Independent Comparisons among Calibration and Output of Energy Balance Components Estimated by the METRIC Procedure

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ABSTRACT

An accurate estimation of evapotranspiration (ET) is an integral part of the hydrological cycle and is increasingly important in local and regional water resource management in central and western United States. Traditionally, estimation of ET included substantial uncertainties, but with the advent of algorithms applied to high resolution (30 m) satellite imagery, ET estimates from bare soil and vegetation can be obtained with greater accuracy. The METRIC image processing model estimates net radiation, soil heat flux and sensible heat flux through a series of steps before estimating ET as the residual from the energy balance. This paper describes a comparison of the METRIC surface energy balance model outputs produced by two different research groups when using the same two 2007 Landsat 5 images as input. One of the research groups is based at the USDA Conservation and Production Research Laboratory in Bushland, Texas where the images and ground-based data were captured, and the other group is from the Kimberly Research Center, University of Idaho where METRIC was developed.

INTRODUCTION

Considerable uncertainty exists regarding the spatial and temporal variability and distribution of the consumptive water use (CWU), not only for agricultural crops but also for rangeland, riparian zones and other areas with natural vegetation. The variability is caused by local and regional differences in weather, precipitation distribution and quantity, soil, land form and land use, vegetation type, cultivar and cropping system, irrigation application method and land management. Normally the vast majority of CWU is made up by evapotranspiration, ET. A common method to

estimate actual ET (ET_a) from the ground and vegetation include multiplying weather-based reference evapotranspiration (ET_r) with a crop coefficient (K_c) (Allen et al., 1998; ASCE-EWRI, 2005). Allen et al. (2007b) estimated ET with this procedure and is relatively accurate with an error of up to ± 20 %. Errors may arise from actual vegetation and growing conditions deviating from the idealized K_c values or results from undocumented water shortage in the vegetation. In addition, it is difficult to predict the correct crop growth stages for a large population of crops and fields.

Application of remote sensing algorithms solving the energy balance using high resolution satellite imagery has proven useful for establishing estimates of ET_a and K_c for large populations of fields and water users (Bastiaanssen et al., 1998; Tasumi et al., 2005, Allen et al. 2007a). The METRIC model (Mapping Evapotranspiration at high Resolution with Internalized Calibration) is a satellite image processing model which estimates ET as the residual of the energy balance (Tasumi et al., 2005, Allen et al., 2007b), Eq. 1.

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

where LE is latent heat flux density, R_n is net radiation, G is soil heat flux density and H is sensible heat flux density. In METRIC, R_n is calculated by solving the radiation balance as described by Allen et al. (2007b). Soil heat flux is the rate of heat being conducted into the soil and vegetation, and is estimated based on R_n, surface temperature and the Normalized Difference Vegetation Index, NDVI.

METRIC utilizes the *CIMEC* (calibration using inverse modeling of extreme conditions) procedure (Bastiaanssen, 1995, Bastiaanssen et al., 1998) procedure to calibrate the dT function based on a regression relationship between the dT and radiometric surface temperature of two “anchor” pixels. The advantage of the SEBAL approach to developing a dT vs. T_s relationship by inverting the energy balance at the two calibration points is that many biases in energy balance components are factored out, including those in T_s itself. In addition, the use of a dT that ‘floats’ above the surface may eliminate some of the issues with single source models (Allen et al., 2007b). The anchor pixels ideally represent the conditions of an agricultural field with full and actively transpiring vegetation cover and a bare agricultural field with no vegetation cover. The anchor pixel representing full vegetation cover has the characteristics of green vegetation and its dT is low due to evaporative cooling. This condition is often referred to as the “cold” condition. The anchor pixel representing a bare field has the characteristics of bare soil and its dT is high due to radiometric heating of the surface and is generally referred to as the “hot” condition.

METRIC uses alfalfa based ET_r to establish the energy balance at the cold pixel, thus establishing a ground reference for the satellite image based ET_a estimate. ET_r is calculated outside of METRIC using hourly (or shorter) weather data from a weather station preferably located toward the center of the study area. The use of ET_r is generally effective in tying down the energy balance calibration, especially in arid

and semiarid climates having advection. The use of ET_r for calibration and extrapolation of ET to longer time periods makes the METRIC process congruent with traditional ET_r based estimation methods. One of the outputs from METRIC is a map of the ET from each pixel stated as a fraction of ET_r, ET_rF. The ET_rF is synonymous with the well known K_c (for an alfalfa reference basis). Daily ET_a maps are calculated by multiplying the instantaneous ET_rF calculated for each pixel with the 24-h summed ET_r. The resulting high resolution maps of ET cover regions typically up to 150 km in scale. When used properly, METRIC provides a rapid and cost effective method to determine ET for focused regions.

The METRIC model can be set up to be nearly fully automated, but does require rather essential input from the user to define and interpret e.g. vegetation roughness, land use, and anchor pixels, during image calibration, representing fields with dry soil surface and with a vegetated, fully transpiring surface. Additionally, some of the algorithms for atmospheric attenuation and emission of radiation can benefit from further testing to be used with confidence over vide range of climates.

There is therefore merit in doing an inter-comparison of the output from METRIC produced individually by two independent groups. This paper describes a comparison of the preliminary results of METRIC outputs produced by two different research groups when processing the same two Landsat 5 images from 2007. The images were processed without contact between the two groups. Subsequently, following this comparison, the two groups will continue the collaboration and conduct an additional processing run, integrating local knowledge and experience about e.g. cropping patterns and land management, and long-term experience in METRIC application. Additionally, images from other times during the growing season and other years will be processed for inter-comparison purposes.

METHODS

One Landsat 5 scene from 07/10-2007 from path 31 row 36 have been selected. The scenes cover the central portion of the Texas panhandle, but were not geometrically corrected. To avoid errors caused by geometric incongruencies within the Landsat images and for the purpose of the initial comparison of METRIC output four square fields at the USDA-ARS, Conservation and Production Research Laboratory in Bushland was selected for the comparisons. The relative location of the fields in the Landsat image is shown in Fig. 1. The fields are equipped with four high precision weighing lysimeters each located at the center of each field (Howell et al., 1995). Each lysimeter (3 m length × 3 m width × 2.4 m depth) is located in the middle of 4.7-ha fields and all four lysimeters are arranged in a block pattern. Dryland cropping systems are managed on two lysimeter fields in the west and irrigated cropping systems are managed on two lysimeter fields in the east with a 10-span lateral move sprinkler system. The location of the fields and the 2007 crop cover is shown in Fig. 2.

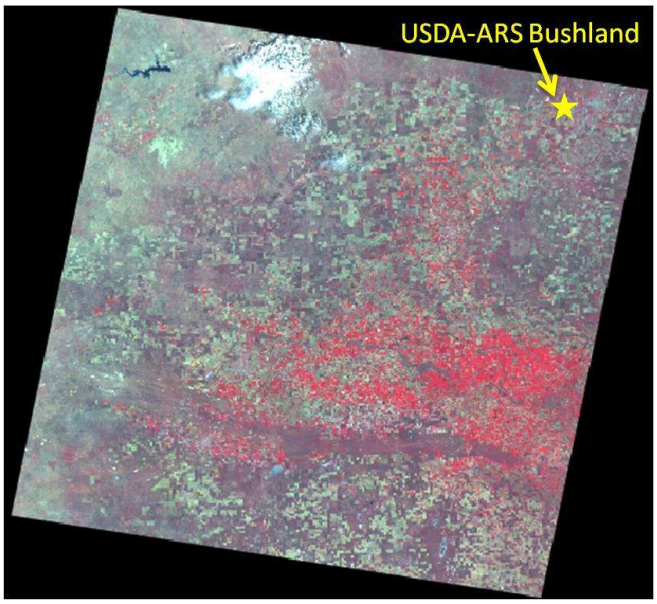

Figure 1. Location of the fields at USDA-ARS in Bushland used for the METRIC output comparison

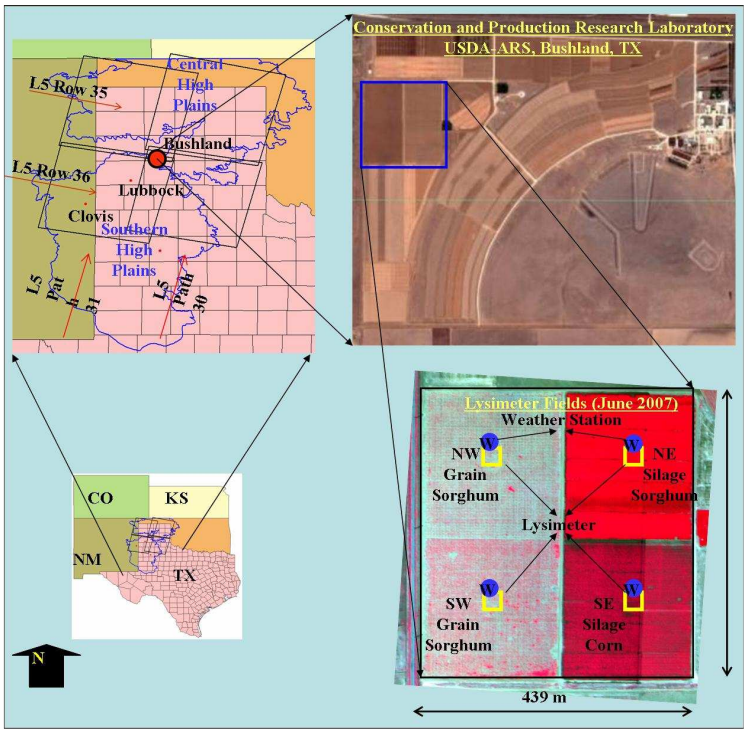

Figure 2. Location of the Bushland weighing lysimeters from. The geographic location of the SE lysimeter is shown in the lower right corner, 35° 11’ 09.96’’ N 102° 05’ 43.35’’ W.

The METRIC model was coded and processed using the ERDAS Imagine Spatial Modeler tool independently by each group. Reference ET was calculated using the RefET software (Allen, 2003) using meteorological data as input. Supporting input information, including a water balance to estimate residual evaporation from bare soil (for the hot pixel calibration) and the iterative numerical solution of the dT function equation based on the cold and hot anchor pixels, were carried out using a regular spreadsheet.

Weather data from the weather station located approximately one km from the fields were used during the processing. The station is part of the Texas High Plains Evapotranspiration network, operated by Texas A&M University. The quality of all meteorological data used in the METRIC processing were checked following the recommendations by Allen (1996), Allen et al. (1998) and ASCE-EWRI (2005). As ET_r was also used to establish a soil water balance several months before each image acquisition date, the integrity of the meteorological data for the entire year 2007 were evaluated. Hourly and daily values for solar radiation R_s were compared to computed clear sky solar radiation (R_{s0}). R_{so} was calculated based on atmospheric pressure, sun angle and precipitable water in the atmosphere. Generally a good agreement was found between observed R_s on days with clear sky conditions and the theoretical R_{s0} values, although the observed R_s values does run a few % higher than the R_{s0} curve during the winter period.

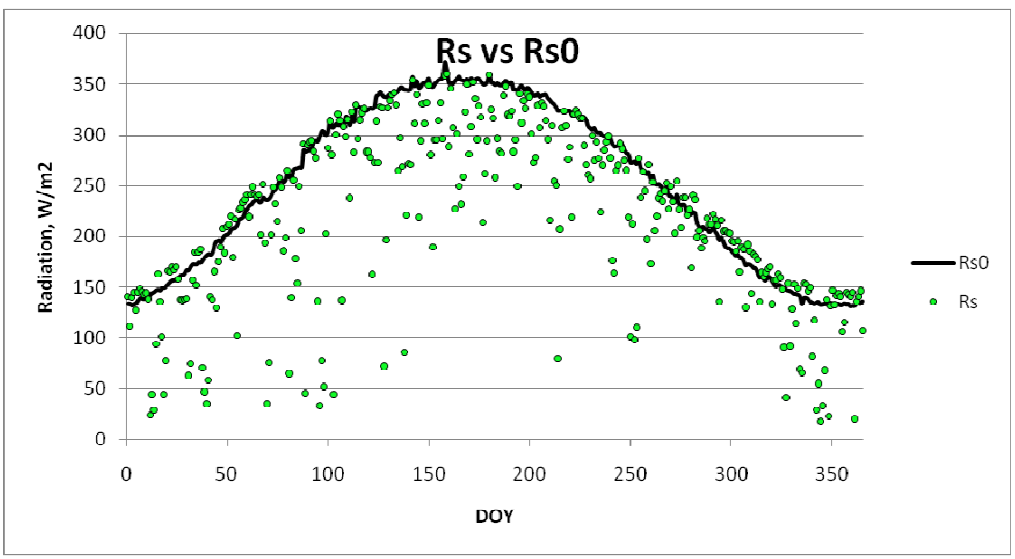

Figure 3. Daily solar radiation observed at the Bushland weather station versus theoretical clear sky solar radiation, R_{s0} during year 2007.

A range test was used to check daily minimum and maximum relative humidity. In addition, daily mean computed dewpoint temperature was compared against daily minimum air temperature following ASCE-EWRI (2005). The air temperature (T_a) was compared to nearby weather stations, and hourly T_a measurements were checked visually for sudden spikes and the expected diurnal

occurrence of minimum and maximum values. Wind speed was checked by calculating the gust factor (ASCE-EWRI, 2005) and comparing average daily wind speed to that of other nearby weather stations.

A daily water balance model based on Allen et al. (1998) was employed to estimate residual evaporation from the hot pixel (Fig. 4). The satellite overpass moment were obtained from the respective image header files and used to estimate the zenith angle of the sun and instantaneous values of wind speed at screen height and 200 m, air humidity and ET_r.

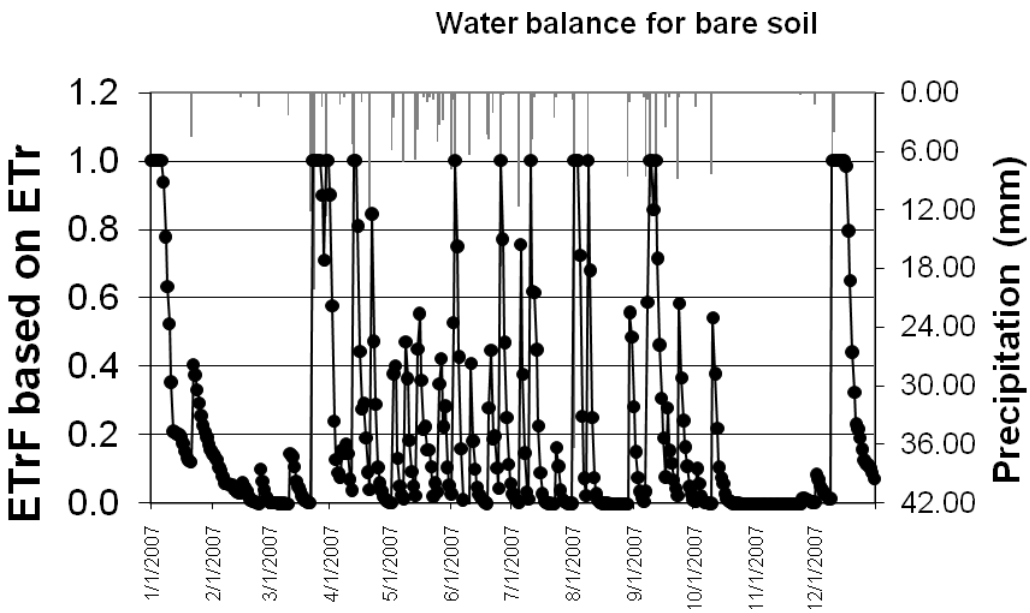

Figure 4. Soil water balance for bare soil calculated using meteorological data from Bushland, Texas 2007 and used to determine ET_rF for the hot pixel calibration.

PRELIMINARY RESULTS AND DISCUSSION

ET estimates from four 30-m pixels located towards the center of each of the four fields are sampled and averaged. Center pixels are generally selected to avoid sampling field edges where the vegetation cover is less due to e.g. traffic, insufficient irrigation and similar. The northwest and southwest fields were grown with grain sorghum under dryland conditions in 2007. Drought damaged the crop and by mid-summer the vegetation cover was relatively sparse. The northeast field was grown with a silage sorghum crop under irrigated conditions, while the southeast field had an irrigated silage corn crop. The crop pattern and the associated ET_rF values are recognized in Fig. 5. The crosshair is at the same geographic location at the four corners of the fields. The ET rates are highest for the corn being at full cover and under relatively good water supply.

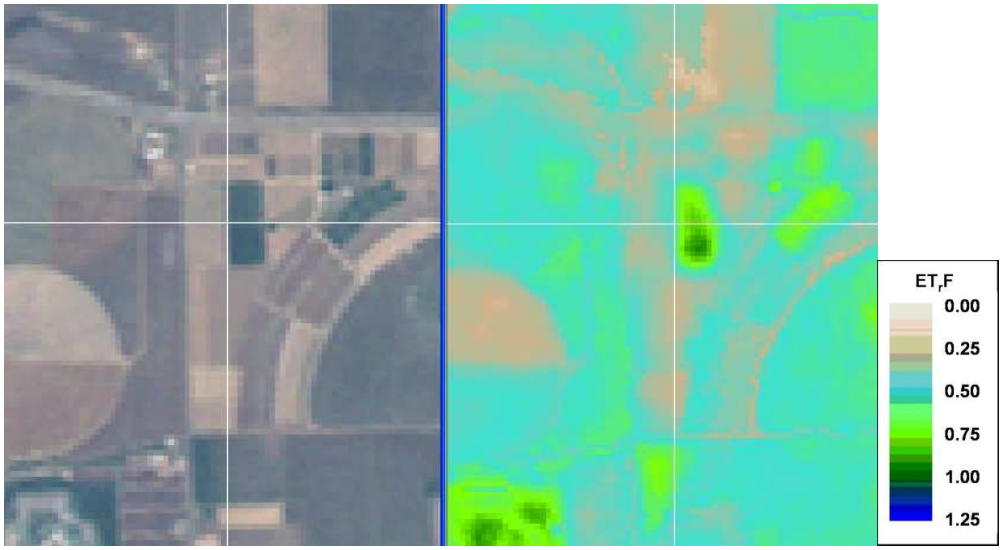

Figure 5. Satellite image in true color (left) and the corresponding resulting ET_rF map on July 10 2007, for the ARS station in Bushland, Tx. The crosshair is at the same geographic location.

A comparison of the instantaneous ET as measured by each of the four lysimeters and as predicted by each of the two research groups producing the estimates using METRIC is shown in Figure 6. The deviation in net radiation estimated by METRIC, Figure 7, is probably caused by differences in the estimation of atmospheric transmissivity and or emissivity of the surface or the atmosphere. For the field grown with silage corn the estimates of ET are close between the lysimeters, while more deviation is found for the two dryland fields. A thin layer of wilted plant material on the soil surface or the presence of senescenced standing crops may cause the differences between the lysimeter and the METRIC estimates. This may increase the "skin" temperature "seen" by the satellite causing H to be overestimated in METRIC and subsequently underestimate ET. A likely cause of the deviation between the estimates of ET between the two groups A and B is that the "hot" pixel selected by one (or both) of the groups does not entirely represent the conditions of a bare, dry field. This causes a deviation in the estimation of H, figure 8, possibly leading to an underestimation of H.

The scale of the fields used for the comparisons between the output produced by the two research groups adds additional uncertainty for the final result. Since each field has a side length of approximately 225 m there will likely only exist one thermal pixel (120 m) within each field. Since the thermal band has been resampled to 30 m resolution using cubic convolution (CC) resampling it is not possible to locate the original thermal pixel. There is therefore a risk that among the four pixels sampled for ET averaging one or more will be from a 120m thermal pixel that is not contained entirely within the field, or is located towards the edge of the field. Such thermal pixels may not be representative for a larger field, and may draw the ET estimates down. Additionally, meteorological sensors mounted on a bench are located near the

lysimeters, which may impact the amount of radiation reflected and emitted from that location.

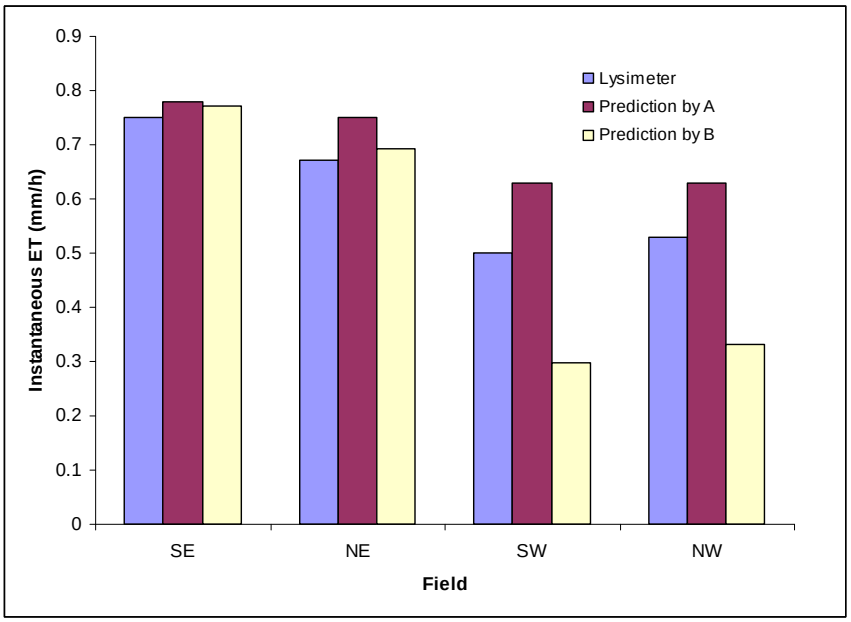

Figure 6. Comparison of instantaneous evapotranspiration (mm/hr) as measured by the four lysimers, and as predicted by user group A and user group B using METRIC.

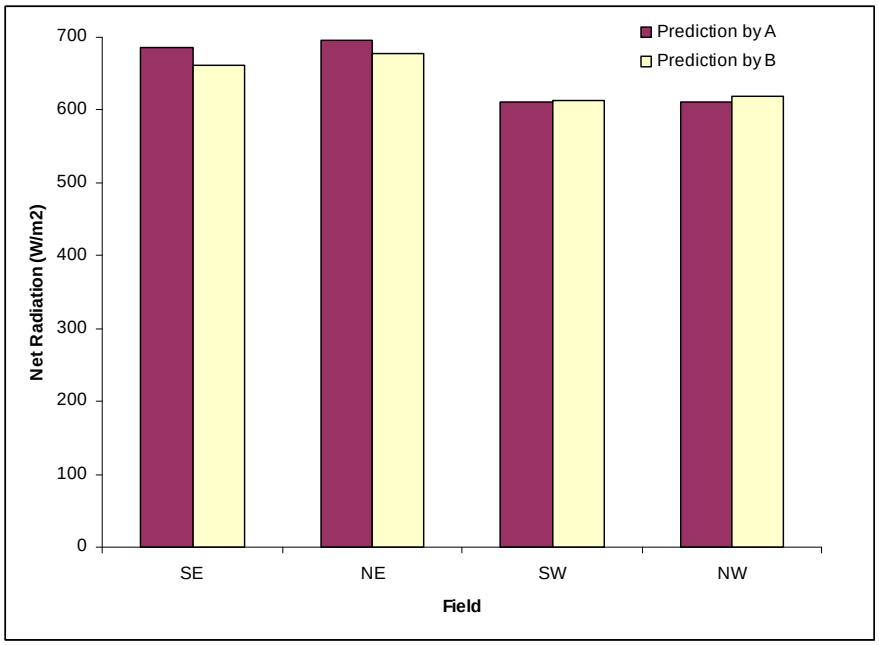

Figure 7. Comparison of net radiation as predicted by user group A and B using METRIC.

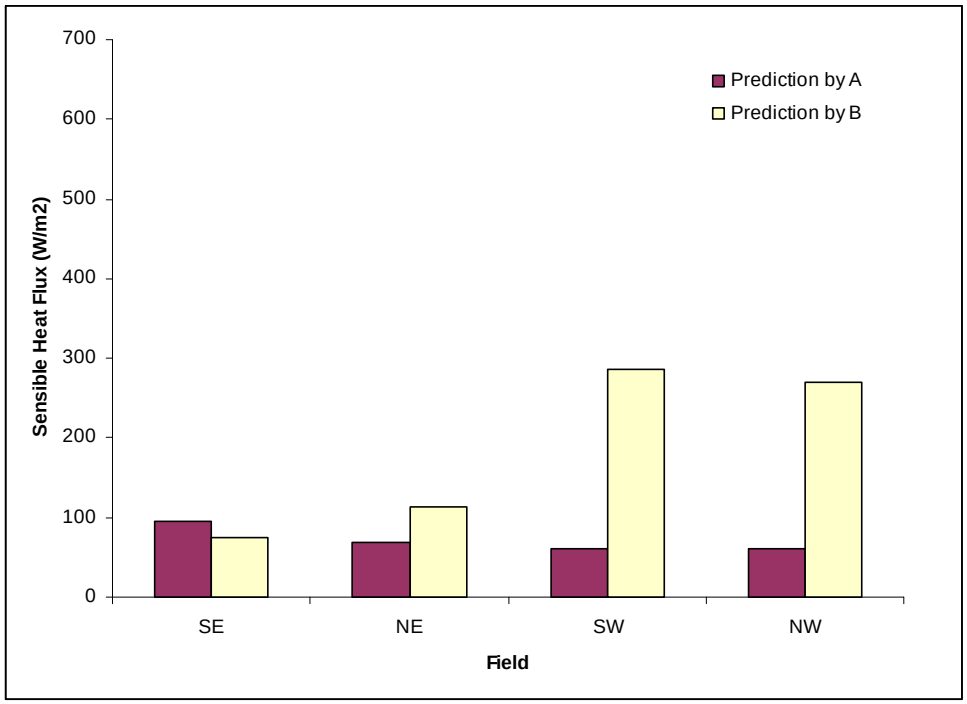

Figure 8. Comparison of sensible heat flux as predicted by user group A and B using METRIC.

Further investigation and comparisons, and through conducting an additional processing run the deviations should be minimized. The results obtained this far underlines the importance of the user being trained in the use of METRIC and having experience with running the model, including selection of hot and cold anchor pixels in order to obtain good and consistent results.

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