2014 UCOWR / NIWR/ CUAHSI
ANNUAL CONFERENCE

WATER SYSTEMS, SCIENCE, AND SOCIETY UNDER GLOBAL CHANGE

June 18-20, 2014
40 Talbot Avenue, Aidekman Arts Center
Tufts University
Medford, Massachusetts 02155

Universities
Council
On
Water
Resources

NIWR
The National
Institutes for
Water Resources

CUAHSI
universities allied for water research

Session 46

Monitoring water use in agricultural fields of Saudi Arabia. ***V.C. Patil,*** K.A. Al-Gaadi, R. Madugundu, E.Tola, S. Marey, A.G. Kayad, A.M. Zeyada, M.E. Abbas, King Saud University; P.H. Gowda, U.S. Department of Agriculture; C.M. Biradar, ICARDA, Jordan..

With growing population, urbanization and irrigated agriculture, water shortages are increasing in arid regions. In 2012, freshwater consumption for the agricultural sector in Saudi Arabia was estimated at 86%. Accurate evapotranspiration (ET) data are crucial for crop water management, especially in hyper arid regions like Saudi Arabia with scarce fresh water resources. In this study, ET of agricultural fields located in the Eastern Province of Saudi Arabia, was monitored using Eddy Covariance (EC) and a dual-beam Surface Layer Scintillometer (SLS) system. Both EC and SLS systems were installed in a 50 ha alfalfa centre pivot field that lies within latitudes 24º10’22.77” and 24º12’37.25” N and within longitudes 47º56’14.60” and 48º05’08.56” E. Field measurements were made between June and October 2013. Point and path-weighted measurements were made by EC and SLS systems, respectively. Measurements were made at a frequency of 1 Hz and 10 Hz and subsequent calculations were made every 30 and 10 minutes with EC and SLS, respectively. The measurements with EC were made at a height of 3.5 m from the soil surface along with bio-met sensors (Self-Calibrating Soil Heat Flux Plates, soil moisture probe, net radiometer etc,). While, SLS measurements were made on a path length of 150 m and a measurement height of 2 m. ET values ranged between 0.05 to 17.81 mm/day for the EC and SLS methods. Much of the variability was attributed to the differences in footprints which contribute to the measurement differences between the two methods of ET measurements.

Keywords: Surface layer scintillometer, Eddy covariance, Sensible heat flux, Saudi Arabia

1. INTRODUCTION

With growing population, urbanization and irrigated agriculture, water shortages are increasing in arid regions. In Saudi Arabia, the agriculture sector accounts for more than 80% of the total annual water consumption (Al-Ghobari 2000). In 2012, freshwater consumption for the agricultural sector in Saudi Arabia was estimated at 86% i.e. an increase of 6% between 2008 and 2012 (FAO 2008).

Accurate evapotranspiration (ET) data are crucial for crop water management, especially in hyper arid regions like Saudi Arabia with scarce fresh water resources. There are many methods used for estimating evaporation rate. In general, ET is estimated from grass reference evaporation (Allen et al. 1998; FAO 56) based on point atmospheric measurements at a single level at an automatic weather station. Various methods of ET measurement, their applications, device requirements, advantages, disadvantages and sources of errors have been discussed by Rana and Katerji (2000) and Allen et al. (2011). ET can be measured in three methods: hydrological approaches (soil water balances and lysimeter measurements), micrometeorological approaches (Eddy Covariance-EC, Surface Layer Scintillometer-SLS, and Bowen Ratio-BR, energy balances) and Plant physiological techniques including chamber systems and sap flow measurements (Rana and Katerji 2000).

Empirical methods, or the Penman- Monteith approach, are used to estimate grass reference evaporation rate, ETo, which uses the crop factor approach to calculate evaporation rate. Commonly, evaporation rate is estimated from grass reference evaporation rate, ETo, at an automatic weather station (AWS) using the Penman-Monteith approach (Allen et al. 1998, 2006), based on daily or hourly point atmospheric measurements at a single level of solar irradiance, air temperature, water vapour pressure and wind speed. In addition, a crop factor is used as a multiplying factor for ETo to obtain the actual evaporation rate. The crop factor effectively distinguishes the vegetation under consideration from a grass reference crop. The dual crop factor approach uses one crop factor for the soil surface and another for vegetation.

Given the limitations of the lysimetric method, the search for an alternative standard for evaporation rate estimation has been the focus of many studies for several decades. Determination of reliable and representative evaporation data using land-based instrumentation is an important issue in atmospheric research with respect to applications in agriculture, applied environmental sciences, hydrology and micrometeorology, and has particular value in validating remotely-sensed evaporation estimates. ET rates can be estimated by micrometeorological and the energy balance equations. However, these equations require several parameters and are difficult to operate. Compared to the use of a lysimeter, the more portable and much less invasive Bowen Ratio (BR) and Eddy Covariance (EC) Surface-Layer Scintillometry (SLS) methods are more popular research methods for the estimation of evaporation rate and can be used to collect unattended measurements for extended periods of time. These methods were the focus of previous research reports (Savage et al. 1997, 2004; Jarmain et al. 2009; Odhiambo and Savage 2009).

Point (single-level), profile and path-weighted atmospheric measurements have been used to estimate sensible heat flux (H). Profile measurements consist of measurements at two vertical positions above the surface in question and are used in the Bowen ratio (BR) method. Sensible heat flux is driven by vertical temperature differences between the canopy or soil surface and overlying air. By contrast, latent energy flux (LE) from which evaporation rate may be calculated, is driven by vertical water vapor pressure differences between that which is measured just above the canopy or soil surface and that of overlying air. Point measurements of $H = H_{EC}$ and $LE = LE_{EC}$ are obtained by eddy covariance (EC), and path-weighted measurements of $H = H_{SLS}$ by scintillometry. All of these flux measurements have footprint representation. The flux footprint refers to the relative contribution of upwind surface sources to H, or LE, measured at a height above the canopy surface. Sensible heat flux H and latent energy flux LE are important components of the shortened energy balance. As mentioned by Drexler et al. (2004) in their review, very few evaporation estimation methods work well for an hourly time step, and in some cases do not even work well for a daily time step. Virtually all of the methods, except for Eddy Covariance (EC), from which direct measurements of HEC and LEEC at a point are obtained, rely on a theoretical framework and certain assumptions or approximations for arriving at an expression for LE, in terms of other measurable quantities.

The eddy covariance (EC) method is a direct method of measuring latent (evaporative) and sensible heat fluxes using high frequency measurements of water vapor concentration, air temperature, and vertical wind speed. Despite the common issues with failing to close the surface energy balance (Twine et al. 2000; Wilson et al. 2002), use of the EC method is prevalent likely because of the advantage of continuous, direct measurement of turbulent sensible (H) and latent (λE) heat fluxes. The EC method essentially yields point estimates of sensible heat flux, H (H_{EC}) and latent energy flux, LE (LE_{EC}) although these flux estimates are influenced by events upwind of the point of measurement. The extent of the footprint area of influence on the flux measurement, using EC method, has received attention. For example, Savage et al. (1995, 1996) investigated the footprint of EC flux measurements. EC method involves measurement, typically at a frequency of 10 Hz, of two atmospheric variables, vertical wind speed and water vapour pressure, from which LE_{EC} is calculated directly by eddy covariance following many corrections. Similarly, using eddy covariance, H_{EC} is calculated from the covariance of vertical wind speed and air temperature measurements over a specified time interval – usually hourly or sub-hourly. Some literature reports on the inadequacy of the EC method for the direct estimation of LE (Wilson et al. 2002; Ham and Heilman, 2003) resulting in $|H_{EC} + LE_{EC}| < Rnet + S$ (Twine et al. 2000). An alternative approach to using a full EC system for measuring H_{EC} and LE_{EC} is to measure H_{EC} only, and to estimate LE as a residual of the shortened energy balance from simultaneous measurements of $Rnet$, S

and $H = H_{EC}$. There have been reports in the literature of a lack of energy balance closure when using EC to measure both H_{EC} and LE_{EC} directly (Twine et al. 2000; Wilson et al. 2002). Under such situations, Surface-layer scintillometry (SLS) has been used.

A scintillometer is used to measure path-weighted *H*. The instrument measures the intensity fluctuations of visible or infrared radiation after propagation above the plant canopy of interest. It optically measures a parameter associated with refractive index fluctuations of air, *Cn* 2, caused by air temperature fluctuations that represent the atmospheric turbulence structure. The sensible heat flux, *H*, may be estimated using the empirically-based Monin-Obukhov similarity theory (MOST). SLS instruments operate over horizontal distances between 50 and 350 m. Typically, for areas of between about 0.25 and 5 ha, the SLS would be appropriate, whereas the LAS is suitable for areas larger than about 6 ha. The frequency of SLS measurements is typically 1 kHz, or 125 Hz for boundary-layer scintillometry for which the path length is up to 10 km, compared to 10 Hz for EC measurements. Because of the high frequency of the SLS measurements, the averaging period for HS_{LS} can be as short as one or two minutes compared to the commonly-used 30 min for EC averaging periods (Savage 2009). The SLS method appears to be a useful, robust and accurate method for obtaining a path-weighted estimate for $H = H_{SLS}$. However, many of the studies employing the SLS method have been very short in duration – in some cases just for a few days as mentioned by Odhiambo and Savage (2009b) and in other cases for a couple of months – and have not compared in detail the SLS method with EC measurement methods.

Given this scenario and the demand on water resources, accurate estimation of ET data is crucial for crop water management studies, especially in hyper arid regions like Saudi Arabia with scarce fresh water resources. Long-term measurements of evaporation at different time scales and from different climate regions are not yet readily available in Saudi Arabia. The main objective of this study was to investigate and compare sensible heat flux estimated by the SLS and the EC systems.

2. MATERIALS AND METHODS

The eddy covariance (EC) and surface layer scintillometer (SLS) are the more popular research methods for estimating ET. EC systems are portable systems that can be used to collect unattended flux measurements, for reasonably long periods of time (Savage et al. 1997). While SLS method, based on Monin-Obukhov similarity theory (MOST), is attractive since it allows for the estimation of path-weighted sensible heat flux (H) over distances between 50 and 250 m (Thiermann and Grassl 1992). A number of studies have already focused on estimation of ET (or LE) from scintillometer measured H (Pauwels and Samson 2006; Savage 2009; Samain et al. 2012) as the rest-term of the energy balance(LE=R_n-G-H). In this study, ET of agricultural fields located in the Eastern Province of Saudi Arabia, was monitored using EC and a dual-beam SLS system. Both EC and SLS systems were installed in a 50 ha alfalfa centre pivot field. Field measurements were made between June and October 2013.

Both Eddy Covariance (Li-COR, USA) and Surface Layer Scintillometer (model SLS-40A, Scintec AG, Germany) systems (Table 1) were installed over an alfalfa field irrigated with centre pivot irrigation system at 24° 10’ 09.34”N and 48° 04’ 06.37” E, at an altitude of 359.36 m in Todhia Arable Farm located between Al-Kharj and Haradh (Fig. 1).

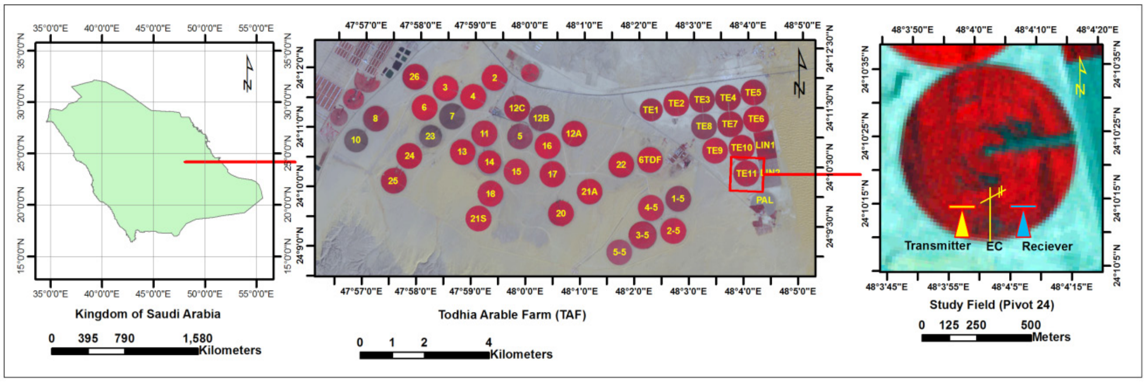

Figure 1. Location map of Eddy Covariance (EC) Surface layer Scientillometer (SLS) systems.

Table 1. Specifications of EC and SLS systems, Todhia Arable Farm, Saudi Arabia.

Si.No	**Eddy Covariance (EC) System**	**Surface Layer Scintillometer (SLS)**
1	Li-7500A Open Path CO_2/H_2O Analyzer	Dual beam SLS-40A (Transmitter and Receiver)
2	Sonic Anemometer	Junction control box (JCB)
3	Analyzer Interface Unit	Signal processing unit
4	Biomet Station and Sensors (includes biomet datalogger, enclosure, and hardware): • Soil Moisture Probes • Soil Heat Flux Plates • Air Temperature/RH Sensors • Quantum Sensor • Net Radiometer	• Barometric Pressure Sensor • Temperature Sensor

2.1 Eddy Covariance System: A fast-responding open-path infrared analyzer for water vapor pressure and carbon dioxide concentration (model LI-7500, LI-COR Inc., Lincoln, Nebraska, USA) and a second Applied Technologies 3-D sonic anemometer (model SATI/3V) with a sonic path length of 150 mm were used to calculate the following fluxes using the EC technique: HEC, LEEC, momentum, and carbon dioxide.

2.2 Surface Layer Scintillometer System: A dual-beam surface-layer scintillometer (model SLS40-A, Scintec Atmospärenmessetechnik, Tübingen, Germany) (Thiermann 1992; Thiermann and Grassl 1992), was used to estimate H = H_{SLS}. The SLS40-A receiver has 4 detectors, with 2 of the detectors used for automatic identification of, and correction for, transmitter vibration by the software used for analysis. In other words, the SLS40-A dual-beam system and its 4 detectors enables the separation of, and correction for, the intensity fluctuations caused by beam movement. There are 2 detectors per beam. The SLS employs a diode laser source with an output wavelength of 670 nm and 1-mW mean output power (2-mW peak). The beam displacement and detector separation distances are 2.5 mm each, with a detector diameter of 2.7 mm. The correlation between the transmitted laser beam signal variances and the covariance of the logarithm of the beam signal amplitude is measured using the 2 detectors. Software, together with the instrument, allows on-line measurements at a frequency of 1 kHz and subsequent calculation every 1 or 2 min (Thiermann and Grassl 1992) of the structure parameter for refractive index fluctuations ($C_n^{\ 2}$, $m^{-2/3}$), structure parameter for temperature ($C_T^{\ 2}$, $K^2\ m^{-2/3}$), the inner scale of turbulence lo (mm), turbulent kinetic energy dissipation rate (ε, $m^2\ s^{-3}$), sensible heat flux (H, W m^{-2}), momentum flux (τ, Pa) and the Obukhov length (L, m). Monin-Obukhov similarity theory (MOST) is assumed.

The methodology for calculating the 2-, 20- or 30-min H_{SLS}, using MOST, is described by Odhiambo and Savage (2009a) and Savage (2009). The direction of H_{SLS} was determined from the sign of the profile air temperature gradient. Data rejection or filtering procedures were applied in a spreadsheet to the 2-min values of $H = H_{SLS}$.

Sensible heat flux values were rejected, blanks were created or data recalculated:

- Data were rejected if the percentage of 1 kHz error-free data (EFD) was less than or equal to 25%, most often due to misty conditions
- Data were rejected for $lo \leq 2$ mm for the 101-m path length or $lo \leq 3.5$ mm for the 50-m path length (Scintec 2006). So-called saturation of the transmitted SLS signal (Lawrence and Strohbehn 1970; Gracheva et al. 1974) generally resulted in smaller-than-expected estimates for the covariance of the logarithm of the amplitude of the radiation intensity for the 2 beams, and, therefore, smaller than- expected signal correlation coefficient values for the 2 beams, smaller *lo* values and greater-than-expected H_{SLS} magnitudes.
- For missing data, designated by zeros, a blank cell was used for H_{SLS}.

2.3 Field measurements: The EC and SLS measurements were performed from June to October 2013 at a frequency of 10 Hz and 1 Hz, respectively. Point measurements of $H = H_{EC}$ and $LE = LE_{EC}$ and path-weighted measurements of $H = H_{SLS}$ were made by EC and SLS systems, respectively. Subsequent calculations were made every 30 and 10 minutes with EC and SLS, respectively. The measurements with EC were made at a height of 3.5 m from the soil surface along with bio-met sensors (Self-Calibrating Soil Heat Flux Plates, soil moisture probe, net radiometer etc.). While, SLS measurements were made on a path length of 150 m and a measurement height of 2 m. The EC method provided direct measurements of latent heat flux (or ET) adopting Bowen ratio. In case of SLS, kinetic energy dissipation rate (ε), sensible heat flux density (*H*), momentum flux density (τ) and the Monin-Obukhov length (L) across the path length at measurement rate were calculated using Monin-Obukhov similarity theory (MOST) and used for ET calculation.

2.4 EC and SLS data analysis: EddyPro (ver 5.0) was used to assess EC data. All the recorded data was fed into EddyPro and analyzed in express mode. While analysis, correction of low-pass filtering effects, spike removal was carried out and the options were set as allowing the omission of 10% of missing samples. The outputs were obtained at 30 min interval. Data rejection rules were fairly simple: sometimes, usually whenever there was condensation, covariances of -9999 were excluded. Missing values and also periods when incorrect sonic temperatures approaching 50 °C were also used to exclude sensible heat data. Net radiation (R_n) Sensible heat (H), latent energy (LE), soil heat flux (G), water and carbon dioxide flux densities were calculated. However, for this study we used EC measured R_n, H and G for computation of Eddy Covariance system based ET (ETEC).

In case of SLS, S_{RUN} (Ver. 1.07) was used to measure/analyze SLS data. Software together with the instrument allows on-line measurements of structure parameter for refractive index fluctuations (C_n^2, $m^{-2/3}$), structure parameter for temperature (C_T^2, $K^2\ m^{-2/3}$), the inner scale of turbulence (l_0, *mm*) as indicated by the inner scale of refractive index fluctuations, kinetic energy dissipation rate (ε, $m^2\ s^{-3}$), sensible heat flux density (*H*, $W\ m^2$), momentum flux density (τ,*Pa*) and the Monin-Obukhov length (L,m). Monin-Obukhov similarity theory (MOST) is assumed. The data rejection or filtering procedures as described in Savage et al. (2004) were followed. If the percentage of Error Free Data (EFD) was greater than or equal to 25 % and $l_0 > 2$ mm, SLS data was rejected to compute ET. In this study, SLS measured H and EC system measured R_n and *G* at a point location (within the path of SLS) was used to measure SLS based ET (ETSLS). Measurements of H and ET by EC and SLS methods were compared at monthly interval.

2.5 Crop Water Use Map: Water use map (WUM) was prepared by using crop evapotranspiration (ET) assuming that the amount of water used by crops was equal to seasonal ETactual. The ET_{24} (per day) was obtained from Landsat 8 (June 19, 2013) thermal data by applying Surface Energy Balance Algorithm for Land (SEBAL) model as described in Bastiaanssen et al (2005). The weather components of SEBAL were taken from the Eddy Covariance (EC) system located in the farm.

3. RESULTS AND DISCUSSION

Temporal data of EC and SLS: The EC and SLS have been operational since 6th June 2013. For the present study, data for five months (from 4 June 2013 through 23 October 2013) were used. Unfortunately, due to logging problems, no EC and SLS data were available for certain periods within these five months: In case of EC, from 17 July 2013 through 18 August 2013, while for SLS, from 12 June 2013 through 2 July 2013 and from 7 July 2013 to 12 July 2013 due to data memory loss, SLS beam misalignments, SLS beam saturation problems, power problems, heavy-rain/flood, etc (Table 2). For this five months period (3672 hourly time steps), no EC and SLS data are available for 792 (21.6%) and 600 (16.33%) hourly time steps respectively.

The data shows that estimated evapotranspiration (ET) out of EC was higher than estimated ET from SLS except in June when ET values were comparable. The mean monthly ET values (energy balance non-closed) collected from EC for the months of June, July, August, September, and October were 2.75, 10.82, 12.35, 8.77, and 7.64 mm, respectively, while the ET values estimated from SLS for the same months were 3.04, 6.49, 10.50, 6.83, and 1.90 mm, respectively (Figure 2). The average daily ET values of EC and SLS for the months of June-October, 2013 are presented in Figures 3. R2 value between EC and SLS estimated ET was 0.26. The crop water use map of the farm prepared from Landsat 8 satellite image is presented in Figure 4.

Table 2. Availability of EC and SLS data.

System	Total measured hourly time steps	Data loss in hourly time steps	% of data loss
EC	3672	792	21.56
SLS	3672	600	16.33

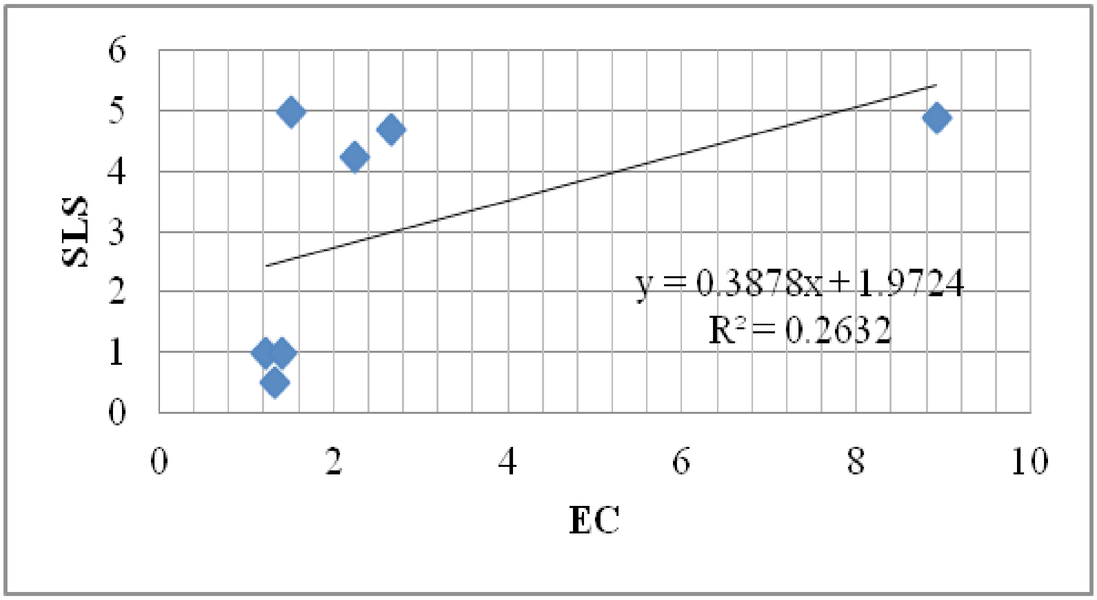

Figure 2. Mean ET from EC and SLS.

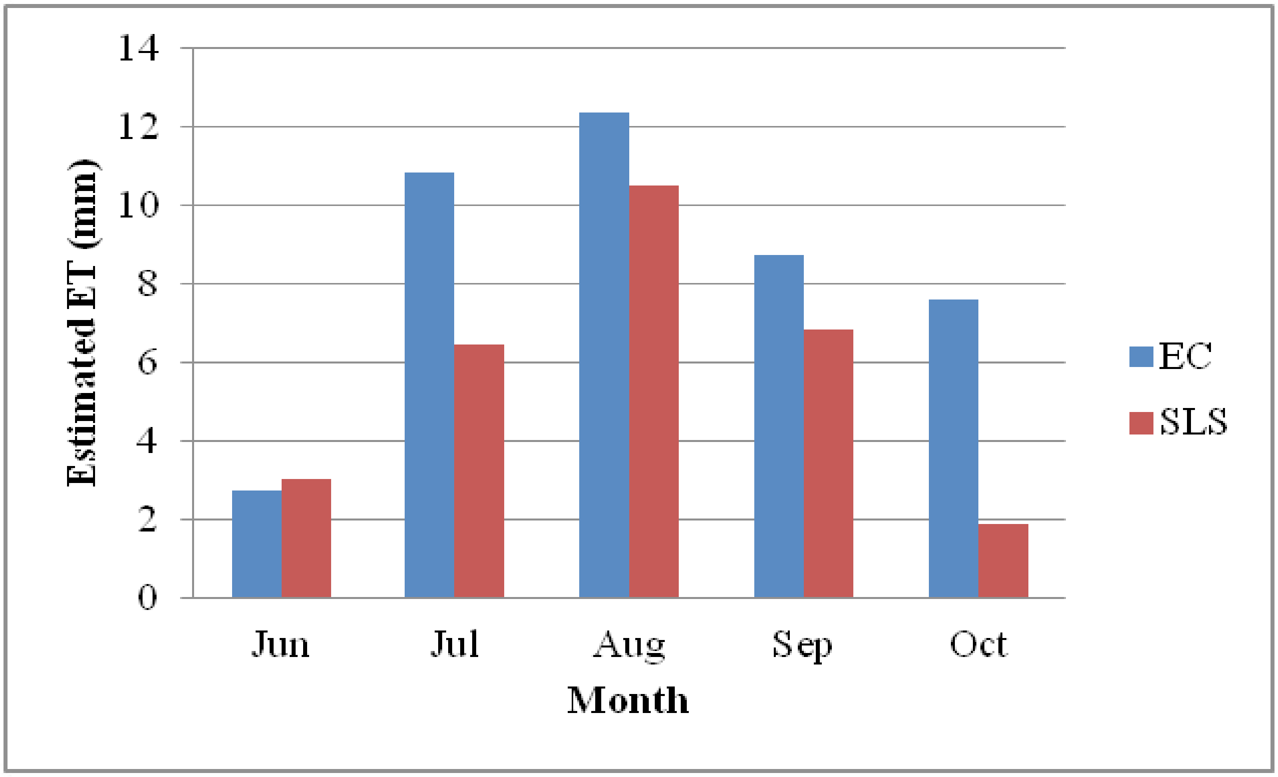

Figure 3. ET (mm) from EC and SLS for the months June-October, 2013

There was spatial and temporal variability in the water use of crops. The irrigation management on the farm has to be based on this spatial variability (Figure 4).

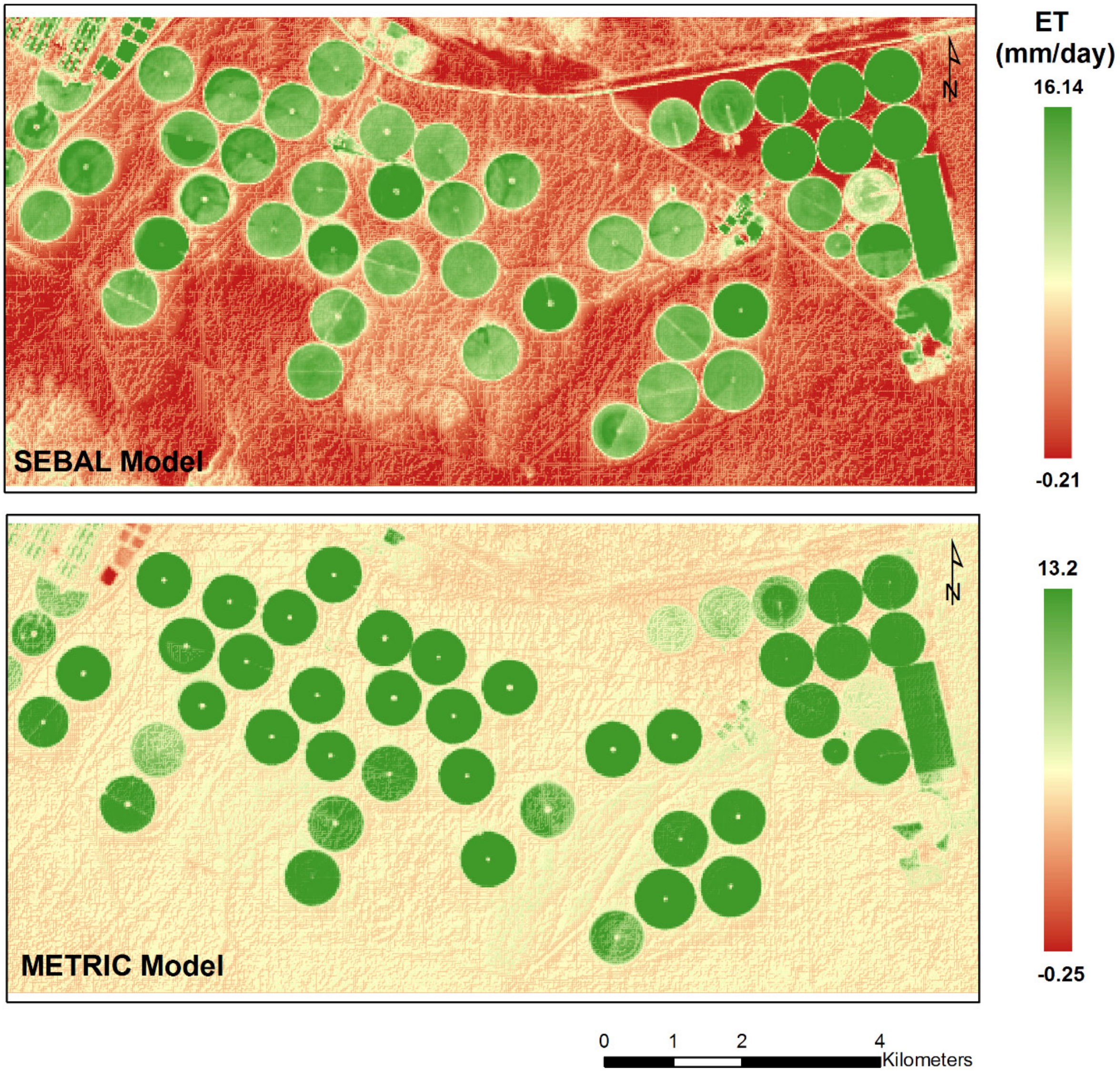

Figure 4. Crop water use map developed from Landsat-8 predicted ET.

Table 3. Energy balance parameters (W m^2/s) and rate of evapotranspiration (mm/day).				
Parameters	**SEBAL**	**METRIC**	**Eddy Covariance**	**Surface Layer Scintillometer**
Net Radiation (R_n)	512.95	512.95	472.88	472.88
Sensible Heat Flux (H)	274.32	249.16	226.45	220.15
Soil Heat Flux (G)	97.52	66.26	40.52	40.52
Latent Heat Flux (LE)	385.09	359.32	345.12	350.65
ET (mm/day)	14.93	13.07	11.93	12.12

The energy balance parameters and measured or predicted ET (Table 3) varied among the methods. In this study, SLS estimated values were closer to the EC measurements. This could be because the parameters except H, l0, temperature and pressure were taken from the EC system. Landsat-8 predicted ET over alfalfa crop was

5.26 mm/day for SEBAL and 4.69 mm/day for METRIC. ET from both models showed 9.6% (METRIC) and 25.7% (SEBAL) of error compared to ET from EC.

4. CONCLUSIONS

The measurement of actual ET using Eddy Covariance (EC) and Surface Layer Scintillometer (SLS) systems was useful in improving the quality of crop water use maps prepared using satellite imagery. The protocols developed in this study could be extrapolated to the regional and national level for developing crop water use maps that would help in making management decisions related to water use in agriculture.

5. REFERENCES

Al-Ghobari, H.M. 2000. Estimation of reference evapotranspiration for southern region of Saudi Arabia. Irrigation Sciences 19:81–86

Allen R. G., W.O. Pruitt, J. L. Wright, T. A. Howell, F. Ventura, R. Snyder, D. Itenfisu, P. Steduto, J. Berengena, J. B. Yrisarry, M. Smith, L.S. Pereira, D. Raes, A. Perrier, I. Alves, Walter and R. Elliott. 2006. A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. Agricultural Water Management 81(1-2):1-22

Allen, R.G, L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements.in FAO Irrigation and drainage paper 56. FAO - Food and Agriculture Organization of the United Nations Rome, Italy. 315 p

Allen, R.G., L.S. Pereira, T.A. Howell, and M.E. Jensen. 2011. Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agricultural Water Management 98:899–920

Bastiaanssen W.G.M., E.J.M. Noordman, H. Pelgrum, G. Davids, B.P. Thoreson, and R.G. Allen. 2005. SEBAL Model with remotely sensed data to improve water resources management under actual field conditions. Journal of Irrigation and Drainage Engineering 131(1):85-93

Drexler J. Z., R.L. Snyder, D. Spano and U.K.T. Paw. 2004. A review of models and micrometeorological methods used to estimate wetland evapotranspiration. Hydrological Process. 18:2071-2101

Gracheva M. E., A. S. Gurvich, S.O. Lomadze, V.I. Pokasov and A.S. Khrupin. 1974. Probability distribution of strong fluctuations of light intensity in the atmosphere. Radiophysics Quantum Electron 17:83-87

Ham, J. M. and J. L. Heilman. 2003. Experimental test of density and energy-balance corrections on carbon dioxide flux as measured using open-path eddy covariance. Agronomy Journal 95:1393-1403

Jarmain, C., C.S. Everson, M.J. Savage, M.G. Mengistu, A.D. Clulow, S. Walker and M.B. Gush. 2009. Refining Tools for Evaporation Monitoring in Support of Water Resources Management. In WRC Report No. 1567. Water Research Commission, Pretoria, South Africa. 137 p

Lawrence, R.S. and J.W. Strohbehn. 1970. A survey of clear-air propagation effects relevant to optical communications. Proceedings of the IEEE 58(10):1523-1545

Odhiambo, G.O. and M.J. Savage. 2009a. Surface layer scintillometer and eddy covariance sensible heat flux comparisons for a mixed grassland community as affected by Bowen ratio and MOST formulations. Journal of Hydrometeorology. 10(2):479-492

Odhiambo, G.O. and M.J. Savage. 2009b. Surface layer scintillometery for estimating the sensible heat flux component of the surface energy balance. South African Journal of Science 105:208-216

Pauwels, R.N. and R. Samson. 2006. Comparison of different methods to measure and model actual evapotranspiration rates for a wet sloping grassland. Agricultural Water Management 28: 1 – 24.

Rana, G. and N. Katerji. 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. European Journal of Agronomy 13:125–153

Samain, B., G.W.H. Simons, M.P. Voogt, W. Defloor, N. Bink, and J. Pauwels. 2012. Consistency between hydrological model, large aperture scintillometer and remote sensing based evapotranspiration estimates for a heterogeneous catchment. Hydrology and Earth System Sciences Discussions 8:10863-10894

Savage, K., E.A. Davidson, A.D. Richardson, and D.Y. Hollinger. 2009. Three scales of temporal resolution from automated soil respiration measurements. Agricultural and Forest Meteorology 149:2012–2021

Savage, M.J., C.S. Everson, and B.R. Metelerkamp. 1997. Evaporation measurement above vegetated surfaces using micrometeorological techniques. In Water Research Commission Report No. 349/1/97, p248, ISBN No: 1 86845 363 4

Savage, M.J., C.S. Everson, G.O. Odhiambo, M.G. Mengistu, and C. Jarmain. 2004. Theory and practice of evaporation measurement, with special focus on surface layer scintillometry as an operational tool for the estimation of spatially averaged evaporation. In Water Research Commission Report No. 1335/1/04, p204, ISBN No 1-77005-247-X

Savage, M.J., J.L. Heilman, K.J. Mcines and R.W. Gesch. 1995. Placement height of eddy correlation sensors above a short grassland surface. Agricultural and Forest Meteorology 74:195-204

Savage, M.J., K.J. Mcines and J.L. Heilman. 1996. The "footprints"of eddy correlation sensible heat flux density, and other micrometeorological measurements. South African Journal of Science 92:137-142

SCINTEC. 2006. Scintec Surface Layer Scintillometer SLS20/SLS40 SLS20-A/SLS40-A User Manual (including OEBMS1). In Scintec Atmosphärenmesstechnik AG, Tübingen, Germany. 105 pp.

Thiermann, V. 1992. A displaced-beam scintillometer for line-averaged measurements of surface layer turbulence. In 10th Symposium on Turbulence and Diffusion. Portland, Oregon, USA.

Thiermann, V. and H. Grassl. 1992. The measurement of turbulent surface-layer fluxes by use of bichromatic scintillation. Boundary-Layer Meteorology 58:367-389

Twine, T.E., W.P. Kustas, J.M. Norman, D.R. Cook, P.R. Houser, T.P. Meyers, J.H. Prueger, P.J. Starks, and M.L. Wesely. 2000. Correcting eddy-covariance flux underestimates over a grassland. Agricultural and Forest Meteorology 103:279–300

Wilson, K., A. Goldstein, E. Falge, M. Aubinet, D. Baldocchi, P. Berbigier, C. Bernhofer, R. Ceulemans, H. Dolman, C. Field, et al. 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology 113:223–243

Author contact information:

Prof. V. C. Patil, Precision Agriculture Research Chair,
King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia.
+966565892442; vpatil@ksu.edu.sa