

ESTIMATING SURFACE FLUXES OVER THE SGP SITE WITH REMOTELY SENSED DATA

Thomas Schmugge, Andrew French, and William Kustas
USDA Hydrology Laboratory, Beltsville MD 20705, USA
Tel: 301-504-8554, FAX: 301-504-8932, email: schmugge@hydrolab.arsusda.gov

ABSTRACT The estimation of surface energy fluxes requires the combination of data from several sources. Typically land use and vegetation cover are obtained from visible and near infrared (VNIR) data, while a surface state variable, the surface temperature, is obtained from thermal infrared (TIR) data. Approaches to combine these data for the estimation of surface energy fluxes were studied as part of the SGP97. Toward this end TIR and VNIR images for four days were collected over the El Reno and ARM Cart sites of SGP using the TMS (Thermal Infrared Multispectral Scanner) TMS (Thematic Mapper Simulator) instruments. At both sites intensive ground measurements are available. Most of the imagery were acquired at an altitude of 5 km yielding a pixel resolution of approximately 12 meters. One flight line was flown at a 1.5 km altitude yielding 4 meter resolution. The observed brightness temperatures were corrected for atmospheric effects using MODTRAN and nearby, in both space and time, radiosoundings. Comparisons with bulk water temperatures of small ponds are within 0.5 to 1C. The Temperature Emissivity Separation (TES) algorithm developed for use with ASTER data was applied and the results compared with laboratory measurements of the soil emissivity. The resulting surface temperatures are used in a two source (soil and vegetation) model to estimate surface fluxes on an areal basis. The concurrent VNIR imagery were used to estimate the fractional vegetation cover. The resulting fluxes were in good agreement with ground measurements. The spatial scales of surface temperatures and the resulting fluxes were also analyzed..

INTRODUCTION

The monitoring of the land surface fluxes at regional spatial scales is recognized as important for applications such as the modeling of atmospheric behavior and the monitoring of water resources. When one looks at a thermal infrared image, e.g. Fig. 1, it is clear that the large variations in surface brightness or radiant temperatures, T_r , which are seen arise from differences in the surface energy balance for the land surfaces. Recall that T_r is a measure of the emitted radiation from the surface is directly related to the temperature of the surface and its emissivity. The temperature contrasts seen between fields with different vegetation conditions imply a different partition of the incoming solar energy into latent and sensible heat components. Cooler temperatures usually indicate that there

is sufficient moisture available so that most of the incoming energy goes into latent heat or evaporation, while hotter temperatures indicate that most of the incoming energy goes into the sensible or convective heating of the atmosphere. However there is another aspect of the problem of determining the surface fluxes which arises due to the differences in the heat transfer coefficients caused by variations in the surface roughness. Thus a 20 m tall pine forests can be just as cool as a well-watered field but transpiring much less because of its greater heat transfer capability. The problem is to quantify these fluxes in terms of the remotely sensed T_r and other observables such as vegetation indices. As part of the Southern Great Plains (SGP97) experiment conducted in Oklahoma during the summer of 1997 data were acquired with the TMS (Thermal Infrared Multispectral Scanner) TMS (Thematic Mapper Simulator) instruments from an aircraft platform over the El Reno Grazing Lands Research Laboratory of USDA-ARS which was also the site of numerous ground measurements during the course of the experiment. TMS has six channels in the thermal infrared (8 - 12 μm) region of the electromagnetic spectrum. The instantaneous field of view is 2.5 mrad, yielding pixel sizes of 4 and 12 m for the 1.5 and 5 km altitudes flown over the site. In addition to the TMS data Landsat TM data were used for vegetation mapping and to estimate other surface parameter. Thus it is clear that data from more than one source is required to estimate surface fluxes.

SURFACE ENERGY BALANCE

The energy balance at the land surface is given by:

$$R_n - G - H - LE = 0 \quad (1)$$

where R_n is the net radiation, G the soil heat flux, H the sensible heat flux and LE the latent heat or moisture flux into the atmosphere. The net radiation, the driving force in Eq. 1, is the sum of the incoming and outgoing short and long wave radiation fluxes:

$$R_n = (1 - \alpha) \cdot R_s + (1 - \epsilon) \cdot R_{L_i} - \epsilon \sigma T^4 \quad (2)$$

where α is the surface albedo, R_s is the incoming solar radiation, R_{L_i} is the incoming long-wave radiation, ϵ the surface emissivity and T the surface temperature in Kelvins.



Figure 1 Brightness temperature image for TIMS band 5 (10.8 μm) over the El Reno AGP'97 study area. Temperatures range from 27°C over water bodies (black) to 34 - 40°C over bare soil (white). Fields labeled 01, 05, 09, and 13 in the image contain the EC flux measuring systems.

The surface albedo and emissivity are estimated from the TM data.

In (1) the flux term we will concentrate on is the sensible heat flux into the atmosphere give by:

$$H = \rho c_p \cdot (T_{\text{aero}} - T_a) / r_a \quad (3)$$

where ρ is the air density, c_p is the specific heat of air at constant pressure, T_{aero} is the aerodynamic temperature in the canopy, T_a is the air temperature just above the canopy, and r_a is the aerodynamic resistance. The latter, r_a , is a rather complex function of various geometrical factors such as roughness lengths, displacement heights, etc., and the wind speed. T_{aero} is the temperature of the source for the convective heat transfer and can be determined from the profiles of temperature and windspeed in the boundary layer. For an aerodynamically smooth surface, T_{aero} and T_R are equivalent since such a surface is the source for both the radiative and convective or sensible heat fluxes. However for most natural surfaces, T_{aero} and T_R are not equivalent and their difference is thoroughly discussed in the recent paper by Norman et al. [1].

Recently, a two source model has been developed which considers the contributions from the soil and canopy separately

and which requires only a few additional parameters for implementation [2]. The surface energy balance is evaluated for each elemental area (defined by the pixel size of remotely sensed data), i , using the dual-source model. In this model the soil surface and vegetative canopy fluxes are considered in parallel with their own resistance to heat transfer. With these parallel paths, the sensible heat flux, (3), can be expressed as the sum of the contribution from the soil, H_s , and from the canopy, H_c , yielding the total flux by the following equation:

$$H = H_c + H_s = \rho c_p \left[\frac{(T_c - T_a)}{r_{AH}} + \frac{(T_s - T_a)}{(r_{AH} + r_s)} \right] \quad (4)$$

where r_s is the resistance to heat flow in the boundary layer immediately above the soil surface, r_{AH} is the resistance to heat transfer from the vegetated layer, T_a is the air temperature at a reference height in the atmosphere, and T_s and T_c are the soil and canopy temperatures, respectively.

Two assumptions are used to obtain a solution using (4) with the composite radiometric temperature of the surface, T_R . The first assumption is that T_R is related to canopy and soil temperatures, T_c and T_s , by the following approximate expression:

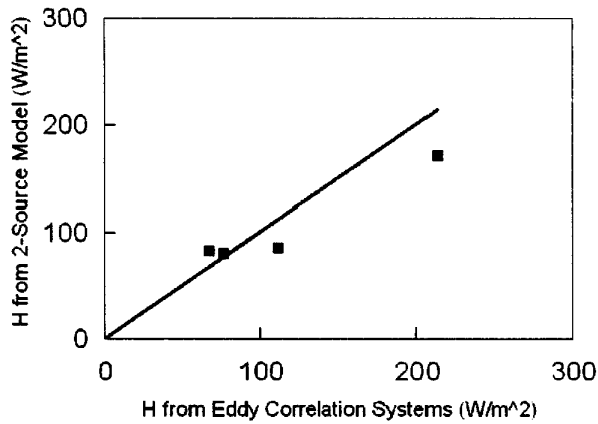


Figure 2 Comparisons of model estimates of the sensible heat flux, H , with the EC measurements for the 4 sites.

$$T_R = [f_\theta T_C^4 + (1 - f_\theta)T_S^4]^{1/4} \quad (5)$$

where f_c is the fraction of vegetation viewed by the radiometer. The parameter f_c is related to the Leaf Area Index, LAI , assuming a random canopy with a spherical leaf angle distribution [2].

The second assumption is that the net radiation absorbed by the plant canopy, R_{nc} , is partitioned between H_c and LE_c according to the Priestley-Taylor approximation [3]. From this estimate of H_c the canopy, T_c , soil, T_s , temperatures can be determined.

An estimate of R_{nc} is computed using LAI and assuming that the extinction of R_n inside the canopy layer can be approximated using Beer's Law, namely,

$$R_{nc} = R_n (1 - \exp(-\beta LAI)) \quad (6)$$

where the constant β is the extinction coefficient. The soil heat flux is then estimated by taking a fraction of the net radiation at the soil surface,

$$G = c_G (R_n - R_{nc}) \quad (7)$$

Time dependent functions for estimating β and c_G have been developed and are used here.

With the estimates of the canopy and soil temperatures, H_s can be determined from (4). During daytime conditions, the model is not allowed to compute condensation. Thus soil evaporation and plant transpiration (i.e., LE_s and LE_c) must be positive or away from the surface. This constraint is required when there exists large temperature differences between surface and air, as in the case of water-stressed vegetation having elevated canopy temperatures. In this case,

transpiration would need to be lower than that predicted by the Priestley-Taylor approximation so the model can override the prediction in order to satisfy (4) and the surface energy balance and reach a point where $LE_c = 0$ and $H_c = R_{nc}$. This permits the model to accommodate water-limiting conditions where the use of the Priestley-Taylor approach would not be valid. For further details of the logic for obtaining a solution for limiting conditions see Norman et al. [2].

The model requires measurements of T_w , u , R_n , $T_R(\theta)$, h_c , approximate leaf size, s , and LAI . To apply on a spatial basis R_n and LAI need to be estimated from remotely sensed data. In this case 30m Landsat TM data were used.

RESULTS

The surface fluxes and meteorological data were acquired with four eddy correlation (EC) stations located within the El Reno Grasslands site. The stations were in fields designated as ER01, ER05, ER09, and ER13 in Fig. 1. Fields ER01 and ER05 are rangeland sites with heavy grass cover, ER09 is an actively grazed pasture site, and ER13 is a winter wheat field which had recently been harvested and plowed. In addition to the fluxes the wind speed, air temperature and humidity were measured at each site. The values of H from the two-source model versus the observed at the four EC sites is presented in Fig. 2. The model values are for an area of about 90m centered on each site. The agreement appears reasonable.

CONCLUSIONS

This paper presents preliminary results from a data fusion activity in which aircraft thermal infrared data, Landsat TM data, and land use data from a GIS are combined in a model to estimate the surface sensible heat flux. The results are in reasonable quantitative agreement with the ground flux measurements and indicate the potential for this approach in the future. While at the present time this model does make use of a number of empirical relations that may be site specific it should be possible to generalize this approach for wider applications.

REFERENCES

- [1] J.M Norman, M. Divakarla, and N.S Goel,.. Algorithms for Extracting Information from Remote Thermal-IR Observations of the Earth's Surface. Remote Sensing Environment, 51:157-168, 1995.
- [2] J.M Norman, W.P. Kustas, and K.S. Humes, A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. Agric. Forest Meteorol., 77:263-293, 1995.
- [3] C.H.B. Priestley and R.J. Taylor, On the assessment of surface heat flux and evaporation using large-scale parameters, Monthly Weath. Rev, 100:81-92, 1972.