). The approach entails the following steps:

- At all stations the magnitude (mm) of the local bias is calculated for each day. Similar to the distribution approach only stations are included where data are reported.
- The daily bias at each station is then spatially interpolated using a spline interpolator. The spline method is an interpolation method that estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes exactly through the input points. There are two different options in using a spline interpolator: the tension and regularized approach. The tension approach is used in this application as it results in a smoother surface. An important parameter in using the tension option is the weight. The higher the weight the coarser the resulting surface. The weight can be specified by the user and is by default set to 1000.
- As a final step the interpolated bias is added to uncorrected SRE.

The user can impose two different thresholds while using this approach. Similar to the distribution approach the user may specify a minimum number if stations that needs to be reporting on a specific day. If this condition is not met the default bias correction will be applied. Because the magnitude of the bias is interpolated areas which are very far away from a reporting station are assigned an unrealistic bias. To overcome this problem the use can specify a maximum distance until where the influence of the nearest stations reaches. Currently this is set to 2 degrees (~ 200 km).

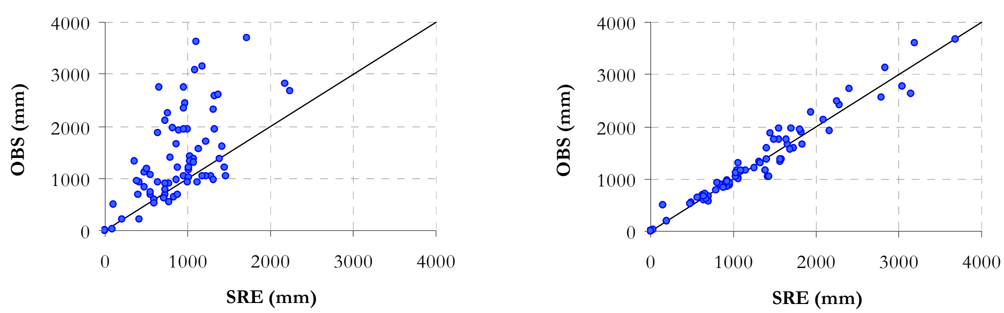
Figure 15 shows the results of this method for 15 July 2009. It shows that the result is a hybrid of the spatial pattern of the uncorrected SRE and the interpolated station data (Figure 11). The rain system over Cambodia is for example now clearly visible in the corrected SRE.



Uncorrected

Figure 15 Example of 5 July 2009. The left map shows the uncorrected SRE and the right map shows the corrected SRE for the entire basin using the spatial bias method.

Figure 16 shows the total precipitation sums for 2008. The right graph shows an excellent match between the OBS and the corrected SRE. When the daily values are plotted at Vientiane it is clear that the majority of points are now on the 1:1 line. There are a number of outliers and these points correspond to days when the criterion of the minimum number of reporting stations is not met. The final test is the assessment of the probability on extreme precipitation (Figure 18), which shows excellent agreement between observed and corrected SRE.



uncorrected corrected

Figure 16 Total precipitation sum for 2008 for the uncorrected and corrected SRE (spatial bias method)

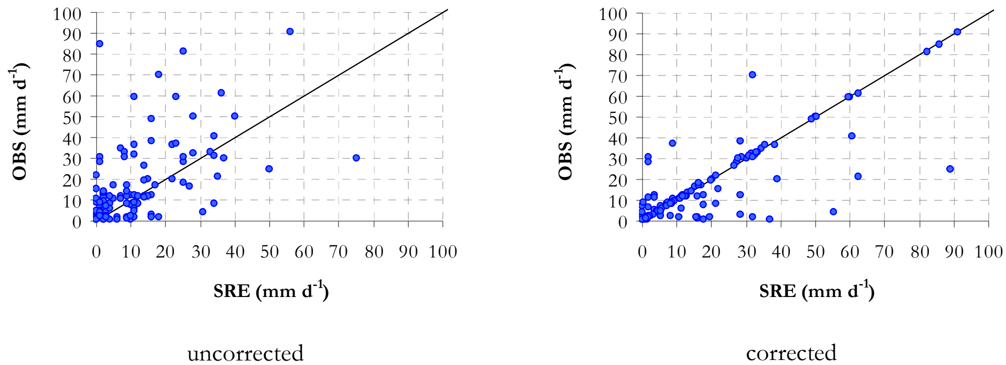


Figure 17 Daily regression of 2008 rainfall in Vientiane for the uncorrected and corrected SRE (spatial bias method)

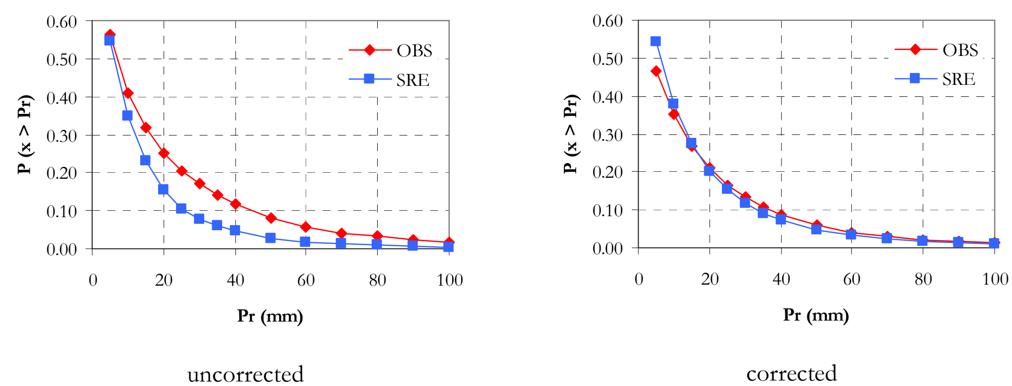


Figure 18 Probability of extreme precipitation for 2008 for the uncorrected and corrected SRE (spatial bias method).

5.3 Effects on simulated water levels

For both periods in 2008 and 2009 the corrected SRE were used as input in the FEWS-URBS-ISIS model to make a preliminary assessment of the effects of the changes in precipitation on the simulated water levels. The results showed a mixed response. In the upstream part of the basin the simulated water levels generally increased significantly and were higher than the observed water levels. This is logical as the rainfall has increased by about 30%. When the model is run with uncorrected SRE, which we assume to be too low, the match between observed and simulated water levels was better. The only explanation is that the calibration of the rainfall runoff processes need to be evaluated, specifically in the upstream part of the basin. Particular attention should be paid to the partitioning of rainfall in actual evapotranspiration and runoff and how this affects the unit hydrographs that are used in each sub-basin. In the lower parts of the basins show a mixed response; clear improvements in model performance for certain stations and an overestimation in others. Before a full analysis of the effects on the models results can be performed it is required to first ensure that reported rainfall at the stations is as accurate as possible. In particular the earlier mentioned issue with the stations reporting no rainfall as no data will have a large effect and the increase in precipitation will be less than 30%.

5.4 Implementation of the bias correction algorithms

Both algorithms have been programmed in ArcView GIS 3.x. This software is very accessible and used by most employees of the MRC RFMMC. The procedure has been fully automated and when the station precipitation data arrive the SRE is corrected for both approaches by a single mouse click. The results of the tool are in ArcGIS ASCII raster format, which can be directly read by the FEWS-URBS-ISIS system. The users have full access to the source code and a small workshop was organized to train everyone on the use of the tool and configure it correctly.

6 Conclusions and recommendations

There are two operational products available that provide rainfall estimates at daily or sub-daily time steps. Firstly, the NOAA RFE2.0 algorithm which merges thermal infrared, passive microwave and gauge data to provide daily estimates at a 10 km spatial resolution. Secondly the TRMM 3B42RT product which combines active radar, visible and infrared and passive microwave to generate 3 hourly precipitation estimates at a 25 km spatial resolution. As the TRMM algorithm also includes an active radar system it is more advanced.

Recommendation 1:
The MRC RFMMC should evaluate the quality and use of the TRMM3B42RT product in the Mekong basin as an alternative or back-up for the currently used NOAA rainfall estimates.

There are some inconsistencies in the reported rainfall by the different line agencies:

- The number of stations that report daily varies and the number is the highest during the flood season.
- There are some cases where extremely high rainfall is observed.
- There are some stations that report *zero rainfall* as *No Data*. These stations are ignored in the analysis and this leads to a significant overestimation of the bias.
- There are no reporting stations in the Chinese part of the basin and this reduces the quality of the bias correction algorithm. In the south-western part of the basin the station density is also low.

Recommendation 2:
Solving the problem with line agencies reporting zero rainfall as No Data should have the highest priority. If this cannot directly be solved it is recommended to use expert knowledge and replace No Data values with 0 for these stations where this expected to occur.

Recommendation 3:
When the station data are reported it is recommended to quality check the data on unrealistic values using a number of simple decision rules that put for example a threshold on the maximum daily precipitation or difference in precipitation between two nearby stations.

Recommendation 4:
It is recommended to integrate the WMO GTS stations with the operational SMS system. This would further improve the station coverage in the Northern part of the basin.

Recommendation 5:
It would be advisable to discuss with the line agencies to report data throughout the year so the data base can also be used for low flow and drought studies.

The analysis shows that the SRE underestimates observed rainfall by 33% on average. Some care is warranted with this conclusion as the percentage will be lower when all stations report zero rainfall instead of No Data. The extreme rainfall in particular is underestimated significantly by the SRE. This is inherent to the SRE algorithm which depends largely on the principle of cold cloud duration, which is more suitable for stratiform precipitation rather than convective precipitation. Both bias correction methods provide an appropriate means to correct the SRE data and this will eventually improve the flood forecasting performance of the FEWS-URBS-ISIS model. The spatial bias method is most promising as it provides a combination of the spatial pattern given by the stations and the SRE.

Recommendation 6:
It is recommended to use the spatial bias correction algorithm the correct the NOAA SRE and it is advisable to further fine tune the default bias correction factors after paying attention to the recommendation concerning the reported rainfall.

Recommendation 7:
While analyzing and correcting SRE data it is very important to consider the difference in date between the OBS and SRE. The OBS data are reported at 7 AM daily and correspond to the 24 hours preceding that time. Therefore the SRE data of the preceding day have to be used.

The preliminary FEWS-URBS-ISIS results show a mixed response in both the Mekong and the tributaries. This conclusion is based on the 2008 and 2009 analysis given the current dataset with reported rainfall. In the upstream part water levels are mainly overestimated, while further downstream some improvements are observed in simulated water levels. As the rainfall input is changing considerably some of the assumptions underlying the calibration of the rainfall runoff model need to be revisited. In particular the changed partitioning of rainfall into actual evapotranspiration and runoff may affect the unit hydrographs currently used.

Recommendation 8:
After paying attention to the recommendation for the reported rainfall a historical time series with corrected SRE should be generated. Subsequently this corrected SRE time series should be analyzed and compared with the uncorrected SRE to fully understand where and how precipitation is changing. Once this is clear the corrected SRE should be used in a model simulation and its results can be used to indentify key areas where the calibration of rainfall runoff processes can be improved.

The performance of the flood forecasting system depends for a large part on the quality of the NWP future rainfall forecasts, which is also subject to considerable errors.

Recommendation 9:
For improving the forecast mode of the model a reanalysis of the NWP rainfall forecasts is recommended. Based on a historical analysis of relation between observed rainfall and forecasted rainfall at different lead times it may be possible to detect systematic deviation in time and space. Based on this analysis correction factors could be derived and applied to the new forecasts.

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