Sensitivity of hydrological response of Lake Chad basin (Africa) to satellite rainfall and GCM atmospheric data

SATISH BASTOLA[1] & FRANCOIS DELCLAUX[2]

1 *ICARUS, NUIM, Maynooth, Kildare, Ireland*
satish.bastola@nuim.ie

2 *Institut de Recherche pour le Développement, UMR HydroSciences Montpellier, Montpellier II University, Place Eugene Bataillon, Case courrier MSE, 34095 Montpellier, France*

Abstract As part of the hydrological modelling of the Lake Chad basin (LCB), monthly grids of precipitation and potential evapotranspiration (PET) have been updated using satellite derived estimates and re-analysis datasets. These data sets are then evaluated using the modified THMB model. The precipitation satellite products GPCP and TRMM are compared with observed rainfall and with the CRU grids: it appears that satellite rainfall products tend to underestimate the precipitation in mountainous areas and to overestimate it in central LCB. Five rainfall scenarios, calculated by concatenation and by correlation between CRU data and satellite data, were compared using the THMB model. While concatenating data, the satellite data were kept during the common period. The rainfall from GPCP, TRMM and their average yield gives better results than the simulation forced by CRU rainfall on the sub-basin of LCB. The PET is calculated with a Hargreaves model, radiative model, using solar radiation and air temperature extracted from climate simulations of NCEP/NCAR.

Key words hydrological models; Lake Chad basin; pair wise comparison; satellite rainfall products

INTRODUCTION

The rainfall estimates from gauging stations are sharply declining due to constraints in financial resources. In this context, monitoring rainfall from satellite imagery is an attractive alternative. As the performance of rain estimates derived from satellite imagery is likely to vary depending on rain regime and resolution of each dataset, evaluation of their utility, especially for hydrological applications, is necessary. Several studies on the satellite estimated rainfall in Africa were published in recent years (McCollum *et al.*, 2000; Hughes, 2006). These studies reported some differences between satellite estimates and data from a network of gauging stations in Africa. Most of these studies either focused on the evaluation of satellite rainfall algorithms or focused on the accuracy of precipitation products in their specified region. However, comparisons of these estimates in central and western Africa, where slight changes in precipitation can result in dramatic changes in the runoff response due to the nonlinearity of the runoff generation, are rare. Since Lake Chad basin (LCB) expands across different climatic zones, the impact of error in rainfall estimates will have varying impact on runoff. Therefore, the sensitivity of precipitation data on the hydrological response is essential to evaluate these products from a hydrological point of view. Similarly, estimation of reliable potential evapotranspiration (referred to as PET) is also important to the hydrological model. Over the years, many relations for the estimation of PET from standard meteorological variables have been developed. The details of these methods can be found in Singh & Xu (1997). Although Penman's method has been widely used because of its strong theoretical foundation and more general applicability than other methods, the dependency of Penman's method on weather data, which are not readily available in most of the stations, limits its application in data-sparse regions such as Africa. Consequently, empirical models such as simple temperature and radiation based methods are widely preferred in data-sparse regions since they often provide simulation that are comparable to Penman method ones.

DATA AND METHODS

Lake Chad basin (2.4 M km^2) lies between latitude 5°N and 26°N and longitude 7°E and 24°E in central Africa. The theoretical hydrological basin can be divided into a southern part (hydrologically active) and a northern part (hydrologically inactive). Under the present climate, the lake receives water mainly from the Chari–Logone River system. Chari is the longest river in the basin with a catchment area of 0.6 M km^2, a quarter of the total area of the basin, and produces 90% of the surface inflow into the lake, while the remaining 10% is supplied by minor tributaries such as the Komadougou River. The principal lake water losses are due, first to evaporation (>2 m $year^{-1}$), second to infiltration. Another important feature of the basin concerns depressions and flood plains. As the basin is predominately flat with an overall median slope of 1.3%, it houses extensive flood plains and many local depressions. These depressions and flood plains play a pivotal role in the regional water balance as they provide more opportunity for evaporation.

Rainfall products and potential evaporation data

Rainfall datasets Several satellite rainfall products combine the high-quality microwave data from polar orbiting satellites, the high resolution infrared data from geostationary satellite, and ground-based observations, differently. The TRMM3B43 (0.25°), a product of Tropical Rainfall Measuring Mission (TRMM), and GPCP (1°), a product of Global Precipitation Climatology Project (GPCP), are two such datasets that are easy to access, and cover our target regions. The GPCP, which is available from 1997 until the present, is a satellite gauge blend product of Global Precipitation Climatology Center (GPCC) and was developed by Huffman *et al.* (2001). The TRMM3B43 is a satellite gauge blend product which use: the 3-hourly merged high-quality/IR estimates, and either the monthly accumulated Climate Assessment and Monitoring System, or GPCC raingauge analysis. The algorithm is based on the techniques by Huffman *et al.* (1997). The TRMM3B43 only covers an area of the Earth extending from 50°N to 50°S. It is available from 1998 until the present. The CRUTS2.1 (Mitchell & Jones, 2005), referred to as CRU hereafter, is another such dataset that has been used in many global studies. It is a database of monthly climate observations constructed at a spatial resolution of 0.5° from meteorological stations and is available until 2002. Despite the data collection efforts, the CRU data in many regions still only represent a sub-set of the potentially available stations.

Satellite rainfall datasets are generally available for relatively shorter periods of time than generally required for hydrological modelling. As all three dataset used in this study have different spatial resolution, the TRMM (0.25°) was regridded to 0.5° using spatial averaging, and the GPCP (1°) was regridded to 0.5° using bilinear interpolation so that both datasets conform to the spatial resolution of CRU. Within LCB, the only gridded precipitation product that is available at a finer scale, yet extends for a long period of time, is the CRU dataset. Therefore in this study the five rainfall datasets (1901–2007) (see Table 1), referred to as test datasets interchangeably, were constructed by utilizing regridded satellite precipitation products and CRU.

Table 1 Data products.

Sn	Data source	Regridding to 0.5°	Date	Derived products (1901–2007)	Product name
1	CRU (0.5°)	--	1901–2002	CRU+f(CRU,GPCP) CRU+f(CRU,TRMM)	CRU_GPCP CRU_TRMM
2	GPCP (1°)	Bilinear Interpolation	1997–2007	CRU+GPCP	GPCP
3	TRMM (0.25°)	Averaging	1998–2007	CRU+TRMM CRU+(TRMM+GPCP)/2	TRMM Ave (GPCP, TRMM)

Both CRU_GPCP and CRU_TRMM in Table 1 are obtained by concatenating CRU and estimates inferred from the linear relationship between GPCP and CRU and TRMM and CRU, respectively, over the overlapping period. For the construction of CRU_TRMM and CRU_GPCP, an overlapping period of five years from 1998 to 2002 was used. The point estimates of 26 gauging stations for which records are mostly available during the satellite data period were extracted from the Système d'Informations Environnementales sur les Resources en Eau et leur Modélisation (SIEREM) (Boyer *et al.*, 2006) and compared with the values estimated from satellite-based products. Within LCB, there are too few stations with data that overlap with the satellite rainfall data. Therefore, at this stage of the study, no attempt has been made to construct a rainfall grid from the gauge data.

PET datasets As the time series of meteorological variables that are even required for empirical models are not readily available, the prospect of utilization for re-analysis data that are generally available at coarse spatial resolutions is revisited. Owing to the simplicity of empirical methods and their potential to reproduce results comparable to more physically-based models, a generalized form of Hargreaves method (see Xu & Singh (2000) for details) is considered in this study. It is an empirical method that utilizes solar radiation and temperature (equation (1)) to compute daily/monthly PET:

$$\mathrm{PET} = a(T+b) * Rs/\lambda \tag{1}$$

where Rs is the incoming solar radiation ($\mathrm{Wm^{-2}}$), T is the air temperature (°C), a and b are constants, λ is the latent heat of vaporization expressed in MJ $\mathrm{Kg^{-1}}$, and the unit of PET is mm $\mathrm{month^{-1}}$. Since the value for the constants of equation (1) given by Xu & Singh (2000) (referred to as constants from literature hereafter) may only be reliable in the areas and over the periods for which they were determined, the constants needs recalibration for the LCB region. As the time series of solar radiation are not readily available within LCB, and the temperature data from CRUTS2.1 database is available only until 2002, the downward solar radiation flux and surface or near surface air temperature for the period 1948–2007 were extracted from the National Center for Atmospheric Research (NCEP/NCAR) re-analysis project for recalibration of the constants of equation (1). The air temperature of NCEP/NCAR is strongly influenced by observation data, whereas the solar radiation is solely derived from model fields. Originally at a resolution of 2.5°, these data were re-gridded to conform to a resolution of 0.5° by using bilinear interpolation. Subsequently, the PET simulated from constants recalibrated from NCEP/NCAR can be evaluated by comparing them with PET simulated by the parameters adopted from the literature and calibrated from limited input data collected from within the LCB region.

Sensitivity of hydrological response to input datasets

The sensitivity of the test datasets is evaluated by analysing the discrepancies between the outputs of the model forced with: (a) the test data and control data (model propagated error), (b) test data and observed streamflow (model error). Control data are the model forcing data that have been used for model calibration. Both model error and model propagated errors are estimated using Nash Sutcliffe Efficiency (NSE) and overall Volume Error ($Vol.Err = (\overline{m} - \overline{e})/\overline{m}$), where $\overline{e}$ is the average estimated quantity and $\overline{m}$ is the average value of measured (control) quantity for model propagated error (model error). Since the gridded precipitation data of CRU and the LCB_PET have been used in a number of studies in the past in the LCB region, they were used as control precipitation and control potential evapotranspiration data.

To evaluate the estimated meteorological records, we used the GR+THMB flow simulation model. The GR+THMB is a gridded model (Delclaux *et al.*, 2008) that takes into account the spatial variability in climate inputs and watershed characteristics and provides information on the water fluxes at each grid cell. The model includes the GR model (Makhlouf & Michel, 1994), a conceptual hydrological model for runoff production, and the Terrestrial Hydrology Model with Biochemistry (THMB) (Coe, 2000) for routing flow through rivers and lakes. The capacity of soil water content (A) and a parameter that adjusts both potential evaporation and rainfall in the same proportion by multiplying them ($X1$) are the two parameters of the GR model. Gridded value of maximum soil water content A was estimated from maximum water holding capacity derived from the soil map of FAO. THMB routes the surface runoff and subsurface runoff generated by the runoff production model GR to the outlets of basins or sills of lakes. The detailed description on the structure of routing model can be found in Coe (2000). The version of THMB model used here differs from the original THMB version of Coe (2000) in the way the flow directions are calculated. In this study the flow directions within topographic depressions and prescribed flood plains are dynamically calculated by using water head as a controlling factor for the determination of flow direction, whereas the flow direction elsewhere within the basin is derived based on the ground elevation. In addition to gridded rainfall and PET, the local topography, drainage direction map, and potential water area maps derived from SRTM3″ DEM by filtering and then resampling to 5′ DEM via the nearest neighbour method were used. Owing to the computational limit, and due to the unavailability of forcing data at higher resolution, the model was simulated with a 5′ × 5′ grid size.

In this study the Latinized Hypercube Sampling (LHS) technique was used as a tool for model calibration. The time constants for surface and subsurface reservoirs of THMB, which are both spatially lumped parameters over the basin, were selected from an earlier application of the same model within LCB (e.g. Delclaux *et al.*, 2008). However, the reference velocity, a basin average parameter, and the adjustment factor *X1* of GR, a lumped value over sub-basins, were estimated through model calibration. The observed monthly flows from the River Chari at Sahr, River Chari at Manda, River Logone at Bongor, and River Chari at N'Djamena, were utilized. The LCB_PET and CRU rainfall were used as model inputs for the calibration of these parameters. Although the length of flow time series is available from 1938 to 2007 for Chari-Logone, and from 1948 to 2007 for Logone at Bongor, the period 1960–1975 was chosen for model calibration as this period represents both wet and dry climates within the basin.

RESULTS

Comparison of precipitation products with observation

The rainfall scenarios constructed for Lake Chad basin were first evaluated by comparing them with the data from the network of gauging stations (location of gauging stations are shown in Fig. 1). The station that is closest to the centre of the grid is used while comparing it with grid points. The period from 1998 to 2007 was used for all datasets, except for the CRU/raingauge. For the CRU/raingauge, the period from 1990 to 2002 was used because CRU is available only until 2002. On average, all six datasets, including CRU, indicated good agreement with the raingauges. However, one apparent difference observed among the datasets is the systematic error in the satellite estimated values compared to gauge values such as overestimation of low rainfall and underestimation of high values. The estimates from CRU_GPCP and CRU_TRMM result in rainfall values that are significantly similar to the estimates from CRU. Pair-wise comparison of

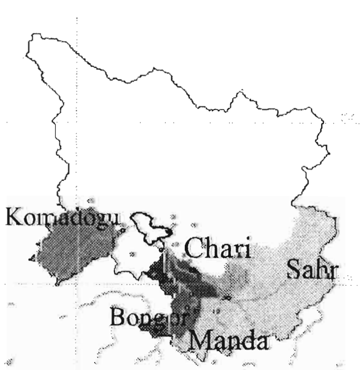


Fig. 1 Lake Chad basin showing major sub-basin and network of hydro-metrological stations.

daily values between satellite-derived estimates and raingauges is shown in Fig. 2 and Table 2. Mostly at stations located in the southern humid part of the basin, the bias values show underestimation in rainfall for CRU and satellite datasets, but there is good agreement in terms of NSE with raingauges. In contrast, CRU and satellite data overestimate raingauges in the northern semi-arid part of the basin. Pair-wise comparisons were also made between spatial estimates from CRU and satellite derived products using the common period (1998–2002). In particular, the spatial bias for GPCP is higher than TRMM (not shown).

Table 2 Pair wise comparison of satellite estimated rainfall with raingauges.

SN	Static	Gridded rainfall estimates					
		CRU	GPCP	TRMM	CRU_GPCP	CRU_TRMM	Ave (GPCP,TRMM)
1	Correl	0.89	0.88	0.88	0.9	0.89	0.9
2	Bias (mm/month)	1.74	19.17	1.83	1.04	–0.89	11.01
2	RSME (mm/month)	34.3	44.6	36.2	33.41	34.04	35.84
4	NSE	0.78	0.64	0.77	0.8	0.8	0.78

Correl (correlation coefficient 0, RSME (Root Mean Square Error), NSE (Nash Sutcliffe Efficiency).

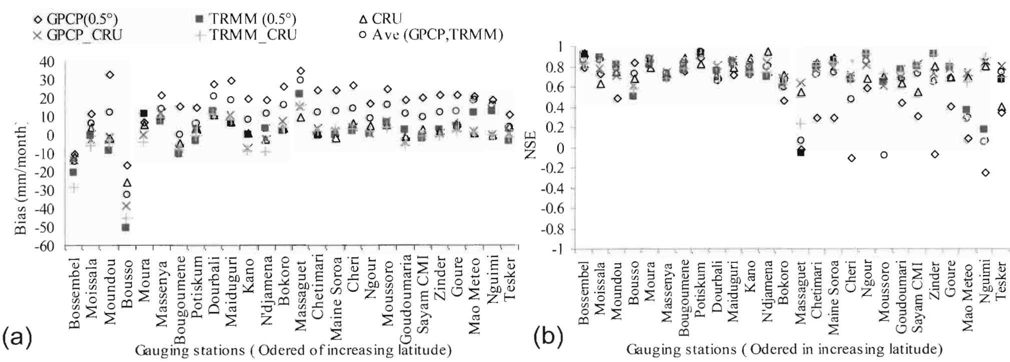


Fig. 1 Pair wise comparison between satellite and gauge precipitation values at specified gauging stations: (a) Bias (mm/month), (b) NSE (gauging stations are ranked from a south to north direction).

Both GPCP and TRMM have a tendency to underestimate the values in the N/NW and eastern mountainous part of LCB. Probable explanation for this underestimation in these regions is the inability of satellite algorithms to account for rainfall process due to warm air and the elevation effect that is included in interpolation algorithms of CRU estimates. In the central part of the basin, both GPCP and TRMM overestimate the CRU values, but the overestimation by GPCP is higher than TRMM. This overestimation can be related to the way these products are derived. First, satellite algorithms tend to overestimate rainfall in this region of Africa due to an abundance of aerosol content and higher base of clouds, as mentioned by McCollum *et al.* (2000). Second, GPCP and TRMM products utilize GPCC raingauge data, which themselves overestimate CRU data in northwestern Africa (Fiedler & Doll, 2007). These combined effects probably lead to an overall overestimation of satellite products rainfall in the central part of LCB with respect to CRU data.

Sensitivity of runoff response to rainfall data

The period of 1998–2002, which overlaps with both control data and constructed data was used for the evaluation of these datasets. The NSE and overall Volume Error for the simulated flow of

Chari at N'Djamena during calibration (1960–1975) was 0.87 and –7%, respectively. For the validation period (1998–2002), the NSE and Volume Error in the annual runoff of River Chari at N'Djamena was 0.81 and –20%, respectively. Despite underestimation, the model could reasonably reproduce the variability in observed discharge in climatic conditions other than for which model was calibrated and subsequently used for the evaluation of new meteorological records. The calibrated model was forced with five precipitation datasets constructed for LCB (i.e. GPCP, TRMM, CRU_GPCP, CRU_TRMM, and Ave(GPCP, TRMM)). For all simulations, the identical PET estimate, i.e. LCB_PET, was used. The spatial average rainfall values over sub-basins, estimated from satellite-based products, are significantly similar to the spatial average estimates from CRU (not shown). However, spatial and temporal differences exist between satellite products and CRU, thereby resulting in different simulated flows. Table 3 shows the performances (NSE, Volume Error) of GR+THMB in four sub-basins applied with different rainfall datasets. These performances were measured with respect to simulated control output (Table 3(a)) and observed flow at basin outlet (Table 3(b)). These results indicate that the model propagated errors are less for CRU_GPCP and CRU_TRMM compared to GPCP, TRMM and Ave(GPCP, TRMM) (it is not surprising because these datasets were prepared from CRU and satellite estimates using a common period). Table 3(c) shows the bias in the spatial average value of satellite rainfall with respect to CRU and consequent bias in the streamflow. Compared to CRU, GPCP overestimates spatial average rainfall by nearly 15% in all sub-basins. The bias in the spatial average rainfall for TRMM is lower than GPCP. TRMM underestimates the values over the Sahr sub-basin, but overestimates over the Bongor sub-basin. This discrepancy between TRMM and GPCP can be attributed to differences in the rainfall processes accounted for by respective satellite algorithms, the error model implemented to merge various types of information and spatial resolutions. Furthermore, it is also evident that the reductions in runoff are

Table 3 Sensitivity of models to satellite estimated rainfall (1998–2002): (a) model performance with respect to control flow, (b) model performance with respect to observation, (c) sensitivity of model measured with respect to control flow.

SN	Dataset	Chari at N'Djamena NSE	Vol.err	Chari at Shar NSE	Vol.err	Chari at Manda NSE	Vol.err	Logone at Bongor NSE	Vol.err
(a) Model propagated error (performance measured width respect to flow simulated from CRU rainfall									
1	GPCP	0.51	49.84	0.01	107.14	0.83	36.13	0.69	37.37
2	TRMM	0.61	36.92	0.82	–17.87	0.55	59.02	0.45	40.77
3	Ave (GPCP, TRMM)	0.53	46.23	0.59	43.83	0.70	51.65	0.53	42.30
4	GPCP_CRU	0.91	1.99	0.74	–20.12	0.88	–3.76	0.88	13.02
5	TRMM_CRU	0.83	–18.00	0.84	–29.67	0.77	–27.86	0.85	–7.15
(b) Model error (performance measured against observation)									
1	CRU	0.81	–20.30	0.61	–52.03	0.65	–28.77	0.44	–38.58
2	GPCP	0.79	19.43	0.75	–0.64	0.64	–3.03	0.71	–15.62
3	TRMM	0.83	9.13	0.49	–60.61	0.51	13.27	0.78	–13.53
4	Ave (GPCP, TRMM)	0.82	16.55	0.75	–31.01	0.61	8.02	0.77	–12.59
5	GPCP_CRU	0.80	–18.71	0.36	–61.68	0.51	–31.45	0.57	–30.58
6	TRMM_CRU	0.72	–34.64	0.39	–66.26	0.46	–48.61	0.51	–42.97
(c) Percentage change in simulated runoff due to percentage change in rainfall with respect to CRU									
1	GPCP	15.18	49.84	13.83	107.14	15.12	36.13	14.17	37.37
2	TRMM	–0.21	36.92	–3.12	–17.87	9.02	59.02	7.47	40.77
3	Ave (GPCP, TRMM)	8.45	46.23	6.31	43.83	13.04	51.65	11.78	42.30
4	GPCP_CRU	3.52	1.99	2.30	–20.12	6.69	–3.76	5.56	13.02
5	TRMM_CRU	0.13	–18.00	0.10	–29.67	0.27	–27.86	0.27	–7.15

proportionately greater than reductions in rainfall. For GPCP, TRMM, and Ave(GPCP, TRMM), the percentage changes in rainfall are typically amplified four times into runoff in most of the sub-basins. Such variation in amplification can be attributed to the differences in the nature of land surface within the sub-basins. Surprisingly, the comparison of the performances of the model run with rainfall scenarios against the observed streamflow data reveals that TRMM rainfall results in improved simulation in flow at N'Djamena and Bongor, while GPCP performed better at Manda and at Sahr compared to CRU. Model errors are less for GPCP, TRMM and Ave(GPCP, TRMM) compared to CRU, CRU_GPCP and CRU_TRMM. In this context, extension of rainfall records using satellite imagery is appealing from a hydrological modelling point of view. Furthermore, since GPCP and TRMM tend to perform differently among basins and since the amplification of bias in rainfall into runoff is markedly different among basins, the possibility of combining different sources of datasets for simulation modelling of LCB is plausible. Owing to the facts that: (a) CRU data are only available until 2002, (b) gauging stations network is steadily decreasing, and (c) satellite based products are becoming readily accessible, such results obviously put forth the prospect of satellite-based datasets for hydrological model application.

PET comparison with observed data

Figure 2 shows the scatter plot of observed PET and PET estimated from the Hargreaves model with three different coefficients, i.e. adopted from literature, calibrated using limited gauged data, and calibrated using re-analysis data. The coefficient from re-analysis resulted in better simulation compared to the other two. Pairwise comparisons of the Hargreaves estimated PET with the gridded time series of LCB_PET were made based on the same criteria that were used for comparison of precipitation. Spatial value of RMSE and bias calculated from the time series of Hargreaves PET and LCB_PET (1960–1975) revealed that within the Chari-Logone basin, the Hargreaves method overestimates PET in the range 0–20 mm month^{-1}, but in the northern part it underestimates (not shown). Regarding RMSE, it varies from 10 to 20 mm month^{-1} within the Chari-Logone basin. These discrepancies can be attributed mostly to solar radiation data from NCEP/NCAR which is completely a model product and is highly dependent on the GCM parameterization and partly to the calibrated constants as they were derived from measures in the Bol Matafo station located in more arid area compared to the southern part of the basin.

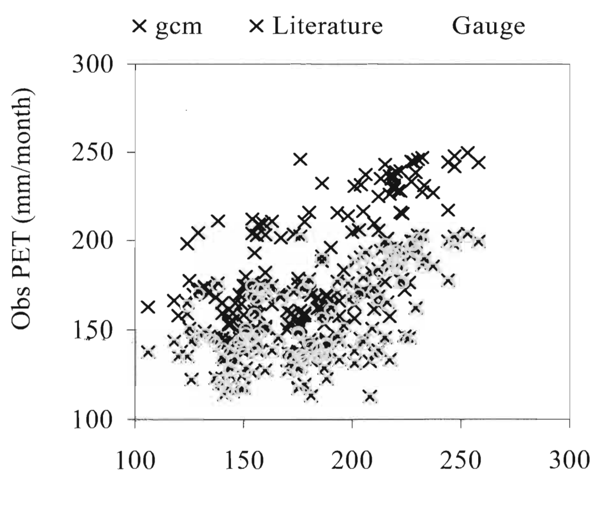


Fig. 3 Scatter plot showing the performance of the Hargreaves model with three different coefficients.

Table 4 Sensitivity of runoff to potential evaporation data (1960–1975).

SN	Basin	Sensitivity of Runoff to PET		Model performances with respect to control data	
		% PET	% Runoff	NSE	Vol Err
1	N'Djamena	1.75	–0.94	0.98	0.02
2	Bousso	7.98	–0.90	0.98	0.09
3	Sahr	5.85	–4.17	0.96	0.08
4	Manda	–6.08	0.54	0.99	0.06
5	Bongor	8.63	–1.52	0.99	–0.06

Sensitivity of PET data to runoff responses

Table 4, which illustrates the bias in the Hargreaves PET with respect to LCB_PET and consequent bias in the runoff at five outlets, shows that the THMB is relatively insensitive to PET estimates. This was also observed by Oudin (2004) in four parameter GR model. Consequently, the effect of performances of GR+THMB measured with respect to control simulation (1960–1975) for each sub-basin when the model is forced with Hargreaves PET is less detrimental than rainfall. Hargreaves PET and LCB_PET are similar from the hydrological model prospective. In particular, Sahr and Bousso sub-basins are sensitive to PET estimate compared to Bongor and Manda. This is likely due to the large wetlands located within their basin, which provide additional opportunity for water loss through evaporation.

CONCLUSIONS

Estimation of reliable rainfall data for the hydrological modelling of Lake Chad basin over the present decade poses a hindrance to the utilization and evaluation of a wide range of new and relevant hydrological information that can be extracted from satellite altimetry, gravitometry and imagery. This is mainly due to sparse distribution of gauging stations and difficulty in assessing the data. In this study records of rainfall and potential evapotranspiration were constructed for flow simulation on LCB and were evaluated using existing datasets. Pair-wise comparison between station measured rainfall and satellite derived rainfall shows that, in LCB, estimates from satellite have a systematic error such as overestimating low values in the northern semi-arid region and underestimating high values in the southern humid area. Satellite products tend to overestimate the flows that are earlier modelled with CRU datasets. However, flows simulated with the satellite products are in closer agreement with observed discharges than when modelled with CRU. Simulation of flow with different rainfall estimates also shows that the simulated runoffs are highly sensitive to the differences in rainfall volume by a positive factor of 4–7. Regarding the potential evapotranspiration (PET), Hargreaves PET is in good agreement with the time series of PET estimated with the Penman method. The model appears less sensitive to differences in Hargreaves PET and Penman PET than differences in satellite rainfall and CRU rainfall. However, the increase in the simulated runoff is proportionately greater than the reduction in estimated PET. This study thus demonstrates the usefulness of monthly rainfall extracted from satellite based products, and PET estimated from empirical methods forced with air temperature and solar radiation from NCEP/NCAR re-analysis, for the hydrological modelling of LCB. In particular, scenarios based on average of TRMM and GPCP rainfall, and PET estimated from Hargreaves method with meteorological variables from re-analysis for further studies in LCB, including flood plain dynamics assessment and evaluation of new satellite information.

Acknowledgements This work received support from SAHELP and GHYRAF projects supported by the French National Agency and from UMR Hydro Sciences Montpellier, France.

REFERENCES

Boyer, J. F., Dieulin, C., Rouche, N., Cres, A., Servat, E., Paturel, J. (2006) SIEREM: an enviornmental information system for water resources. In: *Climate Variability and Change – Hydrological Impact* (ed. by S. Demuth *et al.*). IAHS Publ. 308. IAHS Press, Wallingford, UK.

Coe, M. T. (2000) Modelling terrestrial hydrological systems at the continental scale: testing the accuracy of an atmospheric GCM. *J. Climate* **13**, 686–704.

Delclaux, F., Lecoz, M., Coe, M., Favreau, G., & Ngounou, N. B. (2008) Confronting models with observations for evaluating hydrological change in the Lake Chad basin, Africa. In: *13th IWRA World Water Congress* (Montpelier, France).

Fiedler, D. & Doll, P. (2007) global modelling of continental water storage changes – sensitivity to different climate data sets. *Adv. Geosci.* **11**, 63–68.

Huffman, G. J., Adler, R. F., Arkin, P., Chang, A., Ferraro, R., Gruber, A. *et al.* (1997) The global Precipitation Climatology Project (GPCP) combined precipitation data set. *Bull. Am. Meteorol. Soc.* **78**, 5–20.

Huffman, G. J., Adler, R. F., Morrissey, M. M., Curtis, S., Joyce, R. J., McGavock, B. *et al.* (2001) Global precipitation at one degree daily resolution from multi-satellite observations. *J. Hydrometeorol.* **2**, 36–50.

Hughes, D. A. (2006) Comparision of satellite rainfall data with observation from gauging station networks. *J. Hydrol.* **327**, 399–410.

Oudin, L. (2004) Recherche d'un modèle d'évapotranspiration potentielle pertinent comme entrée d'un modèle pluie-débit global. PhD Thesis, CEMAGREF, Paris, France.

Makhlouf, Z. & Michel, C. (1994) A two parameter monthly water balance model for French watersheds. *J. Hydrol.* **162**, 299–318.

McCollum, J. R., Gruber, A. & Ba, B. (2000) Discrepancy between gauges and satellite estimates of rainfall in equatorial africa. *J. Appl. Meteorol.* **39**(5), 666–679.

Mitchell, T. D. & Jones, P. D. (2005)An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol.* **25**, 693–712.

Singh, V. P. & Xu, C. Y. (1997) Evaluation and generalization of 13 equations for determining free water evaporation. *Hydrol. Processes* **11**, 311–323.

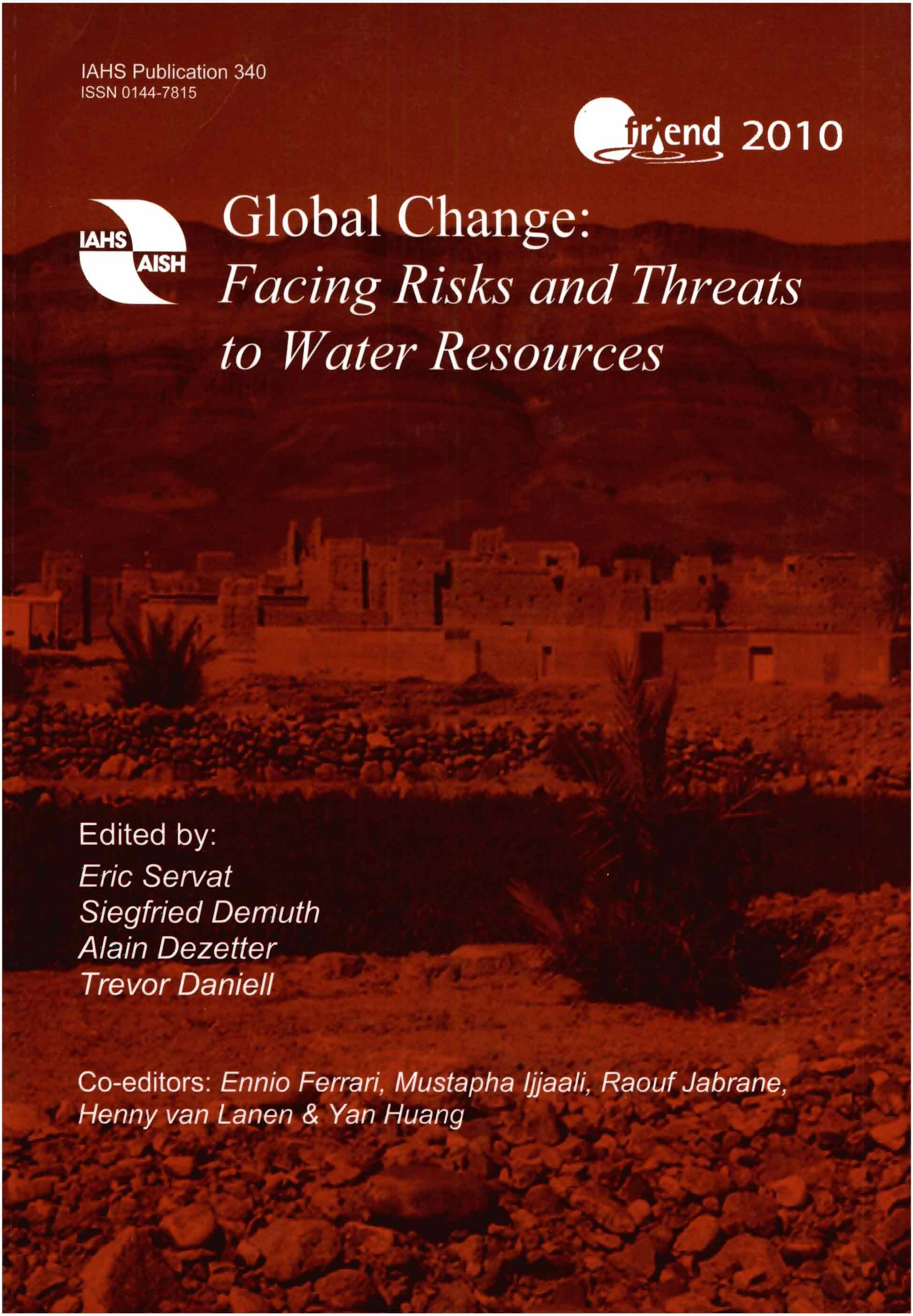
Xu, C. Y. & Singh, V. P. (2000) Evaluation and generalization of radiation based methods for calculating evaporation. *Hydrol. Processes* **14**, 3339–3349.

IAHS Publication 340
ISSN 0144-7815

friend 2010

IAHS AISH

Global Change: *Facing Risks and Threats to Water Resources*



Edited by:
Eric Servat
Siegfried Demuth
Alain Dezetter
Trevor Daniell

Co-editors: *Ennio Ferrari, Mustapha Ijjaali, Raouf Jabrane, Henny van Lanen & Yan Huang*

Global Change:
Facing Risks and Threats to Water Resources

Edited by:

ERIC SERVAT
UMR HydroSciences Montpellier (HSM), Université Montpellier 2, France

SIEGFRIED DEMUTH
Hydrological Processes and Climate Section, Division of Water Sciences, Natural Sciences Sector, UNESCO, Paris, France

ALAIN DEZETTER
UMR HydroSciences Montpellier (HSM), Université Montpellier 2, France

TREVOR DANIELL
School of Civil and Environmental Engineering, University of Adelaide, Australia

Co-edited by: ENNIO FERRARI, MUSTAPHA IJJAALI, RAOUF JABRANE, HENNY VAN LANEN & YAN HUANG

Proceedings of the Sixth World FRIEND Conference, Fez, Morocco, 25–29 October 2010.

IAHS Publication 340
in the IAHS Series of Proceedings and Reports

Published by the International Association of Hydrological Sciences 2010

IAHS Publication 340

ISBN 978-1-907161-13-1

British Library Cataloguing-in-Publication Data.
A catalogue record for this book is available from the British Library.

The papers included in this volume have been reviewed and some were extensively revised by the Editors, in collaboration with the authors, prior to publication.

IAHS is indebted to the employers of the Editors for the invaluable support and services provided that enabled them to carry out their task effectively and efficiently.

Publications in the series of Proceedings and Reports are available from:
IAHS Press, Centre for Ecology and Hydrology, Wallingford, Oxfordshire OX10 8BB, UK
tel.: +44 1491 692442; fax: +44 1491 692448; e-mail: jilly@iahs.demon.co.uk

Printed by Information Press

Cover picture: Southern Morocco by Eric Servat