Hydrol. Earth Syst. Sci. Discuss., 3, 793–817, 2006
www.hydrol-earth-syst-sci-discuss.net/3/793/2006/


Hydrology and Earth System Sciences Discussions

Papers published in *Hydrology and Earth System Sciences Discussions* are under open-access review for the journal *Hydrology and Earth System Sciences*

# Satellite-based evapotranspiration and crop coefficient for irrigated sorghum in the Gezira scheme, Sudan

**M. A. Bashir[1], T. Hata[1], A. W. Abdelhadi[2], H. Tanakamaru[1], and A. Tada[3]**

[1]Dept. of Food Systems and Field Sciences, Graduate School of Science and Technology, Kobe University, Nada, Kobe 657–8501, Japan
[2]Agricultural Research Corporation, PO Box 126, Wad Medani, Sudan
[3]Faculty of Agriculture, Kobe University, Japan

Received: 10 February 2006 – Accepted: 21 March 2006 – Published: 2 June 2006

Correspondence to: M. A. Bashir (bashir70us@yahoo.com)

## Abstract

The availability of the actual water use from agricultural crops is considered as the key factor for irrigation water management, water resources planning, and water allocation. Traditionally, evapotranspiration (ET) has been estimated in the Gezira scheme by multiplying the reference evapotranspiration ($ET_o$) by crop coefficient ($k_c$) which is derived from the phenomenological crop stages. Recently, advanced developed energy balance models assist to estimate ET through remotely sensed data. In this study Enhanced Thematic Mapper Plus (ETM+) images were used to estimate spatial distribution of daily, monthly and seasonal ET for irrigated sorghum in the Gezira scheme, Sudan. The daily ET maps were also used to estimate $k_c$ over time and space. Results of remotely sensed based energy balance were compared with actual measurements conducted during 2004/05 season. The daily actual ET values estimated using the energy balance model during the satellite acquisition dates (28 July, 29 August, 16 October and 17 November) were 4.7, 5.5, 7.1 and 2.7 mm/day, while the average seasonal evapotranspiration for irrigated sorghum estimated to be around 596 mm. The remotely estimated $k_c$ values in the initial, crop development, mid-season and late-season stages were 0.62, 0.85, 1.15, and 0.48 respectively. On the other hand the widely used tradition $k_c$ values during the pervious mention stages are 0.55, 0.94, 1.21 and 0.65, respectively. This research shows that remotely sensed measurements can help objectively analyzed the irrigation water requirement for different field crops on daily and seasonal time step. Moreover, the remotely sensed real-time data availability provides the system managers with information that not previously available.

## 1 Introduction

The yield of the rain-fed sub-sector in the Sudan has progressively declined with time, owing to changes in both quantity and distribution of the rainfall (El-Karori, 1986; Olsson and Rapp, 1991). This has put a great pressure on the irrigated sub-sector to increase the acreage to meet the population food demand. Moreover, it estimated that by 2025 cereal production will have to increase by 38% to meet world food demands (Seckler et al., 1999), putting even more stress on the scarce water resources. However, the limited quantity of water available and the cost of its pumping make it mandatory irrigation water be used efficiency. Therefore, balancing the limited water resources is a big challenge facing the irrigation system managers and engineers in the coming years.

Accurate estimate of evapotranspiration is considered as the key factor in water resources management. Recently computer simulation models are being used to estimate evapotranspiration from heterogeneous natural landscapes, which are in dynamic state due to spatial and temporal variations of interactions between soil, vegetation and atmosphere (Allen, 2000b). Such models require complex and high quality input data to obtain precise results. One of the most important developments in the field of remote sensing hydrology is the determination of distributed areal actual evapotranspiration from spectral satellite data, based on the energy balance approach (Menenti, 1984; Parodi, 1993; Bastiaanssen, 1995; Bastiaanssen et al., 1998; Su, 2002). The main advantage of the energy balance based on remotely sensed data is that large areas are covered, and that data is easily obtainable without extensive monitoring networks in the field.

In this study, a satellite-based energy balance model for surface fluxes, known as surface energy balance algorithm for land (SEBAL) developed by Bastiaanssen et al. (1998) has been used with ETM+ data to estimate actual evapotranspiration for irrigated sorghum on daily and seasonal basis. SEBAL enables the calculation of the actual evapotranspiration during the time of satellite over pass, it involves complex procedures and determination of a number of variables such as surface temperature, Normalized Difference Vegetation Index (NDVI), emissivity and albedo. A temporal integration of the daily ET for the period July–November season was used to provide the seasonal actual ET map. The seasonal ET map information is available on a pixel basis.

The objectives of this study were (i) to estimate the spatial seasonal actual evapotranspiration of irrigated sorghum in the Gezira scheme and compare the results as determined with the actual measurements (ii) to apply SEBAL to derive actual $k_c$ for sorghum (iii) to compare sorghum remotely derived $k_c$ with the widely used $k_c$ in the Gezira scheme.

## 2 Materials and methods

### 2.1 Study area and conditions

The study was carried out in the Gezira scheme during 2004/05 season. The scheme is located between latitudes 13°30′ N and 15°15′ N, and longitudes 32°15′ E and 33°45′ E. The climate is semi-arid with annual precipitation of about 280 mm (20 year average) most of it occurring in the period from July to October. The agriculture depends on supplementary irrigation from the Blue Nile. Furrow irrigation is the main irrigation system in the scheme. Temperatures are hot in summer, reaching an average of 41.5°C in May, while the average minimum temperature is 14.1°C in January, the mean dry temperature is about 28.7°C. The average annual relative humidity is about 41%. The mean annual bright sunshine duration and solar radiation are about 9.3 h and 22.1 $MJ/m^2/d$, respectively (Fig. 1). The major crops are cotton, sorghum, groundnut and wheat. However, sorghum is considered as the main staple food in the Sudan. The area which is annually cultivated by sorghum in the scheme is estimated around 0.25 million hectares.

### 2.2 Remote sensing input

The remote sensing input for this study included Landsat ETM+ data from the day time, descending mode images, having spatial resolution of 28.5 $m^2$ at satellite nadir. In this study four Landsat satellite images (path 173/row 50) acquired July–November 2004 by Landsat 7 were processed. Images with zero percent cloud cover were selected for the processing. The four image dates selected are 28 July, 29 August, 16 October, and 17 November. The Landsat overpass time was approximately 09:58:07 a.m. local standard time (LT). Images were radiometrically and geometrically corrected and geo-registered. An overview of some parameters (e.g. inverse relative distance Earth-Sun dr, solar incidence angle $\theta$, incoming shortwave radiation Rs $\downarrow$ and incoming longwave radiation L $\downarrow$) of the images used in this study are provided in Table 1. Due to an instrument malfunction occurred onboard Landsat 7 on 31 May 2003, the total loss of the image data has been estimated to be approximately 22% over any given scene. The impacts are most pronounced along the edge of the scene and gradually diminish toward the center of the scene. The middle of the scene (approximately 22 km) should be very similar in quality to pervious Landsat image data that acquired prior to the failure of scan line corrector, in this study, the analysis were applied to middle part of the scene using four Landsat ETM+ images acquired on different dates to estimate seasonal actual evapotranspiration for summer sorghum crop during 2004 season.

### 2.3 Energy balance approach

There are many remote sensing algorithms for estimating the energy balance fluxes on the surface, each algorithm has its own advantages and disadvantages. The surface energy balance algorithm for land (SEBAL) is the most promising algorithm that requires minimum input data of ground based variables and it has been widely applied in several countries of the world due to its accurate estimation of actual evapotranspiration. SEBAL calculates both the instantaneous and 24-h integrated surface heat fluxes. The latent heat flux represents the energy required for ET, and is computed as the residual of the surface energy balance. The simplified form of the energy balance equation is given by

$$Rn = H + G_o + \lambda E \quad (1)$$

where $Rn$ is net radiation (W/m$^2$), $H$ is sensible heat flux to warm or cool the atmosphere (W/m$^2$), $G_o$ is soil heat flux to warm or cool the soil (W/m$^2$), and $\lambda E$ is latent heat flux (W/m$^2$), the latent heat flux associated with the evaporation from soil, water and vegetation. SEBAL has been used to estimate monthly and seasonal ET by linearly interpolations the ET values for periods in between two adjacent images (Bastiaanssen, 2000).

SEBAL is a one-layer approach that computes surface energy fluxes using both physical and semi-empirical relations. The net radiation is computed from spatially variable reflectance and emittance of radiation. This model requires spectral radiances in the visible, near infrared and thermal infrared regions of the spectrum to determine the intermediate parameters such as surface albedo, normalized difference vegetation index (NDVI) and surface temperature. Net radiation Rn is computed as algebraic sum of the shortwave and the long wave radiation components. The soil heat flux is the energy engaged to soil warming, and it is computed as an empirical fraction of the net radiation using surface temperature, surface albedo and NDVI as the depending variables.

In SEBAL method, the initial estimate of surface roughness length for momentum transport ($z_{om}$) is based upon the soil adjusted vegetation index (SAVI) using an empirical relation (Moran and Jackson, 1991). Observed wind speed measurements are used to determine the friction velocity ($u_*$) at each pixel based on the assumption that the wind speed at blending height (200 m) is areally constant. Reference heights $Z_1$ and $Z_2$ (usually 0.01 and 2.0 m above the ground respectively) are defined as the vertical limits for specifying sensible heat flux (H) and near surface temperature difference dT. Then according to the sensible heat transfer equation these limits become applicable for aerodynamic resistance ($r_{ah}$) (Farah and Bastiaanssen, 2001). The extremes wet (zero sensible heat flux assumed, $Rn=G_o+\lambda E$) and dry (zero latent heat flux assumed, $Rn=G_o+H$) pixels within the image enable to partition the available energy on the surface. This implies that $dT_{wet}=0$ and $dT_{dry}=(Rn-G_o)\,r_{ah}/\rho_a Cp$ and allows the estimation of $dT_{dry}$ using the initial estimate of $r_{ah}$. It is assumed that dT is linearly related to $T_o$ at all pixels and hence the determination of the relationship is possible with the aid of the extreme pixels. The first estimate of sensible heat flux is used to correct turbulent heat transport for buoyancy effects according to Monin-Obuhkov similarity hypothesis. The estimation of sensible heat flux requires internally iterative until H converges to the local non-neutral buoyancy for each pixel.

The evaporative fraction (EF) describes the partitioning of the surface energy balance as the latent heat flux/net available energy, with the net available energy being defined as the difference in net radiation and soil heat flux. In this study we used the concept "ETr fraction" (ETrF), which represents the ratio of ET of each pixel to the reference ET (ETr) as computed by Penman-Monteith method (ETrF is the same as the crop coefficient, $k_c$), ETrF is calculated and applied instead of EF:

$$\text{ETrF} = k_c = \text{ET}/\text{ETr} \tag{2}$$

The instantaneous EF and ETrF are shown in the literature to be similar to the 24-h evaporative fraction and 24-h ETrF respectively, (Shuttleworth et al., 1989; Brutsaert and Chen, 1996; Trezza et al., 2003) and this allows estimating the latent heat flux at a 24-h basis.

In this study the daily values of actual evapotranspiration was simulated to get an accurate estimation of seasonal ET. The monthly and seasonal ETrF and ET are estimated by linear interpolating the ETrF values for periods in between two adjacent images. ETr or crop reference evapotranspiration is estimated using Penman-Monteith method as follows:

$$\text{ET}_o = \frac{0.408(Rn - G_o) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{3}$$

where $\text{ET}_o$ denotes the crop reference evapotranspiration (mm/d), $Rn$ the net radiation at crop surface (MJ/m$^2$/d), $G_o$ the soil heat flux density (MJ/m$^2$/d), $T$ the mean daily air temperature at 2 m height (°C), $u_2$ the wind speed at 2 m height (m s$^{-1}$), $e_s$ the saturation vapour pressure (kPa), $e_a$ the actual vapour pressure (kPa), $e_s - e_a$ the saturation vapour pressure deficit (kPa), $\Delta$ the slope vapour pressure curve (kPa °C$^{-1}$), $\gamma$ the psychometric constant (kPa °C$^{-1}$). The REF-ET software version 2.0 that developed by Allen (2000a) is used to compute $ET_o$. The temporal integration of the daily actual $ET_{SEBAL}$ for the whole season was under taken in four steps: (i) determination of the period represented by each image (ii) computation of $ET_o$ using Penman-Monteith method for the whole period represented by each image (iii) computation of multiplier $K_m$ for each period to used to convert ET for the day of the image into ET for the period and (iv) computation of accumulative seasonal actual ET using the following equation:

$$ET_s = \sum_{i=1}^{n} (ET_{SEBAL})_i \times (K_m)_i \quad (4)$$

where $ET_{SEBAL}$ is the daily ET predicted by SEBAL, and $K_m$ is the multiplier factor for ET for the representative period, n is the number of satellite images processed. For more details description and calculations of SEBAL refer to Bastiaanssen et al. (1998) and Tasumi et al. (2000).

### 2.4 Calculation of actual crop evapotranspiration

The water content in the effective root zone is estimated by using the water balance equation, for the Gezira clay soil due to negligible values of runoff, deep percolation and capillary rise, water balance equation reads in its most simplified form as:

$$\Delta S = I + P - ET \quad (5)$$

where $\Delta S$ is the change in soil moisture storage (mm), $I$ is the irrigation applied (mm), $P$ is the precipitation (mm) and ET is the evapotranspiration (mm). Irrigation and precipitation are the deposits in water balance and are measured or calculated values. In this study irrigation water applied was measured using intensive gravimetric samples just before each irrigation and 2–3 days after irrigation. Rainfall was measured using the rain gauges. During the short post irrigation periods the roots suffer from temporary anaerobic conditions and consequently ET was very small and hence neglected

(Fadl, 1978). Slight modification has to be made to cater for the evaporation from free water surface as water was expected to pond between the ridges on the first day of irrigation before the crop emerged and during the early growing stages. The data of the soil volume weight ratios introduced by Abdine and Farbrother (1969) were used to generate regression equations that relate soil bulk density to soil depth and moisture content. Second degree polynomial equations were used in the regression for the 0–60 cm depth while linear regression was used for the 60–100 cm depth. The generated regression equations were used to transform the gravimetric moisture contents to volumetric values. The actual evapotranspiration during each irrigation cycle was calculated from soil moisture depletion between each post and pre-irrigation moisture sampling cycles (Abdelhadi et al., 2006).

## 3 Results and discussions

### 3.1 Evaporative depletion of the study area

During 2004/05 season the actual evapotranspiration ($ET_a$) via SEBAL model and soil moisture depletion approach (MD) has been quantified for irrigated sorghum in the Gezira scheme, Sudan. In particular, the soil of the study area is a deep heavy soil with 58–66% clay, 0.5% organic matter, water infiltration rate of 1 mmh$^{-1}$ and pH 8.5. Figure 2 shows the daily actual evapotranspiration estimated by SEBAL and calculated by MD method ($ET_a$ computed as a residual of soil water balance, Eq. 5). The results from Fig. 2 indicate that $ET_a$ estimated by SEBAL were similar to those calculated by MD method during the last three dates (29 August, 16 October and 17 November), while at the beginning of the season the SEBAL overestimated the MD, the underestimation of MD method could be attributed to the difficulties of measuring actual ET by MD during the first irrigation due to special nature of Gezira Vertisols. During 28 July, 29 August, 16 October and 17 November the SEBAL $ET_a$ values were 4.7, 5.5, 7.2, and 2.7 mm/d, respectively, while for MD method the calculated $ET_a$ were 2.6, 5.9, 7.1, and 3.0 mm/d. The comparison provides an indication of the amount of confident that can be given to ET estimated via remotely sensed based-energy balance model such as SEBAL.

The frequency distribution of daily actual ET and the basic statistics for different image dates including all land use types are presented in Fig. 3 and summarized in Table 2, respectively. The histograms in Fig. 3 associate the higher ET to irrigated crop grown in the study area, while low ET was observed from bare soil and settlements. In 28 July irrigated crops showed relatively high ET, although most of the crops were at initial stage this could be attributed to high soil moisture at the root zone at the time of the satellite overpass. From the frequency distribution histograms the absolute minimum and maximum actual ET values during 28 July, 29 August, 16 October and 17 November were 1.6–9 mm/d, 0.04–7.8, 1.0–9, and 0.03–8.9, respectively, with standard deviation 1.4, 1.93, 1.94, and 1.92, respectively. In Fig. 3 two clear peaks appear in the histograms distinguish between vegetation fields and fallow areas (sparse vegetation), on 28 July one peak around 3.5 mm/d (fallow soil) and the second one around 4.6 mm/d (irrigated crops), cotton crop obtained more than 4 mm/d during 29 August, during 16 October the first peak represents fallow soil (2.7 mm/d) and the other peak represent sorghum and cotton areas, while during 17 November the fallow soil shows very low $ET_a$, it should be noted that during 17 November the high evaporation signature (greater than 6 mm/d) represents cotton field as sorghum was harvested or due to harvest, its ET was reduced to less than 3 mm/d.

In this study, the monthly and seasonal evapotranspiration $ET_s$ maps on a pixel-by-pixel basis were produced through the integration of all daily ET maps for the summer irrigated season of 2004/05. Figure 4 demonstrates the comparison of monthly ET (mm) estimated using SEBAL and monthly ET calculated using moisture depletion approach (MD) for irrigated sorghum in the Gezira scheme. It is clear from Fig. 4 that the absolute error% values between monthly estimated ET by SEBAL and monthly calculated ET by MD for sorghum during September, October and November were 4%, 4%, and 19%, respectively.

Figures 5 and 6 illustrate respectively the spatial distribution map and frequency distribution of $ET_s$ (mm/season) for the summer season (28 July to 27 November), whereas Table 3 represents the comparison of $ET_s$ as estimated by SEBAL and calculated by MD method for sorghum. In Fig. 5 the pattern of ET determined with SEBAL for all features in the image is compared to a simple false color composite of ETM+band 4, 3, and 2 (RGB) the degree of associations is noteworthy. However, such simple band combination gives a first approximate visual impression of the relative ET distribution in the study area. The estimated seasonal ET lie between 80–813 mm using the MD approach the accumulated ET of irrigated sorghum for a period of 92 days (28 August to 27 November) was 489 mm. SEBAL results for exactly the same period (92 days) were 468 mm. Consequently, the absolute error $\left(|ET_{\text{SEBAL}} - ET_{MD}|\right)$ and relative error $\left(|ET_{\text{SEBAL}} - ET_{MD}| / ET_{MD} \times 100\right)$ values were 21 mm and 5%, respectively (Table 3).

Owing to the fine resolution of ETM+ imagery different land cover classes can be easily distinguished and coincided $ET_s$ can be determined. The quantification of accurate daily and seasonal evapotranspiration for different land cover types in the irrigated scheme will provide valuable information for the farmers and irrigation engineers to determine the delivered amount of water and hence enhanced the irrigation and application efficiencies for the whole system. Consequently, this will leads towards sustainable management of the limited water resources in the country.

### 3.2 Remotely derived crop coefficient, $k_c$

SEBAL derived $k_c$ values were determined by dividing the actual ET on a pixel-based by reference crop evapotranspiration $ET_o$, as estimated using Penman-Monteith equation. Table 4 demonstrates the comparison of SEBAL derived $k_c$ with wide use experimental crop coefficient by Farbrother (1973) for irrigated sorghum in the Gezira scheme at different crop stages. Farbrother and his co-workers during early 1970s related crop reference $ET_o$ to evaporation from open water and called the ratio crop factor ($k_f$). These crop factors were converted later to crop coefficients ($k_c = 1.1 \times k_f$) and it has been used to quantify crop water requirements for all irrigated crops in the



HESSD

3, 793–817, 2006

Seasonal ET and $k_c$ values for irrigated sorghum in Sudan

M. A. Bashir et al.



EGU

scheme. SEBAL derived $k_c$ values for the different dates 28 July (initial stage), 29 August (crop development stage), 16 October (mid season stage), and 17 November (end season stage) are 0.62, 0.85, 1.15, and 0.48, respectively, while the experimental $k_c$ values for the corresponding crop periods mentioned above are 0.55, 0.94, 1.21 and 0.65, respectively.

According to the results of this study, the estimated value of crop coefficient by SEBAL during mid-October looks similar to the $k_c$ values suggested by Farbrother (during early 1970s) with only 5% deviation. In the initial stage (late July), the derived $k_c$ value was overestimated the experimental value by 13%, while during crop development stage (late August) the SEBAL $k_c$ value underestimated the Farbrother by 10%. Significant differences were observed during the late season stage (mid November), SEBAL derived $k_c$ understated Farbrother by 26%. Above variations could be attributed to differences in crop varieties, differences in the date of sowing, change in the climatic conditions and cultural practices. Such variations explain the difficulties of interpolating traditional $k_c$ determined for specific crop variety and specific region to be used for large scale region. Thus SEBAL can be used successfully to derive and update crop coefficient curves for large populations of crops in the Gezira arid conditions as the determination of field-measured $k_c$ is expensive and time consuming.

## 4 Conclusions and future remarks

This study focused on the evaluation of multi-temporal ETM+ data to calculate daily and seasonal actual ET based upon satellite energy balance model such as SEBAL. The remotely sensed measurements and SEBAL provide the estimation of spatial distribution of instantaneous ET, which can be integrated into daily and seasonal ET values. The seasonal spatial distribution maps help to explain the water consumption for the different land use classes throughout the cropping season.

A comparison of the seasonal ET estimated by SEBAL with actual measurements for irrigated sorghum for a period of 92 days shows a deviation of 5%. Spatial daily maps were used to compute the crop coefficient curve, for the irrigated sorghum, the derived crop coefficient values during initial stage, crop development, mid-season, and late season stages were 0.62, 0.85, 1.15 and 0.48, respectively. The results above show that satellite-based energy balance model such as SEBAL is very useful in updating and verification of crop coefficient and even developing a new $k_c$ curve for new crop varieties for specific locations. The study also shows that the real-time and accurate remotely sensed measurements provide irrigation managers and farmers with information that not previously available, that information can enhance irrigation performance for sustainable management of limited water resources.

Owing to low temporal resolution of high spatial resolution image and the cost involved with the acquisition make their use unattractive. Therefore, the availability of free of charge daily basis satellites such as NOAA-AVHRR (National Oceanograhic and Atmospheric Agency – Advanced Very High Resolution Radiometer) and MODIS (Moderate Resolution Imaging Spectroradiometer) makes them a viable alternative for future estimation of ET.

*Acknowledgements.* The research upon which this paper is based was supported in part by the Grant-in-Aid (No. 16405031) for Scientific Research from the Japan Society for the Promotion of Science (JSPS). The research was also supported in part by JSPS AA Science Platform Program. The authors are grateful to S. Maxwell, senior scientist of USGS National Center for Earth Resources Observation and Science for providing the ETM+ data.

## References

Abdelhadi, A. W., Bashir, M. A., Farah, S. M., and Hata, T.: Implications of late sown irrigated grain sorghum on productivity and water management, Sudan Journal of Agricultural Research, 6, 1–10, 2006.

Abdine, A. Z. and Farbrother, H. G.: Prog. Rep. Exp. Status, Sudan, Cotton Research Corporation, London, 67–68, 1969.

Allen, R. G.: REF-ET: Reference evapotranspiration calculation software, University of Idaho, Moscow, Idaho, 2000a.

Allen, R. G.: Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration inte-comparison study, J. Hydrol., 229, 27–41, 2000b.
Bastiaanssen, W. G. M.: SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey, J. Hydrol., 229, 87–100, 2000.
Bastiaanssen, W. G. M., Menenti, M., Feddes, R. A., and Holtslag, A. A. M.: A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation, J. Hydrol., 212–213, 198–212, 1998.
Bastiaanssen, W. G. M.: Regionalization of surface flux densities and moisture indicators in composite terrain, a remote sensing approach under clear skies in Mediterranean climates, Report 109, Agricultural Department, Wageningen, The Netherlands, 1995.
Brutsaert, W. and Chen, D.: Diurnal variation of surface fluxes during thorough drying (or severe drought) of natural prairie, Water Resour. Res., 32(7), 2013–2019, 1996.
El-Karori, M. O. H.: The impact of desertification on land productivity in Sudan, in: Physics of desertification, edited by: El Baz, F. and Hassan, M. H. A., Martinus Nijfoff Publishers, Dordrecht, 52–58, 1986.
Fadl, O. A. A.: Evapotranspiration measured by a neutron probe on Sudan Gezira Vertisols, Experimental Agriculture, 14, 341–347, 1978.
Farah, H. O. and Bastiaanssen, W. G. M.: Impact of spatial variations of land surface parameters on regional evaporation: a case study with remote sensing data, Hydrol. Process, 15, 1585–1607, 2001.
Farbrother, H. G.: Water requirements of crops in the Gezira, annual report of the Gezira Research Station, 1972/73, 139–172, 1973.
Menenti, M.: Physical aspects and determination of evaporation in deserts applying remote sensing techniques. Report 10 (special issue), Institute of Land and Water Resources Management, Wageningen, The Netherlands, 202p, 1984.
Moran, S. M. and Jackson, R. D.: Assessing the spatial distribution of evaporation using remotely sensed inputs, J. Environ. Qual., 20, 725–737, 1991.
Olsson, K. and Rapp, A.: Dryland degradation in central Sudan and conservation for survival, Ambio, 20(5), 192–195, 1991.
Parodi, G.: An up-to-date inventory of remote sensing potentially in the energy balance equation approach for actual evapotranspiration mapping. Basic Theory and Prospects, Msc thesis, ITC, Enschede, The Netherlands, 1993.
Seckler, D., Barker, R., and Amarasinghe, U.: Water scarcity in the twenty-first century, Water

Resour. Development, 15, 29–42, 1999.
Shuttleworth, W. J., Gurney, R. J., Hsu, A. Y., and Ormbsy, J. P.: FIFE: the variation in energy partitioning at surface flux sites, remote sensing and large scale global processes, in: Proceedings of the Baltimore Symposium IAHS publication no. 186, IAHS press, Oxfordshire, 67–74, 1989.
Su, Z.: The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes, Hydrol. Earth Syst. Sci., 6, 85–99, 2002.
Tasumi, M. and Allen, R. G.: Application of the SEBAL methodology for estimating consumptive use of water and stream flow depletion in the Bear River Basin of Idaho through Remote Sensing, Appendix A: The theoretical basis of SEBAL, Final Report, The Raytheon Systems Company, EOSDIS Project, 2000.
Trezza, R., Allen, R. G., Tasumi, M., and Wright, J. L.: Observed ETrF and EF values, Appendix 13, in: Tasumi 2003. Progress in operational estimation of regional evapotranspiration using satellite imagery, Ph.D. Dissertation, University of Idaho, Moscow, ID, 2003.



HESSD
3, 793–817, 2006

Seasonal ET and $k_c$ values for irrigated sorghum in Sudan

M. A. Bashir et al.



EGU

HESSD

3, 793–817, 2006

Seasonal ET and $k_c$ values for irrigated sorghum in Sudan

M. A. Bashir et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

EGU

**Table 1.** Landsat images used in this study.

| Image date | dr (AU) | Θ (degrees) | L ↓ | Rs ↓ |
|---|---|---|---|---|
| 28 July 2004 | 0.97 | 28.4 | 335 | 883 |
| 29 Aug 2004 | 0.98 | 27.8 | 335 | 899 |
| 16 Oct 2004 | 1.01 | 33.6 | 348 | 864 |
| 17 Nov 2004 | 1.02 | 41.0 | 340 | 793 |

HESSD

3, 793–817, 2006

Seasonal ET and $k_c$ values for irrigated sorghum in Sudan

M. A. Bashir et al.



**Table 2.** Basic statistics for the daily ET of all features during image acquisition dates.

| Image date | Mean | Mode | Stand. Dev. |
|---|---|---|---|
| 28 July 2004 | 4.3 | 1.60 | 1.40 |
| 29 Aug 2004 | 3.2 | 1.01 | 1.93 |
| 16 Oct 2004 | 5.6 | 7.30 | 1.94 |
| 17 Nov 2004 | 3.2 | 1.10 | 1.92 |



EGU

HESSD

3, 793–817, 2006

Seasonal ET and $k_c$ values for irrigated sorghum in Sudan

M. A. Bashir et al.



**Table 3.** Comparison of seasonal evapotranspiration of irrigated sorghum estimated by SEBAL and calculated by moisture depletion (MD) for the period between 28 August 2004 to 27 November 2004 during 2004/05 season.

| Method | SEBAL | MD | AE* ($\lvert ET_{\mathrm{SEBAL}} - ET_{MD} \rvert$) | RE** ($\lvert ET_{\mathrm{SEBAL}} - ET_{MD} \rvert / ET_{MD} \times 100$) |
|---|---|---|---|---|
| Seasonal ET (mm) | 468 | 489 | 21 | 5 |

*AE is absolute error in mm and **RE is relative error in percent



EGU

**Table 4.** SEBAL derived average crop coefficient compared with experimental $k_c$ from Farbrother (1973) for irrigated sorghum at different growth stages.

| Method | Crop coefficient values initial (30 July 2004) | crop-develop. (29 Aug 2004) | mid-season (16 Oct 2004) | end-season (17 Nov 2004) |
|---|---|---|---|---|
| Farbrother $k_c$ | 0.55 | 0.94 | 1.21 | 0.65 |
| SEBAL $k_c$ | 0.62 | 0.85 | 1.15 | 0.48 |



HESSD
3, 793–817, 2006

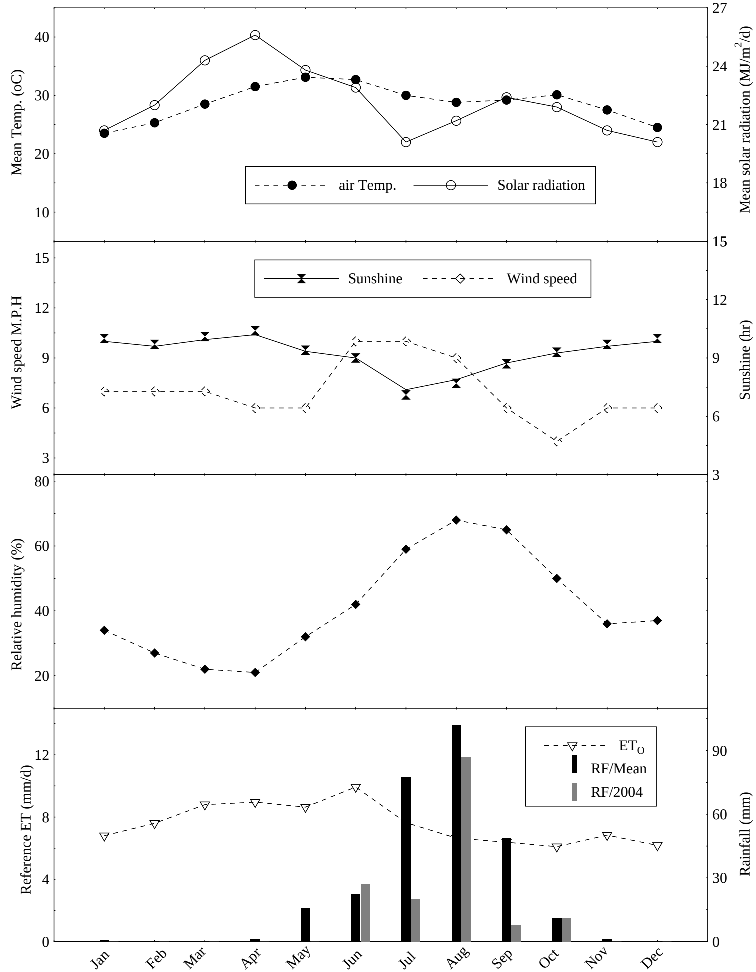


**Fig. 1.** Monthly mean of various weather variables of the study area (Sudan Meteorological Authority 1971–2000).

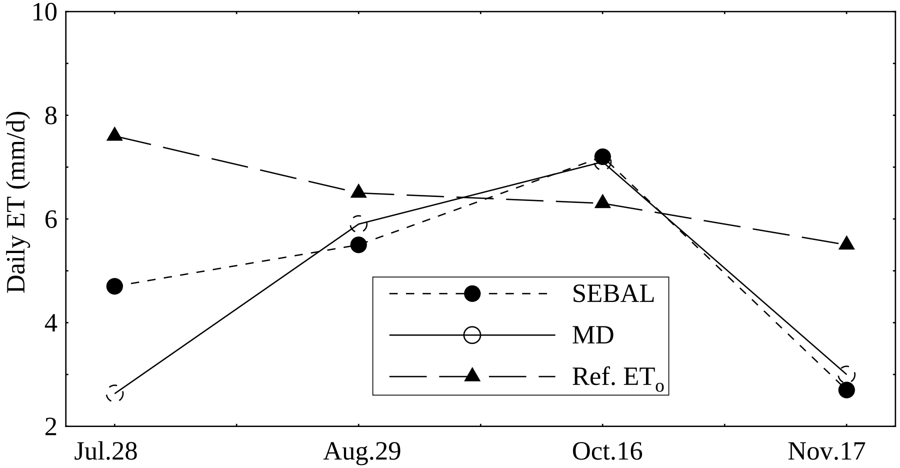


**Fig. 2.** Comparison of daily actual ET (mm/d) estimated by SEBAL and daily actual ET calculated by moisture depletion (MD) method.

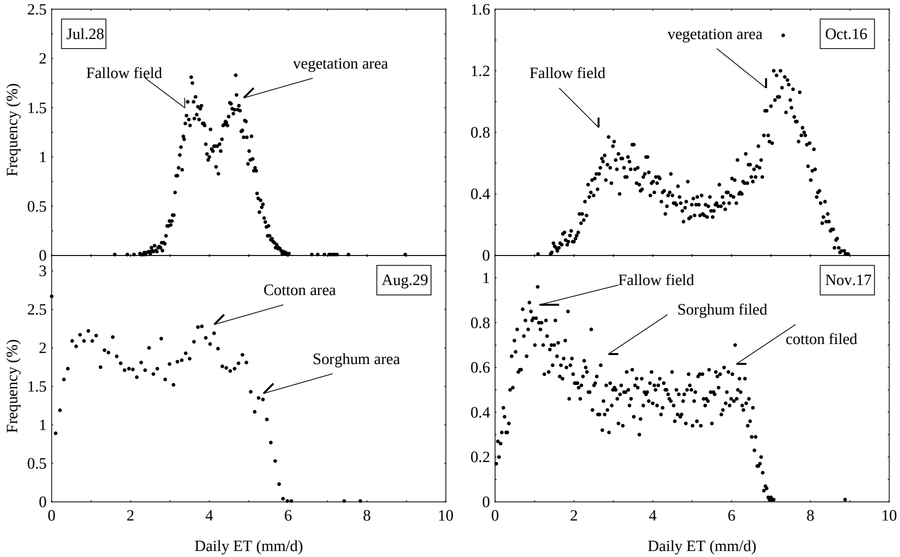


**Fig. 3.** Histogram showing the actual evapotranspiration (mm/d) of the study area during the acquisition time.

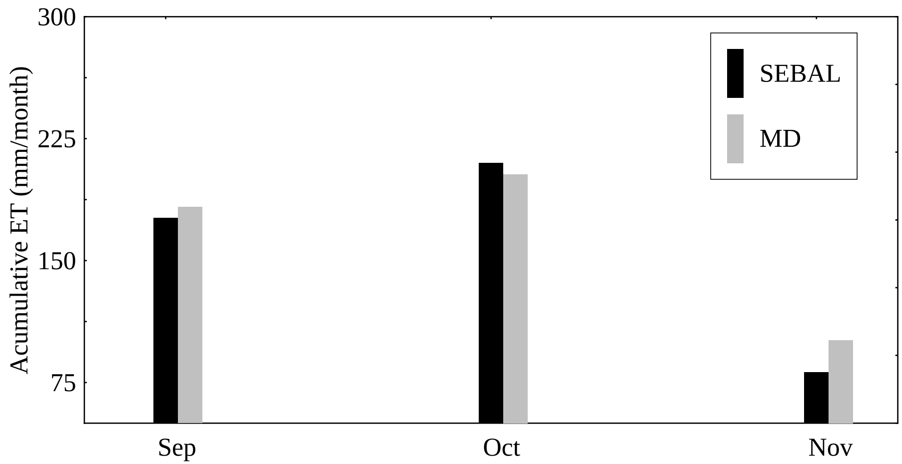


**Fig. 4.** Monthly accumulated actual ET (mm) as estimated by SEBAL and calculated by soil moisture depletion (MD) method.



HESSD
3, 793–817, 2006

HESSD

3, 793–817, 2006

Seasonal ET and $k_c$ values for irrigated sorghum in Sudan

M. A. Bashir et al.



EGU

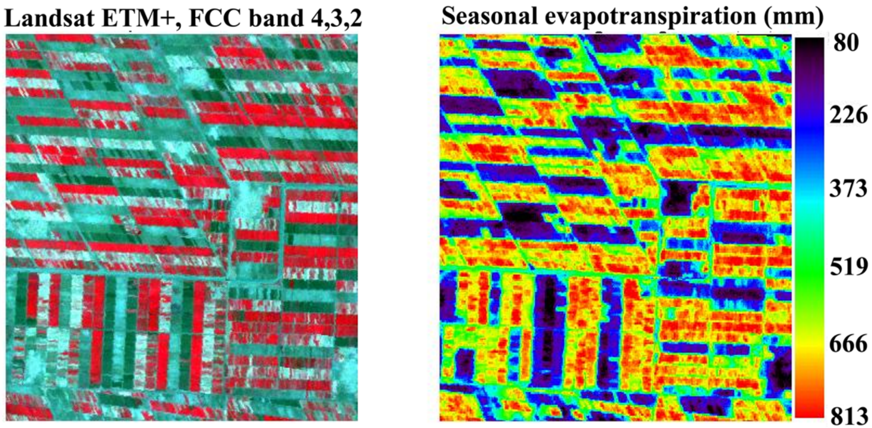


**Fig. 5.** False color composite (FCC, 17 November 2004) and spatial distribution map of seasonal evapotranspiration ($ET_s$) of the study area during 2004/05 season.

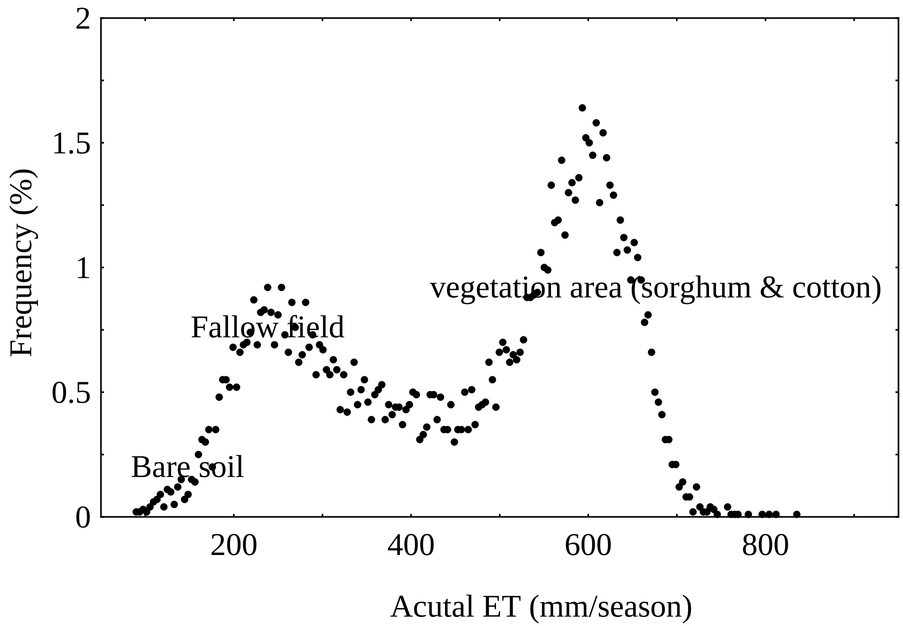


**Fig. 6.** Histogram showing seasonal actual evapotranspiration (mm) of the study area.