An improved empirical method for large spatial scale surface soil heat flux estimations

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Abstract: In this paper, a novel method to simulate soil heat flux for large spatial scale is proposed. This method is constructed with the ratio of soil heat flux and net radiation \((G_0/R_n)\) and surface characteristic parameters, such as ratio vegetation indices, surface temperature, surface shortwave infrared reflectance, soil moisture content, solar zenith angle. Field calibration is carried out using measured data in 2009 from Yingke, Huazhaizi, Arou, and Dayakou stations located in Heihe River Basin, Northwest of China. The estimated soil heat flux is compared with field observation data from Yingke and Arou stations in 2008. The overall deviation basis and correlation coefficient between the soil heat flux estimation and measured data are 13.4\% and 0.804 in the Yingke station and 12.5\% and 0.893 in the Arou station respectively, and also the correlation coefficient are 0.905 in the Maliantan station and 0.817 in the Binggou station respectively. Results indicated that the proposed method performed well in Heihe River Basin. This new method could be an optimal choice to estimate surface soil heat flux for large spatial scale in the future.

1. INTRODUCTION

The surface soil heat flux \((G_0)\) is a key component of the Earth’s surface energy balance, which quantifies the energy transport through the interface between the air-vegetation continuum and the soil. It also affects the surface soil temperature regime which exerts a substantial influence on various plant biological activities. Therefore accurate estimation of surface soil heat flux is important for researchers working in meteorology, hydrology, and agronomy science.

The surface energy budget at the land surface is given as following:

\[
R_n = H + LE + G_0
\]  

Where \(R_n\) is the net radiation, \(H\) is the sensible heat flux, \(LE\) is the latent heat flux and \(G_0\) is the surface soil heat flux. Normally, \(H\) and \(LE\) are relatively easy to obtain using current micrometeorological techniques. However, it is difficult to assess \(G_0\) accurately. Heat flux plates are originally used to make direct measurements of soil heat flux at a certain depth. After that, soil temperature profile data and thermal soil properties data are required to calculate surface soil heat flux. Estimation of surface soil heat flux according to an aforementioned method seems to be expensive especially when large spatial coverage and high sampling frequency is desired. A possible solution for field-average values, \(G_{0v}\), is to use remotely sensed data.
Remote sensing technology has been proved to be an effective tool in estimating the surface soil heat flux at regional scales. Generally, the methods to derive $G_0$ based on remotely sensed data can be grouped into two categories. The first kind of method is empirical approach based on the relationship between the ratio of soil heat flux and net radiation ($G_0/R_n$) and vegetation index, vegetation coverage fraction, surface temperature, surface albedo[1][3][4][5][7][10][11][14]. It is the most commonly used method due to its simplicity and operability. This kind of method usually performed well under high vegetation cover condition, but performed bad under low vegetation cover condition. Another kind of method is soil heat transfer approach based on one-dimensional soil heat conduction equation and harmonic analysis or the integral of soil surface temperatures. Although it is a promising method, it is very complex to be used because of the requirements of the diurnal variation of surface temperature and many different soil parameters, such as soil porosity and soil thermal conductivity. It is also difficult to be implemented at the regional scale. Furthermore, it is often computationally expensive for operational applications. It is well known that surface soil heat flux changes greatly with different land use and soil texture. Without considering the impact of different land use and soil texture on the surface soil heat flux estimates, no empirical methods can get reasonable result.

In this study, a novel method to estimate soil heat flux for large spatial scale was proposed and calibrated based on field observation data from Linze, Yingke, Huazhaizi, Arou, Binggou and Maliantan stations from 2008 to 2009 in Heihe River Basin, and the introduction of surface key variables include ratio vegetation indices (RVI, to enhance radiation differences between the vegetation and soil background), shortwave infrared reflectance ($b_3$ and $b_4$, to reflect the changes in the soil texture), solar zenith angle (to reflect the seasonal changes of soil heat flux), surface temperature, and soil moisture content. More work will be done to investigate the model performance in other region.

2. Study area and data description

2.1. Study area
The Heihe river basin (~128,900 km$^2$) is the second largest inland river basin in China[16], which located between 97°24′–102°10′E and 37°41′–42°42′N on the Northwest arid area of China with an average rainfall of 108 mm/a. The elevation for this region roughly ranges from 5000m in the upper stream to 1000m in the downstream [12]. The landscapes are various, including glacier, frozen soil, alpine meadow, forest, irrigated crops, riparian ecosystem, bare gobi, and desert. The highest air temperature was about 40° C in the downstream area in summer, and the lowest air temperature falls to about -40° C in the upper stream in winter. The mean annual rainfall across the basin between 1980 and 2010 was 110.9 mm yr$^{-1}$.

2.2. Field observation data collection
Data used in this paper were measured under six sites over the Heihe River Basin from 2008 to 2009, namely the Linze, Yingke, Arou, Huazhaizi, Binggou and Maliantan sites (see Table 1). At each site, an observation system consisting of radiation four-component and Automatic Weather Station (AWS) was set up to acquire the radiation measurements and meteorological information, including shortwave radiation, longwave radiation, air temperature, net radiation, surface infrared temperature, soil heat flux at 0.05 m and 0.15 m, soil temperature and soil moisture content at 0.05m, 0.1m, 0.20 m, 0.40 m, 0.80 m, 1.20 m and 1.60m.
Table 1. Location of ground-based observation sites

| Site     | longitude   | latitude     | landscape          | location  |
|----------|-------------|--------------|--------------------|-----------|
| Yingke   | 100°24′37.3″E | 38°51′26″N   | Orchard and maize  | Midstream |
| Huazhaizi| 100°19′8.2″E | 38°45′54.5″N | Bare gobi          | Midstream |
| Linze    | 100°4′20.5″E | 39°15′14.8″N | Lawn               | Midstream |
| Arou     | 100°27′52.9″E | 38°02′39.8″N | Alpine meadow      | Upstream  |
| Binggou  | 100°13′18.6″E | 38°04′02.7″N | Sparse grass, Riverbed gravel | Upstream  |
| Maliantan| 100°17′45.0″E | 38°32′53.4″N | Sparse grass       | Upstream  |

For all those stations, the surface soil heat flux was derived by the temperature prediction-correction method [17] based on the measurements of soil temperature and soil moisture content at 0.05m, 0.1m, 0.20 m, 0.40 m, 0.80 m, 1.20 m and 1.60m.

2.3. Remote sensing data

The MODIS data used in this study are the MOD021KM, MOD02QKM, MOD02HKM and MOD03 product files provided by the NASA Goddard Space Flight Center (GSFC) Distributed Active Archive Center (GDAAC) (http://reverb.echo.nasa.gov/reverb). The MOD02QKM and MOD02HKM products including the 250 m and 500 m resolution bands are aggregated to 1 km resolution TOA radiances and reflectance. The MOD03 products are the geolocation fields' data calculated for each 1 km MODIS Instantaneous Field of View (IFOV) for all daytime orbits. The geolocation fields include geodetic latitude, longitude, solar zenith and azimuth angles, satellite zenith and azimuth angles, and a land/sea mask for each 1 km sample. The solar zenith and azimuth angles, satellite zenith and azimuth angles are used to estimate net shortwave radiation in this study. MODIS 2.1-μm band was used to detection of dark targets, estimating their reflectance in the blue and red channels and using them for remote sensing of aerosol according to Kaufman' paper [9]. Using the aerosol optical thickness as input, a lookup table was established based on 6S model to carry out the atmospheric correction [15]. A practical split-window approach was used to retrieve LST from MODIS data based on the algorithm proposed by Mao [13].

3. An improved empirical method of soil heat flux

3.1. Model setup

Because the underlying surface of the six sites selected in this paper is relatively uniform, so we assume that the following equation in the MODIS pixel:

$$\frac{G_{0\text{-obs}}}{R_{n\text{-obs}}} = \frac{G_{0\text{-sat}}}{R_{n\text{-sat}}}$$ (2)

Where $G_{0\text{-obs}}$ and $G_{0\text{-sat}}$ are the surface soil heat flux from ground observation and remote sensed, $R_{n\text{-obs}}$ and $R_{n\text{-sat}}$ are the net radiation from ground observation and remote sensed. If we obtain the relationship between $G_{0\text{-obs}}/R_{n\text{-obs}}$ (that is $G_{0\text{-sat}}/R_{n\text{-sat}}$) and each surface key variable respectively, then we can estimate $G_{0\text{-sat}}$ based on $R_{n\text{-sat}}$ and the relationship between $G_{0\text{-obs}}/R_{n\text{-obs}}$ (that is $G_{0\text{-sat}}/R_{n\text{-sat}}$) and each surface key variables respectively. In this study, $R_{n\text{-sat}}$ was calculated from the incoming and outgoing all wave radiation fluxes based on the remote sensed data and meteorological data [2].

According to surface soil heat flux estimation methods [2][6][8][10], several parameters, including surface temperature, solar zenith angle, soil moisture content, ratio vegetation indices and soil texture, have effect on the change of the ratio of soil heat flux and net radiation. Figure.1 shows that $G_{0\text{-obs}}/R_{n\text{-obs}}$ varies according to the change of surface key variables. So a model to derive $G_{0\text{-obs}}/R_{n\text{-obs}}$ can be expressed as following:
The authors reconstruct the ratio of soil heat flux and net radiation \((G/R)\) from band 6 and band 7 of MODIS. Where

\[
\frac{G_{\text{obs}}}{R_{\text{obs}}} = \frac{G_{\text{est}}}{R_{\text{est}}}
\]

is the surface soil heat flux, \(R_{\text{obs}}\) is net radiation, \(G_{\text{obs}}\) is soil heat flux, \(R_{\text{est}}\) is net radiation, \(G_{\text{est}}\) is surface soil heat flux, \(RVI\) is Ratio vegetation index, \(b3\) and \(b4\) are the shortwave infrared reflectance retrieved from band 6 and band 7 of MODIS.

### 3.2. Model coefficients calibration

The authors reconstruct the ratio of soil heat flux and net radiation \((G/R)\) by analysis of the relationship between \(G/R\) and each surface key variable. The ground data measured in 2009 were used to calibrate the equation coefficients. After that, a new equation to estimate surface soil heat flux is proposed as following:

\[
\frac{G_0}{R_n} = \frac{T_s}{14.27} \left(0.39 - 0.121 RVI + 0.013 RVI^2\right) \left(0.48 b_3 + 0.76 b_4 + 0.35\right) e^{0.1s - 0.25 \cos(s_{\text{soz}})}
\]  

Where \(G_0\) is the surface soil heat flux, \(R_n\) is net radiation, \(T_s\) is surface temperature, \(RVI\) is Ratio vegetation index, \(b3\) and \(b4\) are the shortwave infrared reflectance retrieved from band 6 and band 7 of MODIS, \(sm\) is the soil moisture content retrieved from AMSR-E.

### 4. Results

The aforementioned empirical method to simulate soil heat flux are validated using field data measured from Yingke, Arou, Maliantan and Binggou stations in Heihe River Basin during 2008. The correlation coefficient between estimated results and observed data are 0.804 in the Yingke station, 0.893 in the Arou station, 0.905 in the Maliantan station, and 0.817 in the Binggou station respectively. Comparison of the soil heat flux estimation results between the improved empirical method and SEBAL model was also showed in Figure 2, Figure 3, Figure 4 and Figure 5 respectively. The validation results indicated that the proposed method performed well in Heihe River Basin. This new method could be an optimal choice to derive surface soil heat flux for large spatial scale in the future.
5. Conclusions

An improved empirical method of soil heat flux for large spatial scale was recommended in this paper. Because the introduction of surface key variables and net radiation can be retrieved by remote sensing data, the proposed empirical method provides a convenient and high accurate way to estimate soil heat flux based on remote sensing data.

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