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Water balance in the complex mountainous terrain of Bhutan and linkages to land use

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ABSTRACT

Study Region: Bhutan

Study Focus: Located in the Himalayas with elevation ranging 100–7550 m and with an area equivalent to Switzerland, Bhutan has great biodiversity despite its small area. A monsoon-dominated climate causes generally wet summer and dry winter. Bhutan is highly dependent of climatic conditions for its developmental activities. Using multiple regression analysis we have established models to predict the evapotranspiration (ETo) and water balance and test the linkage to vegetation and land cover using meteorological data from 70 weather stations across Bhutan. Temperature-based ETo equations were evaluated in reference to the Penman-Monteith (PM) method and a calibrated Hargreaves (H) equation was used for computing the ETo. New Hydrological Insights for the Region. The calibrated Hargreaves equation gave good estimates of average daily ETo comparable to the PM ETo. The spatial variation in PM ETo is linked to variation in sunshine hours in summer and temperature in other seasons. Seasonal and annual ETo was mainly affected by elevation and latitude, which is linked to temperature and sunshine duration. Precipitation and water balance correlated positively with the Southern Oscillation Index (SOI) while ETo correlated negatively. Our models for predicting ETo and water balances performed clearly better than the global CRU gridded data for Bhutan. A positive water balance is found in broadleaf forest areas and small or negative water balance for coniferous forests.

1. Introduction

Bhutan is a small country with an extremely complex terrain located in the Himalayas, within the south Asian monsoonal region. About 60–90% of the total rainfall for Bangladesh, Nepal and Bhutan is from summer monsoon rainfall (Alam and Murray, 2005). The region has seen a significant change in climate over recent decades, as Himalayan mean annual temperature have increased with 0.06 °C y^{-1}, and average annual precipitation have increased with 6.5 mm y^{-1} during 1982–2006 (Shrestha et al., 2012). The rate of warming in Himalaya is thus observed to be greater than the global mean surface temperature increase of 0.8 °C over the past century, and also of the 0.6 °C increase of the last three decades from 1975 to 2005 (Hansen et al., 2006). This indicates that the Himalayas may be among the regions most affected by the ongoing and future climate change.

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IPCC (2014) reported that the impacts of climate change will in general be most adverse in developing countries and in resource-poor societies with little adaptive capacity and preparedness. Bhutan is one of the least developed countries in the world (Sovacool et al., 2012) and the effects of climate change are already perceived to affect agricultural activities (Wangchuk and Siebert, 2013). Bhutan's agriculture constitutes about 79% of the national livelihood, income and employment, while hydropower constitutes about 45% of the national government revenue (Meenawat and Sovacool, 2011). Both activities are highly related to the water balance and water resources, and the amount, timing and variability of water availability are thus of key importance for the economy of Bhutan. Accurate estimates of evapotranspiration are needed in complement to the existing network of precipitation data for assessing current water balance and for addressing the effects of climate change.

Evapotranspiration (ET) is the process of water transfer to the atmosphere by transpiration and evaporation from land. In combination with precipitation, ET determines the amount of water available for ecosystems, including water required for transpiration and thus for sustaining photosynthesis. The level and inter-annual as well as intra-annual variation in both precipitation and ET are therefore of key importance for the functioning of most ecosystems (Vicente-Serrano et al., 2012), not the least for agriculture and forestry. In the Asian region, this temporal variation in the water balance components is linked to both natural cycles in the climate, especially the El Niño Southern Oscillation (ENSO) influencing the monsoonal pattern, and to anthropogenic climate change which in many parts of the world is projected to lead to enhanced ET and increasing frequency of drought (Dai, 2013). The ENSO is a coupled ocean-atmosphere phenomenon centered in the tropical and subtropical Pacific region, strongly influencing precipitation patterns as well as wind systems (trade winds, monsoon) in the greater Pacific region (Philander, 1990).

The Penman-Monteith (PM) method (Allen et al., 1998) is commonly used as the reference for calculating reference evapotranspiration (ETo) from meteorological variables. This ETo estimation is taken as the evapotranspiration of a hypothetical crop with an assumed height of 0.12 m, a surface resistance of 70 $\mathrm{s\,m^{-1}}$ and an albedo of 0.23, closely resembling the evaporation from an extensive surface of short green grass of uniform height, actively growing and adequately watered (Allen et al., 1998). The PM method is well documented and it has been further developed to estimate ETo for different parts of the world (Droogers and Allen, 2002). However, in developing countries like Bhutan, the required range of meteorological variables to calculate ETo are mostly lacking in terms of quantity and quality and other avenues must be taken to estimate ETo. Hence, in such areas the use of other methods of estimating ETo is often necessary, in particular methods which only requires information on temperature that is more generally available from climate stations. This includes the Thornthwaite equation that uses mean temperature and day length, and Hargreaves (H) that only requires information on minimum and maximum temperatures (Allen, 1993; Hargreaves, 1994; Droogers and Allen, 2002).

We therefore aimed to assess the applicability of simplified temperature-based equations under the varying climatic conditions of Bhutan in reference to the PM method. Furthermore, our goal was to develop simple models that would allow prediction of the climatic variation in ETo and water balance across the complex terrain of Bhutan. Our final objective was to analyze the intra-annual and spatial variation in ETo and water balance as defined by the difference between precipitation and ETo, to evaluate the influence of large-scale climate phenomena (i.e. ENSO), and to assess how the water balance relates to the vegetation types in Bhutan.

2. Materials and methods

2.1. Data

The meteorological data for Bhutan was supplied by the Meteorology Division, Department of Hydro-Met Services (DHMS), Ministry of Economic Affairs, Bhutan. Data are available from 75 meteorological stations which are not irrigated and have the required vegetation around the stations as required by the PM model (Fig. 1); the majority of the data series ranged from 10 to 20 years. However, of the 75 weather stations available, 4 stations were excluded from our analysis due to the absence of geographical coordinates, elevation and/or sufficient amount of recorded data. Therefore, 71 stations with a total of 321,019 observations were available for further studies. These were all used in the H equation for ETo computations (for method description see below). However, due to poor recordings, missing data and short measurement periods, only data from 15 stations with a total of 41,597 observations with detailed data on temperature, sunshine duration, relative humidity and wind speed spanning from 3 to 13 years (Table 1) could be used for ETo calculations using the PM method (see below) and consequently used for calibration and validation of the H equation.

The relative humidity (RH) and annual precipitation averages were also calculated from this dataset. Daily meteorological data from each station, i.e. maximum and minimum air temperature, precipitation, relative humidity, number of sunshine hours, and wind speed, were compiled for the study. Missing, extreme or unreasonable values were detected by data screening and were excluded from the analysis. Sunshine hours of more than 14 h per days were excluded from analysis as the maximum possible daylight duration in Bhutan is 14 h. Bhutan's windiest places show average wind speed of 8–10 $\mathrm{m\,s^{-1}}$ at 20 m mast height, with maximum values as high as 12–15 $\mathrm{m\,s^{-1}}$ (Chophel, 2011). Thus, wind speeds exceeding 15 $\mathrm{m\,s^{-1}}$ were excluded from the analysis. When the maximum temperature was equal to or smaller than minimum temperature, data were excluded from the analysis. Years having data recorded for less than 360 days were also excluded from the analysis. The daily mean temperature was calculated as the average of maximum and minimum temperature. Data on station elevation, latitude and longitude used in our analysis were also supplied by DHMS along with meteorological data. Station

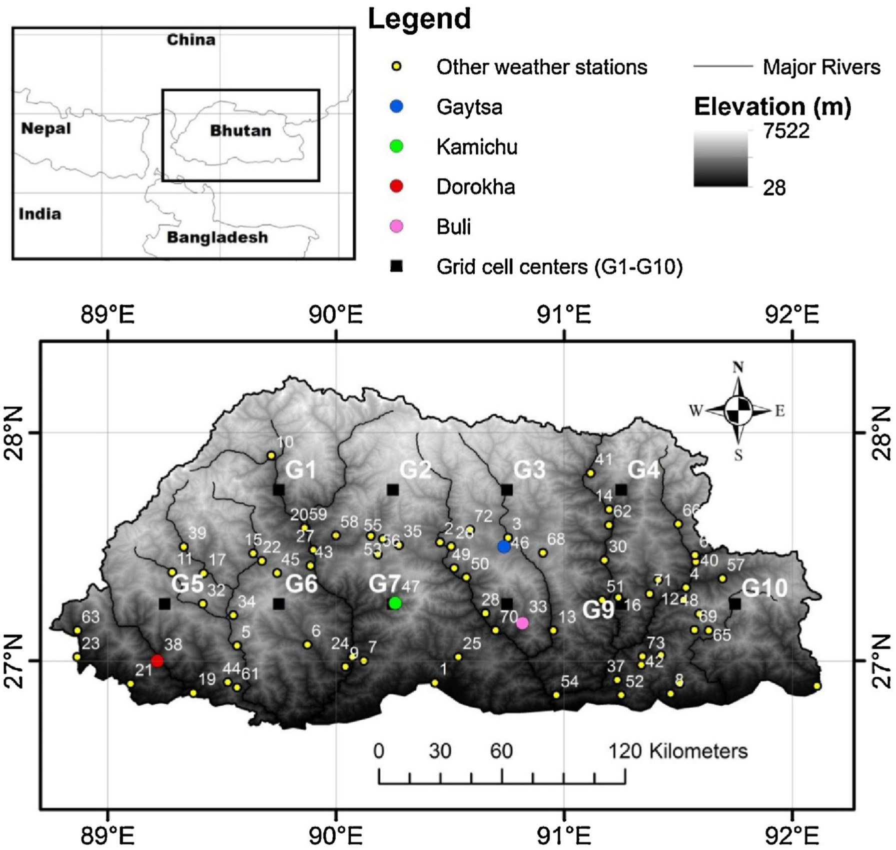

Fig. 1. Location, elevation and CRU grid cell points, weather stations and major river systems of Bhutan. The four stations illustrated in Fig. 5 are shown with different colors. (Map by Ugyen Dorji; data source: MOAF 1994).

Table 1
Meteorological stations with full data available for PM calculation.

Station	Elevation (m)	Longitude	Latitude	Period	Years included in analysis
Bhur	375	90.434	26.904	1998–10	8
Chamkhar	2470	90.755	27.540	2003–10	8
Damphu	1520	90.122	27.000	1996–10	13
Deothang	300	91.467	26.856	1999–10	7
Haa	2720	89.282	27.388	2008–09	2
Kanglung	1930	91.522	27.268	1996–10	13
Mongar	1600	91.238	27.278	2001–10	9
Paro/DSC	2406	89.420	27.383	1996–08	7
Pema Gatshel	1618	91.424	27.025	2007–10	4
Phuntsholing	220	89.375	26.860	2000–10	10
Semtokha	2310	89.675	27.438	1998–10	9
Sipsoo	550	88.866	27.017	2000–10	5
Trongsa	2120	90.505	27.502	2008–10	3
Wangdue	1180	89.901	27.487	2000–09	8
Zhemgang	1905	90.655	27.208	2000–10	8

slope of each station was calculated from the Aster Global Digital Elevation Model, ASTER GDEM V3, resolution 30 m with the help of ArcGIS 10.2 (ESRI, 2014).

We compared our estimated values of precipitation, ETo and water balance with the global monthly gridded ($0.5 \times 0.5^{\circ}$) data on precipitation and evapotranspiration from Climate Research Unit (CRU TS3.22), which were accessed from http://badc.nerc.ac.uk/data/cru/from 10 grid cells located between 27−−28°N and 89–92°E (G1–G10, Fig. 1). For comparison, we used spatial models based on our station observations to calculate ETo and water balance for 16 points equally spaced with $0.1 \times 0.1^{\circ}$ within each CRU grid cell, excluding points that fall on the boundaries of the cells.

To examine the relation between the water balance (precipitation—evapotranspiration) and land-use, the station water balances were overlaid the land-use map of Bhutan (LUPP dataset, Ministry of Agriculture and Forests, Royal Government of Bhutan) with the help of ArcGIS 10.2 (ESRI, 2014).

2.2. Estimation of ETo

The reference evapotranspiration (ETo) was computed by the FAO Penman-Monteith (PM) equation (Allen et al., 1998) as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}). The magnitude of the daily soil heat flux (G) beneath a fully vegetated reference surface is relatively small and therefore ignored here. Calculations were all done by the equations given in (Allen et al., 1998; Allen, 2000; Zotarelli et al., 2010)

The PM equation requires data on solar radiation, air humidity and wind speed, which was only available for few (15) stations and a relatively short period of time. The weather stations are not irrigated and the requirements for short vegetation are not always met. This does not directly affect the calculations of ETo using the PM equation, but there may be indirect effects through measured temperature and humidity. Since we had no measured data on net radiation (R_n) the R_n value was computed as follows (Allen et al., 1998; Allen, 2000; Zotarelli et al., 2010).

Net radiation (R_n, MJ m^{-2} day^{-1}) was calculated as

$$R_n = R_{ns} - R_{nl}$$

where R_{ns} and R_{nl} are net shortwave and longwave radiation (MJ m^{-2} day^{-1}), respectively.

Net shortwave radiation is calculated as

$$R_{ns} = (1\text{-}\alpha)R_s$$

where α is the albedo, which is set to 0.23 for the hypothetical grass reference crop, and R_s is the solar radiation calculated as

$$R_s = \left[a_s + b_s\frac{n}{N}\right]R_a$$

where n actual duration of sunshine (hour), N is maximum possible duration of sunshine or daylight hours (hour), and a_s and b_s are set to 0.25 and 0.50, respectively. R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}), which is calculated as

$$R_a = \frac{G_{sc}}{\pi}d_r\left[\omega_s\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right]$$

where G_{sc} is the solar constant (118.1 MJ m^{-2} day^{-1}), φ is latitude (radian), δ is solar declination, ω_s is the sun set hour angle, and d_r is the relative inverse distance between earth and sun.

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)]$$

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right)$$

where J is Julian day, i.e. number of the day in the year between 1(1 January) and 365 or 366 (31 December).

Net longwave radiation is calculated as

$$R_{nl} = \sigma\left[\frac{T_{\max}{}^4 + T_{\min}{}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left[1.35\frac{R_s}{R_{so}} - 0.35\right]$$

where σ is the Stefan-Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1}), T_{max} is daily maximum absolute temperature (K), T_{min} is minimum absolute temperature (K), e_a is the air vapour pressure (kPa), and R_{so} is the clear sky solar radiation (MJ m^{-2} day^{-1}), which is calculated as

$$R_{so} = [0.75 + 2 \times 10^{-5}Z]R_a$$

where Z is elevation of the climate station above sea level (m).

Three different methods for estimating ETo were tested for situations where only information on temperature was available. This included a simplification of the PM equation, the Thornthwaite equation and the Hargreaves equation. For

Table 2
Performance of Thornthwaite (1948), simplified PM and 3 different versions of the Hargreaves equations for Bhutan monthly evapotranspiration (ETo) as compared with PM calculated with all input variables for 15 weather stations (mm month^{-1}).

	Thornthwaite (1948)	Simplified PM	Hargreaves (1994)	Allen (1993)	Droogers and Allen (2002)
RMSE	26.5	27.0	25.8	35.2	31.1
MBE	−7.3	22.7	19.7	30.5	25.3
R^2	0.51	0.70	0.71	0.76	0.72

the simplified PM equation information in radiation, relative humidity and wind speed was obtained from other observations according to Allen (2000);

$$u_2 = \text{windspeedsubstitutedbyglobalwindspeedaverageof2 m}^{-1}.$$

$$e_a\ e_a = 0.6108 \exp\left[\frac{17.27\,T_{dew}}{T_{dew}+237.3}\right] \text{where } T_{dew} = T_{min} - 2\,^{\circ}\text{C}$$

$$R_S = k_{Rs}\sqrt{(T_{\max} - T_{\min})}R_a$$

where T_{max} is maximum air temperature (°C), T_{min} is minimum air temperature (°C), and k_{Rs} is an adjustment coefficient (0.16. 0.19) (°C$^{-0.5}$) for interior locations k_{Rs} = 0.16 and for coastal locations k_{Rs} = 0.19.

The ETo was calculated from the Thornthwaite equation (Thornthwaite, 1948) as follows:

$$\text{ETo} = 16(10\,T/I)^a$$

Where $i = (T/5)^{1.514}$, ETo is potential evapotranspiration (mm month^{-1}), T is mean monthly temperature, i is monthly heat index, I is the sum of heat index over the year (12 months), and

$$a = 0.000000675 * I^3 - 0.0000771 * I^2 + 0.01792 * I + 0.49239$$

The following three published versions of the Hargreaves (H) equations were tested in the study as they provided a better correlation with PM than the Thornthwaite equation and the simplified PM (Table 2).

Hargreaves (1994):

$$ETo = 0.0023(0.408R_a)(T_{mean} + 17.8)(T_{\max} - T_{\min})^{0.5}$$

Allen (1993):

$$ET_o = 0.003(0.408R_a)(T_{mean} + 20)(T_{\max} - T_{\min})^{0.4}$$

Droogers and Allen (2002):

$$ET_o = 0.0025(0.408R_a)(T_{mean} + 16.8)(T_{\max} - T_{\min})^{0.5}$$

where $T_{\max}$ is maximum daily air temperature (°C), $T_{\min}$ is minimum daily air temperature (°C), T_{mean} is mean daily air temperature (°C), and R_a is extra-terrestrial radiation (MJ m^{-2} day^{-1}).

In addition, we estimated the parameters (a–c) in the H equation based on data from the stations in Bhutan that also allowed comparison with PM ETo. The general H equation from above is rewritten as:

$$ET_o = a0.408R_a(b + T_{mean})(T_{max} - T_{min})^c$$

These model parameters were estimated by non-linear regression using solver in MS Excel 2010, and this H equation with estimated parameters is hereafter referred to as Study Hargreaves (SH).

2.3. Evaluation of ETo estimations

To explore possible causes for differences in ETo estimations between the PM and H methods, station and monthly average ETo values were calculated using different versions of H and PM based on (1) average daily data, (2) wind speed substituted by international average wind speed of 2 m s^{-1}, and (3) ETo computed by reducing daily RH by 10% as Bhutan RH is about 10% higher than the global land surface RH (Dai, 2006).

To assess the contribution of climatic variables to ETo variability for the 15 weather stations, average seasonal ETo (computed by PM with full climatic variables) of 15 weather stations were correlated with the corresponding seasonal stations mean temperature, sunshine hours, wind speed and relative humidity.

The root mean square error (RMSE), mean bias error (MBE) and coefficient of determination (R^2) were used to evaluate the H-approximated ETo values by taking the PM estimates as the reference (observed) values. These evaluation criteria were calculated as follows (Jacovides and Kontoyiannis, 1995; Tabari et al., 2013)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$

$$MBE = \frac{\sum_{i=1}^{n}(P_i - O_i)}{n}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(P_i - \overline{P}\right)\left(O_i - \overline{O}\right)\right]^2}{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}$$

where P_i and O_i are predicted and observed values respectively, $\overline{P}$ and $\overline{O}$ are averages of P_i and O_i and n is the total number of observations.

2.4. Statistical analyses

Daily ETo was calculated for all stations using the Study Hargreaves (SH) equation, which was subsequently averaged for each station for four different seasons DJF (winter; December-January-February), MAM (spring; March-April-May), JJA (summer; June-July-August), and SON (autumn; September-October-November). We similarly calculated precipitation for the different seasons and estimated the average seasonal water balance as the difference between precipitation and ETo. Other independent variables used in our analysis are elevation, latitude, longitude and slope.

The autoregressive properties of seasonal ETo were tested separately for the six stations (Chukha, Khomachu, Punakha, Samtse NIE, Sunkosh and Wangdue) with more than 20 years of data using the AUTOREG procedure of SAS with the Durbin-Watson statistic (SAS Institute Inc., Cary, NC). The trend for ETo was also tested in this analysis. Significant first-order positive autoregressive properties were found for all seasons varying from 3 to 4 stations with significant autoregressive responses for each season. One of the stations (Wangdue) showed significant increase ($P < 0.05$) in winter ETo, whereas ETo at Khomachu-lhuntse during both summer and autumn showed a significant decrease over time. In addition summer ETo at Sunkosh decreased significantly over time.

The significant autoregressive properties of ETo indicate linkages with other large-scale atmospheric cycles at multi-year scales. We analyzed the correlation between ETo, precipitation and water balance with the standardized Southern Oscillation (SOI) index (a measure of ENSO) taken from the NOAA archive of monthly time series (http://www.esrl.noaa.gov./psd/data/climateindices/list). The Pearson correlation coefficients were calculated for seasonal and annual values.

To analyze the relationship between ETo and water balance with geographical features in Bhutan, we applied a mixed linear model, using the MIXED procedure of the statistical program SAS (SAS Institute, Cary, N.C.). The response of seasonal and annual ETo and water balance to elevation, latitude, longitude and slope was tested. A stepwise procedure with backward elimination was used to exclude variables not contributing significantly to explaining variation in ETo and water balance. Station and year was used as random variables in the mixed model to capture the random structure of the data and to allow for any decadal patterns in the data. This was also done to increase the robustness of the parameter estimates and to allow for different time periods of the different station series. The linear models developed for ETo and water balance is hereafter referred to as study models (SM).

3. Results

3.1. Selection of Hargreaves equation

Table 2 shows the RMSE, MBE and R^2 values of different methods for estimating ETo, including Thornthwaite (1948), PM with missing values estimated, and three Hargreaves equations compared with PM full variables computed ETo for 15 weather stations. The different simplified methods have similar RMSE, but they differ in MBE showing that the Hargreaves methods and the simplified PM method overestimate ETo, whereas the Thornthwaite equation underestimates ETo. However, based on the R^2 values, a better correlation between PM estimates and the simplified equations is obtained for Hargreaves compared with Thornthwaite and simplified PM.

3.2. Calibration of the Hargreaves equation

Evapotranspiration calculated by the Penman-Monteith (PM) method gave an average ETo of 2.6 mm day^{-1} for the 15 stations, on average (Figs. 2 and 3). The Hargreaves (H) temperature-based equation optimized for the first eight weather

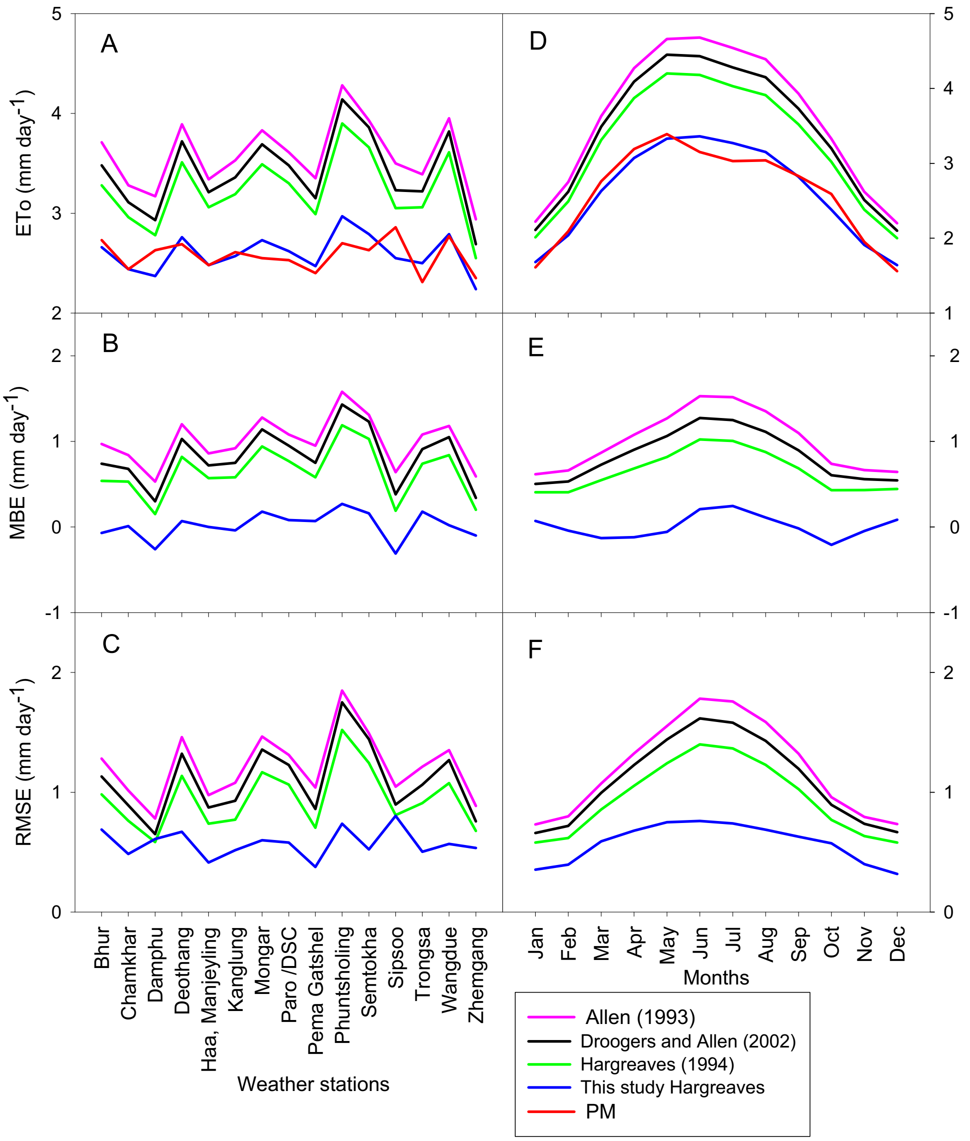

Fig. 2. Mean annual ETo (A), MBE (B) and RMSE (C) across the 15 weather stations with full datasets. D-F shows the same as A-C but for each month across all 15 stations.

stations (see Fig. 2, Table 1) in reference to PM equation gave the coefficients a = 0.0020, b = 33.9 and c = 0.296 (Fig. 3, Table 4). When validated for the remaining 7 weather stations with 17,149 observations, the H method produced very similar RMSE and R^2 as for the calibration with an insignificant MBE (Table 4).

Table 5 and Fig. 2 show the performance of different versions of the H equation, including our SH equation, in reference to the PM method. The published H equations calculated consistently higher ETo than the PM and SH equations. The RMSE and MBE values of the published H equations are quite high, considerably exceeding those of the SH equation. The highest ETo value, MBE and RMSE were obtained for the H equation by Allen (1993), followed by Droogers and Allen (2002), Hargreaves (1994) and lowest by SH.

The PM method uses wind speed as one of the determining variables. When the observed wind speed was replaced by an international average wind speed of 2 m s^{-1}, the PM calculated average ETo increased by around 20% (Fig. 3A, B). By reducing daily RH by 10%-points, ETo increased the average ETo with additionally >30%, totaling in excess of 50%. The PM estimated ETo is thus sensitive to both wind speed and relative humidity.

An average relative humidity of 78% was found for stations with annual precipitation less than 1000 mm and 81% with annual precipitation more than 1000 mm (data not shown). Regions with elevation greater than 2000 m had mean relative humidity of 76%, whereas this was 81–82% for stations with elevation less than 2000 m. The RMSE of the difference between

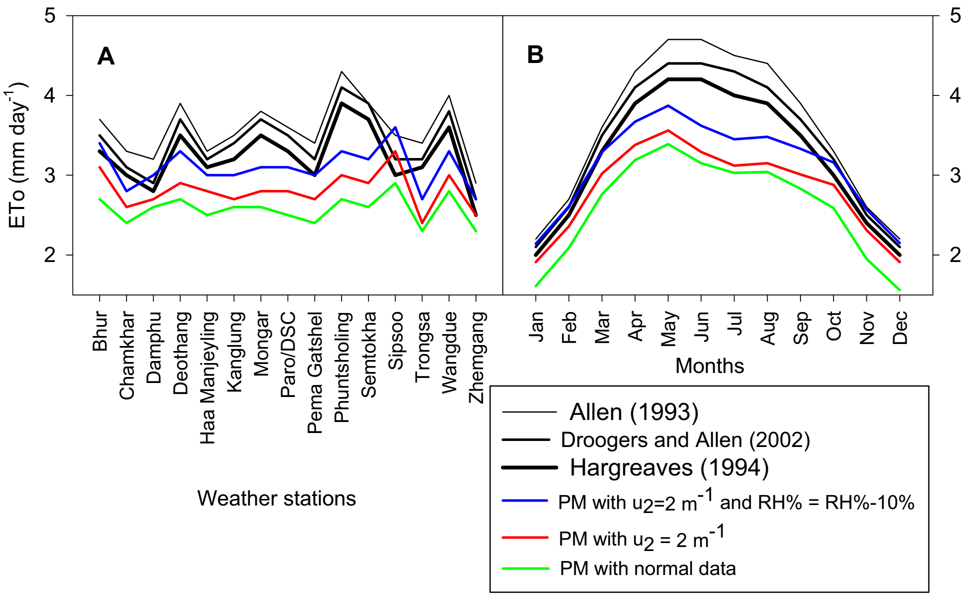

Fig. 3. The red lines show ETo by PM with daily wind speed (u2, ms-1) substituted by global average of 2 ms-1 (Allen, 2000) and blue lines show ETo estimated by PM with wind speed with global average and daily RH reduced by 10%-points. Results are shown for individual stations (A) and for each month as average over the stations (B).

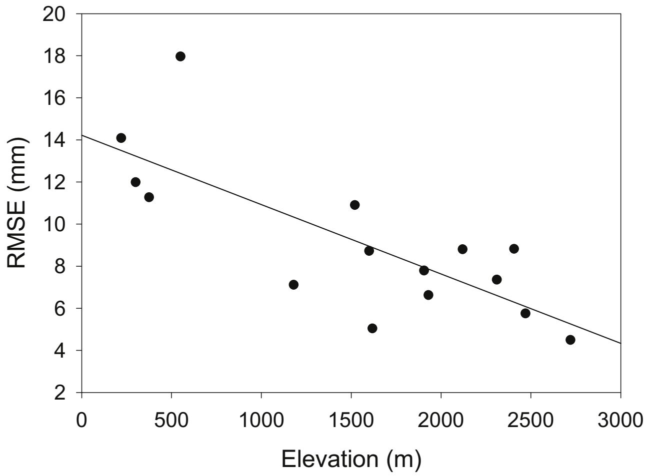

Fig. 4. RMSE of the difference between monthly estimated evapotranspiration using the modified Hargreaves and the FAO Penman-Monteith equation for stations with different elevation.

monthly estimated evapotranspiration by SH and PM equations declined with increasing elevation (Fig. 4) and MBE did not vary with elevation (data not shown).

3.3. *Evapotranspiration and water balance*

Table 3 shows that, other than June-July-August (JJA), temperature is the main contributor to ETo variability with highest R^2 values followed by wind and RH and finally by sunshine hours. But in JJA sunshine becomes the strongest contributor with R^2 value of 0.72, followed by RH, then wind and finally by temperature.

The water balance and precipitation vary considerably between months, seasons and geographical areas as illustrated in Fig. 5 for four stations, selected as examples. These four stations show large differences in annual water balance varying from 5065 mm for Dorokha to −544 mm for Kamichu. This difference is mostly caused by variation in precipitation; the precipitation at Dorokha exceeds 2000 mm for July, whereas the other stations show less than 180 mm per month, except Buli with around 500 mm of precipitation in July.

Table 3
Coefficient of determination (R^2) of mean seasonal ETo computed by PM with full variables for 15 weather stations correlated with corresponding station seasonal mean temperature, sunshine hours, wind speed and relative humidity (RH).

Season	Temperature (°C)	Sunshine (hours)	Wind speed (m^{-1})	RH (%)
DJF	0.64	0.03	0.18	0.19
MAM	0.50	0.07	0.33	0.01
JJA	0.01	0.72	0.17	0.39
SON	0.85	0.02	0.09	0.04

Table 4
Hargreaves evapotranspiration (ETo, mm day^{-1}) equation optimized its coefficients for 8 stations and validated for the remaining 7 weather stations.

Hargreaves equation	a	b	c	RMSE	MBE	R^2	n
Optimized for 8 stations	0.002	33.9	0.296	0.586	−0.008	0.57	24,448
Validated for remaining 7 stations				0.607	0.057	0.58	17,149

Table 5
Performance of different versions of the Hargreaves equation for Bhutan daily reference evaporation (ETo) as compared with Penman Monteith estimated evapotranspiration for 15 weather stations (mm day^{-1}). The analysis included 41,597 observations.

Source	a	b	c	RMSE	MBE	R^2
Hargreaves (1994)	0.0023	17.8	0.5	0.99	0.65	0.54
Allen (1993)	0.0030	20.0	0.4	1.26	1.00	0.56
Droogers and Allen (2002)	0.0025	16.8	0.5	1.15	1.00	0.54
This study	0.0020	33.9	0.296	0.59	0.01	0.57

Table 6
Relationship of seasonal and annual evapotranspiration (ETo) (mm) with station elevation (m) and latitude (°) analyzed by a mixed linear model. The root mean square error (RMSE, mm $season^{-1}$ and $annual^{-1}$) is also shown.

Season	Intercept	Elevation	Latitude[A]	RMSE
DJF	155	−0.023***	28.0**	11.1
MAM	252	−0.039***	65.0***	18.8
JJA	259	−0.036***	76.8***	22.7
SON	198	−0.027***	42.6*	16.3
Annual	865	−0.125***	211.1**	56.8

[A]Latitude expressed as latitude-(minus) 26°.
Significance levels: *0.05 > P > 0.01, **0.01 > P > 0.001, ***0.001 > P.

Table 7
Relationship of seasonal and annual water balance (mm) with station slope (°), station elevation (m), latitude (°), longitude (°) analyzed by mixed linear model. The root mean square error (RMSE, mm $season^{-1}$ and $annual^{-1}$) is also shown.

Season	Intercept	Elevation	Station slope	Latitude[A]	Longitude[B]	RMSE
DJF	−38	−0.018*	−0.2	−74***	1	43.6
MAM	1172	0.033	−3.7	−751***	−28	249.6
JJA	4377	−0.015	−14.5*	−1942***	−209*	249.2
SON	988	−0.029	−4.6**	−438***	−67**	191.6
Annual	6484	−0.014	−22.6*	−3178***	−308*	724.2

A: Latitude expressed as latitude-(minus)26°, B: Longitude expressed as longitude- (minus) 88°.
Significance levels: * 0.05 > P > 0.01, ** 0.01 > P > 0.001, *** 0.001 > P.

The statistical analysis of the relationship between ETo and geospatial factors showed that the variation in ETo is mainly due to a strong negative relation with elevation and to a small positive response to latitude. All the seasonal, winter (DJF), spring (MAM), summer (JJA) and autumn (SON), as well as the annual ETo showed statistically significant relation with elevation and latitude (Table 6). The water balance is strongly correlated with latitude, followed by longitude and station slope. Water balance of DJF and MAM showed statistically significant relationship with latitude, while JJA, SON and annual water balance showed additional significant relationship with longitude and station slope (Table 7).

Table 8 presents the Pearson correlation coefficient values between the SOI index and ETo, precipitation and water balance of the six weather stations with more than 20 years of data. SOI showed statistically significant correlations in the summer (JJA), autumn (SON) and annual water balance components. All the significant correlations between ETo and SOI are negative, indicating that a higher ETo is found during periods of lower SOI index (i.e. El Niño years), while all significant correlations with precipitation and water balance are positive, indicating that a high SOI index (La Niña years) enhances monsoonal rain and water balance in our study area. Several stations not showing any significant correlations between SOI and ETo indicate significant correlation coefficients of 0.43–0.68 with precipitation and water balance.

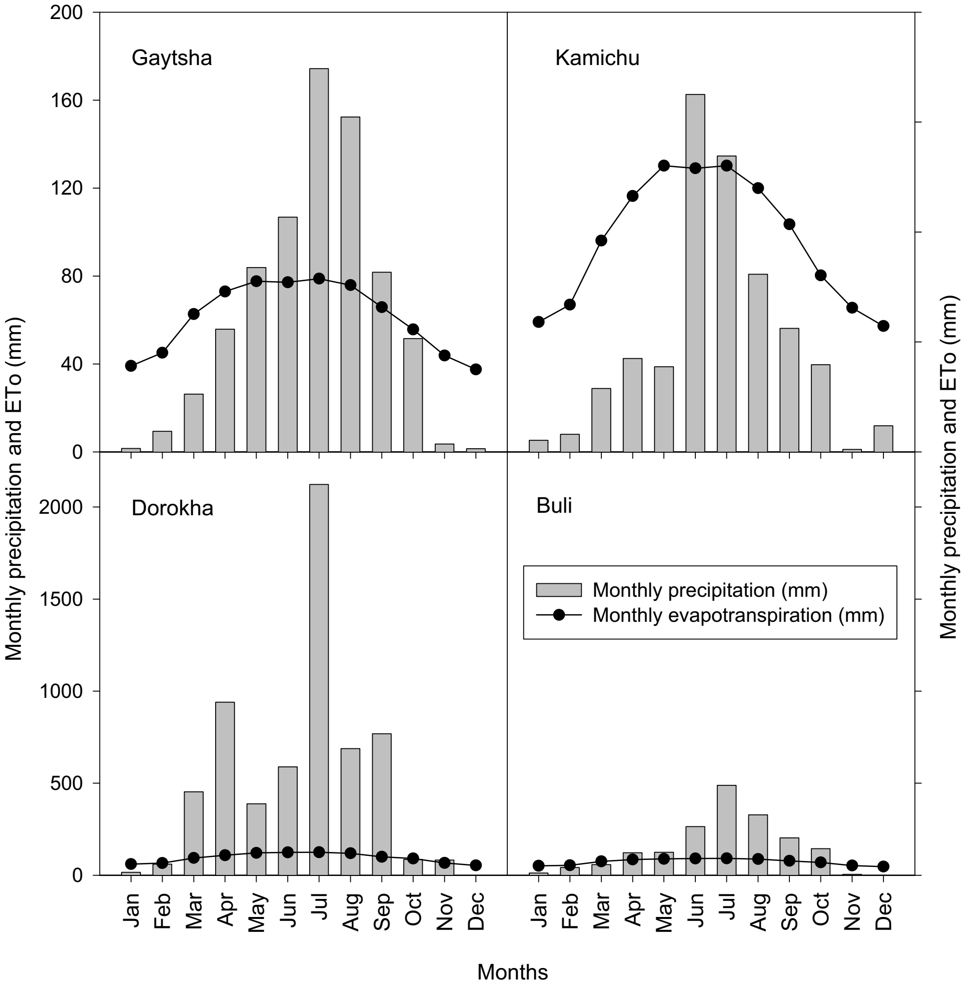

Fig. 5. Mean monthly evapotranspiration (dots) and precipitation (bars) for four stations(two stations with highest and lowest precipitation and two other with average precipitation) in Bhutan. Annual average water balance (precipitation minus ETo) for the stations are Gaytsa = 16 mm, Buli = 924 mm, Dorokha = 5065 mm and Kamichu = −544 mm.

Table 8
Pearson correlation coefficients between the SOI index and ETo, precipitation (P) and water balance (precipitation minus ETo (WB)) at six stations for each season and annually.

	Station	DJF	MAM	JJA	SON	Annual
ETo	Chukha	−0.12	−0.07	−0.02	0.11	−0.13
	Khomachu-lhuntse	−0.23	−0.20	−0.46*	−0.34	−0.45*
	Punakha	−0.19	−0.32	−0.03	−0.31	−0.47*
	Samtse NIE	−0.36	−0.09	−0.55**	−0.18	−0.47*
	Sunkosh	0.01	0.05	−0.26	−0.29	−0.26
	Wangdue	0.23	0.09	−0.23	−0.04	0.01
P	Chukha	−0.30	0.32	0.58**	0.15	0.63**
	Khomachu-lhuntse	−0.17	−0.07	−0.04	0.64**	−0.23
	Punakha	−0.19	0.04	−0.17	0.00	−0.37†
	Samtse NIE	0.06	−0.03	0.43*	0.34	0.36†
	Sunkosh	−0.31	−0.34	0.56**	−0.25	0.05
	Wangdue	−0.26	0.05	0.14	0.25	0.20
WB	Chukha	−0.20	0.33	0.58**	0.13	0.63**
	Khomachu-lhuntse	−0.02	−0.01	0.08	0.68***	0.03
	Punakha	−0.17	0.13	−0.17	0.11	−0.31
	Samtse NIE	0.14	−0.02	0.45*	0.35	0.39†
	Sunkosh	−0.28	−0.34	0.57**	−0.22	0.08
	Wangdue	−0.29	0.03	0.18	0.25	0.18

Significance levels: * 0.05 > P > 0.01, ** 0.01 > P > 0.001, *** 0.001 > P.

Table 9
Annual ETo (mm) and water balance (WB, mm) of CRU and study model predictions (SM) and their differences for different CRU grids (G1-G10, see Fig. 1).

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
Annual ETo CRU	720	766	768	822	711	705	830	844	932	855
Annual ETo SM	835	719	727	873	755	784	836	842	939	807
CRU-SM	−115	47	42	−52	−44	−79	−5	2	−7	48
Annual WB CRU	784	929	698	865	1229	1133	1416	1358	1313	1179
Annual WB SM	−366	−380	−621	−803	1350	1236	1110	1002	659	698
CRU-SM	1150	1309	1319	1669	−120	−102	306	355	654	481

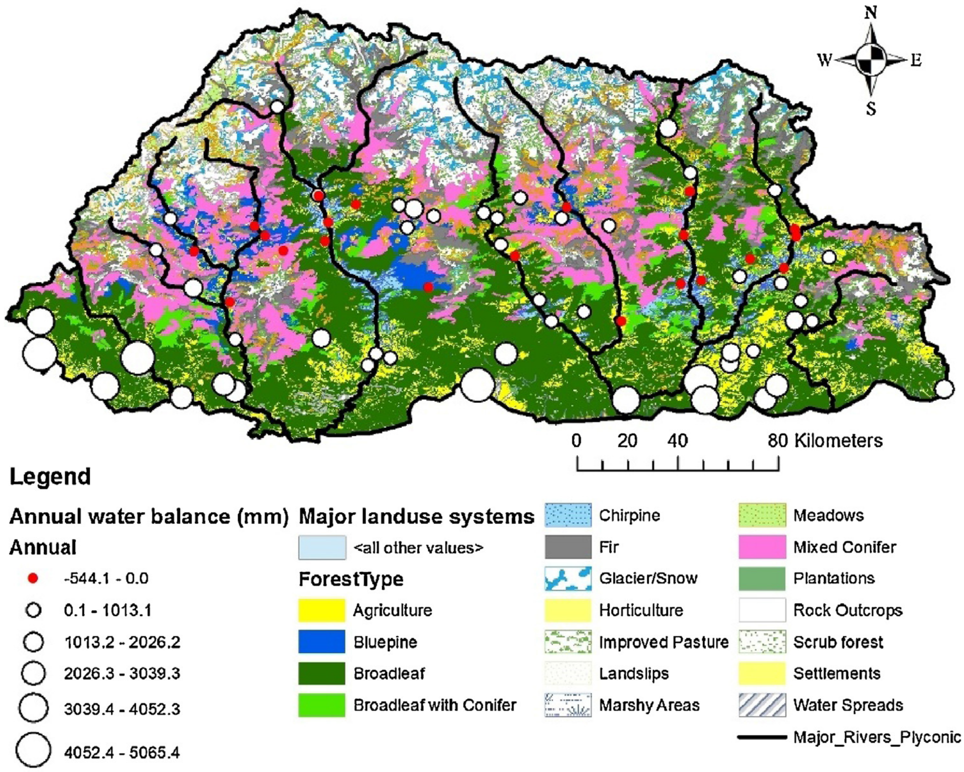

Fig. 6. Bhutan major land use systems and water balance at weather stations (after Dorji et al. (2016)).

Table 9 presents the annual evapotranspiration and water balance for 10 grid cells predicted by our study regression models (SM) and using average values from the CRU gridded data. Based on the differences between the CRU and SM ETo, the evapotranspiration show relatively stronger agreements between CRU and SM ETo estimations in grid cell G7, G8, and G9, than for other grid cells. The differences in estimated ETo between the two data sources vary little between cells, indicating that our SM equation of evapotranspiration agrees well with the CRU estimates.

The comparison of water balance between the CRU and SM estimates shows a much wider gap. Grid cells G5 and G6 show good agreement, cells G7 to G10 show weak agreement and the rest (G1–G4) show large discrepancies.

The mapping of annual water balance against major land-use systems (Fig. 6) shows that almost all positive water balances are found in the southern one third of the country, with decreasing values northwards. Hence, a positive water balance dominates in areas covered by broadleaf forest and mixed conifer forests, while very small or negative water balances are found in the valleys with mainly Chir pine forest. The northern east-west belt also seems to show a positive water balance, whereas the dry central east-west belt of Bhutan, dominated by coniferous forest, has very small or negative water balances.

4. Discussion

4.1. Optimisation of Hargreaves equation

The Penman-Monteith (PM) equation is considered the standard and foremost procedure for calculating average daily ETo (Jabloun and Sahli, 2008), and it is recommended for estimation of ETo across the world (Tabari et al., 2012). We therefore considered the ETo computed by PM with the full set data from the 15 weather station, where this was possible, as a reference record of ETo for Bhutan. However, for calculating the ETo across Bhutan a simpler method was needed that only requires information on temperature. Here we selected that Hargreaves approach, which was found to provide a better agreement with PM ETo than the Thornthwaite equations and PM equation with missing values estimated (Table 2).

The temperature-based Hargreaves equation of the present study (SH) was calibrated in reference to PM so that ETo for Bhutan could be computed without the full set data required for PM. RMSE of ETo between SH and PM was observed to be higher for sites from lower elevations than from higher elevations (Fig. 4). This could be due to higher and seasonally more variable RH at lower elevation sites (data not shown). This higher RH is likely related to the monsoonal climate with high rainfall and associated high humidity at these lower elevations during summer (Xie et al., 2006; Dorji et al., 2016).

In our study, the ETo computation by three separate published H equations all consistently overestimated ETo compared with PM. Shahidian et al. (2013) also noted that output from H models is inconsistent in many areas, despite the fact that it is intended for use in data-poor regions.

Substitution of the measured wind speed with the global average wind speeds of 2 m s^{-1} (Allen et al., 1998) increased ETo by about 20%, more so in the dry months than in wet months. Additionally reducing daily RH by 10%-points resulted in an overall increase of ETo by more than 50%, and again the increase is greater in dry than in wet months. Gavilán et al. (2006) found that the H model performs better in windy areas. Even when correcting for wind speed, the ETo difference between H and PM were large in the wet months (April–September). This is likely a results of the humid (high RH) conditions during the monsoon season, which reduces ETo. So the ETo difference between PM and H could be largely due to higher RH and lower wind speed than observed globally. ETo has also been observed to be sensitive to RH and wind speed in China (Fan and Thomas, 2013), and Zhang et al. (2011) found humidity as the most sensitive parameter for ETo variation. This shows that ETo varies due to variation in wind speed and relative humidity, which are not among those parameters which are directly used as input for the Hargreaves ETo model. Consequently, calibrating the H model in reference to PM appears to be necessary when used to estimate ETo in local settings such as for Bhutan.

Temperature is the main contributor to the Bhutan ETo variability other than June July and August (JJA) season with either lesser or no precipitation period (Dorji et al., 2016). Wind speed seems to be the next contributor in line and is followed by RH% and sunshine hours. However, sunshine hours becomes the strongest contributor in JJA when the precipitation is high (Dorji et al., 2016).

4.2. *Evapotranspiration and water balance*

The weather stations in Bhutan are not irrigated and do not have the required vegetation around the stations as required by the PM model. This may lead to higher temperature and lower RH, resulting in possible overestimation of ETo. Seasonally, this ETo overestimation could be higher in the dry winter non-monsoon season (Table 3). Moreover, spatially the ETo overestimation could be more severe in the east-west central belt of Bhutan as this region receives significantly lower annual precipitation than the southern and northern east-west belts of Bhutan (Dorji et al., 2016). Given that observed RH is in general high for the stations in Bhutan, we do not consider this possible bias to be severe, even though it may have led to slight overestimation of ETo and accordingly underestimation of the water balance.

Excluding the northern and southern edges of Bhutan, most of the area does not show large-scale spatial variation in seasonal (result not shown) or annual ETo (Fig. 1, Table 9). The variation in CRU and SH annual ETo across CRU grid cells vary from about 700 mm yr^{-1} to about 900 mm yr^{-1} and similar variations are seen in the other seasons (results not reported). This indicates that the evaporative demand is more or less the same throughout the region. The water balance varies greatly between stations in Bhutan, and this is therefore mainly caused by spatial variation in precipitation. Annual water balance varies from −544 mm to 5065 mm among the 71 weather stations, and annual precipitation varies from less than 800 mm to more than 6000 mm (Dorji et al., 2016). The climatic conditions therefore vary from extremely dry to extremely wet over relatively small distances in Bhutan, resulting in a large variation in hydrological regimes and associated vegetation types.

Annual and seasonal average ETo show a strong negative relationship with station elevation (Table 6). The temperature lapse rate of Bhutan is around 0.5° C per 100 m elevation change (Dorji et al., 2016), which explain the negative relationship of ETo with elevation since the SH model uses temperature as the main input for ETo computation. Diurnal temperature range did not show significant relation with station elevation (data not shown) and this may thus not have much effect in ETo calculation. ETo also showed a positive, but weaker, correlation with latitude. The reason could again be due to temperature where the mean temperature showed positive relationships with station latitude (Dorji et al., 2016). The error between PM and SH-computed ETo was greater at lower elevations having higher precipitation than the higher elevation sites with less precipitation (Fig. 4). Therefore, it is fortunate that relatively more accurate ETo and water balance information are needed in the negative water balance areas that are primarily located at the higher elevations with less precipitation and thus resulting in lower error.

The DJF and MAM water balance showed statistically significant negative relationship with latitude, and JJA, SON and annual showed additional significant effect of station slopes and longitude. Since water balance is directly related with precipitation, these relationships could be explained by spatial variation of precipitation. Bhutanese annual precipitation has shown an negative relationships with station slope, latitude and longitude, with the strongest relation with latitude (Dorji et al., 2016). Thus, the water balance variation is directly related to variation in precipitation where water balance also showed strongest relation with latitude (Table 7).

4.3. Inter-annual variation in the water balance and link to SOI

For Nepal less rainfall has been reported to be associated with negative SOI and more rainfall with positive SOI (Shrestha, 2000), and also India experiences floods in the cold phase (La Niña, positive SOI) and vice versa (Krishnamurthy and Goswami, 2000). In some weather stations our calculations also show that La Niña (positive SOI) correlate significantly to abundant monsoonal rain, while the opposite is the case for El Niño (negative SOI) periods (Table 8). However there are also some weather stations with either no relation or where this relation is more pronounced for autumn than for summer, indicating that the above mentioned relationship shows some local variation (Table 8).

If a positive SOI brings more precipitation to Bhutan then it will negatively affect ETo by increasing RH (Fig. 3A, B). Consequently, increased precipitation and lower evaporative demand under positive SOI result in an even larger effect on the water balance.

4.4. Comparison with gridded CRU dataset

The ETo prediction by our regression model (Table 6) show very close resemblance to the CRU ETo computed by the PM method, using CRU half degree gridded data with fixed monthly climatology for wind speed (Harris et al., 2014). The differences are less than 10% except in JJA with 13% deviation. However, the water balance predictions are very different for our interpolated model and that based on the CRU dataset with a systematic offset from north to south and from west to east. It is unlikely that this large difference, with systematic variations, may be explained by biases in the 71 weather stations used in our study as it would mean a persistent, systematic error in the recordings for all weather stations over the last two decades. Also, the temperature pattern derived from these stations show a very stable pattern that is primarily related to elevation and latitude (Dorji et al., 2016). We thus conclude that our models would be better options for prediction of the average water balance in Bhutan than using CRU data. Using CRU data will cause overestimation of the water balance and the water balance error will be very high, especially for the northern parts of Bhutan.

4.5. Vegetation patterns and water balance

The areas falling within the 10CRU grid cells in our study area are mostly occupied by dry coniferous forest types like Chir pine and mixed conifer forest (Fig. 6). Chir pine forest occur in areas of 832–2055 m elevation, 883–1718 mm annual rainfall and annual temperatures from 15 to 21 °C (Dorji et al., 2016). Our weather station data show positive annual water balances in the southern and northern belts of the country, while the central, east-west ranging belt shows very dry conditions, with low or even negative water balances. This is directly related to the distribution of precipitation across the country, where the heaviest precipitation (summer monsoon) falls in the southern belts and moderate precipitation (including winter monsoon) in the northern belts and least in the central east-west belt (Dorji et al., 2016).

4.6. Implications of changes in climatic conditions

With the projections of climate change, evapotranspiration and water balance will also be affected, partly though elevated temperatures enhancing temperatures and partly through changes in precipitation. Rising temperature will increase ETo and with an increase of the temperature by 1 °C annual ETo will increase by 30 mm (Shekhar, 2012). This may be expected to have greater consequences in parts of the country with a current low or negative water balance.

The significant link between SOI and our ETo, precipitation and water balance estimations infers that the water balance will decrease during El Niño periods but rise in La Niña periods. Climate change may impact on ecosystem structures in terms of species composition, their life history, geographical range, as well as structure and function of ecosystems (Mccarty, 2001). For instance, the alpine and nival vegetation (above 2800 m) respond faster to climate change (Cannone et al., 2007). With the large variation in water balance across Bhutan, such assessments not only need to include effects related to changes in temperature, but also effects on evapotranspiration and precipitation.

The above effects are not only relevant for Bhutan but may likely impact much of those regions of South Asia that are affected by monsoon precipitation, especially the mountainous regions of the Himalayas. In general the countries affected by the South Asian monsoon will receive increasingly abundant precipitation during in La Niña periods with increasing strength of SOI and the opposite could occur in El Niño periods with weakening strength of SOI (Krishnamurthy and Goswami, 2000; Shrestha, 2000). Water balance and evapotranspiration will vary accordingly and so will their impact on agriculture and ecosystems.

5. Conclusions

An optimized (parameters calibrated) temperature-based Hargreaves equation was used to estimate ETo across Bhutan, resulting in comparable values to those estimated using the Penman-Monteith (PM) method with a full set of meteorological data. In contrast, a standard temperature-based Hargreaves equation consistently computed average ETo values around 32% higher than the average ETo computed by PM.

The spatial variation in PM ETo is mainly controlled by temperature in DJF, MAM and SON and sunshine in JJA season. All annual and seasonal ETo estimations showed a statistically significant relationship with station elevation and latitude. Seasonal ETo can be computed in any study area with RMSE 11–23 mm. Annual water balance across station Bhutan varies from −544 mm to 5065 mm. Water balance is significantly affected by station slope, latitude and longitude. Seasonal water balance can be computed in any study area with RMSE 44–250 mm. The SOI was positively correlated with precipitation and water balance in Bhutan and negatively with ETo for some weather stations. The southern and northern east-west belts of Bhutan have a positive water balance and vegetation is dominated by broadleaf forest. The central east-west belt is dry with low to negative water balance and is characterized by coniferous forest.

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