JP3.5 SENSIBLE, LATENT AND GROUND HEAT FLUX MODEL

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1. INTRODUCTION

Currently, there is a need for more accurate and simple expressions for the surface heat fluxes. Since the atmospheric variables are strongly dependent on net radiation *Q*, Camuffo and Bernardi (1981, 1982) proposed the following form of equation to describe latent heat fluxes (*LE*), sensible heat fluxes (*H*) and ground heat fluxes (*G*):

$$fluxes = a_1 Q + a_2 \frac{\partial Q}{\partial t} + a_3 \tag{1}$$

They assumed that the coefficients in the equation will vary for different days based on changing weather conditions, without a general expression.

Based on the equation above, we proposed the new models which could be used broadly for variety of surface and atmospheric conditions. Since net radiation measured by common net radiometer consists of four terms, which are: the short wave radiation from the sky (S_u), the short wave radiation from the ground (S_d), the long wave radiation from the sky (L_u), and the long wave radiation from the ground (L_d), we decided to use all four components in the equation (1). Also, assuming the coefficient of each term is different, as the different ratio of each term may take different surface/soil type and weather conditions into account, the new model can be expressed as:

$$fluxes = c_1 S_u + c_2 S_d + c_3 L_u + c_4 L_d + c_5 \frac{\partial S_u}{\partial t} + c_6 \frac{\partial S_d}{\partial t} + c_7 \frac{\partial L_u}{\partial t} + c_8 \frac{\partial L_d}{\partial t} + c_9 \tag{2}$$

For latent heat flux, which is more complicated to reproduce than sensible heat fluxes since it is affected significantly not only by radiation and surface type but also by soil moisture (Camuffo, 1981), after investigating the diurnal correlations of latent heat flux and relative humidity, we decided to introduce $1/q$ into equation (2) to construct latent heat flux model as:

$$LE = c_1 S_u + c_2 S_d + c_3 L_u + c_4 L_d + c_5 \frac{\partial S_u}{\partial t} + c_6 \frac{\partial S_d}{\partial t} + c_7 \frac{\partial L_u}{\partial t} + c_8 \frac{\partial L_d}{\partial t} + c_9 (\frac{1}{q}) + c_{10} \tag{3}$$

We have separately developed models for Daytime and Nighttime. Daytime or Nighttime is determined based on a positive or negative value of the net radiation at a given time, respectively. Details of three heat flux models are given in section 3, following the field measurements described in section 2.

2. FIELD EXPERIMENTS

For the models development and validation, we deployed data from four different sites: 1) Citrus Grove site (N 33°64'52" W 117°2'661"), data were collected from January 31st to March 1st, 2006; 2) rural Moreno Valley site (N 33°55'18", W 117°10'25"), data were collected from March 30th to May 2nd, 2007; 3) Palm Spring site (N33°49'04", W116°31'29"), data were collected from July 1st to 24th, 2008, and 4) Wilmington site (N $33°46'09''$, W $118°16'02''$), data were collected from June 17th to 30th, 2005.

The solar net radiation and its components were measured by CNR1 Net Radiometer (Kipp & Zonen). CSAT3 Sonic Anemometers (Campbell Sci.) were used to measure the sensible heat fluxes, while KH2O Krypton Hygrometers (Campbell Sci.) were used to measure the fluctuations in water vapor. The ground heat fluxes were measured by two heat flux plates buried 8cm below the ground surface, together with the soil thermocouples and water

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content reflectometer. All measured heat fluxes and radiation components were averaged over one hour.

3. MODEL DEVELOPMENT

By applying multiple linear regression, heat flux models are constructed based on one site data and tested with available data from other sites. The coefficients for new models and Camuffo's model are given in table 1 and 2, respectively. The comparison results are listed in Table 3, in which the r^2 is the correlation coefficient, and Fact 1.2 represents the number of data points within a factor of 1.2 (20%) of the observed data.

Table 1 Coefficients of new models. Coefficients c_1 through c_4 are dimensionless, coefficients c_5 thru c_8 have units of time (s), while c_9 and c_{10} have units of W/m^2.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}
H-day	0.20	0.63	-0.23	0.07	720.09	-4381.74	-505.36	-3483.20	34.22	
H-night	0.75	-1.41	0.25	-0.20	-2584.09	10479.90	1050.64	-4340.31	-0.47	
LE-day	0.07	0.01	0.27	-0.50	-262.19	76.30	-858.75	1551.36	4.63	95.74
LE-night	0.03	-0.64	0.01	-0.01	-1163.87	3441.12	-485.14	1341.80	2.82	4.62
G-day	0.001	0.03	-0.05	0.28	18.61	-332.68	-956.58	-2299.82	-91.72	
G-night	0.01	-0.74	-0.24	0.72	-521.86	2946.59	1920.93	-4693.81	-186.39	

Table 2 Coefficients of Camuffo model. Coefficient a_1 is dimensionless, coefficient a_2 has unit of time (s), while a_3 and a_4 have units of W/m^2.

	a_1	a_2	a_3	a_4
H-day	0.34	-872.59	-9.48	
H-night	0.39	-1518.09	31.89	
LE-day	0.04	28.92	2.98	10.17
LE-night	0.07	-218.87	2.65	2.22
G-day	0.05	-861.67	-3.32	
G-night	-0.41	-1600.21	-20.27	

Table 3 The comparison results between new models and measured data as well as between previous model and measured data

		Citrus Grove	rural Moreno Valley	Palm Spring	Wilmington
H-day	New model	r^2: 0.80 Fact1.2: 36.3%	r^2: 0.83 Fact1.2: 37.4%	r^2: 0.92 Fact1.2: 50.6%	r^2: 0.94 Fact1.2: 53.7%
	Camuffo model	r^2: 0.73 Fact1.2: 27.0%	r^2: 0.86 Fact1.2: 18.4%	r^2: 0.90 Fact1.2: 56.8%	r^2: 0.94 Fact1.2: 1.3%
H-night	New model	r^2: 0.01 Fact1.2: 11.0%	r^2: 0.45 Fact1.2: 6.0%	r^2: 0.57 Fact1.2: 8.3%	r^2: 0.97 Fact1.2: 24.1%
	Camuffo model	r^2: 0.008 Fact1.2: 9.0%	r^2: 0.45 Fact1.2: 10.7%	r^2: 0.61 Fact1.2: 7.1%	r^2: 0.92 Fact1.2: 17.7%
LE-day	New model	r^2: 0.45 Fact1.2: 31.3%		r^2: 0.51 Fact1.2: 0%	
	Camuffo model	r^2: 0.37 Fact1.2: 28.1%		r^2: 0.65 Fact1.2: 24%	
LE-night	New model	r^2: 0.43 Fact1.2: 13.5%		r^2: 0.25 Fact1.2: 17.9%	
	Camuffo model	r^2: 0.39 Fact1.2: 16.1%		r^2: 0.32 Fact1.2: 3.6%	
G-day	New model	r^2: 0.91 Fact1.2: 37.4%	r^2: 0.41 Fact1.2: 12.0%		
	Camuffo model	r^2: 0.73 Fact1.2: 24.8%	r^2: 0.31 Fact1.2: 12.7%		
G-night	New model	r^2: 0.91 Fact1.2: 40%	r^2: 0.82 Fact1.2: 23.4%		
	Camuffo model	r^2: 0.42 Fact1.2: 13.9%	r^2: 0.55 Fact1.2: 9.1%		

4. CONCLUSIONS AND DISCUSSION

Based on the approach proposed by Camuffo and Bernardi (1982), we tried to construct models which can be applied without site or season limitations.

The new models allow flux estimates with measured radiation components for ground and sensible heat flux. In addition to the radiation components, relative humidity is required for the modeling of latent heat flux. There is no need for temperature measurements or surface characteristics clarification since radiation component distribution is assumed to take the surface type into account. The new model for sensible heat flux reproduced the measured data in the four sites that cover four types of land use over daytime periods, including citrus grove, desert plain, concrete surface, etc. Figure

1 shows the comparison result among measured data, new model and Camuffo's model in rural Moreno Valley site.

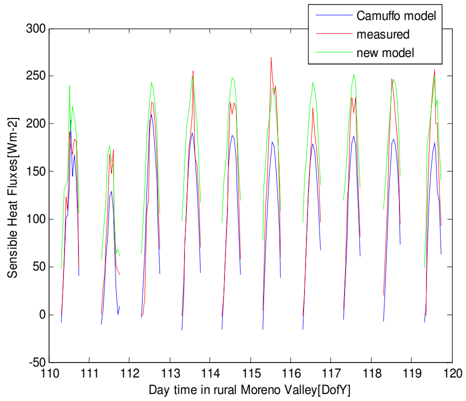

Figure 1: Modeling of sensible heat flux during daytime condition in rural Moreno Valley site

Concerning the performances of the new nighttime sensible heat flux model, it works better during warm seasons, i.e. from April to August. For cold season condition, the nighttime sensible heat flux model does not perform satisfactorily.

The new model for ground heat flux did not perform as well as the sensible heat flux model but led to results better than Camuffo's model, especially for nighttime condition, as shown in figure 2.

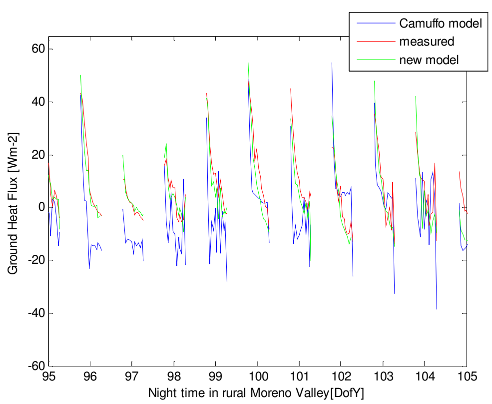

Figure 2: Modeling of ground heat flux during nighttime condition in rural Moreno Valley site

After adding term $1/q$ into the new model and Camuffo's model for latent heat flux during both daytime and nighttime conditions, performance of both models improved. Still the latent heat flux model performance is not as good as the sensible heat flux model.

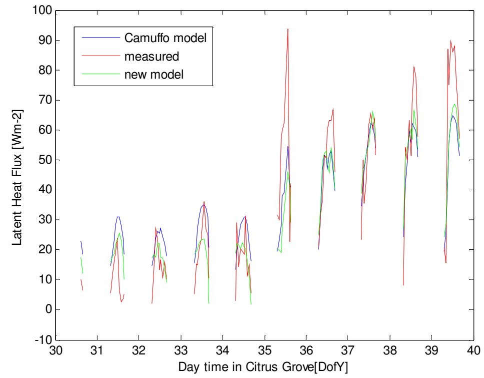

Figure 3: Modeling of latent heat flux during daytime condition in Citrus Grove site

Limitation of the proposed models is in the availability of all four components of net radiation. Generally, the new models improve the modeling of heat energy fluxes based on net radiation, while more validations including more land types and seasons from September to February are necessary to confirm the conclusion.

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