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EVALUATION OF A SIMPLE METHOD TO ESTIMATE SURFACE HEAT FLUXES FOR A MIDWESTERN DECIDUOUS FOREST, USA.

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1. INTRODUCTION[*]

The surface energy balance (SEB) is an important control on regional climates and hydrology. Long term measurements over forest sites are relatively rare, yet provide useful insight into seasonal and annual dynamics. Developing models to predict SEB fluxes is important for many applications, including the estimation of the SEB over data-sparse regions, and to fill gaps in flux data when observations are missing. This study evaluates the soil-canopy-air heat storage flux term and SEB closure over a mid-latitude deciduous forest. Using the forced closed fluxes, coefficients for simple models of three SEB terms are fitted and independently evaluated.

2. PHYSICAL SETTING AND OBSERVATIONS

Observations were made over a mixed hardwood deciduous forest (mean canopy height of 26 m) in the Morgan Monroe State Forest (MMSF), south-central Indiana. At 46 m net all wave radiation (Q^*) is measured with a Kipp & Zonen CNR-1 net radiometer and turbulent heat fluxes with a CSI CSAT3 sonic anemometer and Licor Li-6262 closed path gas analyzer. Further detail can be found in Schmid *et al.* (2000).

3. STORAGE HEAT FLUX (ΔQ_S)

Storage heat flux is calculated (McCaughey 1985):

$$\Delta Q_S = Q_g + Q_a + Q_w + Q_v \qquad (1)$$

where Q_g is the ground heat flux, based on soil heat flux plates and soil temperature and moisture, Q_a and Q_w are the sensible and latent heat storage fluxes, based on profiles of air temperature and vapor pressure respectively, and Q_v is biomass heat storage determined from tree bole temperatures and vegetation density surveys. At four sites, upwind of the flux tower pairs of REBS heat flux plates were inserted between 5.8 and 7.3 cm below ground with CSI TCAV thermocouples inserted into the overlying layer and CSI CS615 TDR soil moisture sensors nearby. Weekly gravimetric samples were also taken. The profiles of air temperature and vapor pressure were measured from the tower at 1, 6, 12, 22, 32 and 46 m above ground level. Thermocouples (20) were inserted into tree boles with a further 13 thermocouples located in branches, at heights ranging from 1.3 to 30.5 m above ground level. The trees included six of the major species that make up the MMSF (Ehman *et al.* 2002). The relative contribution of each component to ΔQ_S for four days with complete datasets closest to the summer and winter solstices and equinoxes are shown in Figure 1. Q_g is generally the largest contributor to ΔQ_S for any given time, particularly on day 97 when it represented 85-90% of the total ΔQ_S. Q_v and Q_a have similar magnitudes, while Q_w is generally the smallest contributor to ΔQ_S.

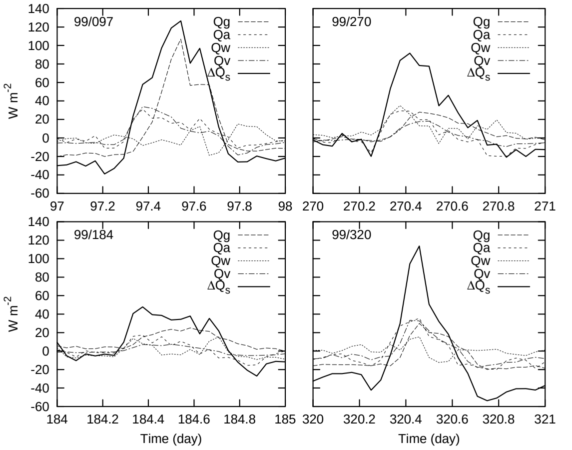

Figure 1. Storage component comparison for four days in 1999.

4. ENERGY BALANCE CLOSURE

Given all the energy balance components are measured directly at the MMSF site, the lack of SEB closure can be determined by regression analysis between the sum of hourly average sensible and latent heat fluxes (Q_H and Q_E respectively) and $Q^* - \Delta Q_S$ (Wilson and Baldocchi 2000). As with many other forested studies, observations at MMSF show that turbulent fluxes make up about 71% of the total available energy with significant consistency ($r^2 = 0.87$).

Energy balance closure was forced for each hour when all components were available. First Q^* was assumed to contain an error of 2.5% (over-estimate) based on comparison between two identical CNR1 at 46 m on the tower. The remaining error was then attributed to the other SEB fluxes. The partitioning of the error in the turbulent terms was based on the Bowen ratio (β) for each hour, provided the β was reasonable (i.e. not close to –1). ΔQ_S was assumed to have the average fractional error of Q_H and Q_E. When β was ~-1, the error term was partitioned equally between ΔQ_S, Q_H and Q_E.

5. MODELING ΔQ_S

Given the intensive measurements needed for ΔQ_S a series of different models that are only a function of Q^* were evaluated. These include a simple linear function:

$$\Delta Q_S = a_1 Q^* \qquad (2)$$

and a hysteresis form (Camuffo and Bernardi 1982):

$$\Delta Q_S = a_1 Q^* + a_2 \frac{\partial Q^*}{\partial t} + a_3 \qquad (3)$$

where t is time. The a_1, a_2 and a_3 coefficients were determined for a variety of conditions using the closed energy balance values (Zutter, 2002). Table 1

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summarizes the coefficients which yielded the best statistical results from the evaluation period (2000/135 - 2001/120). Overall the best performance was with the hysteresis model (eqn 3), r^2 =0.57, RMSE=26.7 W m^{-2}, which amounted to an underestimation of 44%. The month of March has the best of performance, r^2 0.84, underestimation on average of 6%. Model performance in December was poorest.

Table 1: Coefficients determined based on data collected for 1998-2000/134 at MMSF

Eqn 2		Q*> 0	Q*< 0
Growing season	a_1	0.112	0.479
Non-growing season	a_1	0.172	0.438
Eqn 3			
Growing season	a_1	0.093	0.439
	a_2	0.112	0.063
	a_3	7.9	-2.9
Non-growing season	a_1	0.163	0.418
	a_2	0.035	0.034
	a_3	2.4	-1.5

As expected there is a larger fraction of energy going into storage during the leaf off period when there is more mass directly exposed for solar radiation receipt (Table 1). Average ΔQ_S /Q*, the a_1 coefficient (eqn 2), for the growing season (all Q* hours) is 0.126, and for the non-growing season is 0.201. During the growing season the actual daily pattern shows a distinct hysteresis pattern, with more energy going into storage in the morning and less later in the day (Table 1). In the non-growing season, the a_2 term (egn 3) is much less important suggesting that the available energy ($Q^*-\Delta Q_S$) is more symmetrical around solar noon.

6. MODELING Q_H and Q_E

To predict Q_H and Q_E the deBruin and Holstag (1982)/ Holtslag and van Ulden (1983) method is used:

$$Q_H = \frac{(1-\alpha)+(\gamma/s)}{1+(\gamma/s)}(Q^*-\Delta Q_S)-\beta \qquad (4)$$

$$Q_E = \frac{\alpha}{1+(\gamma/s)}(Q^*-\Delta Q_S)+\beta \qquad (5)$$

where γ is the psychrometric constant (Pa °C^{-1}) and s is the slope of saturation vapor pressure vs temperature curve. The two coefficients are α, which accounts for the strong correlation of Q_H and Q_E with $Q^*-\Delta Q_S$, and β which accounts for the non-correlated portion. An α of 0.8-1.3 and a β of 20 W m^{-2} have been suggested for forest areas (Beljaars and Holtslag 1991). Here α and β were derived for 10-day periods using observed Q_E, to assess the seasonal variability and inter-annual consistency (Figure 2). A distinct seasonal pattern, reflecting ecosystem functioning is apparent.

Seasonally varying α and β coefficients determined from the first full year of measurement at MMSF (1999) were used for 2000 and model performance was evaluated with closed SEB fluxes. There is good overall agreement, particularly for Q_H (Table 2). Model performance for both Q_H and Q_E shows strong seasonal patterns; Q_H is most accurately predicted in all seasons except summer, when a general under-prediction is exaggerated and model consistency is weakest. Conversely, Q_E is predicted most accurately in summer and early fall when evapotranspiration is at a maximum.

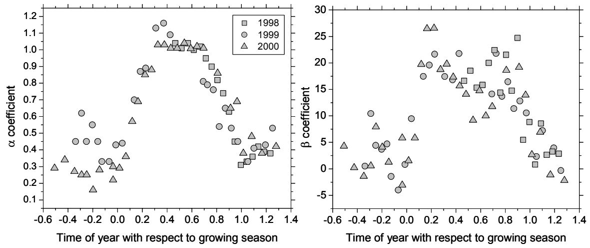

Figure 2: α and β coefficients at 10-day intervals over 3 years. Time is fraction through the growing season.

Table 2: Modeled performance statistics by month for 2000 at MMSF

	Q_H			Q_E		
Mon	Slope	Inter.	r^2	Slope	Inter.	r^2
Jan	0.91	1.9	0.98	0.78	-0.2	0.54
Feb	0.82	-4.1	0.98	1.22	8.0	0.56
Mar	0.90	1.4	0.99	1.18	3.6	0.66
Apr	0.82	-3.6	0.95	1.29	10.0	0.72
May	0.72	3.3	0.90	1.05	3.8	0.88
Jun	0.50	-3.5	0.87	1.13	1.2	0.96
Jul	0.67	-7.1	0.87	1.05	10.0	0.98
Aug	1.21	12.0	0.80	0.78	6.9	0.97
Sep	1.10	10.1	0.91	0.81	4.8	0.94
Oct	0.97	3.8	0.92	0.74	6.0	0.84
Nov	0.95	-0.8	0.95	0.45	5.0	0.40
Dec	0.97	-2.3	0.99	0.84	3.8	0.72

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8. REFERENCES

Beljaars ACM., AAM Holtslag 1991: Flux parameterization over land surfaces for atmospheric models. *JAM*, **30**, 327-341.

Camuffo D., A. Bernardi 1982: An observational study of heat fluxes & the relationship with net radiation. *BLM* **23**, 359-368.

de Bruin HAR, AAM Holstag 1982: A simple parmeter-ization of surface fluxes of surface fluxes of sensible and latent heat during daytime compared with the Penman-Monteith concept. *JAM,* **21,** 1610-1621.

Ehman J, HP Schmid, CSB Grimmond, JC Randolph, PJ Hanson, CA Wayson, F D Cropley 2002: An initial inter-comparison of micrometeorological & ecological inventory estimates of carbon sequestration in a mid-latitude deciduous forest. *Global Change Biology* ***8,*** 1-15.

Holstag AAM, AP van Ulden, A.P. 1983: A simple scheme for daytime estimates of the surface fluxes from routine weather data. *JCAM*, **22**, 517-529.

Schmid HP, CSB Grimmond, F Cropley, B Offerle, HB Su 2000: Measurements of CO_2 and energy fluxes over a mixed hardwood forest in the midwestern US, *AFM* **103**, 357-374.

Wilson KB, D.D Baldocchi 2000: Seasonal and inter-annual variability of energy fluxes over a broadleaved temperature deciduous forest in North America. *AFM* **100**, 1-8.

Zutter H.N. 2002. Convective Boundary layer development over a mid-latitude deciduous forest. Unpublished MS Thesis, Indiana University, Dept. Geography.