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A baseline regional evapotranspiration (ET) and change hotspots over Indian sub-tropics using satellite remote sensing data

Shweta[a,*], Bimal K. Bhattacharya[b], Akhouri Pramod Krishna[c]

[a] Center of Excellence in Climatology, Department of Physics, Birla Institute of Technology Mesra, Ranchi, India
[b] Agriculture and Land Ecosystem Division, Biology, Planetary Sciences and Applications Group, EPSA, Space Applications Centre (SAC) Ahmedabad, India
[c] Department of Remote Sensing, Birla Institute of Technology Mesra, Ranchi, India

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ABSTRACT

The annual water loss through evapotranspiration (ET) is an uncertain but significant component of India's water budget. The present study generated independent estimates of baseline annual ET, calibrated with in situ micrometeorological data over Indian sub-continent, using surface energy balance framework and satellite-based long-term thermal remote sensing, visible and near-infrared observations as the primary data sources. Thirty years' (1981–2010) of satellite-based ET estimates at 0.08° grid resolution were used to assess trend in regional ET, to find out change hot-spots and probable causes. Long-term collateral data, influencing ET, such as gridded (0.5° × 0.5°) annual rainfall (RF), annual mean surface soil moisture (SSM) at 25 km resolution from ESA scatterometers and annual mean incoming shortwave radiation from MERRA-2D reanalysis were also analyzed. Mean annual ET loss was found to be the highest for Indian cropland (890 Cubic Km) than forest (575 Cubic Km). Annual water consumption pattern over vegetation systems showed declining ET trend at the rate of -16 Cubic Km yr^{-1} upto 1995 during 30 years which might be due to declining rainfall and solar dimming. This was followed by increasing ET trend (34 Cubic Km yr^{-1}). During 2001–2010, irrigated cropland showed a steep increase in water consumption pattern with an average rate of 4 Cubic Km yr^{-1} while grassland and forest showed declining consumption patterns since 2003 and 2007, respectively thus showing crossover points of their consumption patterns with irrigated cropland. Four agriculturally important Indian eastern, central, western and southern states showed significantly increasing ET trend with S-score of 15–25 and Z-score of 1.09–2.9 during this period. Increasing ET in western and southern states was found to be coupled with increase in annual rainfall and SSM. But in eastern and central states, no significant trend in rainfall was observed though significant increase in ET was noticed. Region-specific correlation of annual ET with natural forcing variables was higher for incoming shortwave radiation as compared to rainfall. The increase in ET over irrigated croplands as well as over some of the Indian states could be due to increase in anthropogenic factors which need more detailed investigations in future.

1. Introduction

Evapotranspiration (ET) provides a link between energy and water budget in hydrological cycle. Estimation of large-scale ET using space-based observations has gained popularity with the advancement in optical and thermal remote sensing. The long term trends of ET and its forcing factors need to be understood and quantified under changing climatic conditions to address water security issues related to water rights, water allocation, crop water use efficiency, human consumption and industrial water use. Several researchers have studied the impact of ET under various climatic settings. Zeng et al. (2012) estimated annual ET over 59 major river basins for 2003–2009 using water balance approach. Where, globally averaged land ET was noticed to be about 604 mm $yr^{-1}$with a range of 558–4650 mm yr^{-1}. Non-significant trend in global land ET over the last decade were the outcome of this study.

Liu et al. (2013) used dynamic land ecosystem model (DLEM) to simulate ET over a period of 1901–2008 and observed significant decrease in ET over parts of basins of the Gulf of Mexico. Generally, ET decreased in western arid area while increase was observed in eastern part of their study area during the past 108 years. Long term ET was

Abbreviations: NOAA, National Oceanic and Atmospheric Administration; PAL, pathfinder AVHRR land; MODIS, moderate resolution imaging spectroradio meter; AQUA, aqua is the name of satellite initially known as aqua; MERRA, modern era retrospective analysis for research and application; INSAT, Indian National Satellite System; mmyr^{-1}, millimeter/year; ET, evapotranspiration; NFF, natural forcing factors; LULC, land use land cover

* Corresponding author at: Center of Excellence in Climatology, Department of Physics, BIT Mesra, Ranchi 835215, India.
E-mail address: shweta@bitmesra.ac.in (Shweta).

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characterized by (Gao et al., 2012) over the Haihe River basin in China for the period of 1960–2002 using the complementary relationship and the Thornthwaite water balance (WB) approaches. The annual ET was found to exhibit decreasing trends in most parts of the Haihe River basin.

Increasing ET over the past 50 years was reported (Walter et al., 2004) for several large basins across the conterminous United States. Though global ET showed an increasing trend in last two decades and no trend in the recent decade, contrasting trends were reported over different countries, river basins or even over different regions within a country. Moreover, most of the above studies have used water balance methods to estimate ET as residual of water budgeting and also the scale of ET estimates through this approach was coarser in nature.

Specific to Indian sub-tropics, there is a knowledge gap in having long-term trend on country-scale and region-specific finer resolution large-scale ET from surface energy balance and thermal remote sensing. The proper attention has not been paid by water resource managers to bring out independent and reliable estimates of baseline climatic annual ET over India's vegetated landmass using surface energy balance modeling (Narasimhan, 2008).

Goroshi et al. (2017) brought out inter-seasonal and inter-annual variability over India through trend analysis of monthly ET data generated by Zhang et al. (2010) using only 24 years' of NOAA monthly NDVI data (GIIMS : Global Inventory modelling and Mapping Studies) computed from AVHRR observations in optical remote sensing. The ET data were reported to be validated with 48 lysimeter stations of India Meteorological Department though monthly plots were shown for six stations only. The study has certain lacunae which are following: (i) thermal remote sensing has been found to be superior than optical remote sensing to estimate ET (Anderson et al., 2012**)**. Their study did not use any thermal remote sensing data. (ii) The study did not make use of a complete climate series of 30 years' satellite observations. (iii) IMD's lysimeter stations are reported to be 40 (32 gravimetric and 8 volumetric types) with lot of data discontinuity (IMD, personal communication). It was not clear how data gaps have been fulfilled; (iv) Several factors such as differences in height, growth and density of vegetation between the lysimeter and outside vegetation, interruption of deep percolation and horizontal flow components in soil within lysimeter tank, heat flux distortion caused by highly conducive steel walls, heavy rusting and corrosion in tanks due to exposure to soil, water and weather for long period of time can severely affect ET measurements (Farahani et al., 2007) using lysimeters. On the other hand, the tower-based ET flux measurements represent larger foot-print through surface energy balance measurements based on micrometeorological principles depending on the fetch ratios. The above study did not try to use any such micrometeorological measurements available over India. (v) The above study did not involve any new modelling approaches within surface energy balance framework with respect to net radiation, soil heat flux, evaporative fraction specific to Indian sub-tropics. (vi) Though it showed ET variability and trend over major land cover types, inter-play of natural and anthropogenic influences on ET as well as ET trend explicitly over irrigated cropland were not highlighted. Even model simulated soil moisture data were used instead of climatic series of satellite-based (ESA scatterometers) surface soil moisture data. (vii) All these resulted into large validation error of 38% on seasonal and 17% on annual scale with respect to lysimeter stations. No bias correction was made on satellite-based estimates before showing mean from long-term satellite-based ET estimates. (viii) Moreover, the study did not bring out the trend in volume of water consumption pattern in different cover types.

Space Applications Centre of Indian Space Research Organization (ISRO) established a network of 23 micrometeorological towers of 10 m height during the years 2008 to 2011 with on-field data transmission facility through Yagi antenna to INSAT Data Relay Transponder (DRT) and subsequent reception at an earth station (Bhattacharya et al., 2009; Singh et al., 2014; Eswar et al., 2013).These towers have multi-height sensors for recording air temperature, relative humidity and wind speed and direction, four-component net radiation, two-depth soil heat flux and three-depth soil temperature, rainfall with a sampling frequency of 5 min and averaged over 30 min. These towers were located over cropland, grassland, shrubland and young forest spread over northern, southern, eastern, western and central parts of India including north-eastern hill region, Thar Desert and Andaman and Nicobar Islands with a fetch ratio varying from 1:50 to 1:100.

The surface energy balance data from these towers provided unique opportunity to characterize ET behavior and develop scaling functions (Bhattacharya et al., 2013) for net longwave radiation, bias correction of incoming shortwave radiation flux, soil heat fluxes with respect to satellite-based thermal remote sensing data. In the present study, these in conjunction with long-term satellite thermal remote sensing data enabled to estimate evapotranspiration at 0.08 grid resolution through simplified model of surface energy balance whose accuracy has already been evaluated through separate studies (Mallick et al., 2009). The country scale ET data at 0.08° grid resolution were generated through a combination of micro-metrological measurements, scaling functions, optical and thermal remote sensing observations from NOAA series of satellites during 1981 to 2000 and bias-corrected MODIS ET product for the period 2001 to 2010 to complete a climatic series of 30 years. The objectives of the present study are (i) to characterize baseline annual climatic ET over Indian sub-tropical vegetation; (ii) to evaluate the volumetric annual water consumption rates over major land cover types in the sub-tropics over three decades with special emphasis on irrigated cropland in the last decade; and (iii) to assess long-term ET trend to detect change hot-spots and regions of influence of natural and anthropogenic forcing factors.

2. Study Area

Climatic conditions of India are marked by tropical rainy season in its southern and temperate in the northern part. It is home to an extraordinary variety of climatic regions, ranging from tropical in the south to temperate and alpine in the north towards Himalaya where elevated regions receive sustained winter snowfall. The nation's climate is strongly influenced by the Himalayas and the Thar Desert. Strong temperature variations in different seasons and south-west monsoon are one of the most important characteristic of Indian climate. Variability in the onset, withdrawal and quantum of rainfall during the monsoon season has also profound impacts on water resources, power generation, agriculture, economics and ecosystems in the country. Temperature ranges from about 10 °C in winter to about 32 °C in summer season (Attri and Tyagi, 2010). For this study, the Indian landmass extending from 5 to 38" N and 68 to 100" E has been considered as shown in **(**Fig. 1).

3. Data used

3.1. Satellite-based evapotranspiration (ET)

3.1.1. ET from NOAA-AVHRR for 1981-2000

Monthly ET was estimated at 0.08° spatial resolution in terms of latent heat flux as a residual of single-source energy balance approach. Here evaporative fraction and net surface available energy (Mallick et al., 2009) determined from optical and thermal remote sensing data in terms of NOAA Pathfinder AVHRR Land (PAL) data were used. The cloud-gaps were filled through harmonic analysis of land surface variables such as NDVI, Surface albedo and Land surface temprature (LST). It also used bias-corrected shortwave radiation flux reanalysis field and linear and nonlinear scaling functions (Bhattacharya et al., 2013) for net long wave radiation and soil heat fluxes.

3.1.2. MODIS ET data for 2001–2010

The MODIS ET Product commonly known as MOD 16 ET Product