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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 $s m^{-1}$ 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 $m s^{-1}$ at 20 m mast height, with maximum values as high as 12–15 $m s^{-1}$ (Chophel, 2011). Thus, wind speeds exceeding 15 $m s^{-1}$ 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