Comparison of satellite-based and re-analysed precipitation as input to glacio-hydrological modelling for Beas River basin, northern India

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Abstract Precipitation is the most critical input for hydrological models. In this paper we evaluate the usefulness and reliability of re-analysed and satellite-based precipitation datasets in driving a large-scale hydrological model for the Beas River basin, a mountainous region in northern India. The spatial and temporal distribution of gridded precipitation in India is compared with raingauge measurements by using three statistical tests. Then a large-scale glacio-hydrological model (GSM-WASMOD), which couples WASMOD-D and a glacier mass-balance module, is applied for the basin. The three precipitation datasets are used to drive the large-scale GSM-WASMOD for simulating the water balance of the Beas River basin for the period 1997–2001. The model results are compared and assessed based on Nash-Sutcliffe efficiency (NS) and relative volume error (VE). On average, the global gridded satellite-based dataset performs as well as the sparse raingauge data in this region, indicating that the satellite-based dataset can be used as a data source for water resources in basins with little or no ground-based measurements.

Key words global datasets; TRMM; WFD; large scale Glacier and Snow Melt – WASMOD model; raingauge

INTRODUCTION

The Ganga-Brahmaputra and Meghna river system in northern India carries around 60% of the freshwater in India. A majority of tributaries of these rivers are glacier fed and originate in the Himalayan region. Bahadur (1999) estimates an annual volume of 500 km^3 water from Himalayan snow- and icemelt. According to the Fourth Assessment report of IPCC (2007), the ongoing climate change is likely to affect the spatial and temporal availability of water and agriculture, which may lead to an increased risk of hunger and energy availability, as well as more rapid glacier melting. Due to climate change along with population growth and increasing demand arising from higher standards of living, changes in freshwater availability could adversely affect millions of people in this area.

Hydrological models, which provide a framework to investigate relations between climate and water resources, are the best tools to provide information on global, regional and catchment water resources under current and future climate conditions (Doll *et al.*, 2003; Lehner *et al.*, 2006). The snow cover in the Himalayan river basins lacks long-term ground-based monitoring data due to its remoteness, harsh climate and challenging orography. However, in glacierized catchments glacier- and snowmelt are important contributors to the magnitude and variations in streamflow (Jost, 2011). The future contribution of glaciers to runoff in a changing climate is subject to present research since it affects both agriculture and hydroelectric power plants. Modelling melt from glaciers requires glacier mass-balance models which exist in a large range of different complexities (Hock, 2005). Since meteorological data are hardly available in mountainous regions particularly at high altitudes, temperature-index models have been widely used (e.g. Konz & Seibert, 2010; Engelhardt *et al.*, 2013) which just need air temperature and precipitation for computing snow and glacier melt.

During the past two decades, numerous precipitation datasets have been developed for global and regional hydrological assessment and modelling (Huffman *et al.*, 2007; Weedon *et al.*, 2010).

Many studies have evaluated the differences between various gridded precipitation datasets and raingauge data as input for hydrological models (Biemans *et al.*, 2009; Li *et al.*, 2012), but there are only few studies investigating the performance of the Tropical Rainfall Measuring Mission (TRMM) 3B42 dataset and the WATCH Forcing Data (WFD) for glacier-covered basins in northern India.

From the foregoing concerns, the objectives of the study are: (a) developing a parsimonious hydrological model that includes glacier and snowmelt routines for glacierized Himalayan river basins; and (b) evaluating the usefulness and reliability of two global datasets (TRMM and WFD) by comparing them with raingauge data in driving the large-scale glacio-hydrological model for a basin in northern India.

STUDY AREA AND DATA

Study area

The Beas River basin (Fig. 1) is located upstream of the Pandoh Dam with a drainage area of 5406 km^2, of which 780 km^2 is covered permanently by snow or ice. The Beas River is one of the main branches of the Indus River system. Its tributaries, the Parbati and Sainj rivers, are glacier fed. The monthly mean temperature varies between 2 and 20°C. The mean annual precipitation is 1217 mm and the mean annual runoff is 1195 mm, of which 70% and 55% occurs in the monsoon season (July to September), respectively (Kumar, 2007).

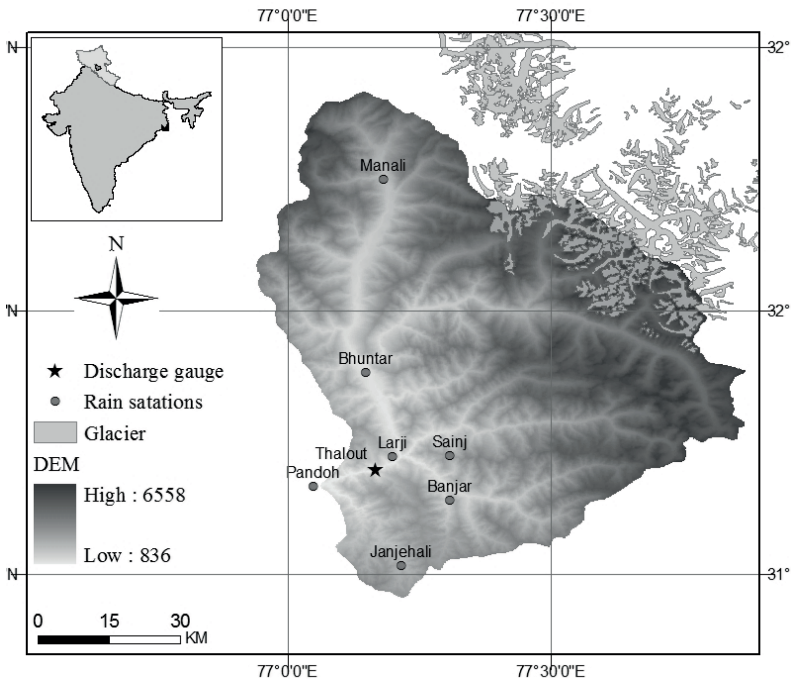

Fig. 1 Topographic map of Beas River basin in northern India with raingauge stations and glacier cover.

Data

Two global precipitation datasets and an observed raingauge dataset are used in this study. The first global dataset is satellite-based and covers the period 1996-2009. The data are constructed by combining a 0.25 and a 1° dataset: the Tropical Rainfall Measuring Mission (TRMM) 3B42 dataset (Huffman *et al.*, 2007), covering the area between 50°S and 50°N, and the GPCD 1DD dataset (Huffman *et al.*, 2001), covering the whole globe. The second global dataset (1958–2001) is the

WATCH Forcing Data (WFD). It has been developed by the Water and Global Change (WATCH) project as input for large-scale land-surface and hydrological models and is based on re-analysed dataset. Furthermore, seven raingauge stations (Fig. 1) were used for evaluating the performance of TRMM and WFD. In order to eliminate the regulation impact by Pandoh Dam, the daily discharge of Thalout station, which is close but upstream to Pandoh Dam, was used for model calibration. The upstream drainage area of gauge Thalout is around 5000 km^2. The overlapping period (1996–2001) of the three precipitation datasets (TRMM, WFD and raingauge) was chosen for this study.

METHODS

Statistical analysis method

The consistency and differences between the two global precipitation datasets, i.e. WFD and the satellite-based datasets were compared by three statistical and hypothesis testing methods. These are the Kolmogorov-Smirnov (K-S) test for checking whether two datasets have the same distribution pattern, and the Student's t-test and F-test for checking the equality of mean value and variance between the two global datasets. A 5% significance level was used for the tests. Details of the methods are given by Li *et al.* (2013).

GSM-WASMOD

The glacier module is only applied on the grid cells representing areas of glacier cover based on the information from the Global Land Ice Measurements from Space (GLIMS) Glacier Database (http://glims.colorado.edu/glacierdata/glacierdata.php) (Berthier, 2006; Raup *et al.*, 2007).

Glacier and snow melt module (GSM) To account for meltwater runoff from the glacierized parts in the catchment, we used a conceptual model to compute glacier mass balances and meltwater runoff. This glacier module uses gridded temperature and precipitation as input. It runs independently for each grid cell within the glacier outline on a daily time step. The model is applied to the period 1997–2001 and three preceding spin-up years using the data of 1996. It accounts for mass gain due to accumulation of snow S and mass loss due to meltwater runoff. A threshold temperature for snow T_s distinguishes between rain and snow. The transition occurs within a temperature interval ΔT where the precipitation linearly shifts from rain to snow. Thus,

$$S=\begin{cases} P \;\forall\; T \le T_s - \Delta T/2 \\ P \cdot [(T_s - T)/\Delta T + 0.5] \;\forall\; T_s - \Delta T/2 < T < T_s + \Delta T/2 \\ 0 \;\forall\; T \ge T_s + \Delta T/2 \end{cases} \tag{1}$$

where T and P are the temperature and precipitation input data from TRMM, WFD and gauge data, respectively. In this study the parameters are $T_s = 1$ °C and $\Delta T = 2$ K.

To account for the transition of snow to firn and ice, snow that has not melted away during summer is assumed to become firn on 1 October. Additionally, 20% of the existing firn is assumed to become ice, leading to an average transition time of 5 years from firn to ice. The conceptual model calculates melt M by using a temperature-index approach as used e.g. in Hock (2003) or Engelhardt *et al.* (2012):

$$M = DDF * (T - T_0) \tag{2}$$

where DDF is the degree day factor, T the air temperature and T_0 the melt threshold factor.

Besides melting, the model also accounts for refreezing processes due to retention of liquid water in the snow from rain or melt which infiltrates and refreezes in the snowpack. All liquid water is assumed to first fill the available storage which is dependent on the daily updated snow depth. Only when the storage is filled does runoff occur. The refrozen water melts as ice, when all snow has melted. Since the melt efficiency of firn and ice is higher than for snow, we used a degree-day-factor of firn and ice that is 15% and 30% higher than for snow, respectively. The firn starts to melt when the refrozen water has melted and finally (glacier) ice starts to melt, when the firn has melted away.

Non glacier hydrological module (WASMOD-D) The water and snow balance modelling system at macro scale (WASMOD-D) (Gong *et al.*, 2009; Widen-Nilsson *et al.*, 2009; Li, *et al.*, 2013), developed based on WASMOD (Xu *et al.*, 1996; Xu, 2002), was used in the study. The input data included daily values of precipitation, temperature and potential evapotranspiration. The daily WASMOD-D calculates snow accumulation and melt, actual evapotranspiration, and separates runoff into fast flow and slow flow.

Routing algorithm The aggregated network-response-function (NRF) routing algorithm developed by Gong *et al.* (2009) was used for routing the runoff calculated by GSM-WASMOD. The NRF method preserves the spatially distributed time-delay information in the 1 km HYDRO1k flow network in the form of simple cell-response functions for low-resolution grid (0.5°), where runoff is generated.

Model calibration

The GSM-WASMOD, which integrates GSM and WASMOD-D, has six parameters to be estimated (Table 1). Calibration was performed by searching for an optimal parameter set at the Thalout discharge station. In total 5000 parameter sets were obtained by Latin-Hypercube sampling with prior uniform distribution from initial parameter-value ranges (Gong *et al.*, 2009, 2011; Li *et al.*, 2013). GSM-WASMOD was run with the 5000 parameter sets and the resulting runoff-generation time series were used as input to the routing model. The wave velocity with the highest efficiency was chosen (Gong *et al.*, 2009). The runoff-generation parameters were then calibrated with the efficiency criteria, including the Nash-Sutcliffe coefficient (NS) (Nash & Sutcliffe, 1970) for model efficiency, which has a best possible value of 1; relative volume error (VE) which has a best possible value of 0; and the performance measure of flow-duration curve by using equal interval of flows ($R_{FDC,Q}$) (Westerberg *et al.*, 2011; Li *et al.*, 2013) which has a zero low bound yielding best performance with values close to 0.

Table 1 The parameters of GSM-WASMOD by driving TRMM, WFD and raingauge datasets.

Data	*a1*	*a2*	*a4*	*c1*	*c2*	*DDF_s*
TRMM	1.45	–2.52	0.33	2.09E-03	2.61E-05	4.36
WFD	2.81	–1.63	0.54	1.29E-04	4.00E-06	4.9
Raingauge	2.81	–2.31	0.54	5.17E-04	8.00E-06	4.08

Note: the snowfall temperature a_1, the snow melt temperature a_2, the actual evapotranspiration parameter a_4, the fast-runoff parameter c_1, the slow-runoff parameter c_2 and the glacier parameter *DDF_s* (degree day factor for snow).

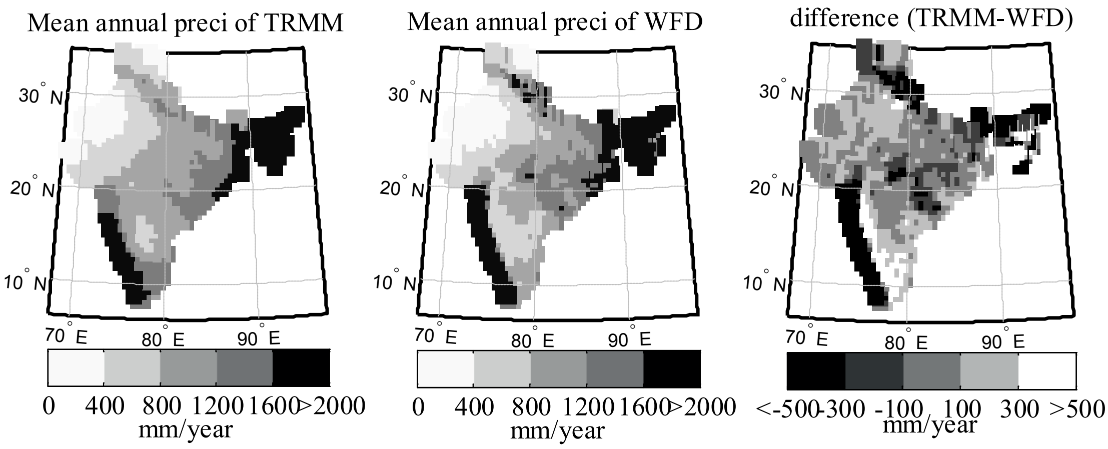

Fig. 2 Comparison of the spatial distribution of mean annual precipitation in India between the global datasets TRMM and WFD (1997–2001). (Note: diff. = TRMM-WFD).

RESULTS

Comparison of two global precipitation datasets

Figure 2 shows the difference in annual precipitation between the TRMM and the WFD datasets for 1997–2001. The spatial distributions patterns of annual precipitation for the period derived from these two datasets are quite similar, whereas the magnitude precipitation derived from the TRMM data is considerably less than that from WFD in the mountainous regions of northern India.

The results of the consistency test of the two global precipitation datasets in terms of their distribution patterns (KS test), long-term mean values (t-test) and variances (F-test) are shown in Fig. 3 for India. It shows that: (a) the hypothesis of the data belonging to the same distribution is rejected at the 5% significance level in most parts of the region; (b) in northwest India, north-central India and east India, long-term mean values of the two datasets are statistically equal at the 5% significance level, while this is opposite in the rest of India, and (c) the hypothesis of variances of each pair of grid data are equal is rejected at the 5% significance level in most parts of this region.

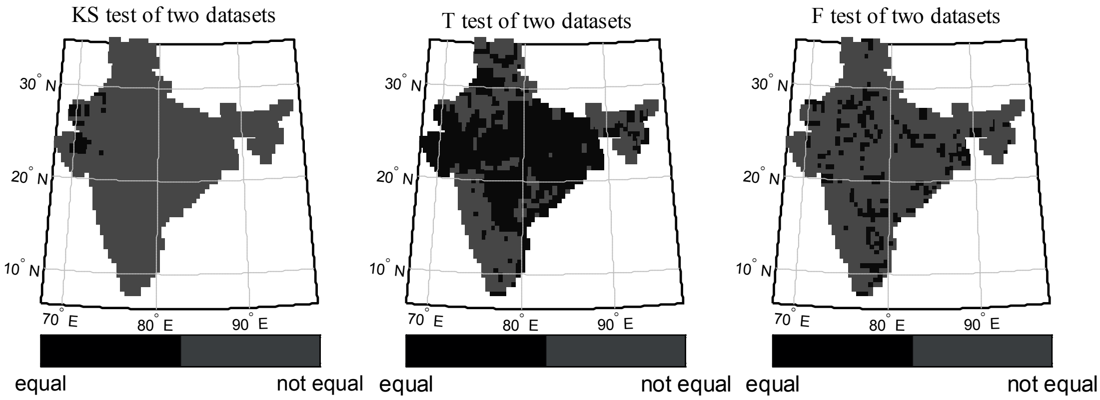

Fig. 3 Comparison of spatial distribution of general pattern by KS test, mean by student t-test and variance by F test of daily precipitation between TRMM and WFD datasets in India (1997–2001).

Model performance

The calibrated parameters of GSM-WASMOD driven by TRMM, WFD and gauge data are shown in Table 1. Table 2 shows the NS values and their associated VE and $R_{FDC,Q}$ values based on TRMM, WFD and raingauge datasets. The calibrated daily NS are 0.70 from TRMM, 0.68 from WFD and 0.74 from the raingauge data in the Beas River basin. The VE are –5% for both TRMM and WFD datasets and +4% for the raingauge data. Thus, in terms of the NS and VE, the gauge data performs best. In addition, the NS values including daily NS and monthly NS, derived from TRMM, are closer to the gauge rainfall and slightly higher than that from WFD. Furthermore, $R_{FDC,Q}$ from TRMM is the best of all datasets. This might be due to the low resolution of the hydrological model which averages the details from the gauge data. In addition, there are hardly any snow gauges in the Beas river basin due to the rugged terrain (Kumar *et al.*, 2007). The results from the global gridded satellite dataset are close to the results from the gauge data, when the model resolution is low (i.e. 0.5 degree in the study) and raingauge condition is poor.

Table 2 The calibration results of NS, VE and $R_{FDC,Q}$ in Beas River basin.

Data	Daily NS	Monthly NS	VE	$R_{FDC,Q}$
TRMM	0.70	0.89	–5%	0.90
WFD	0.68	0.88	–5%	1.01
Raingauge	0.74	0.89	4%	1.15

Water balance

The mean annual rainfall, evapotranspiration and glacier contributions to flow in the Beas River upstream of Thalout station are shown in Table 3. The mean annual runoff in Beas River basin simulated with GSM-WASMOD based on TRMM is slightly larger than that based on WFD, but smaller than that from gauge rainfall. The absolute annual evapotranspiration based on TRMM is quite close to that based on gauge rainfall compared with WFD. WFD overestimates glacier- and snowmelt due to the overestimation in precipitation. The average annual contribution of glacier- and snowmelt to flow from 1997 to 2001 is 2.63 km^3/year by TRMM, 3.18 km^3/year by WFD and 2.56 km^3/year by raingauge accounting for 46%, 56% and 41% of the total sreamflow, respectively. Compared with the previous study of Kumar *et al.* (2007), glacier and snow contributions estimated in this study are larger, which may be because the Thalout station used in this study is upstream of Pandoh station (used in the study of Kumar *et al.*, 2007). The observed data at Thalout are not affected by the water level of Pandoh reservoir.

It can be seen that the simulated discharge from gauge rainfall performs best especially for the peak flow in summer (Fig. 4(a)). WFD overestimates the glacier- and snowmelt while those from TRMM are closer to the results from the raingauge (Fig. 4(b)).

Table 3 The mean annual rainfall, evapotranspiration and snow-and glacier contribution to flow in the Beas River upstream of Thalout station from 1997 to 2001.

Data	Rainfall (km^3)	Evap (km^3)	Observed runoff (km^3)	Simulated runoff (km^3)	Rainfall contribution (km^3)	(%)	snow/ice melt (km^3)	(%)
TRMM	6.14	0.37	6.08	5.77	3.14	54	2.63	46
WFD	6.90	1.33	6.08	5.73	2.56	44	3.18	56
Raingauge	6.74	0.43	6.08	6.32	3.75	59	2.56	41

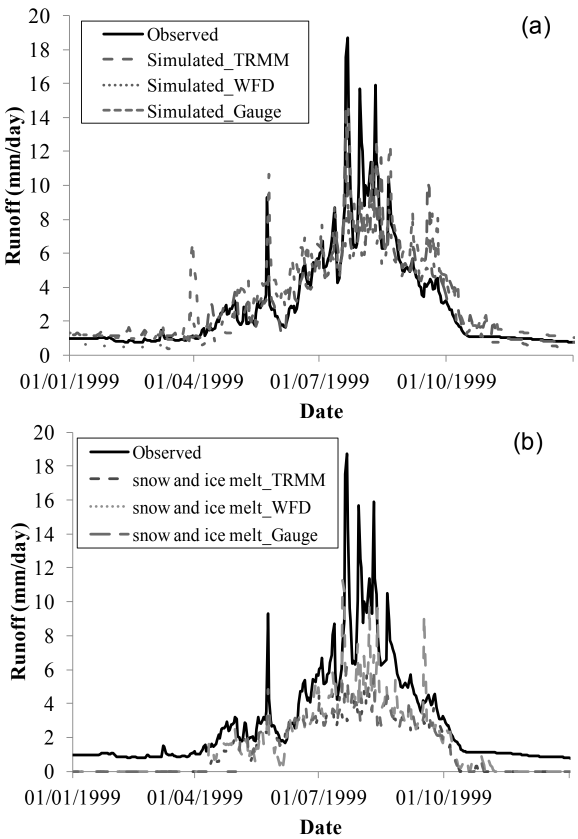

Fig. 4 The hydrographs of Thalout station simulated by GSM-WASMOD based on TRMM, WFD and Gauge: (a) Observed and simulated daily discharge; (b) Observed discharge and simulated glacier- and snowmelt.

CONCLUSIONS

The average annual precipitation in India (1997–2001) from TRMM is in general less than that from WFD, especially in the mountainous regions of northern India. More remarkable differences exist in the variances than in the mean values. Besides, application of the GSM-WASMOD in Beas River basin based on the three datasets produced satisfactory results with model performances in terms of NS coefficients around 0.7 and <5% VE. In addition, the average annual contribution of glacier- and snowmelt to streamflow (1997–2001) is 2.56 km^3/year accounting for 41% of total flow. In this study, the satellite-based rainfall dataset performs slightly better than the re-analysed dataset. Furthermore, the results indicate that the global satellite-based dataset might be considered as a potential data source for water resources estimates by driving large-scale hydrological models in small basins where the availability of gauged data is poor. However, more case studies are needed to confirm this assumption. The results of this study may also be useful for estimating the impact of climate change on hydrological response and providing insights on the selection and applicability of global weather datasets in other basins.

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