Bias correction of CMORPH satellite rainfall estimates in the Zambezi River Basin

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Outline

- The need for satellite rainfall estimates (SREs)
- Gauge based analyses
- Methods for bias correction
- Findings on bias correction
- Conclusions and implications on water resources management in the Zambezi Basin

Introduction

- Rainfall plays a central role in the livelihoods of people
- Obtaining reliable measurements of rainfall is a major challenge
  - low number of rain gauges, poor spatial distribution of the rain gauges
- Satellite-derived rainfall estimates (SREs) are timely & cost efficient
- SREs are an indirect rainfall retrieval from visible, Infrared (IR), and/or Microwave (MW) based information of cloud properties
  - Prone to large systematic and random errors (also known as bias).
- Errors exhibit a topographical, latitudinal, regional and seasonal dependency in terms of rainfall depth, occurrence and intensity
- Overwhelming evidence compelling us to perform **bias correction**

Choice of bias correction algorithms

- Depends on
  - desired level of accuracy, reliability & quantitative consistency of corrected product.
  - assumptions to represent spatial and temporal rainfall characteristics
  - application the bias corrected product is to be used for (Habib et al., 2014).

- Methods for bias correction developed in multi-sensor, radar-gauge approaches (Vernimmen et al., 2012), climate models (Lafon et al., 2013) and triggered applications in satellite remote sensing.
  - Mean bias correction (Seo et al., 1999)
  - histogram equalisation (Thiemig et al., 2013)
  - regression analysis (Cheema and Bastiaanssen, 2010;Yin et al., 2008)
  - PDF matching (Gudmundsson et al., 2012; Gutjahr and Heinemann, 2013).

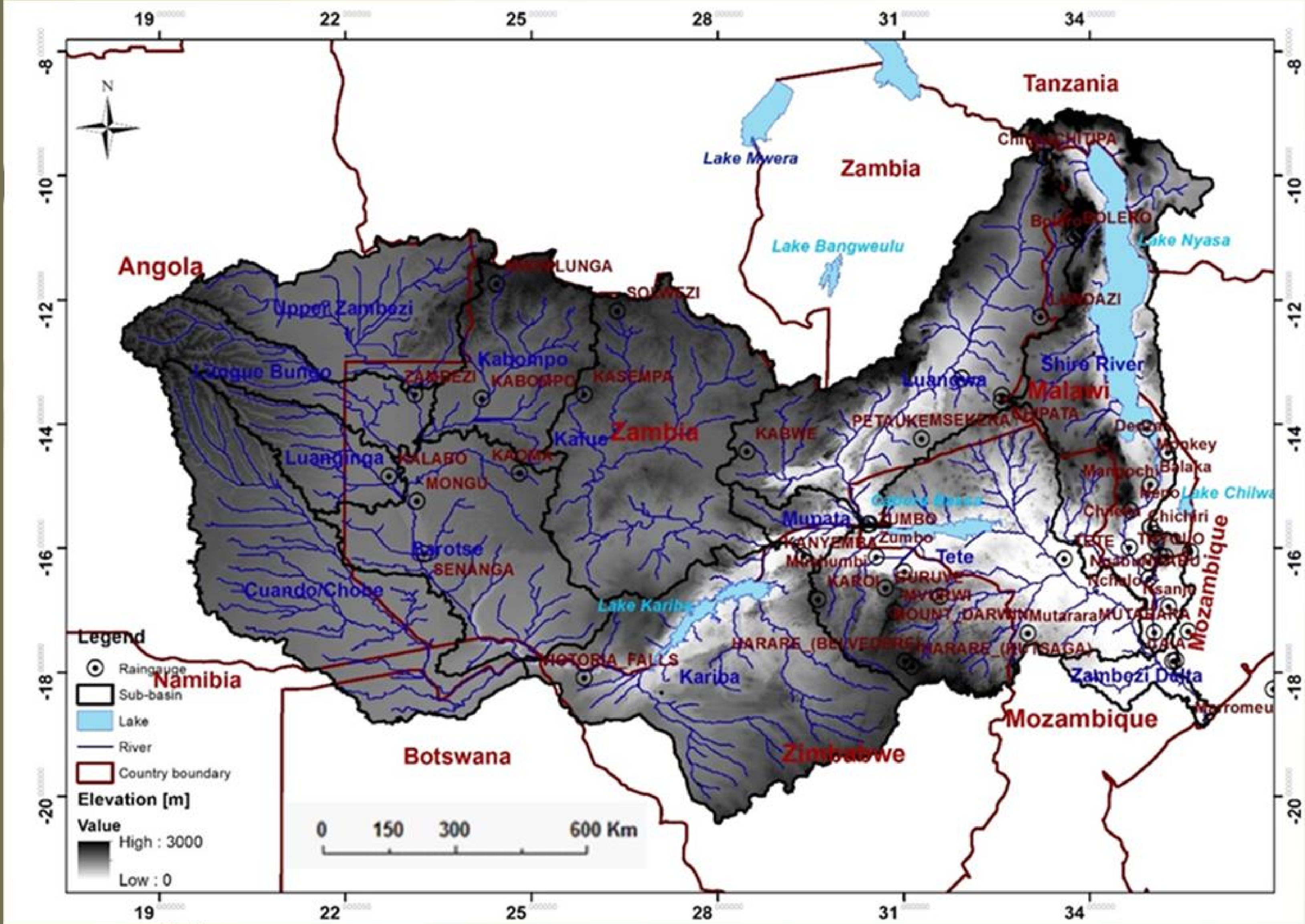
Review of bias correction algorithms

- Bias correction algorithms (e.g. empirical function & stochastic modelling, regression techniques) have background in climate models.
  - aim to adjust/correct errors in the magnitude of rainfall, but do not consider its temporal variability (Botter et al., 2007).
  - Reported distortion of frequency and intensity of rainfall (Botter et al., 2007).
  - For operation hydrology, the correct representation of daily precipitation and timing of rainfall frequency within the season is extremely important.

- Studies (e.g. Habib et al., 2014) recommend accounting for spatial patterns in bias
  - huge impact, particularly on volumetric estimation of rainfall

- Non-linear bias correction factors mitigates underestimation of SREs in dry months and overestimation during wet months

Why bias correction algorithms for Zambezi



- So far, bias correction algorithms focus on Europe, America & Australia
- No bias correction algorithm developed for Zambezi Basin
- Despite strategic importance of the basin in providing water to over 50 million people.

Objectives

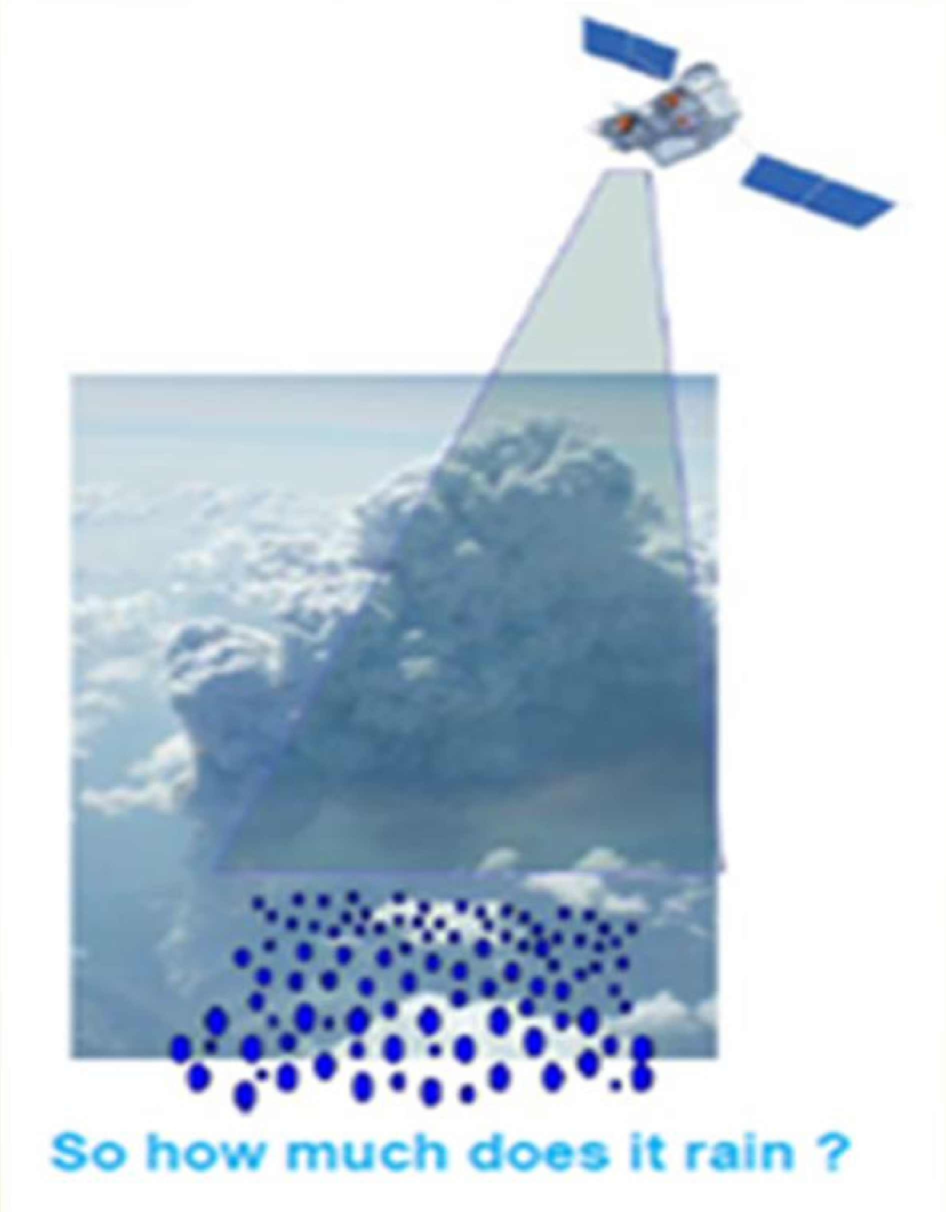
Main Objective

- To perform bias correction of CMORPH satellite rainfall estimates in the Zambezi River basin using 54 rain gauge stations for period1998- 2013.

Specific objectives

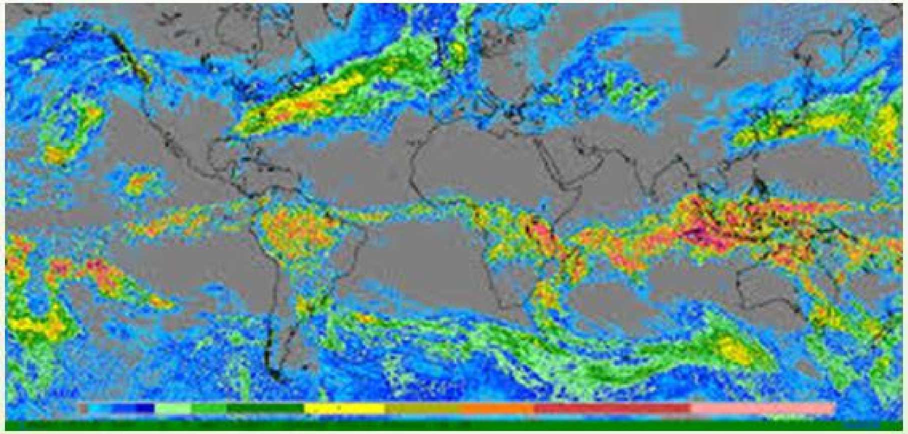
- 1) To perform quality control on gauge based estimates
- 2. to develop spatially varying linear and non-linear bias correction algorithms using gauge based estimates
- 3) to apply and compare the developed correction algorithms to CMORPH satellite rainfall.

Materials and Methodology

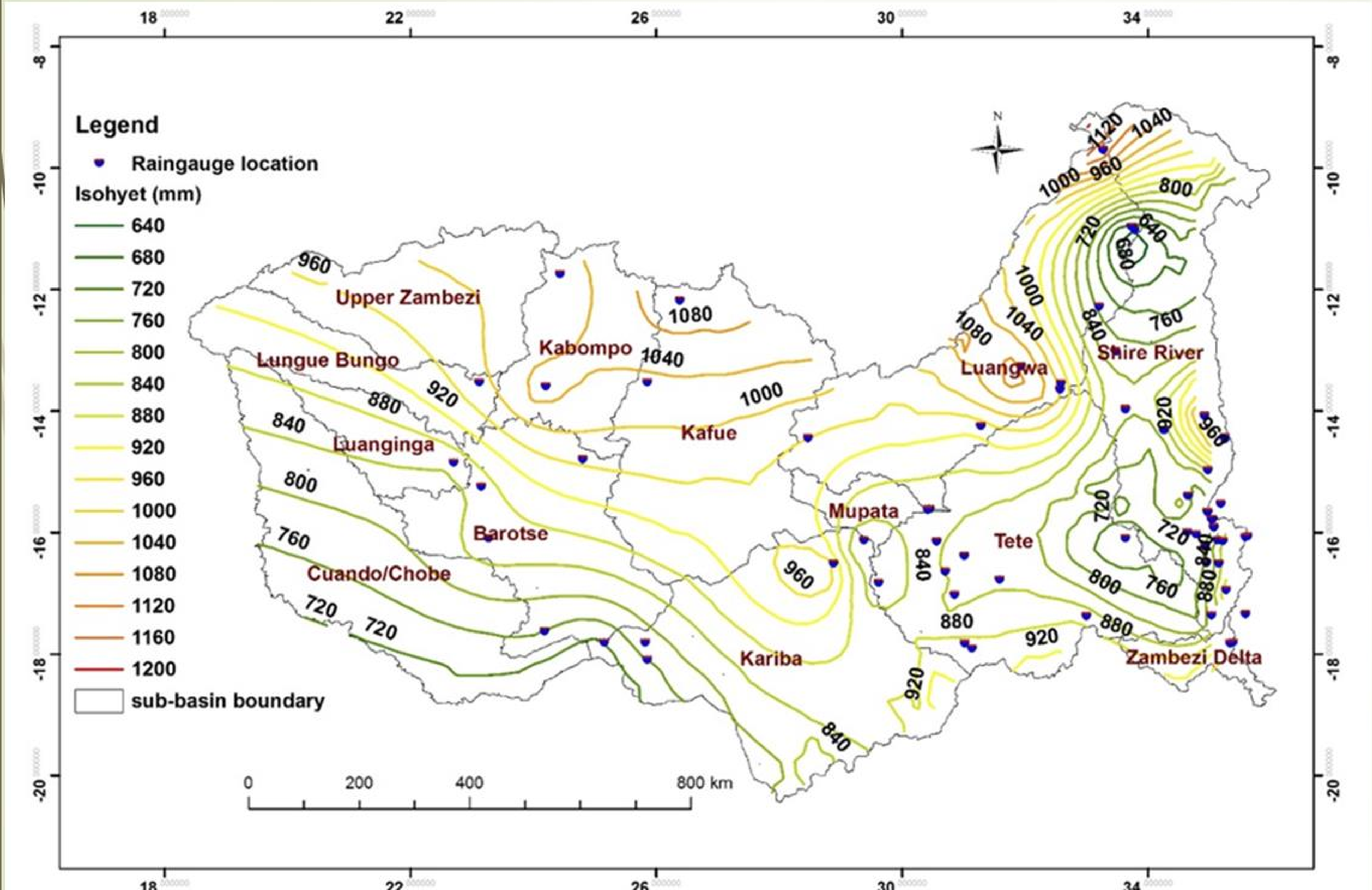


Satellite derived rainfall & extraction

- Daily CMORPH rainfall data was downloaded from the GeoNETCAST's ISOD toolbox
- CMORPH has near real time global coverage @ 8 km spatial res & 30 min temp res
- CMORPH uses motion vectors derived from half-hourly interval geostationary satellite IR imagery to propagate the relatively high quality precipitation estimates derived from passive microwave data (Joyce et al., 2004).
- CMORPH rainfall was extracted in a GIS environment for each of the 54 stations.



Gauge based Mean Annual Rainfall (MAR)



- ✓ Quality check on gauge estimates before bias correction

Gauge based analysis: topographic influences

- The Hierarchical cluster 'within-groups linkage' method used to classify the Zambezi basin into 3 regions based on elevation vs station correlation
- ASTER based 30m DEM was used to retrieve elevation values across the Zambezi domain
- Analyses using Taylor diagrams

Cluster	Elevation range	Cluster Membership
Cluster 1	< 250 m	Marromeu, Caia, Nsanje, Makhanga, Nchalo, Ngabu, Chikwawa, Tete (Chingodzi)
Cluster 2	250- 950 m	Chingodzi, Zumbo, Mushumbi, Kanyemba, Muzarabani, Monkey, Mangochi, Rukomechi Mutarara, Mfuwe, Mimosa, Balaka, Thyolo, Chileka, Neno
Cluster 3	> 1600 m	Mt Darwin, Chipata, Makoka, Livingstone, Senanga, Petauke, Msekekera, Kalabo, Mongu Kasungu, Victoria Falls, Bolero, Zambezi, Kabompo, Chichiri, Chitedze, Lundazi, Guruve Kaoma, Bvumbwe, Kasempa, Kabwe, Chitipa, Mwinilungu, Karoi, Solwezi, Harare (Belvedere), Harare (Kutsaga), Mvurwi, Dedza, Morrumbala

Bias correction methods

- Bias in CMORPH rainfall estimates was assessed and corrected using **5** algorithms.

1. Spatio-temporal bias correction (STB)

- Linear bias correction algorithm with origin in the correction of radar based precipitation estimates (Tesfagiorgis et al., 2011) & climate models.

- Bias is corrected at individual station and at daily time scale (i.e., space & time varying)

$$\mathrm{BF}_{\mathrm{STB}} = \frac{\sum_{t=d}^{t=d\text{-}l} S(i,t)}{\sum_{t=d}^{t=d\text{-}l} G(i,t)}$$

- The $\mathrm{BF}_{\mathrm{STB}}$ calculated for a certain day for min of 5 rainy days recorded within the preceding 7-day window with a min rainfall accumulation depth of 5 mm

- Advantages
  - simplicity & modest data requirements
  - it adjusts the daily mean of CMORPH at each station.

2. Elevation zone bias correction (EZB)

- New bias algorithm aimed at correction of satellite rainfall by understanding the topographic influences in the rainfall distribution and retrieval mechanism.
- The method spatially groups raingauge stations into 3 elevation zones (clusters)
- Assumption: Stations in the same elevation zone have the same error properties and are assigned their lumped bias correction factor (BF_{EZB})

$$BF_{EZB} = \frac{\sum_{t=d}^{t=d-l} \sum_{i=1}^{i=n} S(i,t)}{\sum_{t=d}^{t=d-l} \sum_{i=1}^{i=n} G(i,t)}$$

- Merits of this bias correction algorithm:
  - daily time variability is preserved up to a constant multiplicative factor
  - accounting for spatial heterogeneity in topography.

3. Power Transform Bias correction (PT)

- Nonlinear correction algorithm aimed at achieving closer fit (monthly CMORPH vs gauge)
- Origins in climate models, extended to runoff modelling & drought monitoring (Vernimmen et al., 2012).
- The bias corrected CMORPH rainfall (P*) is obtained using equation:

$$P^{*} = {}_{a}P^{b}$$

  - P=Raingauge monthly rainfall
  - a= prefactor such that the mean of the transformed CMORPH = mean of gauge values
  - b =factor determined iteratively such that for each station the CV of CMORPH matches gauge estimates
- Merits of bias algorithm
  - variability of the daily series is preserved
  - adjusts extreme precipitation values in CMORPH estimates

4. Distribution transformation (DT)

- Additive approach with background in statistical downscaling of climate data (Bouwer, 2004)
- Statistical distribution of all raingauge and CMORPH data on a particular day and same stations.
- Bias correction factor for the Mean and St dev $DT_\mu = \frac{G_\mu}{S_\mu}$ and $DT_\tau = \frac{G_\tau}{S_\tau}$
  - Where: $$S_{DT} = (S_o - S_u) DT_\tau + DT_\mu * S_\tau$$

S_{DT} = corrected CMORPH

S_o = uncorrected CMORPH

- Merit of bias algorithm
  - mean frequency of CMORPH above a certain threshold matches the gauge based mean frequency.

5. Probability Distribution Transformation Function Matching (PDF)

- PDF of CMORPH matched against daily gauge to define and remove the bias
- Collection of co-located pairs of gauge & CMORPH over grid boxes within a spatial window centering at the target grid box and a time period ending at target date
- Cross validation has been done for the PDF matching
  - Each time, gauge analysis at 10% randomly selected grid boxes is withdrawn
  - PDF bias correction performed using gauge data over the remaining 90% grid boxes
- Merits of bias correction algorithm
  - corrects errors in rainfall depth
  - important for long term water resources assessments

Performance evaluation of CMORPH rainfall types

$$Bias = \frac{\Sigma(P_{satellite} - P_{rain\ gauge})}{N}$$

$$Rbias = \frac{\Sigma(P_{satellite} - P_{rain\ gauge})}{\Sigma P_{rain\ gauge}}$$

$$RMSE = \sqrt{\frac{(P_{satellite} - P_{rain\ gau\ ge})^2}{N}}$$

$$CC = \frac{\Sigma(P_{raingauge} - \bar{P}_{raingauge})(P_{satellite} - \bar{P}_{satellite})}{\sqrt{\Sigma(P_{raingauge} - \bar{P}_{raingauge})^2}\sqrt{\Sigma(P_{satellite} - \bar{P}_{satellite})^2}}$$

where:

$P_{satellite}$ = rainfall estimates by satellite (mm/day)

$\bar{P}_{satellite}$ = mean values of the satellite rainfall estimates

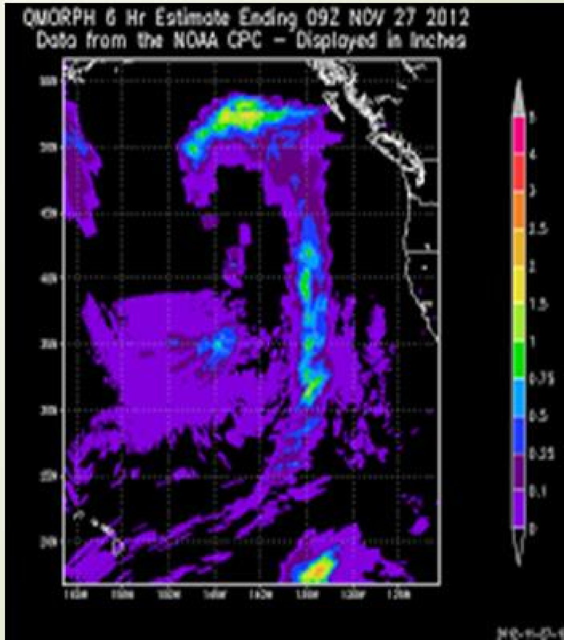
$P_{rain\ gauge}$ = rainfall recorded by rain gauge (mm/day)

$\bar{P}_{raingauge}$ = mean values of the rain gauge observations

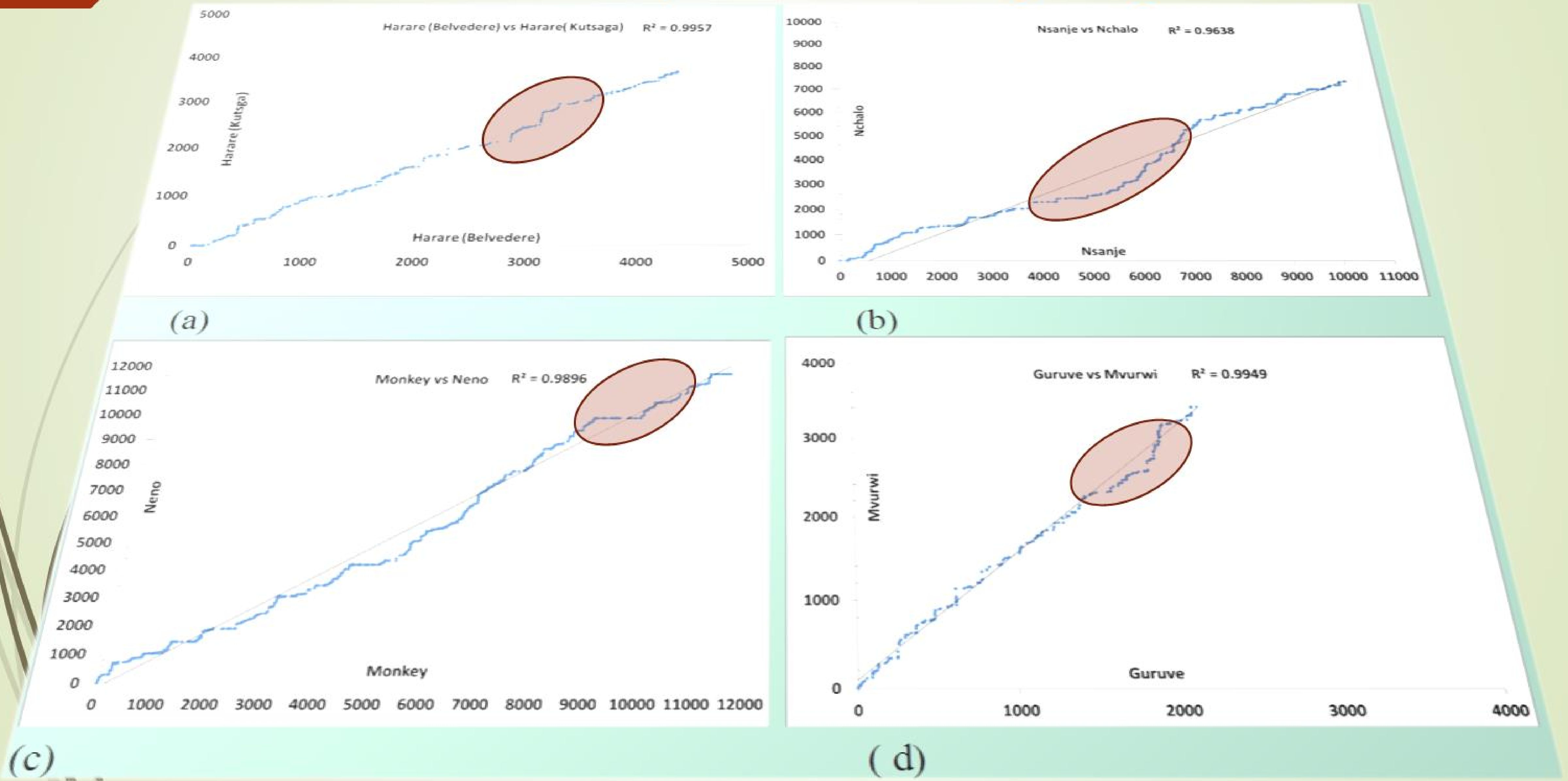
N = sample size (days).

Visual comparison were also done using Double Mass Curves and Taylor Diagrams (Taylor, 2001)

Results  Discussion

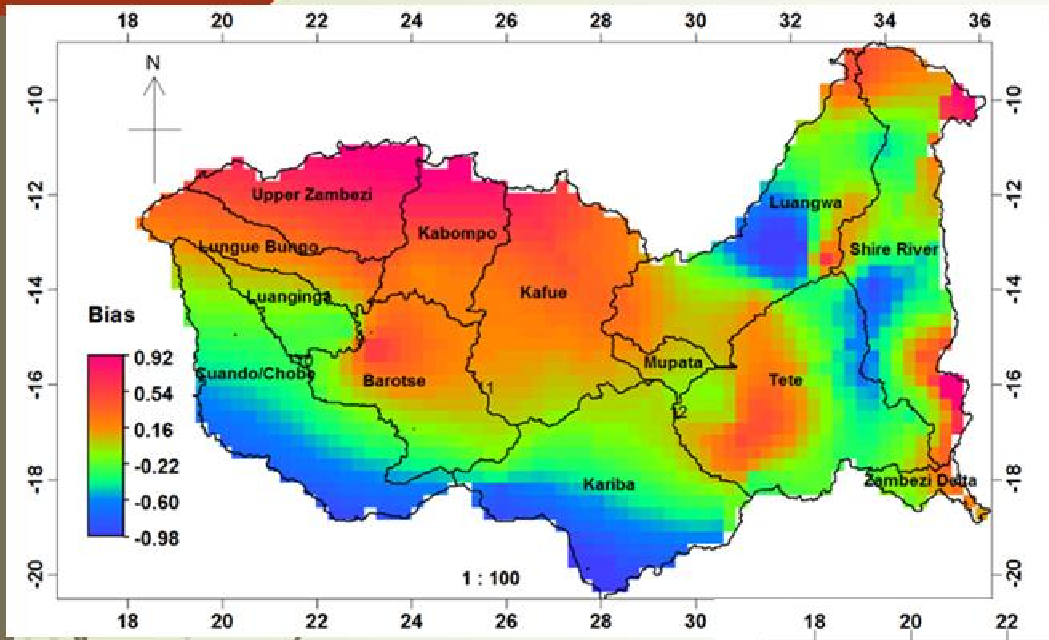


Quality check using double-mass curves for selected suspicious raingauges

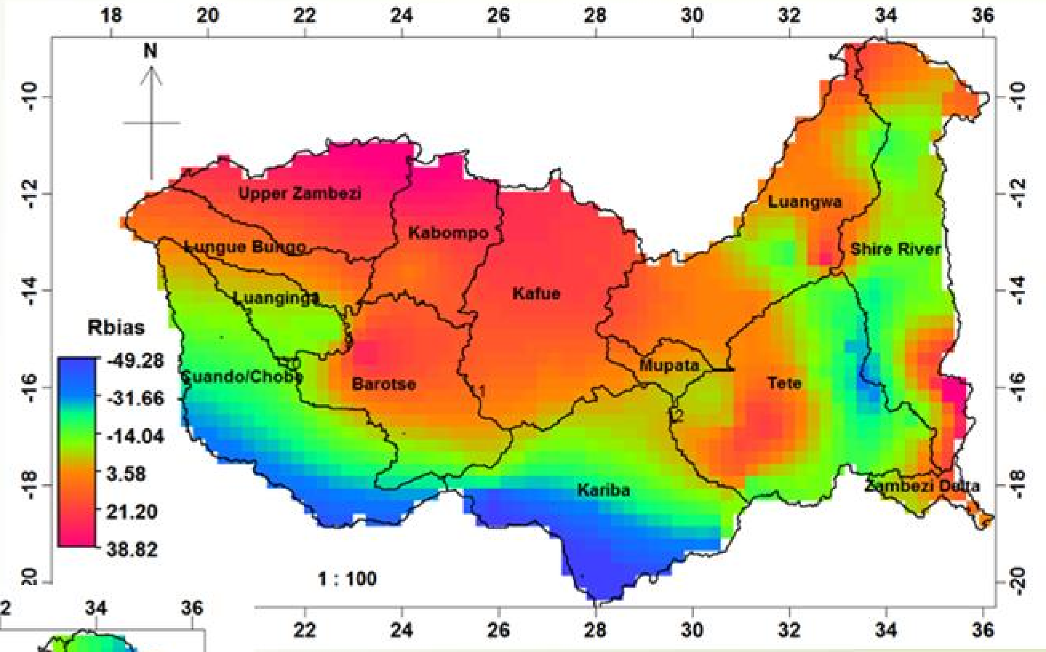


Performance of CMORPH vs Gauge (1998-2013)

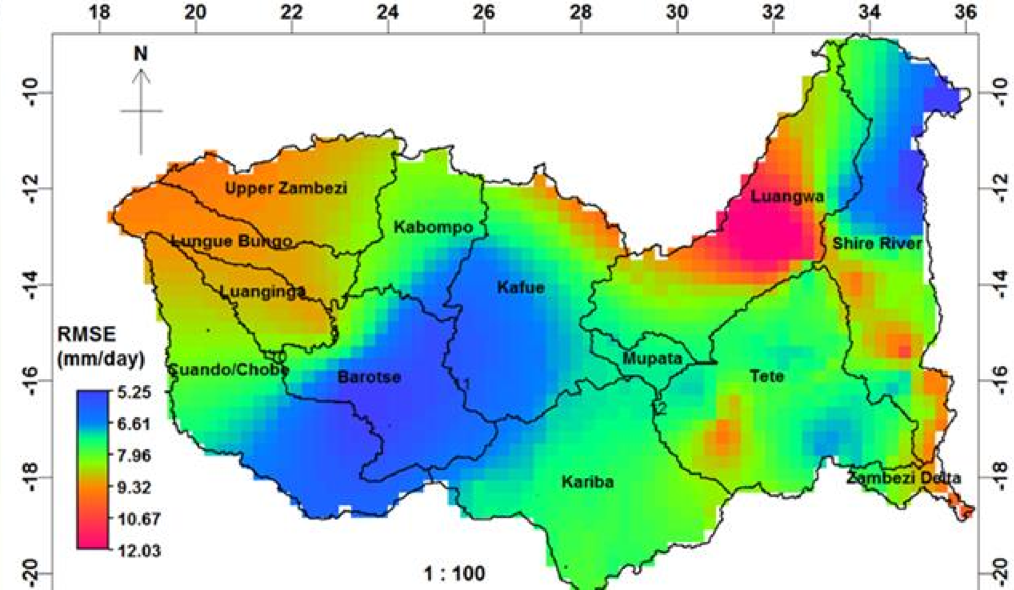
Bias



RBias



RMSE



CMORPH Performance in Lower, Middle & Upper Zambezi

LOWER ZAMBEZI

Stations	Bias	Rbias	RMSE	CC
Marromeu	0.24	8.71	10.89	0.50
Caia	0.46	21.26	9.45	0.43
Nsanje	0.54	27.90	9.42	0.46
Makhanga	-0.06	-3.10	8.13	0.40
Nchalo	-0.05	-2.24	8.98	0.35
Ngabu	0.07	2.96	8.43	0.55
Chikwawa	0.07	3.53	8.01	0.53
Tete	-0.57	-31.49	7.32	0.43
Chingodzi	0.12	6.10	6.41	0.56
Zumbo	-0.17	-8.35	7.62	0.53
Morrumbala	0.84	38.25	10.70	0.51
Monkey	-0.38	-11.52	8.41	0.66
Mangochi	-0.21	-8.32	7.84	0.51
Mutarara	-0.32	-15.82	6.67	0.58
Mimosa	1.57	57.68	9.88	0.60
Balaka	0.20	9.13	8.42	0.42
Thyolo	1.47	68.11	9.44	0.50
Chileka	0.31	14.32	8.26	0.42
Neno	0.41	18.30	10.65	0.30
Chipata	0.94	36.49	11.54	0.43
Makoka	0.82	40.59	7.65	0.57
Kasungu	-0.08	-3.22	7.11	0.57
Chichiri	0.95	40.14	9.36	0.42
Lundazi	0.18	10.25	6.75	0.41
Bvumbwe	1.24	58.62	9.44	0.43
Chitipa	0.50	20.73	8.11	0.51
Dedza	-0.43	-12.36	8.18	0.65
Basin Average	0.32	14.32	8.63	0.49

MIDDLE ZAMBEZI

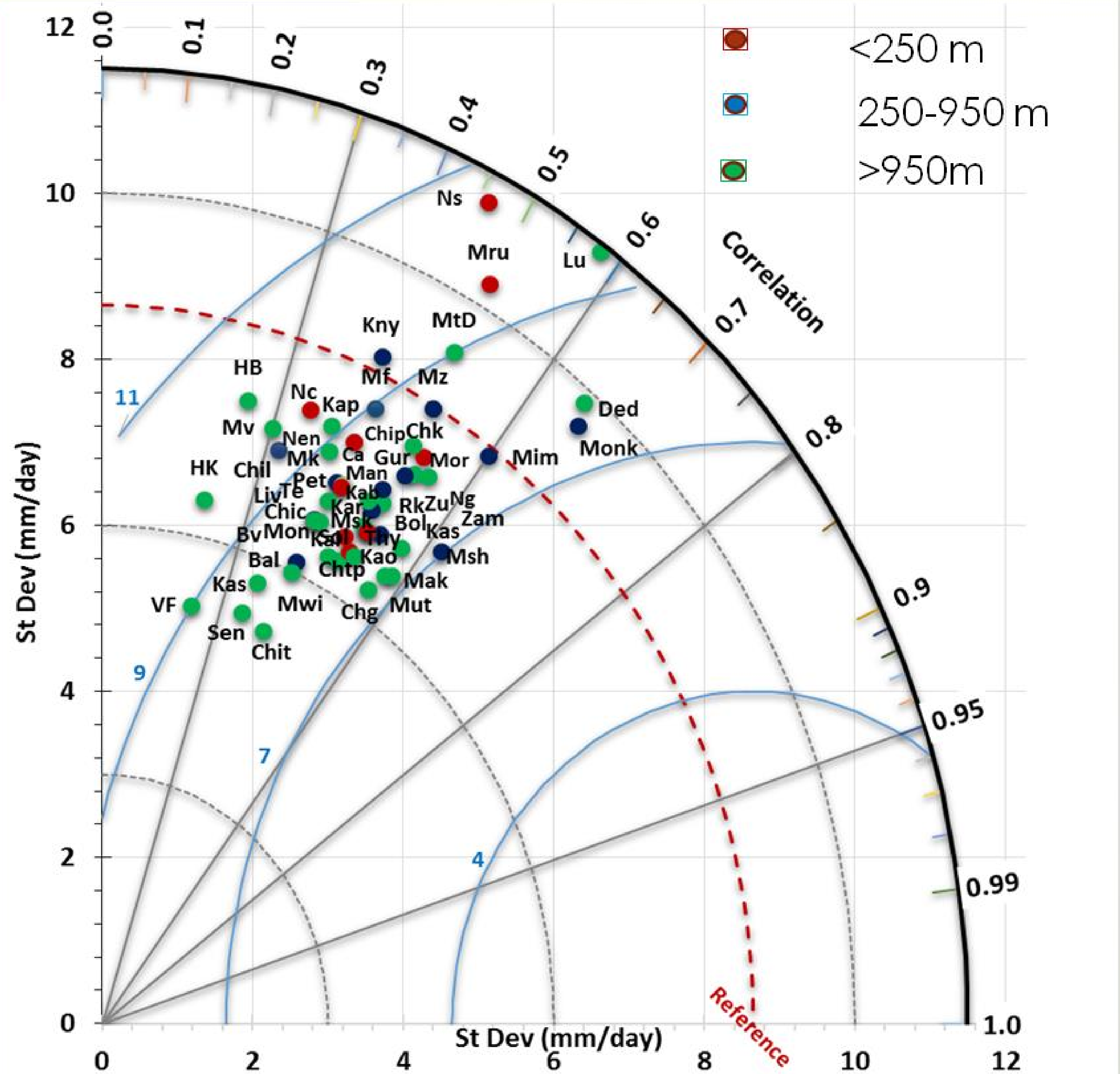
Stations	Bias	Rbias	RMSE	CC
Mushumbi	-0.10	-5.38	7.04	0.62
Kanyemba	-0.33	-13.57	9.16	0.42
Muzarabani	0.42	17.69	9.06	0.51
Rukomechi	-0.08	-3.86	7.22	0.50
Mfuwe	-1.66	-20.86	14.58	0.44
Mt Darwin	-0.15	-10.99	6.78	0.50
Petauke	0.16	6.96	8.19	0.44
Msekera	0.46	22.49	7.81	0.49
Bolero	-0.54	-20.02	7.12	0.53
Chitedze	-0.96	-24.45	9.80	0.58
Guruve	-0.05	-1.97	7.49	0.52
Kasempa	0.28	22.42	6.38	0.36
Kabwe	0.16	6.91	7.81	0.50
Karoi	0.03	1.07	7.32	0.51
Harare (Belvedere)	0.21	9.93	8.57	0.25
Harare(Kutsaga)	-0.34	-16.96	8.51	0.21
Mvurwi	0.53	20.61	9.88	0.32
Basin Average	-0.12	-0.59	8.39	0.45

UPPER ZAMBEZI

Stations	Bias	Rbias	RMSE	CC
Victoria Falls	-0.82	-46.41	7.22	0.23
Livingstone	-0.21	-10.51	6.64	0.47
Senanga	0.07	9.24	4.99	0.35
Kalabo	0.34	19.91	7.45	0.48
Mongu	0.69	32.00	7.82	0.49
Zambezi	0.43	17.47	8.48	0.44
Kapombo	0.19	16.37	5.64	0.39
Kaoma	0.16	7.87	6.90	0.50
Mwinilunga	0.93	40.06	8.27	0.42
Solwezi	0.75	26.38	8.31	0.51
Basin Average	0.25	11.24	7.17	0.43

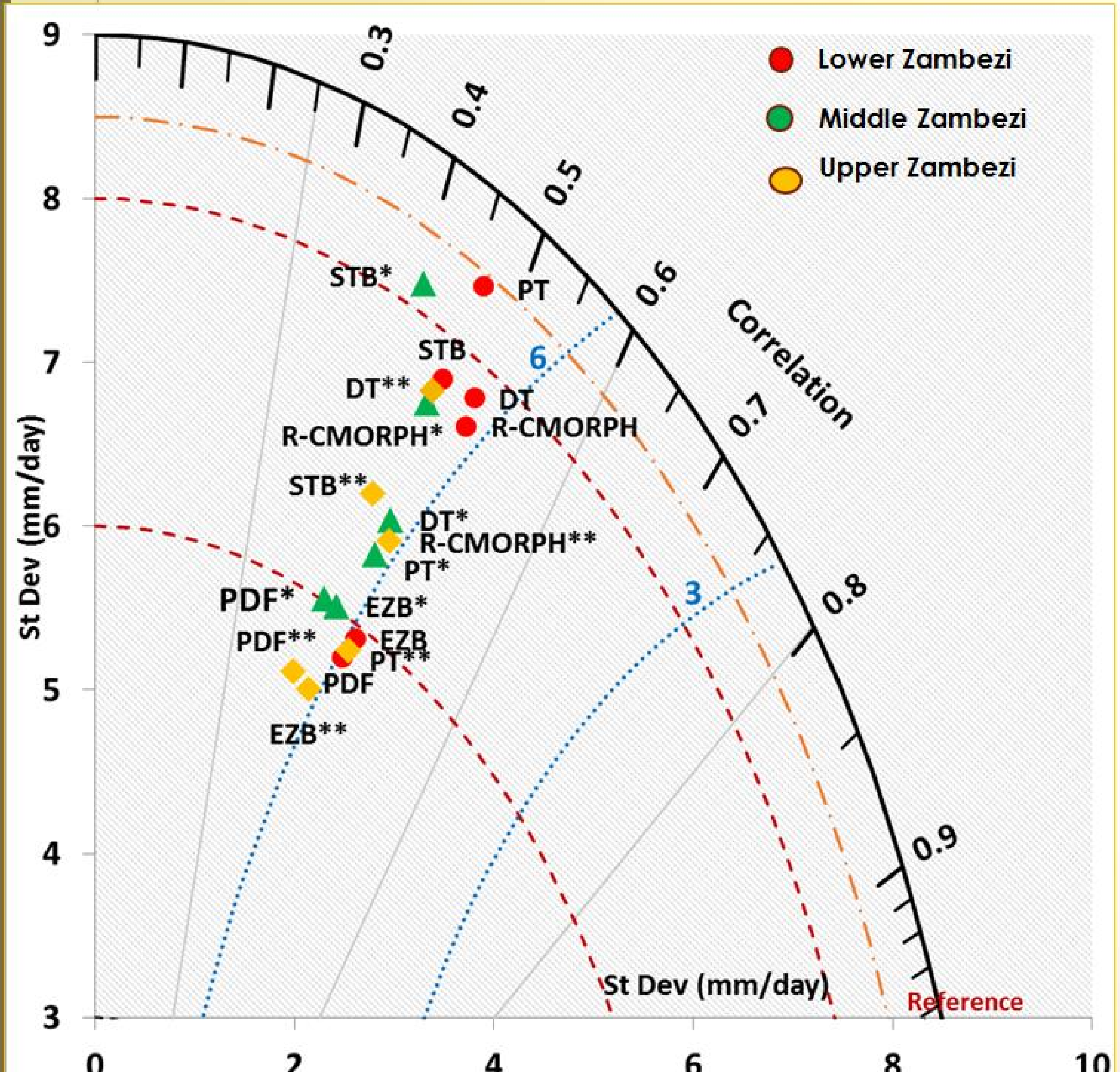
- Poor performance by CMORPH
- Temporal & spatial samples different.
- Low spatial coverage (e.g. for Angola)
- Quality of ground station records a concern

Elevation influences: CMORPH & gauge rainfall



- Made with adjusted rainfall stations
- ~ 90 % of stations fall below the reference mean std dev (8.4 mm/day).
- ~25 % (2/8) of stations in the lower elevation (<250 m) are above the reference 8.5 st dev
- Relationship between CMORPH and gauge rainfall not clearly elevation dependent.
  - in Indonesia, TMPA 3B42RT accuracy not elevation dependent (R2 = 0.0001)
  - in Ethiopia, TMPA 3B42RT accuracy elevation dependent

Bias correction of CMORPH rainfall (Taylor Diagram)



- No bias correction algorithm lies closer to the reference point on the X-axis
- Best performing bias correction algorithm in terms of corr is PDF and EZB- Upper & Middle Zambezi subbasins
- Blue contours indicate the RMSE values, most of the bias correction algorithms lies in the range 6 and 9 mm/day
- No consistent pattern of variability in the bias correction schemes.

Statistics for the gauge, uncorrected and bias corrected CMORPH for Zambezi basins.

Basin	B-scheme	Avg	Std dev	Max	Sum	Ratio
Lower Zambezi	Gauge	2.62	9.17	142.77	10792.58	
	R-CMORPH	2.39	7.58	156.50	9540.65	0.88
	PT	2.12	8.42	139.33	8883.26	0.82
	PDF	2.21	8.07	129.46	9349.42	0.87
	EZB	1.46	5.92	112.77	8529.38	0.79
	DT	2.00	7.78	137.53	11683.35	1.08
	STB	2.60	7.73	165.63	9494.89	0.88
Middle Zambezi	Gauge	2.47	8.33	109.81	10112.74	
	R-CMORPH	2.51	7.74	142.39	10373.64	1.03
	PT	1.93	6.55	109.76	9186.37	0.91
	PDF	1.86	6.78	114.87	8150.50	0.99
	EZB	1.55	6.02	110.61	9039.03	0.89
	DT	1.81	6.73	115.79	10555.56	1.05
	STB	2.45	8.28	214.74	10488.24	1.04
Upper Zambezi	Gauge	2.55	7.82	117.24	13008.24	
	R-CMORPH	2.12	6.44	103.25	10722.09	0.82
	PT	1.94	5.83	90.52	10284.19	0.79
	PDF	1.98	6.22	94.32	8674.54	0.67
	EZB	1.67	5.56	96.43	9750.19	0.75
	DT	2.49	7.72	112.81	14415.79	1.04
	STB	2.08	6.88	175.84	10850.88	0.83

- Serious overestimation of max rainfall amounts (e.g. STB: 216 mm vs Gauge: 107 mm)
- Underestimation of runoff volumes (ratios <1).
- Overally DT effective in removing bias in the CMORPH rainfall.
- Bias algorithms effective in their overall aim they are meant to achieve

Conclusions

1. The relationship between CMORPH and gauge rainfall NOT clearly elevation dependent in the Zambezi Basin .

2. Correction algorithms in the Zambezi Basin vary in the degree to which spatial and temporal variability in the CMORPH bias fields are accounted

2. Distribution transformation is the best performing correction algorithm. Results critical for water resources management in such a basin which is highly vulnerable to extreme weather and landuse changes yet remains largely ungauged.