MAPPING ET IN SOUTHEASTERN COLORADO USING A SURFACE AERODYNAMIC TEMPERATURE MODEL

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ABSTRACT

Accurate estimates of spatially distributed evapotranspiration (ET) using remote sensing inputs could help improve crop water management, the assessment of regional drought conditions, irrigation efficiency, ground water depletion, and the verification of the use of water rights over large irrigated areas.

In this study, ET was mapped using surface reflectance and radiometric temperature images from the Landsat 5 satellite in a surface energy budget algorithm driven by a surface aerodynamic temperature (SAT_ET) model. The SAT_ET model was developed using surface temperature, horizontal wind speed, air temperature and crop biophysical characteristic measured over an irrigated alfalfa field in Southeastern Colorado. Estimates of the remote sensing-based ET for a 4.0 hectare alfalfa field and a 3.5 hectare oats field, during the 2009 cropping season, were evaluated using two monolithic weighing lysimeters located at the Colorado State University Arkansas Valley Research Center (AVRC) in Rocky Ford, Colorado. Although the overall model performance was encouraging, results indicated that the SAT_ET model performed well under dry atmospheric and soil conditions and less accurately under high air relative humidity and soil water content conditions. These findings are evidence that SAT_ET needs to be further developed to perform better under a range of environmental and atmospheric conditions.

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INTRODUCTION

In the Western United States as well as in other semiarid areas of the world, intensifying competition for limited water supplies between urban, industrial and agriculture uses continues to exert profound pressures on the agricultural sector. In the Western U.S., agriculture currently accounts for about 70 percent of consumptive water use, and its water rights are increasingly being transferred to municipal and industrial uses, while in-stream flow requirements for environmental purposes also threaten to curtail diversions for irrigation. Maximizing the services provided by available water supplies for multiple uses imposes an immense responsibility to improve agricultural water management and planning for potential future climate change and population growth.

Irrigation and rainfall water use as crop evapotranspiration (ET) varies spatially and seasonally according to weather and vegetation cover conditions (Hanson, 1991). Modeling variations in ET is essential for providing predictive capabilities to guide planning and management of water resources, especially in arid and semi-arid regions where crop water demand exceeds precipitation and requires irrigation from surface and/or groundwater resources. Remote sensing (RS) based ET methods have been found to be useful for deriving such information for the range of present conditions (Gowda et al., 2008; Choi et al., 2009).

Most RS ET models are driven by a land surface energy balance algorithm in which sensible heat flux (H) is estimated using the radiometric surface temperature (T_s), using a linear surface to air temperature difference function ($dT = a + b\,T_s$), obtained from satellites or airborne sensors. However, H may be over-estimated when T_s is used rather than the surface aerodynamic temperature (T_o) in the bulk aerodynamic resistance equation since T_s is typically larger than T_o. This result would affect the estimation of crop water use or ET since and over-estimation of H would mean an under-estimation of ET, when using the energy balance method, consequently irrigation amounts would be less than required. Therefore, resulting in crop water stress and yield reductions.

The objective of this study was to evaluate ET values obtained remotely, under different atmospheric and environmental conditions, using an empirically developed surface aerodynamic temperature model in southeastern Colorado.

MATERIALS AND METHODS

Study Area

The research was carried out at the Colorado State University (CSU) Arkansas Valley Research Center (AVRC) which is located near Rocky Ford, Colorado, in 2009. The site elevation is 1,274 m (above mean sea level), and its latitude and longitude coordinates are 38º 2' N and 103º 41' W, respectively. The soil type at the AVRC is Rocky Ford silty clay loam. The long term average annual precipitation is 299 mm, with May through August having the largest precipitation amounts. Figure 1 shows the location of the

research site in southeastern Colorado (upper picture) and the location of the large and small weighing lysimeters (lower picture) at the CSU AVRC.
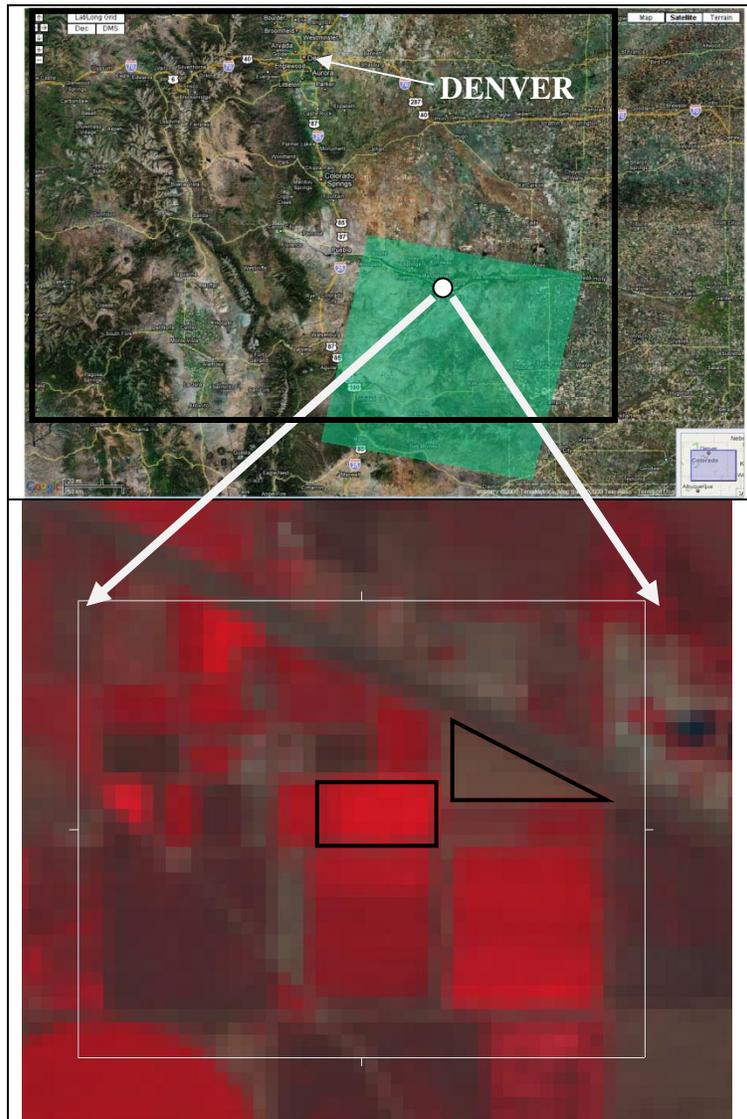
Figure 1. Location of research site (white dot) in southeastern Colorado (upper picture) and lysimeter fields location (lower picture), in a reflectance false color composite image, at the CSU AVRC facility near Rocky Ford, CO. The black rectangle shows the alfalfa field location (large lysimeter site) and the black triangle shows the location of the oat field (smaller lysimeter).

Lysimeter Characteristics

Remote sensing estimates of ET were verified by comparison with measured ET derived from a soil-water mass balance using data from two large monolithic weighing lysimeters. The CSU lysimeters were located in two fields. One field was a furrow

irrigated 4.13 ha field (162 × 255 m) planted to alfalfa in 2007. The large lysimeter (3 × 3 × 2.4 m) was located in this field (Fig.2a). The second smaller lysimeter (1.5 × 1.5 × 2.4 m) was in a 3.12 ha triangular field (180 m long in the North-South direction and 350 m in the East-West direction) was planted to oats in 2009 (Fig. 2b).

The following sensors were installed at the large lysimeter site: one tipping bucket rain gauge (TE525, Texas Electronics, Inc., Dallas, Tex.), a horizontal wind speed/direction sensor at 2 m height (RM Young 03101 Wind monitor, Campbell Scientific, Inc., Logan, Utah), two additional anemometers at 2-m and 3-m height (RM Young Wind Sentry, Campbell Scientific, Inc., Logan, Utah), one air temperature/relative humidity sensor installed at a height of 1.5 m above ground (HMP45, Vaisala, Campbell Scientific, Inc., Logan, Utah), and another air temperature/relative humidity sensor (HMT331, Vaisala, Campbell Scientific, Inc., Logan, Utah) which was located in a "cotton" shelter along with a barometer (PTB101B, Vaisala, Campbell Scientific, Inc., Logan, Utah). In addition, a net radiometer [Q*7.1, Radiation and Energy Balance Systems (REBS), Bellevue, Wash.], two infra-red thermometers, (IRTS-P, Apogee, Logan, Utah), incoming and reflected photosynthetic active radiation (PAR) sensors (Model LI-191 Line Quantum, LI-COR Biosciences, Lincoln, Neb.), an albedometer (CM14, Kipp and Zonen, Bohemia, N.Y.), two pyranometers (an Eppley PSP and a LI200X-L21, LI-COR, Campbell Scientific, Inc., Logan, Utah), 14 soil temperature probes (107, Campbell Scientific, Inc., Logan, Utah), and four access tubes for soil water content readings using a neutron probe (model 503DR1.5, InstroTek Inc., Concord, CA) were installed at and near the lysimeter.

Remote Sensing Data

In this study, two images from the Landsat 5 Thematic Mapper (TM) satellite sensor were used. Landsat 5 produces images in seven bands from 520-600 nm of bandwidth in the visible (VIS) to 10,400-12,500 nm for the thermal band. The image pixel spatial resolution is 30 m for the VIS, near infra-red, and mid infra-red bands while the pixel size is 120 m for the thermal band (which the image supplier had re-sampled to 60 m). The temporal resolution is one scene every 16 days. The satellite sun-synchronous near-polar orbit altitude is 705 km which results in an image swath width of 185 km.

The two images were acquired on May 19 and July 7, 2009. The local overpass time was approximately 17:20 GTM (or 10:20 MST). The images were pre-processed according to the following steps: a) digital number (DN) conversion to radiance values, b) conversion of radiance values of visible and mid infra-red bands to top-of-atmosphere (TOA) reflectance, c) correction of TOA reflectance for atmospheric effects using the atmospheric radiative transfer model MODTRAN4 v3 (Berk et al., 2003), conversion of thermal radiance values to apparent surface radiometric temperature, correction of atmospheric effects on the apparent surface temperature using MODTRAN4 v3 to obtain the at-surface temperature value.
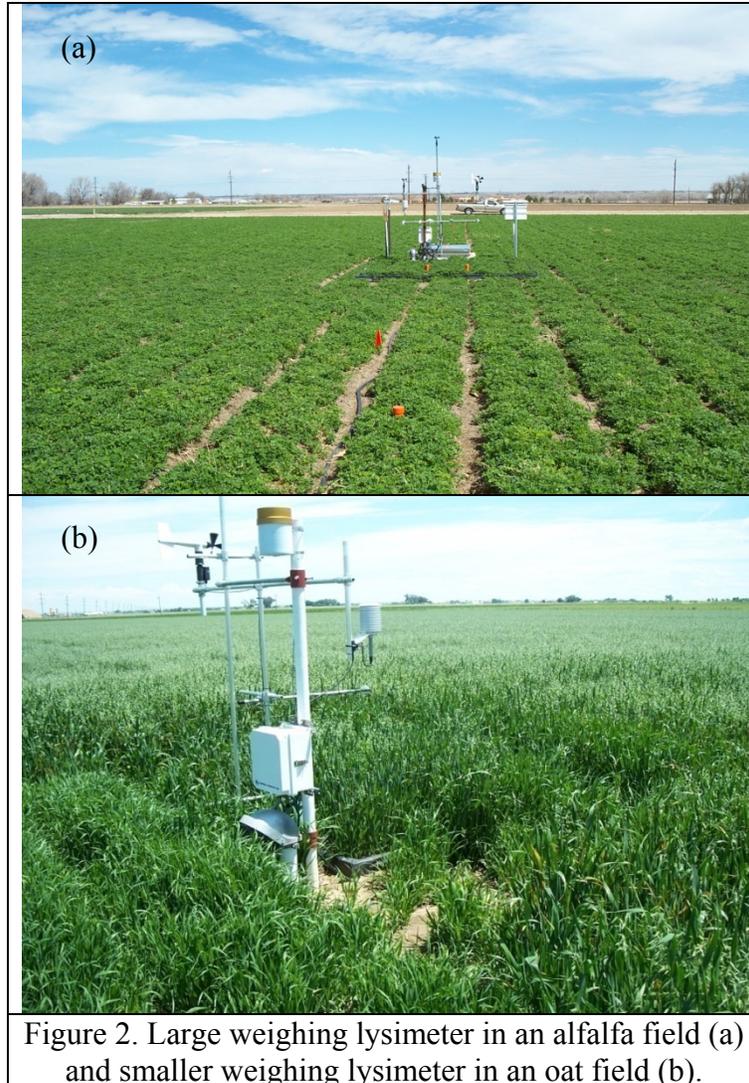
Figure 2. Large weighing lysimeter in an alfalfa field (a)
and smaller weighing lysimeter in an oat field (b).

Weather, Crop and Soil Water Content Data

Weather data was collected from the instrumentation available at the lysimeter sites (see Fig. 2). Table 1 summarizes the 15-minute average recorded weather data as well as the alfalfa biophysical characteristics and soil volumetric water content (average soil moisture at a depth of 0.15-2 m).

Table 1. Weather data for DOYs 139 and 187 collected near the satellite overpass time.

DOY	T_a (ºC)	RH (%)	U (m s^{-1})	BP (kPa)	R_s (W m^{-2})	h_c (m)	LAI (m^2 m^{-2})	θ_v (m^3 m^{-3})
139	31.1	22.9	4.6	87.26	947.4	0.56	4.8	11
187	21.4	76.4	2.3	87.61	853.1	0.58	4.9	28
where, DOY is day of year, T_a is air temperature, RH relative humidity, U wind speed, BP barometric pressure, R_s shortwave incoming solar radiation, h_c crop height, LAI is alfalfa leaf area index, and θ_v volumetric soil water content.								

It is worth noting the difference in the atmospheric and soil water content conditions on both days. DOY 139 is characterized by a dry surface and atmospheric conditions while DOY 187, on the contrary, is characterized by a near field capacity volumetric soil water content and very humid air.

Surface Aerodynamic Temperature based Remote Sensing ET Algorithm

The proposed RS-based ET algorithm uses a surface aerodynamic temperature (SAT_ET) model developed in Colorado (Chávez et al., 2010). The ET algorithm uses the land surface energy balance (EB, Eq. 1) to estimate instantaneous latent heat flux (LE) or evapotranspiration (ET_i) as a residual.

$$LE = R_n - G - H \qquad (1)$$

where R_n is net radiation, G is the soil heat flux, and H is sensible heat flux. Units in Eq. (1) are all in W m^{-2}, with R_n and G positive toward the crop/soil surface and other terms positive away from the surface.

Net radiation was estimated according to Monteith (1973).

$$R_n = (1-\alpha)R_s + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \qquad (2)$$

where α is surface albedo, R_s is shortwave incoming solar radiation (W m^{-2}), ε_a is atmospheric emissivity, σ is the Stefan-Boltzmann constant (5.67E-08 Watts m^{-2} K^{-4}), T_a air temperature (K), and T_s is surface temperature (K). Both surface albedo and T_s are derived from the satellite multispectral imagery. Details on the remote sensing application of R_n can be found in Chávez et al. (2009a) and Chávez et al. (2005).

Soil heat flux was estimated according to Chávez et al. (2005).

$$G = \{(0.3324 - 0.024 \text{ LAI}) \times (0.8155 - 0.3032 \ln(\text{LAI}))\} \times R_n \qquad (3)$$

Sensible heat flux was estimated using the bulk aerodynamic resistance equation (Eq. 4) and the surface aerodynamic equation (Eq. 5) developed by Chávez et al. (2010, 2009b).

$$H = \rho_a Cp_a (T_o - T_a) / r_{ah} \qquad (4)$$

$$T_o = 1.5 T_s - 0.53 T_a + 0.052 r_{ah} + 0.36 \qquad (5)$$

$$r_{ah} = \frac{\ln\left(\dfrac{z_m - d}{Z_{oh}}\right) - \psi_h\left(\dfrac{Z_m - d}{L}\right) + \psi_h\left(\dfrac{Z_{oh}}{L}\right)}{u_* k} \qquad (6)$$

$$u_* = \frac{u\,k}{\ln\left(\dfrac{z_m - d}{Z_{om}}\right) - \Psi_m\left(\dfrac{Z_m - d}{L}\right) + \Psi_m\left(\dfrac{Z_{om}}{L}\right)} \tag{7}$$

where ρ_a is air density (kg m^{-3}), Cp_a is specific heat of dry air ($\approx 1{,}004.5$ J kg^{-1} K^{-1}), T_a is average air temperature (K), T_o is average surface aerodynamic temperature (K), which is defined as the air temperature that occurs at a height equal to the zero plane displacement height (d, m) plus the roughness length for sensible heat transfer (Z_{oh}, m) height, and r_{ah} is surface aerodynamic resistance (in s m^{-1}) to heat transfer from d+Z_{oh} to Z_m (horizontal wind speed measurement height, m). Further, k is the von Karman constant (0.41) and u_* the friction velocity in m s^{-1}. $\Psi_h(\ )$ and $\Psi_m(\ )$ are the atmospheric stability factors for heat and momentum transfer, respectively. L is the Monin-Obukhov stability length (m), and u horizontal wind speed at Z_m.

LE is converted to an equivalent water depth evapotranspirated (mm h^{-1}) using the following conversion formula:

$$ET_i = (3600 \times LE) / (\lambda_{LE} \times \rho_w) \tag{8}$$

where, ET_i is instantaneous remote sensing derived crop ET (mm h^{-1}), λ_{LE} is the latent heat of vaporization (MJ kg^{-1}), and ρ_w is the density of water (1 Mg m^{-3}).

Reference ET fraction (ET_rF) is the ratio of the crop ET_i to the alfalfa reference ET_{ri} that is computed from weather station data at overpass time (hourly average). Finally, the computation of daily or 24-h ET (ET_d), for each pixel, is performed as:

$$ET_d = ET_rF \times ET_{rd} \tag{9}$$

where, ET_{rd} is the cumulative 24-h alfalfa reference ET for the day (mm d^{-1}). Both ET_{ri} and ET_{rd} were computed following ASCE-EWRI (2005) procedures.

RESULTS AND DISCUSSION

ET maps for both DOYs 139 and 187 were produced for the Arkansas River Valley of southeastern Colorado (Fig. 3). In the maps, the location of the city of Rocky Ford and the location of the CSU AVRC lysimeter sites are indicated. For DOY 139 the maximum ET rate was 12.5 mm d^{-1} for well-irrigated crops, due to the large evaporative demand imposed by the atmospheric conditions. For DOY 187 the maximum ET rate was only 8.0 mm d^{-1} for well-irrigated crops due to the air high relative humidity, low air temperature, and calm winds.
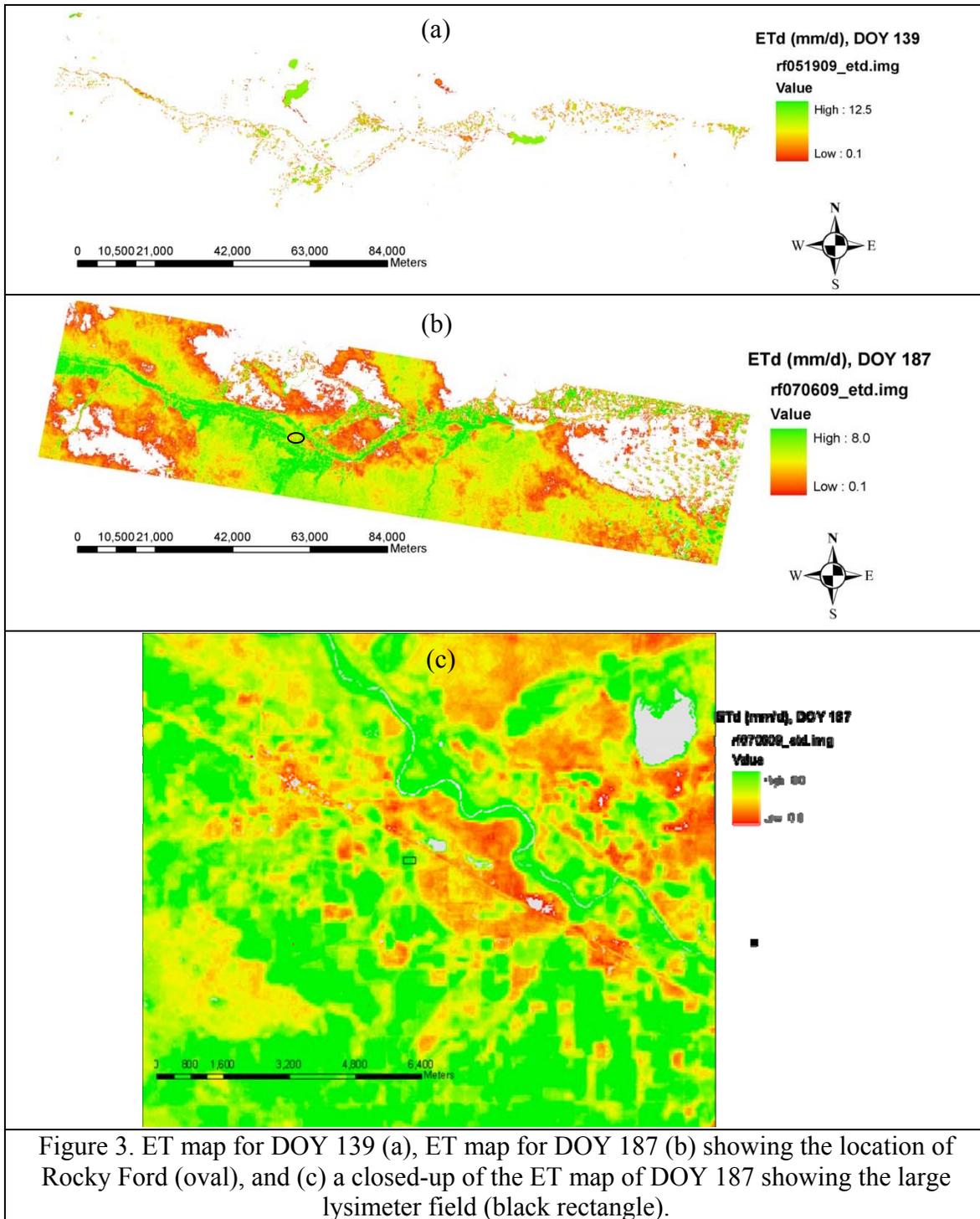
Figure 3. ET map for DOY 139 (a), ET map for DOY 187 (b) showing the location of Rocky Ford (oval), and (c) a closed-up of the ET map of DOY 187 showing the large lysimeter field (black rectangle).

The alfalfa hourly ET was estimated to be 0.45 mm h^{-1} at the time of the satellite overpass (17:20 GMT or 10:20 MST) while lysimeter measured ET was 0.47 mm h^{-1}. Therefore, the underestimation would be 4.3% when the lysimeter hourly alfalfa value of 0.47 mm h^{-1} was used as reference. Otherwise, the difference would be -0.52 mm h^{-1} or an underestimation of 53.6% when the ET_{ri} value of 0.97 mm h^{-1} ("potential hourly ET") was used as reference. This good agreement of estimated and measured hourly ET is not

surprising because aerodynamic temperature in southeastern Colorado was modeled using weather and alfalfa data acquired under similar weather and soil water conditions of those encountered during DOY 139. The discrepancy in relation to ET_{ri} was due to soil water content not being at reference levels, i.e. the alfalfa was experiencing water stress which was not accounted for in the reference ET computation.

Estimated daily ET for the lysimeter alfalfa field for DOY 139 was 5.2 mm d^{-1} while the lysimeter measured an alfalfa water consumption rate of 4.6 mm d^{-1}. Thus, resulting in an overestimation of ET of 13% even though hourly ET resulted in a small underestimation of 4.3%, as explained above. The overestimation on daily ET was caused by the magnitude of ET_{rd} in the adopted extrapolation mechanism of hourly ET to daily ET. The "potential" ET rate (ET_{rd}) was 11.3 mm d^{-1} according to the standardized ASCE PM method; which may be an over estimation due to a higher air temperature and lower relative humidity values recorded under the "non-standard" soil water content conditions. Therefore, the daily alfalfa ET was slightly overestimated. Furthermore, using ET_{rd} as a reference, the alfalfa was evapotranspirating at a rate that was only 46.4% of the potential. This low ET rate was due to limitations imposed by the availability (lack of) of soil water on DOY 139. Average volumetric soil water content measured with a neutron probe to a depth of 2 m, inside and outside of the lysimeter box, was 11%.

For the oat field (small lysimeter field), on DOY 139, hourly ET was estimated to be -0.82 mm h^{-1} while measured ET was +0.82 mm h^{-1}. Extrapolation to a daily value resulted in a negative ET rate of 9.3 mm d^{-1}, while the measured value was +5.7 mm d^{-1}. This result was not a sign error, rather sensible heat flux was grossly overestimated (1,066.5 W m^{-2}) due to a very large surface temperature value (47.1 ℃) derived from Landsat 5 thermal imagery. The large surface temperature value was due to the Landsat 5 TM thermal pixel radiometric contamination at the location of the oat field. The Landsat 5 TM thermal pixel covered and area equal to 120 m × 120 m which may have caused radiometric contamination in the pixel covering the oat lysimeter field due to the incorporation of radiances from more than one surface type (i.e., temperatures from hotter adjacent areas, as roads, to the oat field site being averaged with surface temperatures from the oat field). As shown in Fig. 1(b), the oat field has a triangle shape and it was bound to the north and east by a road and by a fallow land to the south. Therefore, if a thermal pixel does not fully fall or is contained within the field then inevitably it will have average radiometric values including temperatures from surrounding areas. The maximum surface temperature on adjacent dry fallow fields was found to be 58.2 ℃. The oat field contaminated thermal pixels indicated a canopy temperature of 47.1 ℃. When the aerodynamic temperature was calculated it resulted in a value of 56.3 ℃, which is too large. Considering the surface aerodynamic properties of the oat field, every degree difference (overestimation) in surface aerodynamic temperature (due to pixel thermal contamination) caused an overestimation (error) of 0.98 mm d^{-1} in daily ET. Thus, the total net ET error of 15 mm d^{-1} (9.3 + 5.7 mm d^{-1}) meant that the actual aerodynamic temperature was about 41 ℃ instead of 56.3 ℃. This T_o value would have resulted from a surface temperature (true) of 36.5 ℃ (a difference of 10.6 ℃ with the satellite sensed temperature of 47.1 ℃). This situation highlights a significant constraint of applying the SAT_ET model on fields having dimensions that

not fully accommodate an entire satellite thermal pixel. Future research, in this regard, will include the concept of thermal pixel sharpening in which the thermal pixel radiometric and spatial resolutions are enhanced using information from other bands and/or other sensors (platforms).

For DOY 187, the remote sensing estimation of hourly alfalfa ET was 0.67 mm h^{-1}, lysimeter measured hourly ET was 0.76 mm h^{-1}, and "potential" ET$_{ri}$ and ET$_{rd}$ were 0.64 mm h^{-1} and 6.0 mm d^{-1}, respectively. The calculated ET$_r$F was 1.04 and the RS estimated daily ET was 6.2 mm d^{-1}; however measured daily ET was 7.4 mm d^{-1}. The error in the estimation of hourly ET was   -14.3% while the daily ET error was -19.7%. This discrepancy to the lysimeter measured ET value is attributed to an overestimation of the aerodynamic temperature (26.8 ºC) which would have overestimated sensible heat flux (167.2 W m^{-2}) and therefore underestimated latent heat flux (455.1 W m^{-2} or ET 0.668 mm h^{-1}).

To verify this hypothesis an energy balance was performed at the lysimeter box using measured values of R$_n$, G and LE (LE from the conversion of measured hourly ET) in order to calculate the lysimeter derived sensible heat flux (37.5 W m^{-2}). Then, T$_o$ was obtained, from inverting the bulk aerodynamic resistance equation, and was found to be 22.5 ºC. This value was 4.3 ºC less than the remote sensing-based T$_o$ of 26.8 ºC. Furthermore, we used H data (66.8 W m^{-2}) from a Large Aperture Scintillometer (LAS), that was installed in the alfalfa field as part of another experiment, to compute T$_o$ (23.5 ºC).
Therefore, on DOY 187 T$_o$ was overestimated by 3.3 to 4.3 ºC (i.e., an error of 14 to 19%).

On DOY 187 no more oats were available at the small lysimeter field because the oat field had been harvested July 1st (DOY 181). Instead, the field contained a bare soil. At this location the remote sensing ET algorithm estimated an hourly ET rate of 0.12 mm h^{-1} and a daily ET rate of 1.13 mm d^{-1} while the corresponding lysimeter measured values were 0.29 mm h^{-1} and 2 mm d^{-1}, respectively. Hence, the estimation errors were -26.5% for the hourly ET and -14.7% for the daily ET. The discussion regarding thermal pixel contamination applies to the imagery acquired on DOY 187 as well. This means that high surface temperatures were employed in the T$_o$ estimation in addition to the already recognized overestimation of the T$_o$ model for the environmental and weather conditions encountered on DOY 187.

This result is evidence that the aerodynamic temperature model used in this study needs to be further refined incorporating a wider range of surface types (e.g., bare soils, fallow land, and crops at difference development stages), environmental, and atmospheric conditions to improve its performance.

CONCLUSIONS

A remote sensing ET algorithm (SAT_ET) based on surface aerodynamic temperature was applied to two satellite (Landsat 5) images. One image acquired May 19 (DOY 139),

2009 and the other July 6 (DOY 187), 2009. Weather conditions were very different on both days, on DOY 139 the air and the soil were dry and wind speed was high; while on DOY 187 the air and the soil was wet and wind speed was low. Under these conditions the aerodynamic temperature method performed better for DOY 139 with small errors (5.4%) in the estimation of the alfalfa daily ET. However, for DOY 187 the error was larger (-19.7%).

Therefore, the aerodynamic temperature model used in this study needs to be further refined incorporating a wider range of surface types (e.g., bare soils, fallow land, and crops at difference development stages), environmental, and atmospheric conditions to improve its performance. Nevertheless, overall, the results found in this study are very encouraging in that the aerodynamic temperature based energy balance algorithm has the potential to be effectively used in Colorado to monitor crop water use and improve regional water management.

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