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Estimation of evapotranspiration for ungauged areas using MODIS measurements and GLDAS data

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Abstract

On base of Priestley-Taylor Equation combined with the Ts/NDVI space, namely, surface temperature-Normalized Difference Vegetation Index feature space, MODIS (Moderate Resolution Imaging Spectroradiometer) products and GLDAS(Global Land Data Assimilation System) meteorological data are introduced to calculate evapotranspiration (ET) in ungauged basins. The whole procedure is independent of field data. It was then applied to Tekesi River Basin to estimate evapotranspiration from 2006 to 2009.Validation has been made by comparing the estimated ET with the Bowen Ratio measurements from 15th, August to 15th, September in 2009 at Zhaosu site, which shows good agreement between the estimated ET and the observed.

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Keywords: surface temperature; NDVI; evapotranspiration; Temperature Vegetation Dryness Index

1. Introduction

Evapotranspiration (ET) plays an important role in global energy exchanges and water cycle. And it is a key factor in the fields of geography, meteorology, hydrology and ecology. The traditional models for ET estimation mostly depend on in situ meteorological data, e.g. air temperature, air humidity, and wind velocity. However, provision of such data is quite problematic. First of all, in the economically underdeveloped regions, there is little infrastructure and few resources for continuous monitoring of the

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data, resulting from the poor economic conditions; secondly, in the high-cold and remote regions, restrained by the severe environments, it is difficult to set up and maintain stations. Thirdly, because of the differences and obstacles in related policies among different countries and regions, it is of great difficulties to found a common effective data sharing platform, thus, some existing observations are not completely available. Furthermore, even for the regions without the above problems, it is still hard to get enough field data to satisfy the estimation at region scale. Thus, it is of great significance to find a way to estimate ET for regions lack of related field data.

A scatter plot of remotely sensed Ts and NDVI often results in a triangular shape (Price, J.C.[1], Carlson et al.[2]), or a trapezoid shape (Moran et al.[3]) if a full range of fractional vegetation cover and soil moisture contents is represented in the data (Jiang and Islam[4]).This Ts/NDVI space can reflect the surface temperature, vegetation and soil water conditions, and has been widely applied in the estimation of evapotranspiration and soil moisture contents. Considering that either Ts or NDVI can be easily retrieved from Remote sensing data or directly from such products as MODIS, this method is potentially of much interest in the context of the ungauged area.

In this study, on base of Priestley-Taylor Equation combined with the Ts/NDVI space, namely, surface temperature-Normalized Difference Vegetation Index feature space, Moderate Resolution Imaging Spectroradiometer (MODIS) products and Global Land Data Assimilation System (GLDAS) meteorological and radiation products are introduced to calculate the evapotranspiration in ungauged basins .The procedures consist of: (a) GLDAS data preprocessing, especially the surface air temperature downscaling with a DEM-based method; (b) Calculation of Temperature-Vegetation Dryness Index (TVDI) based on Ts/NDVI feature Space (c)Evapotranspiration Estimation using TVDI and Priestley-Taylor Equation . The above procedures need only remote sensing data (MODIS products) and assimilation data (GLDAS), and are completely independent of field observations, thus, it could have large potential for operational application at the region scale in areas lack of field data. The study area is Tekesi River Basin in China, and the results were compared with the Bowen Ratio measurements.

2. Method

2.1. Interpretation of Ts/NDVI space and calculation of TVDI

Sandholt et al. [5] proposed a dryness index (TVDI, Temperature Vegetation Dryness Index) to obtain information on the surface soil moisture from a simplified triangle defining the Ts/NDVI space. In this study, the Ts/NDVI space was represented with a trapezoid rather than a triangle. Following the concept in Fig.3, TVDI can be defined:

$$TVDI = \left(Ts - Ts\_min\right) / \left(a + b * NDVI - Ts\_min\right) \quad (1$$

where Ts_min is the minimum surface temperature in the trapezoid, defining the wet edge; Ts_max is the maximum surface temperature for a given NDVI, defining the dry edge ($Ts\_max=a+b*NDVI$); Ts is the observed surface temperature at a given pixel.

To determine the parameters describing the dry edge, the maximum surface temperature for each NDVI interval (interval size=0.01) was extracted from the Ts/NDVI space, and the resulted scatter plots of maximum surface temperature versus NDVI was fitted using least squares linear regression.

The wet edge, however, was not obtained by linear fitting. Instead, the average temperature of all water surfaces in the whole space was taken as Ts_min.

As is shown in Fig.1, at the upper edge, i.e. the dry edge, TVDI=1, representing that the soil is extremely dry and there is no evapotranspiration in those pixels; while at the wet edge, TVDI=0, indicating that the soil is well-watered and evapotranspiration of those particular pixels at the edge reaches up to its potential rate.

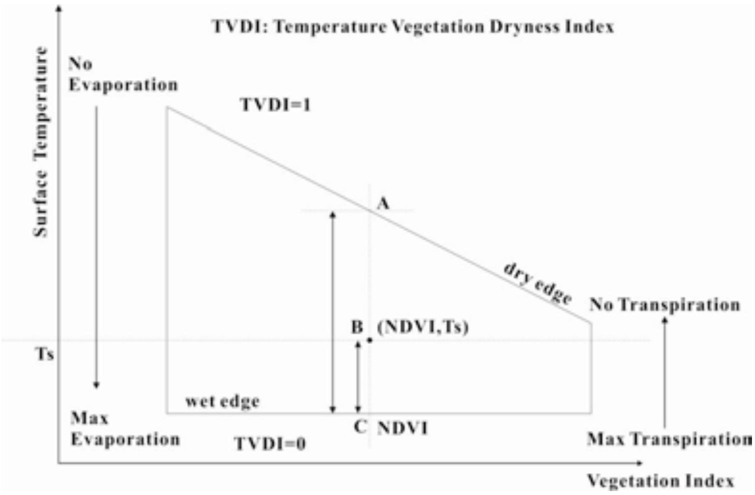


Fig. 1. Definition of TVDI. TVDI for a given pixel is estimatied as the ratio of line BC to line AB (See Eq. (1))

2.2. Parameterization of evapotranspiration based on Priestley Taylor equation and TVDI

According to Jiang and Islam [4] and Sandholt et al. [5], latent heat flux (LE) can be expressed as,

$$LE = \varphi\left(Rn - G\right)\frac{\Delta}{\Delta + \gamma}\left(1 - TVDI\right) \tag{2}$$

where Rn (W m^{-2}) is the net radiation flux, H (W m^{-2}) is the surface sensible heat flux, LE (W m^{-2}) is the surface latent heat flux, G (W m^{-2}) is the surface soil heat flux, Δ (Pa K^{-1}) is the slope of the curve relating saturated water vapor pressure to air temperature, γ (Pa K^{-1}) is the psychometric constant, φ is the Priestley –Taylor coefficient and is set to 1.26 following Priestley and Taylor[6], TVDI is temperature vegetation dryness index calculated from the Ts/NDVI space.

Net Radiation Flux*, Rn* (W m^{-2}) *is* formulated as,

$$Rn = (1-\alpha)R_S \downarrow + \varepsilon_s \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \tag{3}$$

where $Rs\downarrow$ (W m^{-2}) is incoming shortwave radiation,α is surface albedo, ε_s is land surface emissivity, ε_s is air emissivity, Ta (K) is air temperature, Ts (K) is surface temperature, σ is the Stefan-Boltzmann constant ($5.678 \times 10^6 W \bullet m^{-2} \bullet K^{-4}$).

According to Su [7] surface soil heat flux for vegetated areas, G (W m^{-2}), is calculated using,

$$G = R_n\left[\Gamma_c + \left(1 - f_c\right)\left(\Gamma_s - \Gamma_c\right)\right] \tag{4}$$

where Γ_s and Γ_c are the ratios of *G* to *Rn* for full vegetation canopy and bare soil, respectively.

For water bodies, *G* is calculated as half of R_n.

Δ (Pa K^{-1}) can be expressed as,

$$\Delta = 4098\left[0.6108\exp\left(17.27(T_a - 273.15)/\left(T_a - 273.15 + 237.3\right)\right)\right]/\left(T_a - 273.15 + 237.3\right)^2 \quad (5)$$

where *Ta* (K) is air temperature.

Psychometric constant, *γ* (Pa K^{-1}), is calculated using

$$\gamma = \left(M_a / M_w\right)C_p P_r / \lambda \quad (6)$$

where M_a (kg mol^{-1}) is the molecular mass of dry air, M_w (kg mol^{-1}) is the molecular mass of wet air, *Pr* (Pa) is the air pressure, C_p (J kg^{-1} K^{-1}) is the specific heat capacity of air, λ (J kg^{-1}) is the latent heart of vaporization which is the function of air temperature.

Rosenberg [8] and Jackson et al. [9] discovered that the curve of evapotranspiration during daytime under the condition of clear sky is sinusoid approximately. On base of that Xie [10] calculated the daily total value of ET from an instant observation. In this study, similarly, daily ET was estimated from the remote sensing retrieved instant latent heat flux at the satellite overpass time.

3. Study area and data

3.1. Study area

In this study, Tekesi River Basin is taken as the study area, which is shown in Fig.2.It is located in the northwest of China. Tekesi River originates from the north of Khan Tengri which is the main peak of Tian Shan mountain. This region is in the middle latitude temperate zone and belongs to humid continental climate. Its terrain is complex with a large altitude gradient, the elevation ranging from 795 m to 5545 m.

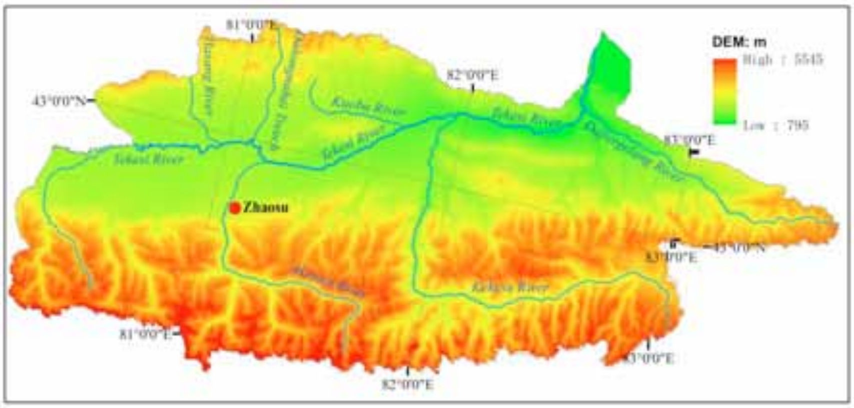


Fig. 2. Study Area: Tekesi River Basin

3.2. Field measurements

From August, 15th to September, 15th in 2009, an experiment was carried out at Zhaosu (see Fig.1) to observe net radiation, air temperature and relative humidity at two different levels, and soil heat flux at two different soil deep levels, using a Bowen Ratio System, to obtain latent heat flux (LE) every 10 minutes. The estimated 10-minute LE values have been interpolated linearly to obtain that at the satellite overpass time, to be used for the validation.

3.3. Data inputs and preprocessing

In this study, the satellite-based data inputs include NDVI, LST, albedo, and land cover, which were all obtained from the MODIS products. MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. The daily NDVI series were derived by temporal linear interpolation of adjacent values of MODIS 16-day NDVI products, while the daily albedo series were calculated from MODIS 16-day albedo products. 500m MODIS-IGBP Collection 5 land cover products were used to identify water bodies on the satellite images.

The remaining daily surface meteorology inputs, such as air temperature, air specific humidity, were obtained from GLDAS products which temporal resolution is 3-hour. To get the data at satellite overpass time, they were interpolated linearly.

It needs to be pointed out that the 1km resolution of MODIS products was chosen as the final resolution of ET calculations. MODIS land cover products were simply resized to 1km with nearest neighbor as the resampling method, so do GLDAS humidity products but with a different resampling method, bilinear interpolation method. SRTM data were introduced to downscale the GLDAS air temperature products to 1km resolution by the following procedures: (a)Taking the air temperature of each GLDAS grid (0.25 degree×0.25 degree) as that at the average elevation of the corresponding grid, calculate the sea-level air temperature for each grid combined with DEM and the vertical lapse rate of temperature;(b) Resize the resulted data at sea-level to 1km by bilinear interpolation; (c) Calculate the air temperature at the original elevation from the resized data, which is the inverse procedure of (a).

For more information about MODIS and GLDAS data, see Table1.

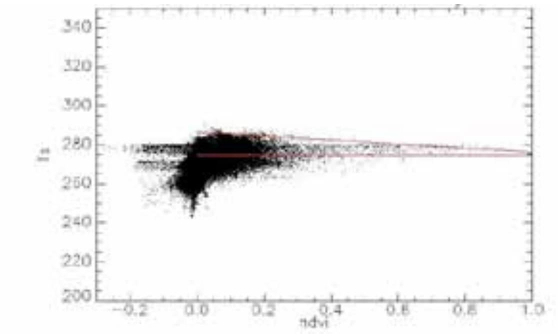
Table 1. MODIS data and GLDAS data used in ET calculations

Parameters	Spatial Resolution	Temporal Resolution
MODIS NDVI	1km	16-day composite
MODIS LST	1km	1 day
MODIS Albedo	1km	16-day composite
MODIS Land Cover	500m	1 year
GLDAS Air Temperature	0.25°	3 hours
GLDAS Specific Humidity	0.25°	3 hours

4. Results and discussion

4.1. Ts/NDVI space

As is shown in Fig.3, from April to October, trapezoids formed from the Ts/NDVI space are shaped well, while in other months, the results are opposite, due to the narrow NDVI variation range. It proved again that the range of NDVI in the full image is the biggest limitation of the application of Ts/NDVI method. For that very reason, only has ET from April to October of each year been estimated in this study.



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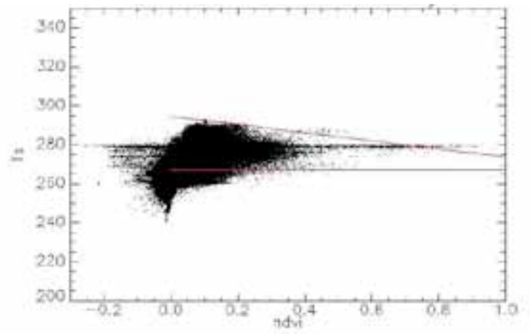

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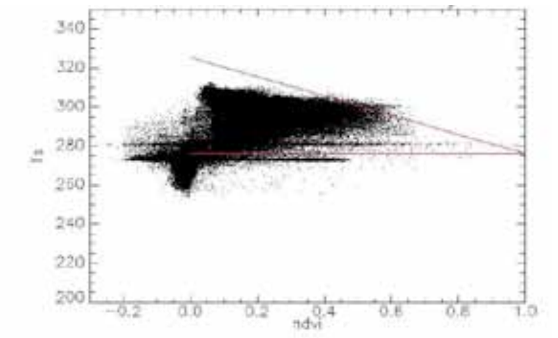

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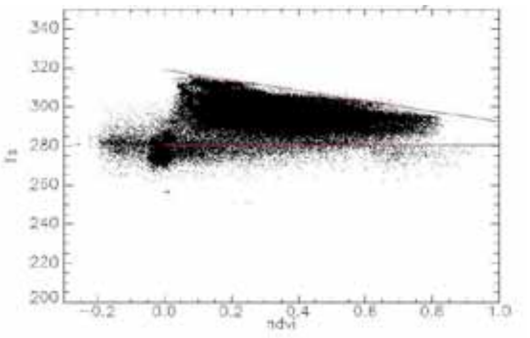

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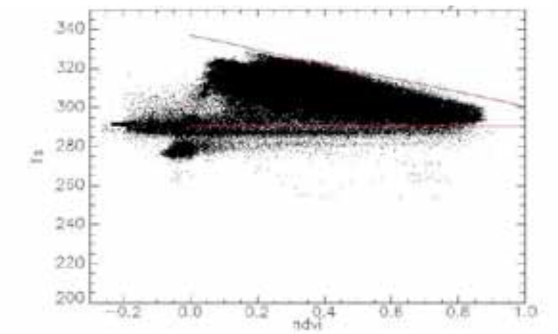

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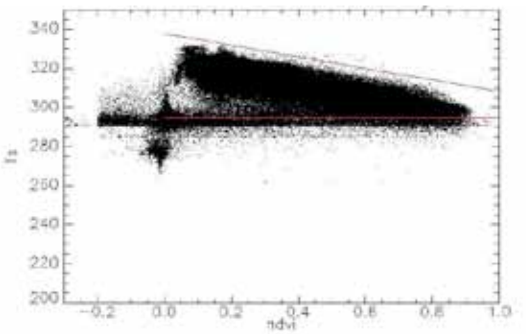

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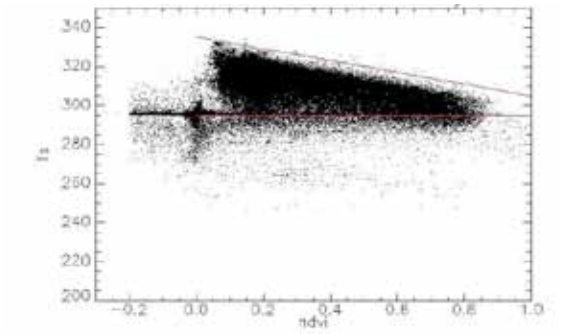

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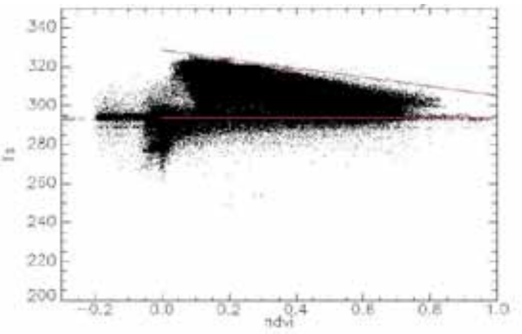

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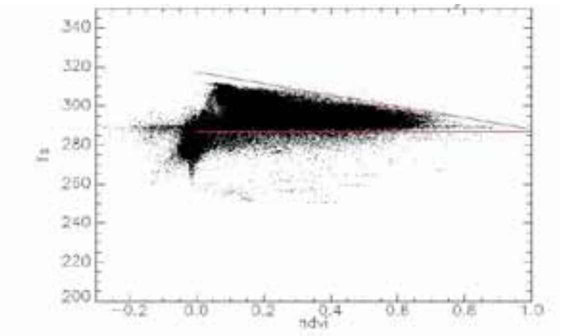

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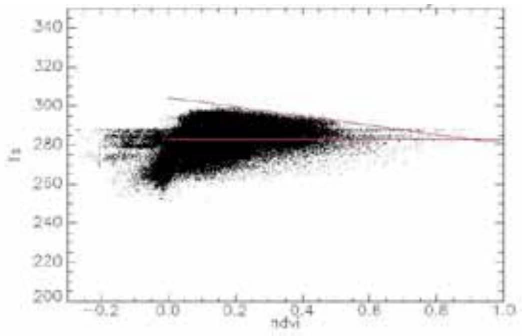

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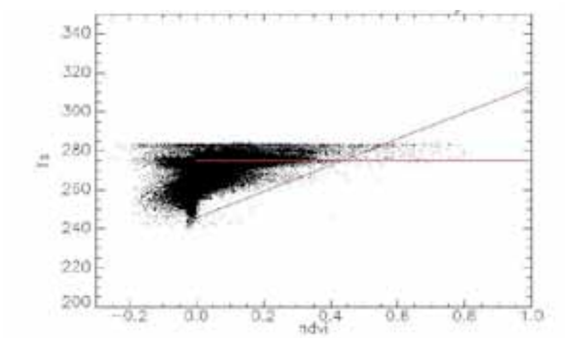

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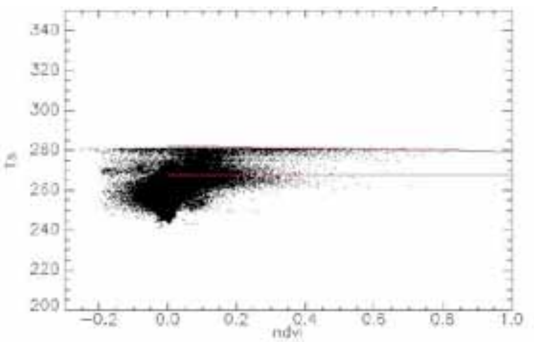

(l) 2009360

Fig. 3. Ts/NDVI space on the days 30, 60, 89, 117 ,178 ,208, 240, 269 ,300, 331, and 360 of 2009

4.2. Spatial distribution of evapotranspiration

Fig.4, Fig.5 and Fig.6 show the spatial distribution of ET at different time levels. Monthly ET and Yearly ET were accumulated from the daily values. The peaks of ET appear along the rivers in the north part of the region. The white points in the mountainous areas don't mean high ET values but errors resulted from snow and ice.

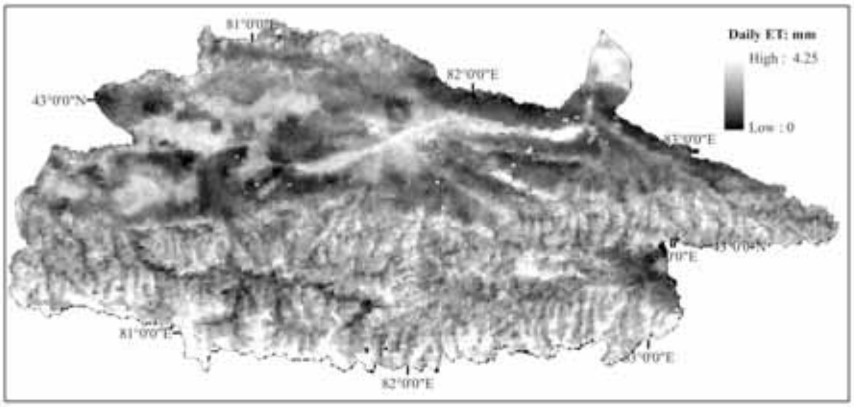

Fig.4 Daily ET on the 235th day of 2009

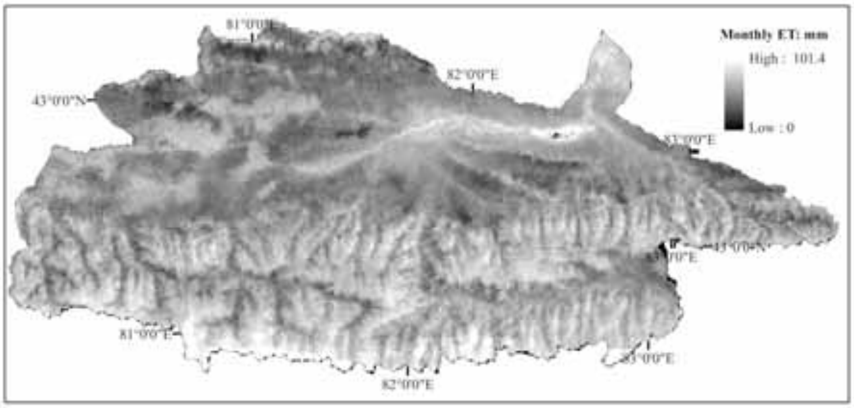

Fig.5 Monthly ET of September, 2009

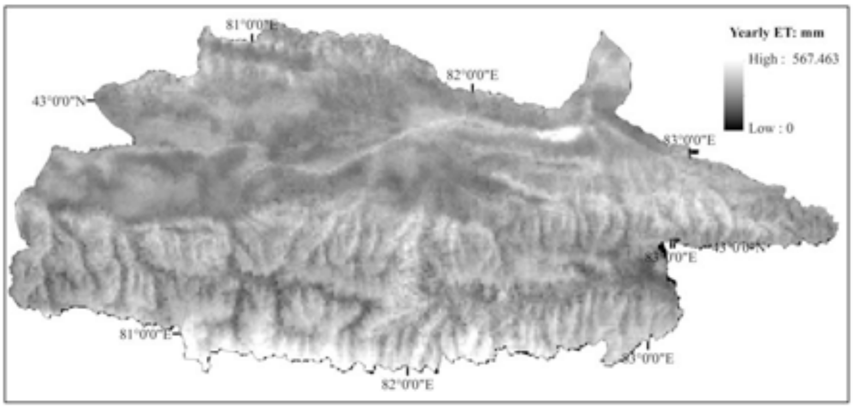

Fig.6 Yearly ET of 2009 (sum from April to October)

4.3. Temporal evolution of evapotranspiration

Based on the above algorithms, ET of Tekesi River Basin from 2006 to 2009 was estimated. Table 2 demonstrates the spatial average of Monthly ET in the whole region. As to each year, Monthly ET reaches its maximum in July, ranging from 68.12 mm to 77.39 mm. And the accumulation of monthly ET from August to October in 2007 is the biggest, which indicates better plant growth conditions to some extent, and that is consistent with the government statistical data.

Table 2. Spatial average of Monthly ET (Unit: mm)

month	2006	2007	2008	2009
4	33.42	33.53	32.28	38.53
5	59.65	58.03	56.10	56.33
6	70.30	70.12	66.60	67.34
7	76.03	77.39	68.12	68.88
8	56.33	60.54	56.06	56.67
9	35.00	36.64	38.83	41.77
10	25.03	23.61	25.99	23.76
total	355.77	359.87	343.98	353.27

4.4. Validation

Because of instrument malfunction and other various reasons during the experiment, LE observations of 13 days have finally been chosen for validation. The coefficient of determination (R^2) of the linear regression equation between estimated LE and observed LE is 0.593(Fig.7), which indicates that this method is applicable to some extent. However, for the wider application, much more validation needs to be done.

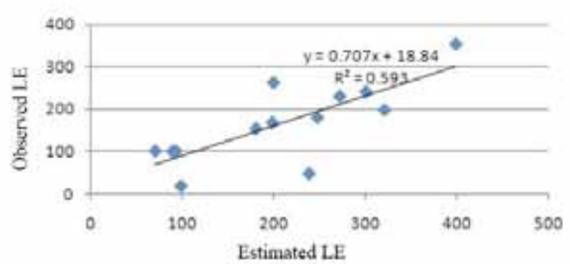

Fig. 7. Comparison between instant latent heat flux values estimated from the model and those obtained from the Bowen Ratio measurements (Unit: W m^{-2})

5. Summary and conclusions

In this study, ET of ungauged areas has been calculated using MODIS products and GLDAS data based on Ts/NDVI space, with Tekesi River Basin as the pilot area. Comparison between the estimated instant latent heat flux and Bowen Ratio measurements shows that this method is operational and applicable. It depends on no field data, and thus can be applied to those regions without ground observations. However, it is important to note that this method only works well when NDVI values vary in a wide range, so that an expected trapezoid can be generated from the Ts/NDVI space. Accordingly, it is recommended that this method is used to estimate ET in Tekesi River Basin from April to October in a year rather than for a whole year.

To simplify ET calculation, so that we can focus on the sensibility of TVDI to seasons, daily ET has been calculated from the instant latent heat flux according to Xie [10], which doesn't take into consideration the evapotranspiration process during the night and the influences of cloud during the day, which will inevitably overestimate daily ET. That needs further study in the future.

Acknowledgements

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