P3.2 USING SURFACE RENEWAL ANALYSIS TO DEVELOP A FIRE RISK INDEX

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1. INTRODUCTION

Using the convention $R_n - G = H + LE$, net radiation (R_n) is positive downwards, both sensible heat flux density (H) and latent heat flux density (LE) are positive upward and soil heat flux density (G) is positive downward. When soil water is not limiting, then sensible heat flux density (H) is typically small relative to latent heat flux density (LE) and $R_n - G$ is a measure of the potential or maximum possible LE. When soil water is limited, evapotranspiration (ET) is reduced and the actual LE decreases relative to $R_n - G$, so

$$R = \frac{LE}{R_n - G} \quad (1)$$

is a measure of water stress. As the plants become more water stressed, the stress ratio (R) decreases and

$$F_i = 1 - \frac{LE}{R_n - G} \quad (2)$$

increases. Therefore, F_i is a fire risk index, which approaches zero when fire potential is low, and it rises as the chances of wildfire increase. If a method to estimate F_i were available via a network of low-cost automated stations, calculation of the fire index could greatly improve characterization of fire potential, reduce labor and travel requirements to evaluate fire potential.

The surface renewal (SR) method for estimating H from surfaces in conjunction with R_n and G estimates provides a simple, robust and low-cost method to estimate latent heat flux density (LE) from grasslands and forests. The method lends itself to distributed, automated networks and it can potentially provide the data needed to obtain spatial estimates of F_i.

The SR method (Paw U and Brunet, 1991) is based on the concept of coherent structures, which are characterized by air sweeps and ejections to and from the surface (Gao et al., 1989). When in or near the canopy, air parcels heat or cool as sensible heat exchanges with canopy elements. The rate of temperature change over time is related to sensible heat flux density (Paw U et al., 1995). Under unstable conditions, cool air sweeps into a canopy from above and the air parcels are gradually heated by the canopy elements. Hence, temperature traces versus time drop sharply followed by a slow rise as the air is heated. Then the warmed air ejects from the canopy and it is again replaced by a sweep of colder air from above. Under stable atmospheric conditions, the pattern is reversed with a sharp temperature increase followed by slow cooling. The air temperature falls slowly as heat is transferred from the air to cooler plant elements. When plotted, temperature traces show ramp like characteristics, and the mean amplitude (a) and inverse ramp frequency ($d + s$) can be quantified using a structure function (Van Atta, 1977; Snyder et al. 1996).

Using conservation of energy, Paw U et al. (1995) showed that H can be expressed as:

$$H = \alpha H' = \alpha \rho C_p \frac{a}{d+s} z \quad (3)$$

where ρ is the air density and C_p is the specific heat of the air. The factor H' is the SR sensible heat flux density assuming uniform heating from the surface up to the measurement height and α accounts for unequal heating of the air volume under the temperature sensor (Paw U et al., 1995). The α factor is determined as the slope of the regression of H from a sonic anemometer against H' forced through the origin.

A data logger program was developed to collect high frequency temperature data and to output half hour means of the 2nd, 3rd, and 5th order moments of the time lag temperature differences using the structure function, which are stored in the logger memory until transferred to a computer. In the computer, H is calculated from the statistical moments (Snyder et al., 1996). On a half-hour basis, the latent heat flux density (LE) is determined as the residual of the energy balance equation using measured or estimated net radiation and soil heat flux density and H from SR.

Reference evapotranspiration (ET_o) is a measure of evaporative demand and, if the vegetation is experiencing water stress, wildfire potential should increase with ET_o. If the vegetation is experiencing little water stress, then higher ET_o rates correspond to higher LE but not necessarily higher fire risk. In this paper, a study to determine F_i using the low-cost SR method and comparisons with ET_o and precipitation are presented to illustrate the potential for use of the approach in a fire risk index network.

2. METHODS

An experiment was conducted over rainfed grasslands near Ione, California from February 9 – October 2, 2002. The site and typical energy fluxes are described in Baldocchi et al. (2003). Two 76.2 μm diameter thermocouples were mounted at 0.6 m height to measure temperature. The sampling frequency was $f = 4$ Hz and time lags $r = 0.25$ and $r = 0.5$ s were used

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for the short canopy. The current reading and two previous temperature readings (e.g., 0.25 and 0.5 s earlier) were stored in the data logger. For the time lags, temperature differences were calculated and the 2nd, 3rd and 5th moments of each temperature difference were computed. At the end of a half hour, the means of the three moments were stored in the output table for each of two time lags for both thermocouples (i.e., a total of 12 moments). In addition, net radiation (W m^{-2}) was measured at a nearby eddy covariance tower. A soil heat flux plate was inserted at d_s = 0.04 m depth to measure the mean heat flux density (G_2) in W m^{-2} at that depth. Sample soil temperature was recorded at the end of each half hour at 0.01 and 0.03 m depth to determine the change in soil heat storage ΔS above the plates. The change in heat storage was calculated as:

$$\Delta S = C_V\left(\frac{T_f - T_i}{t_f - t_i}\right)d_s \qquad (4)$$

assuming an apparent volumetric heat capacity of $C_V = 2.0 \times 10^6$ kg m^{-3} K^{-1}. Soil heat flux density at the surface was calculated as: $G = G_2 + \Delta S$. Finally, LE was calculated as the residual of the energy balance equation.

$$LE = R_n - G - H \qquad (5)$$

Precipitation and ET_o rate data from the CIMIS weather station (Snyder and Pruitt, 1992) near Camino, California were used for comparison with LE measurements over the grassland. Reference evaporatranspiration (ET_o) is a measure of evaporative demand that is commonly used in irrigation management. The methodology to determine ET_o is presented in Walter et al. (2000).

3. RESULTS AND DISCUSSION

Figure 1 shows the regression of H from the EC system versus H' from SR. The slope of the regression through the origin is the α value used to estimate H from H' (Equation 3).

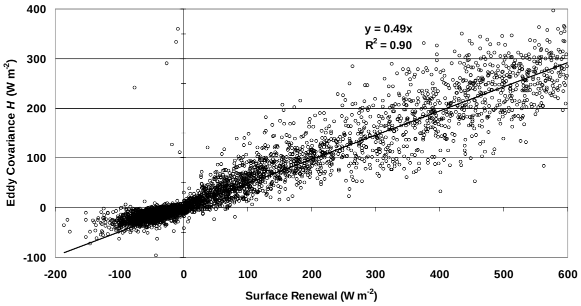

Figure 2 shows the daily energy flux density values from February 9 – October 2, 2002, where H was estimated using the SR method and LE was calculated as the residual of the energy balance equation. Most of $R_n - G$ was contributing to LE from February until early May. Then there was a sharp increase in H and decrease in LE as the soil dried and grass became water deficient.

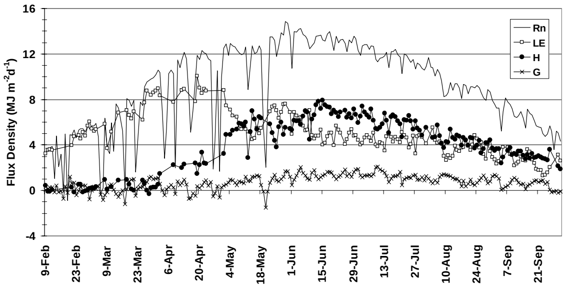

Figure 2. Daily energy balance data measured over grassland during the 2002 experiment.

The fire risk index (F_i) depends on the ratio of LE to R_n - G, so accuracy of the LE measurements is crucial. Figure 3 shows the daily values of LE from EC and SR and values of $R_n - G$ used to make the F_i calculations.

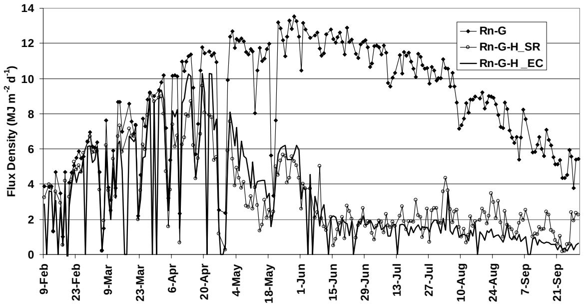

Figure 3. Available energy (R_n - G) and $LE = R_n - G - H$ using the EC and SR methods.

The F_i was calculated (Equation 2) and plotted with the daily precipitation (Figure 4) and with ET_o (Figure 5). Prior to June, the fire risk index increased with ET_o except during or after periods of rainfall, when sharp drops in F_i were observed (Figure 4). Starting in late May, the precipitation stopped and F_i was clearly related to fluctuations in ET_o rate. This is especially clear in Figure 5 where there was a large drop in ET_o and F_i at the end of the sampling period. Since LE from the grass canopy depends on the ET_o rate (a measure of evaporative demand) and water availability for evaporation and transpiration, F_i, which relates actual to potential evapotranspiration, provides a good measure of the wildfire potential.

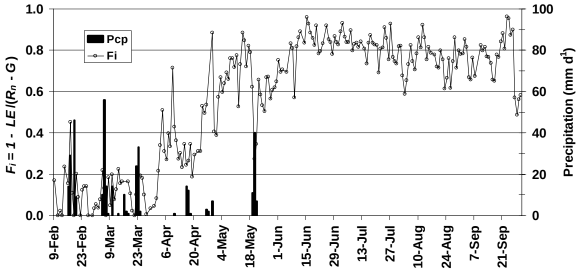

Figure 4. Plots of daily fire risk index (F_i) and precipitation from February 9 – October 2, 2002.

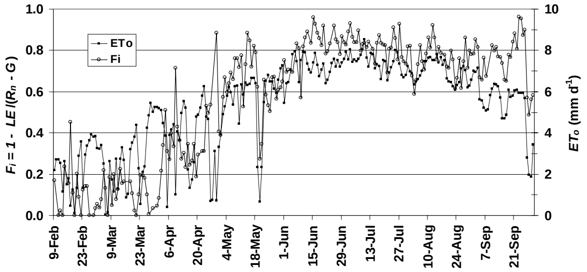

Figure 5. Plots of daily fire risk index (F_i) and ET_o from February 9 – October 2, 2002.

4. CONCLUSIONS

With high frequency temperature data one can estimate sensible heat flux density over grasslands using the surface renewal method. Latent heat flux density can be calculated as the residual of the energy balance equation, where R_n and G are estimated from solar irradiance. With these data, it is possible to determine a fire index using a low-cost remote, automated station that can reduce cost for travel and labor and greatly improve the estimation of fire potential in natural grasslands. It is likely that the same methodology will work in forests.

5. REFERENCES

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