A NEW METHOD TO ESTIMATE EVAPOTRANSPIRATION FROM THE COMBINATION OF MODIS AQUA AND TERRA MEASUREMENTS

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ABSTRACT:

Evapotranspiration(ET) is one of the key fluxes in all water budget studies, satellite remote sensing is a promising tool to establishment operational frame works for estimating ET at large extent. One of the most common ways is to solve LE, as a residual in the land surface energy balance equation: RN - G = H + LE. And the largest uncertainty in estimating H comes from the acquisition and spatialization of near-surface air temperature, Ta. In order to eliminate the input of Ta, we test a combination model of PBL and SVAT, and use two time measurement of surface radiometric temperature introduced from MODIS products. In this study, such model was applied for calculating sensible heat fluxes in a semiarid region on July to August, 2003. The study was conducted in Tongyu site, Jilin Province, China, which is located at 4.416N, 122.867E. Field data from CEOP plan is used for validation. Three MODIS land products are used in this study: the 8-day leaf area indices product (MOD15) and the daily TS product (MOD11A1) at 1-km resolution and the daily atmosphere profile product (MOD07). The sensible heat results show relatively small RMSE compared to eddy-covariance measurements, and Bowen ratio show a promising correlation coefficient(r=0.76) in clear-sky cases with field data. Because of the limited verification data and dates, the model results are preliminary and need further testing. As operational production of ET is our goal, the model is encouraging in the following aspect: 1). Uncertainty in the retrieval of TR and the interpolation of air temperature from the meteorological point measurements is alleviated; 2). Only temporal changes in radiometric temperatures is used in this model rather than absolute real temperature, biases of the derived surface temperature is not as destructive as previous; 3) LAI is used in a simplified function to decompose soil evaporative from plant transpiration. Future work will carry out in temporal-scaling to obtain gap-free dataset caused by cloud contamination and parameterization optimization, and it will provide more insight into the optimal approach for diagnosis of land surface fluxes using remote sensing observations.

1. INTRODUCTION

Evapotranspiration (ET, or latent heat flux) is the most essential and uncertain factor in water resource management. As a result of historical efforts, accurate estimation of ET is becoming available via a number of methods using surface meteorological and sounding observations. However, such approaches just provide points measurement, which usually do not represent area situation because of the heterogeneity of land surfaces. Therefore, satellite remote sensing is a promising tool for estimation of spatial distribution of ET at regional scale with limited ground observations. Remote sensing can be used to define the characteristic of complex underlying. The multi-bands of satellite images can provide vegetation and thermal information, which is closely related with energy and heat transfer process.

The law of conservation of energy states that the available energy reaching a surface is dissipated mainly as latent heat (LE) and sensible heat (H): Rn-G = LE+H . Being, Rn net radiation, G soil heat flux and Rn-G available energy. Since remote sensing could be the only data source providing radiometric temperature and vegetation cover observations over large extents, many methods were promoted to resolve the partition of the available energy into sensible and latent heat[1-4]. Cause the resistance involved latent heat is hard to defined in spatially disaggregated underlying, the so-called "residue-approach" is often applied in previous studies, which means the primary work is to calculated previous sensible heat(H), and obtain LE as the residue of surface-energy-balance-equations. However, the non-remote-sensing parameters were proved to be dilemmas in the "residue-approach", such as air temperature and wind velocity. Because these non-remote-sensing parameters cannot be obtained as spatial-distribution maps and often interpolation from points-measurement, it could raise largely error on large extents. Although some work attempted to derive the air temperature based on the feedback on the underlying [5], the precision of air temperature remains the primary uncertainty in the sensible heat.

The model developed in this paper calculating sensible heat flux using two times land surface radiometric temperature in one day, the combination of planetary boundary layer model and soil-vegetation-transfer-model could eliminate the input of air temperature. The model is applied in a semi-arid region at 1km, and MODIS platform provides necessary information at proper spatiotemporal scale. The preparatory estimation is evaluated with ground measurements of the field experiments in the CEOP3/4 project. The objectives of the paper is to evaluated the potential of two-time-temperature-measurement in the estimation of ET, and an operational algorithm based on MODIS land products could be promoted hereafter.

2. STUDY SITE AND DATA

The Tongyu observation site consists of two stations (figure 1) that are maintained by the Institute of Physics of Jilin province, Chinese Academy of Sciences. The stations are 5 km apart and located at Tongyu, Northeastern China (44.416N, 122.867E, elevation 184 m), on a flat Songliao plain. The area is semi-arid with a mean annual precipitation of 388 mm in Tongyu County, about 30 km northeast of the site. Precipitation totals are highly variable from year to year. Approximately 80% of precipitation occurs between May and September. The mean annual air temperature in Tongyu County is 5.70℃. This experiment provided data at two nearby sites, the so-called Tongyu-cropland (TY-crop) and Tongyu-grassland (TY-grass), from October 2002 to September 2003. TY-crop was a flat cropland and TY-grass was flat and degraded grassland in the summer season, but they turned to bare soils in the winter season. Only the cropland station data was used in this study. The main crops within 1 km of the measurement location are corn and sunflower, which achieve a height of 2 m during the growing season. The ground is partly bare in the winter. Soils are described as sandy, salty alkaline, black humus, or meadow soil. Turbulence measurements are taken by the ultra-sonic anemometer/thermometer at 3.5 m and an open-path infrared gas analyzer. Volumetric soil moisture content is measured using time domain reflectometry at 5, 10, 20, 40, 80 and 160 cm. Meteorological measurements are made from a 20-meter tower. Radiation measurements are made at 3 m height, 20 m away from the tower. More detailed description of the site can be found in the CEOP dataset documentation available at http://www.eol.ucar .edu/projects/ceop/dm/documents/rsite/.[6]

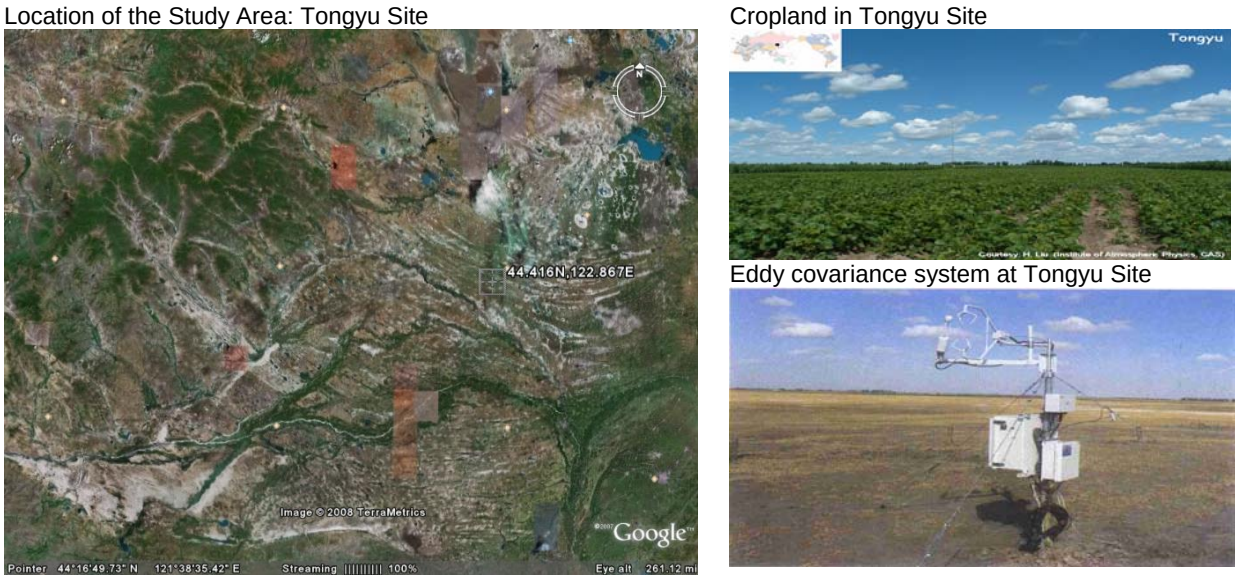

Figure 1: Location of the study area in Google Earth, Jilin province, China. The upper right panel shows cropland picture in the study site(09-10-2003). The lower right panel shows the location of the eddy covariance system for sensible and latent.

3. MODEL DESCRIPTION

In order to define the upper boundary condition of mixture layer using air temperature which can be inferred from surface radiometric temperature using remote sensing, a time-integrated mixture layer model is coupled with a SVAT model. This combination requires no more air temperature as input, and is less sensitive to system errors in the surface temperature derivation. A brief overview of the two parts of this model is giving, when sensible heat flux converges from the comparison in both PBL and SVAT model, latent heat estimation could be possible based on the energy balance equation.

3.1 Time-Integrated PBL Development Components

We represent the convective PBL as a well-mixed slab of air. Above the PBL is the free atmosphere with specified potential temperature $\theta_s(z)$. Air from these levels is progressively entrained into the PBL, where it is instantaneously mixed as the PBL grows. McNaughton and Spriggs give a simplified conservation equation describing the growth of a convective boundary layer over time [7], neglecting the effects of subsidence and horizontal advection:

$$\rho c_p \left(z_2 \theta_{m,2} - z_1 \theta_{m,1} \right) = \int_{t1}^{t2} H(t) dt + \rho c_p \int_{z1}^{z2} \theta_s(z) dz \qquad (1)$$

During the time interval from t_1 to t_2 ,the top of the mixed layer rises from height z_1 to z_2 , and the potential temperature within the mixed layer rises from $\theta_{m,1}$ to $\theta_{m,2}$. Such conservation equation is limit to clear-sky conditions. In order to make the sensible heat flux less sensitive to potential temperature profile and mixture layer height, the surface temperature measurement should happen at the time when large increase in sensible heat goes with large temperature-change and relative-limited boundary height variation.

3.2 SVAT Components

A scheme of two-source surface layer model of Norman [8] is modified to describe SVAT procedure in the surface layer. First, the radiometric temperature of a vegetated surface is an ensemble average of the individual thermodynamic temperature of the soil (T_c) and vegetation (T_s), weighted by their contribution to the radiometric temperature:

$$T_{rad}(\varphi) = f(\varphi)T_c + \left[1 - f(\varphi)\right]T_s \quad (2)$$

Where $f(\varphi)$ is the vegetation fraction at a zenith angle φ :

$$f(\varphi) = 1 - \exp\left(\frac{-0.5LAI}{\cos\varphi}\right) \quad (3)$$

Sensible heat flux of soil (H_s) and vegetation (H_c) is giving as following:

$$\begin{aligned} H &= H_s + H_c = \rho Cp\frac{T_{ac} - T_a}{R_a} \\ H_s &= \rho Cp\frac{T_s - T_{ac}}{R_s} \\ H_c &= \rho Cp\frac{T_c - T_{ac}}{R_f} \end{aligned} \quad (4)$$

The aerodynamic resistance (R_a) can be expressed as:

$$R_a = \frac{\ln\left[\frac{z_n - d}{z_{0m}} - \psi_h\right]\ln\left[\frac{z_h - d}{z_{0h}} - \psi_m\right]}{k^2 u_z} + R_{ex} \quad (5)$$

The canopy boundary resistance (R_f):

$$R_f = \frac{\alpha_w\left[w/u(h)\right]^2}{4\alpha_0 L_0\left[1 - e^{(-\alpha_w/2)}\right]} \quad (6)$$

Here, w is average leaf width, α_w and α_0 is constant (2.5, 0.005, respectively). $u(h)$ is wind velocity at the top of canopy. Soil surface resistance:

$$R_s = \frac{1}{c\left(T_s - T_c\right)^{1/3} + bu_s} \quad (7)$$

u_s is wind velocity at the roughness length, b, c is empirical coefficient provided in [8].

3.3 Solving the SVAT+PBL Energy Budget Equations

To relate the time-integrated sensible heat (H) in Eq.1 to the instantaneous flux estimates given by the surface layer component of two-source model (Eq.3), a functional form of H should be integrated from prediction model of H and Eq.1. We choose a sinusoidal phase to simulate the variation of H in day time:

$$y = a + b\sin\left(\frac{2\pi x}{d} + c\right) \quad (8)$$

Combining the integral of Eq.7 with Eq.1 yields the following predict expression of H at time t_i :

$$H_i = \frac{\rho c_p \sin(at_i + b)}{\cos(at_2 + b) - \cos(at_1 + b)}\left[z_2\theta_{m,2} - z_1\theta_{m,1} - \int_{z1}^{z2}\theta_s(z)\,dz\right] \quad (9)$$

The sensible heat at time t_i also appear in the surface layer model(Eq.3), and the potential temperature θ_m can be related with air temperature T_a by:

$$\theta_m = T_a\left(\frac{100}{p}\right)^{R/C_p} \quad (10)$$

Combining Eq.2 and Eq.3 yields

$$T_{RAD,i} = T_{a,i} + f(\varphi)\frac{H_{c,i}R_{a,i}}{\rho c_p} + \left[1 - f(\varphi)\right] \times \frac{\left(H_i - H_{c,i}\right)\left(R_{a,i} + R_{s,i}\right)}{\rho c_p} \quad (11)$$

Where a first-pass estimates of $H_{c,i}$ is obtained from Priestley-Taylor and energy balance:

$$H_{c,i} = R_{n,c,i}\left[1 - \alpha_{PT} f_g \frac{\Delta}{\Delta + \gamma}\right] \quad (12)$$

When the surface temperature T_{rad} , temperature profile $\theta_s(z)$ is given, the unknown in Esq.(8)-(11) are H_1、H_2、$H_{c,1}$、$H_{c,2}$、$T_{a,1}$、$T_{a,2}$。We need two-times measurement to constitute six equations to resolve six unknowns. When $H_{c,2}$ is resolved, we define H_{day} as:

$$H_{day} = R_{n,day}\frac{H}{R_n} \quad (13)$$

4. RESULT

4.1 Comparison sensible heat and air temperature with field data

Two MODIS instruments have been launched for global studies of the atmosphere, land, and ocean processes. The first

instrument was launched on 18 December 1999 on a morning platform called Terra, and the second was launched on 4 May 2002 on an afternoon platform called Aqua. The Terra overpass time is around 10:30AM (local solar time) in its descending mode and 10:30PM in its ascending mode. The Aqua overpass time is around 1:30PM in its ascending mode and 1:30AM in its descending mode.

Three MODIS land products are used in this study: the 8-day leaf area indices product (MOD15), daily atmosphere profile product (MOD07) and the daily Ts product at 1-km resolution (MOD/MYD11). To examine the validity of using the different time pairs, the H retrieved using four combinations was compared: (1) Terra daytime and nighttime, (2) Aqua daytime and nighttime, (3) Terra daytime and Aqua daytime, (4) Aqua nighttime and Terra daytime. First, MODIS products cover Tongyu site were downloaded from website of EOS Data Gateway and Atmosphere Archive and Distribution System. Second, reprojecting and AOI-subset were done using MRT (for land product) and MRTSwath (for atmosphere product). Third, average situation of clear-sky cases was analyzed using all four combinations to find out which is optimal. Fourth, more clear-sky cases were computed to achieve a preliminary evaluation of the optimal time pair.

The daytime average sensible heat flux is well correlated with the temporal change in surface radiometric temperature, which was illustrated in Fig2. The best choice of time interval will be that which maximizes both of these curves while large temperature difference could be observed as much as possible.

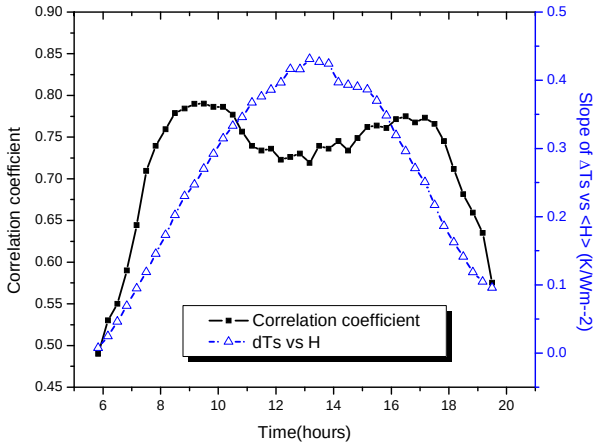

Figure 2:The correlation between surface temperature ΔT_{rad} and daytime average sensible heat <H> vs the time interval between ΔT_{rad} measurement

In that, combination of Terra daytime and Aqua daytime couldn't' work out because too short interval (3hrs) and too small change can be observed (2-3K in summer time) and it is within the bias of surface temperature derivation. To satisfy the aforementioned supposition, we use the nighttime measurement in replacement of a virtual morning measurement. There are also about 3 hours or 3.5 hours between these two measurements. Because sharp slope of radiometric temperature and PBL development happened at this period, the precision of sensible heat flux is better than Terra daytime - Aqua daytime. Considering the bias in different thermal sensors' calibration and cloud cover, we choose Terra nighttime and daytime as optimal time pair, and assume that the temperature at Terra nighttime (10:30pm) is an approximation of these at 7:00am, which can be proven reasonable using field measurement. Table I is the model results using this time interval (7:00am and 10:30am).

The validations were carried out for five days during summer, 2003. They are Julian days (day number of a year) 206, 209, 217, 220, 221, covering a period from July to August. These days are selected because they are clear days for all the validation sites shown in Table 1. The retrievals of MODIS-based H and Ta (Air temperature) are averaged over 3*3 pixels enclosing the ground- based site.

The result shows that RMSE of 20-40 W m-2 for daily average sensible heat. In general, the range of errors reported by other authors in H flux is very variable. [9] Consider around 50 Wm-2 an acceptable error for H. In the literature, errors in the best cases are around 22 Wm-2 and similar internal error (20Wm-2) exists in different measurement instruments (lysimeter, eddy-covariance and BREB). And converge computing procedure improves most error to less than 2 ºC for Ta estimate at 10:30 am. Although quantity of validation field data is small, the result is encouraging.

Date	DOY	Site	Period	RMSE of H	RMSE for Ta
25-Jul	206	Crop	0550-1520	22.69	0.81
28-Jul	209	Crop	0550-1520	36.34	1.88
5-Aug	217	Crop	0550-1520	23.10	1.54
8-Aug	220	Crop	0550-1520	26.52	1.04
9-Aug	221	Crop	0550-1520	21.41	1.76
25-Jul	206*	Grass	0550-1520	31.34	2.16
28-Jul	209	Grass	0550-1520	26.67	1.25
5-Aug	217	Grass	0550-1520	39.14	0.98
8-Aug	220	Grass	0550-1520	30.45	1.48
9-Aug	221	Grass	0550-1520	37.18	1.88

*Fied Measurement from 1150 to 1250 is missing

4.2

Table I. Simulation result using CEOP Tongyu field data, 2003

4.3 Comparison Bowen Ratio(BR) with field data

The average energy balance closure ratio (EBCR) is about 0.75 in the whole year of Tongyu, CEOP03, which means H+LE is smaller than expected, Rn-G, in energy balance theory (TABLE II). For it makes the direct comparison of estimated LE or ET and field data problematic, analysis is carried out on Bowen Ratio(H/LE) between estimation and measurement(Table III).

Month	EBCR(Crop)	Available Measurment	EBCR(Grass)	Available Measurment
1	*missing	*missing	0.66	5.85%
2	0.64	59.90%	0.61	88.69%
3	0.66	89.72%	0.63	95.70%
4	0.71	24.72%	0.64	41.94%
5	0.70	63.51%	0.65	57.19%
6	0.74	100.00%	0.68	100.00%
7	0.74	99.06%	0.69	100.00%
8	0.74	100.00%	0.70	98.59%
9	0.73	98.89%	0.69	98.89%
10	0.73	97.11%	0.69	100.00%
11	0.74	97.22%	0.70	100.00%
12	0.69	100.00%	0.69	100.00%

4.4 Table II. monthly energy balance closure ratio in TOngyu, 2003

Date	DOY	Site	BR(field)	BR(Est)
25-Jul	206	Crop	0.324	0.451
28-Jul	209	Crop	0.945	0.725
5-Aug	217	Crop	0.711	0.510
8-Aug	220	Crop	0.738	0.691
9-Aug	221	Crop	0.466	0.554
25-Jul	206	Grass	0.552	0.561
28-Jul	209	Grass	0.672	0.582
5-Aug	217	Grass	0.666	0.676
8-Aug	220	Grass	0.739	0.682
9-Aug	221	Grass	0.534	0.406

Table III. comparison of Bowen ratio in TOngyu, 2003

Results in Table III show that BR estimated tend to be less variable than field data, partly caused by the spatial average. The H/LE patterns are good consistent with field data(coefficient of correlation, r=0.762), although absolute error in daily ET is about 20% that means error in a single day could reach 2mm/day at most. But for a longer term, such error will decline rapidly.

4.5 Sensible heat maps

Figure III shows results for output sensible heat components, briefly decomposed using fractional vegetation cover, fc. The gross main structure of the sensible heat flux on canopy is explained by the fc derived from MODIS LAI products, but such simplified assumption of thermodynamic temperature decomposed would be improper in refined resolution.

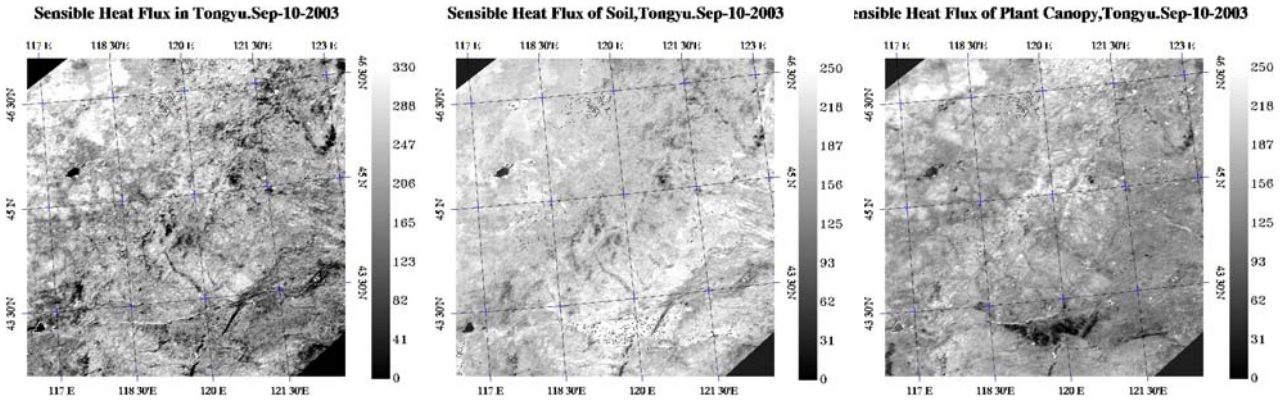

Figure 3: (left)(center)(right),tongyu,09/10/2003

5. CONCLUSION

A new method to estimate surface fluxes using two-time surface temperature measurement is presented. It is a combination of PBL and SVAT: The surface energy balance equations serve as a lower boundary constraint for a simple model of planetary boundary evolution, and the sensible heat flux happened on the surface layer could be related to variation of surface temperature. The primary strength of the methods is that it requires no more precious and spatialized air temperature as model input.

The model has been validated using limited field data from Tongyu site of CEOP experiment, 2003. Comparisons between modeled and measured fluxes and air temperature show relatively small RMSE. And Bowen ratio shows an accepted correlation coefficient(r=0.76) in clear-sky cases. Because of the limited verification data and dates, the model results are preliminary and need further testing.

The model can be improved in the follow aspect: A temporal-scaling component would be introduced to fill the gaps contaminated by cloud; the spatial patterns of Bowen ratio should be compared with refined resolution image such as ASTER or ETM to analyze the influence of linear decomposition of Trad to soil temperature and canopy temperature using LAI.

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