Conference Proceedings Paper

Spatial variability of daily evapotranspiration in a mountainous watershed by coupling surface energy balance and solar radiation model with gridded weather dataset

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Published: date

Abstract: The ET determination using ground-based meteorological data does not adequate capture the spatial patterns of mass and energy fluxes in mountainous areas. In this work we evaluate the daily spatial distribution of ET over mountainous watershed in southeastern Brazil, by coupling Surface Energy Balance Algorithms for Land (SEBAL), global solar radiation (GSR) model and a gridded weather dataset (GWD). To estimate daily tilted GSR, we use the relation between terrain and sun angles over 24h integration time. Tests were performed in summer/wet (01/12/2015) and winter/dry (09/25/2015) periods to evaluate the seasonal differences in ET over tilted surfaces. The results indicated different spatial patterns of daily ET on the watershed in each period. In summer, ET was 9.8% higher on slopes facing the South, while in winter ET was 10.6% higher on slopes facing North and East. High variability in daily ET was found on steeper slopes (above 45°), in both periods. The notable ET spatial heterogeneity indicate the complex partitioning of mass and energy fluxes from different terrain angles, which may influence hydro-ecological processes at local scale. The presented approach allowed a more detailed capture of the spatial variability of ET in a mountainous watershed with scarcity ground-based data.

Keywords: SEBAL; mountainous areas; evapotranspiration.

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1. Introduction

On mountainous and heterogeneous landscapes the evapotranspiration (ET) estimation using remote sensing becomes more complex due, mainly, to the difficulties to estimate net radiation in different slopes and terrain azimuths, and the uncertainties regarding energy and mass transfer processes, such advection and local wind flow.

Some authors have developed techniques to evaluate the influence of topography on actual ET estimate by remote sensing [1], as well as on reference ET [2] and on surface energy fluxes [3]. In these applications the correted net radiation for tilted surfaces was obtained from parametrizations using global solar radiation (GSR) modelling, considering different slopes and azimuths of terrain.

At watershed scale the ET estimate using ground meterological stations does not adequate capture the spatial patterns of mass and energy fluxes. The required ground-based meteorological data of the most used remote sensing models for ET retrieval may affect the spatial accuracy, especially in areas with high weather/environmental variability. This issue was addressed by [4] in an approach using raster meteorological data as input to SEBAL model.

With the availability of gridded weather datasets (GWD) based on atmospheric reanalysis and numerical weather forecast it became feasible to incorporate the spatialized meteorological information into evapotranspiration models in areas with scarcity ground data. The Global Land Data Assimilation System (GLDAS) represents the state of the art of GWD built using advanced land surface modeling and data assimilation techniques that support several water resources applications [5].

In this work we evaluate the daily spatial distribution of ET over a mountainous watershed in southeastern Brazil in summer/wet and winter/dry periods, by coupling Surface Energy Balance Algorithms for Land (SEBAL) and global solar radiation (GSR) model, adapted for tilted surfaces, using the gridded dataset from GLDAS as meteorological input.

2. Experiments

2.1. Study area

This study area was the Paraibuna watershed, in southeastern region of Brazil (Figure 1).

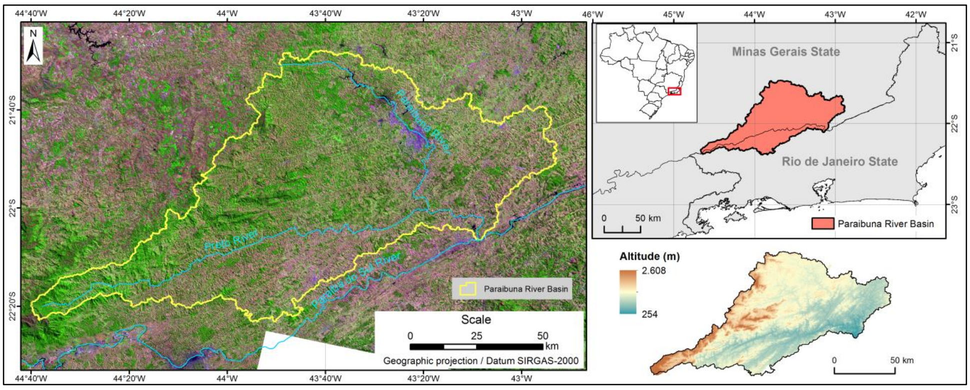

Figure 1. Location of the Paraibuna watershed.

This watershed is a tributary of the Paraiba do Sul river and covers an area of approximately 8,500 km², of wich 64% are covered by pasture and croplands, 34% by forests and only 1.2% by urban areas [6]. The regional climate is mild-mesothermic with an annual average temperature of 21° Celsius and total annual rainfall ranging from 1,000 mm to 2,000 mm. Rugged terrain (slope > 25°) occurs in 14% of basin, and altimetric amplitude is about 2,300 meters, with minimum and maximum altitudes of 254 m and 2,608 m, respectively.

2.2. Materials and Methods

2.2.1. Datasets

Due the studied watershed covers two Landsat-8 scenes, the images were selected from 4 dates, on 12/01/2015 (summer) and 25/09/2015 (close to winter) of path/row 217/75 and 19/01/2015 (summer) and 31/08/2015 (winter) of path/row 218/75. Surface reflectance and thermal data was obtained from Landsat Collection Level-1 and Level-2 products, respectively, through EarthExplorer website (https://earthexplorer.usgs.gov/). These scenes were selected because of low cloud cover, less than 5%.

The input data set used in this study is summarized in Table 1.

Table 1. General characteristics of input datasets used in the study.

Variable	Unit	Source	Spatial res.	Temporal res.	Provider
Surface reflectance	-	OLI/Landsat-8	30m	16 days	USGS
Thermal radiance	*	TIRS/Landsat-8	30m	16 days	USGS
Altitude	meters	SRTMGL1	30m	-	USGS
Temperature	Kelvin	GLDAS-2.1	~25km	3h	NASA
Specific humidity	Kg/Kg	GLDAS-2.1	~25km	3h	NASA
Wind speed	m/s	GLDAS-2.1	~25km	3h	NASA
Pressure	Pa	GLDAS-2.1	~25km	3h	NASA
Land Cover	class	MAPBIOMAS	30m	Yearly	MAPBIOMAS

* Units in: Watts/(m^2. srad.μm)

2.2.2. GLDAS data preparation

The 3-hourly GLDAS data were downloaded from GES DISC website (https://disc.sci.gsfc.nasa.gov/), covering the same dates of Landsat-8 images. The GLDAS data preparation strategy was composed of three main tasks: 1) Temporal fit to Landsat overpass; 2) Daily aggregation and 3) Spatial resample to 30m resolution.

The temporal fit to Landsat overpass time (aprox. 13 UTC) was performed through a linear interpolation of the GLDAS data at 12h and 15h UTC.

Daily aggregation was performed by simple averaging the 3-hourly GLDAS files per day (8 files) for each variable. The method used for spatial resampling to 30m resolution was the bilinear interpolation. For simplification purposes, spatial downscaling methods were not used.

2.2.3. Solar Radiation Model

To estimate daily tilted GSR (GSR_T), the HDKR (Hay, Davies, Klucher and Reindl) solar radiation model was applied for instantaneous calculations, assuming clear sky conditions, according to [7] and [8]. To estimated the 24-hour average of GSR_T, the instantaneous values computed from 9h to 21h UTC were numerically integrated.

2.2.4. SEBAL model adaptations for tilted surfaces

The implementation of SEBAL, adapted for tilted surfaces, was performed basically by modifications in the Surface albedo (α), Incoming shortwave radiation ($R_{S\downarrow}$) and surface temperature (Ts), as described next. These parameters are critical inputs in energy balance formulations. Details about theoretical and operational steps to compute each component of energy balance equation in SEBAL can be found in [9].

The surface albedo (α) was computed through the integration of OLI/Landsat-8 surface reflectance bands using the approach described in [10]. This approach was applied over the terrain corrected OLI bands by the SCS+C algorithm [11] to derive the topographically corrected surface albedo (α_T).

The incoming shortwave radiation ($R_{S\downarrow}$) used in SEBAL was the instantaneous tilted GSR computed by HDKR model instead of the general equation presented in [9].

The surface temperature from TIRS/Landsat-8 thermal data (band 10) was corrected, due temperature gradient caused by elevation, using a lapse rate coefficient derived by a linear regression between the surface temperature (Ts) and the pixel altitude.

The 24-hour actual evapotranspiration (ET_{24}) was calculated using a reference ET fraction (ETrF) at time of Landsat overpass to extrapolate the instantaneous estimates of ET by SEBAL to values for daily periods. The ETrF and ET_{24} was computed by equations 1 and 2:

$$ETrF = ET_{inst} / ET_0 , \quad (1)$$

$$ET_{24} = ETrF \times ET_{0\ 24h} , \quad (2)$$

Where ET_{inst} is the hourly ET estimated by SEBAL, ET_0 and $ET_{0\ 24h}$ are the hourly and daily alfafa reference evapotranspiration computed by ASCE-Penman Monteith equation [12], respectively. Both in the ET_0 and $ET_{0\ 24h}$ computations were used meteorological data from GLDAS and solar radiation from the tilted GSR model.

3. Results

3.1. Spatial distribution of $GSR_{T\ 24}$ and ET_{24} over the terrain angles

In Paraibuna watershed the average value of $GSR_{T\ 24}$ obtained from the solar radiation model was 313.6 $W.m^{-2}$ in summer, ranging from 78.9 to 346 $W.m^{-2}$. In winter the average value was 264.4 $W.m^{-2}$, ranging from 31.7 to 306 $W.m^{-2}$. The average ET_{24} obtained from the modified SEBAL, in summer and winter, were 4,98 and 4,07 $mm.day^{-1}$, whereas the maximum average values were 5.48 and 5.10 $mm.day^{-1}$, respectively.

Table 2 and 3 shows the distribution of Mean and Coeficient of Variation (CV) of ET_{24} take into account different slopes and azimuths of terrain in the two evaluated periods.

Table 2. Mean and CV of ET_{24} on different terrain slopes over Paraibuna watershed.

Terrain Slope		0 to 15°	15 to 30°	30 to 45°	above 45°
Summer	Mean (mm)	5.18	4.85	4.35	2.74
	CV (%)	2.10	6.04	12.82	24.95
Winter	Mean (mm)	4.78	4.35	3.71	2.43
	CV (%)	1.09	3.87	18.06	43.61

Table 3. Mean and CV of ET_{24} on different terrain azimuths over Paraibuna watershed.

Terrain Azimuth		315 to 45° (N)	45 to 135° (E)	135 to 225° (S)	225 to 315° (W)
Summer	Mean (mm)	4.31	4.85	4.94	4.24
	CV (%)	17.87	12.56	11.64	23.62
Winter	Mean (mm)	4.35	4.45	3.84	3.75
	CV (%)	9.52	9.48	26.99	28.58

On steeper slopes (above 45°) was found the higher variability (higher CV) of ET_{24}, with CV of about 25% for summer and 43.6% in winter. In contrast, these areas showed the lowest mean values of ET_{24} with 2.7 and 2.4 $mm.day^{-1}$ in summer and winter, respectively.

According to Figure 2 below, the $GSR_{T\ 24}$ and ET_{24} spatial distribution on the watershed showed differences between the two periods, especially in areas with slopes above 45°. In summer the GSR_{T24} and ET_{24} distribution was more homogeneous with slightly higher values in Southern slopes, with differences of 9.8% for ET_{24}. In contrast, in winter the highest ET_{24} values occurred on slopes facing the North and East, while lowest ET_{24} values occurred on South and West, with average differences about 10.6% and 11.9%, respectively.

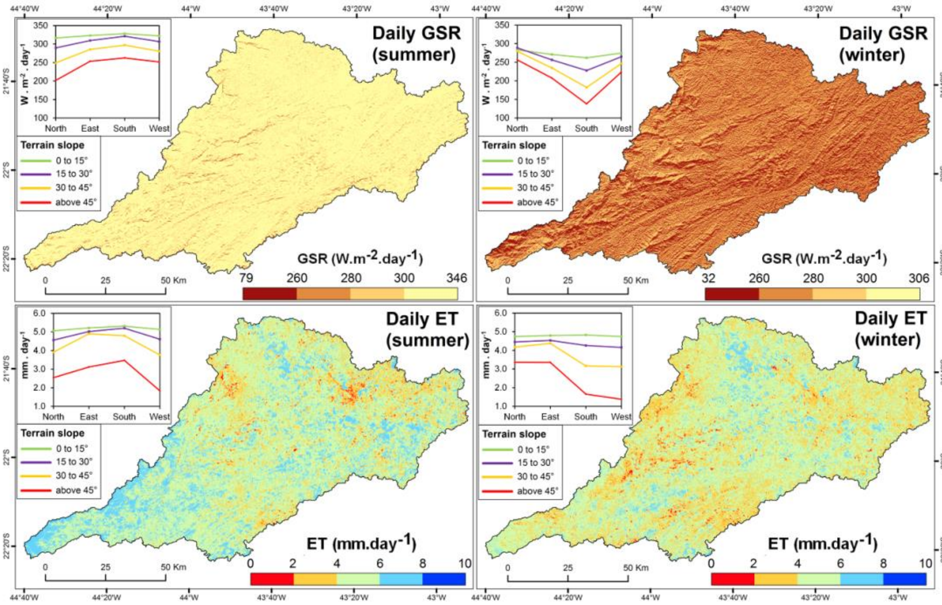

Figure 2. $GSR_{T\,24}$ and ET_{24} maps in summer (Left) and winter (Right) on the Paraibuna watershed.

3.2. Statistical relations between terrain angles, $GSR_{T\,24}$ and ET_{24}

As shown in the plots of figure 3 below, both $GSR_{T\,24}$ and ET_{24} values showed higher relationship with the terrain slope values, with negative correlation coeficient (r) of -0.82 (R^2 0.68) and -0.62 (R^2 0.39) for summer, and -0.54 (R^2 0.29) and -0.67 (R^2 0.45) for winter, respectively. In contrast, the correlation coeficient between $GSR_{T\,24}$ and ET_{24} with the terrain azimuth values were weaker in both periods, with R^2 less than 0.1. In this selected areas was found a significant relation between $GSR_{T\,24}$ and ET_{24} values, with a correlation coeficient of 0.68 (R^2 0.47) in summer and 0.65 (R^2 0.42) in winter.

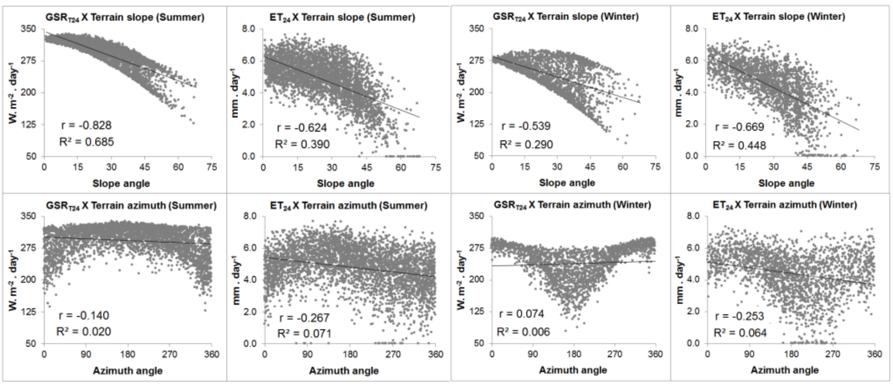

Figure 3. Distribution plot of $GSR_{T\,24}$ and ET_{24} in relation to the Slope (Top) and Azimuth (Bottom), in non-flat forested areas (Slope > 1° and NDVI > 0.7).

4. Discussion

The notable spatial difference in $GSR_{T\,24}$ and ET_{24} between the two evaluated periods can be explained in a way, by the significant influence of topography, mainly the slope angle, as showed by high coefficients of variation in slopes above 45 ° and the R^2 of distribution plots. In general, ET values follow the spatial distribution of GSR. However, average ET in slopes facing West showed inconsistent with average GSR values, especially in winter. This can occur due to some limitation in extrapolating from instantaneous to daily values using the reference ET fraction (ETrF) at time of

Landsat overpass in mountainous areas. Another source of uncertainties is the relationship between the terrain angles and the land surface temperature (LST). Future research should also investigate the impact of topography on remotely sensed LST and ETrF and their influence on ET estimation over this watershed. In addition, future field validation campaigns may better evaluate the preliminary results of this study.

5. Conclusions

In this work the SEBAL adaptations for mountainous areas and the integration with a Solar radiation model for tilted surfaces and the GLDAS meteorological dataset allowed a detailed capture of the spatial variability of ET in the Paraibuna watershed without the use of ground data. The analysis take into account different slopes and azimuths of terrain, wich can improve ET analysis in a mountainous basins with scarcity ground-based data.

Conflicts of Interest: The authors declare no conflict of interest.

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