

Article

## Validation of Global Evapotranspiration Product (MOD16) using Flux Tower Data in the African Savanna, South Africa

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**Abstract:** Globally, water is an important resource required for the survival of human beings. Water is a scarce resource in the semi-arid environments, including South Africa. In South Africa, several studies have quantified evapotranspiration (ET) in different ecosystems at a local scale. Accurate spatially explicit information on ET is rare in the country mainly due to lack of appropriate tools. In recent years, a remote sensing ET product from the MODerate Resolution Imaging Spectrometer (MOD16) has been developed. However, its accuracy is not known in South African ecosystems. The objective of this study was to validate the MOD16 ET product using data from two eddy covariance flux towers, namely; Skukuza and Malopeni installed in a savanna and woodland ecosystem within the Kruger National Park, South Africa. Eight day cumulative ET data from the flux towers was calculated to coincide with the eight day MOD16 products over a period of 10 years from 2000 to 2010. The Skukuza flux tower results showed inconsistent comparisons with MOD16 ET. The Malopeni site achieved a poorer comparison with MOD16 ET compared to the Skukuza, and due to a shorter measurement period, data validation was performed for 2009 only. The inconsistent comparison of MOD16 and flux tower-based ET can be attributed to, among other things, the parameterization of the Penman-Monteith model, flux tower measurement errors, and flux tower footprint vs.

MODIS pixel. MOD16 is important for global inference of ET, but for use in South Africa's integrated water management, a locally parameterized and improved product should be developed.

**Keywords:** evapotranspiration; MOD16; eddy covariance; flux tower; Penman-Monteith

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## 1. Introduction

Globally, water is an important resource required for the daily sustenance and survival of human beings. Water is crucial to facilitate livelihoods and economic growth, e.g., vital for the industrial and agricultural sector. Today, irrigated agriculture is the main fresh water user, accounting for about 70% of the water from lakes, rivers and ground aquifers [1]. In South Africa, almost 50% of the available surface water resource usage is attributed to agricultural activities. In essence, South Africa is a semi-arid environment, with evaporation rates exceeding the rates of precipitation by a considerable margin [2]. Therefore, it is crucial to develop methods or tools to quantify water use and availability (e.g., evapotranspiration, ET) over large spatial scales in order to inform decision makers on sustainable utilization and management of this resource. For example, the program by the South African Department of Water Affairs (DWA) to verify and validate country's water use is critical [2] for water use license purposes, which requires information on ET, water use and river flows. This program is also linked to the legal requirement on the sustainable utilization of water resources outlined in the National Water Act (Act 36 of 1998).

ET is the second most important element of the hydrological cycle after precipitation because it facilitates the continuation of precipitation by replacing the vapor lost through condensation [3]. ET is listed as one of 48 observation priorities of water societal benefit area (Water SBA) by the Group on Earth Observation; see GEO [4,5]. GEO is an intergovernmental organization working to improve availability, access and use of earth observation to benefit society [5]. ET is also crucial for the transportation of minerals and nutrients required for plant growth; creates a beneficial cooling process to plant canopies in many climates; and influences the Earth's energy and water balance because of the direct association with latent heat flux (LE). ET consumes large amounts of energy during the conversion of liquid water to vapor, hence playing an important role in hydrology, agriculture, climatology and meteorology. Accurate estimates of ET contribute to improved quantification of the catchment water balance and in the facilitation of decision making for sustainable water resource management [6–8].

ET is a difficult component to measure, especially in arid and semi-arid regions where the magnitude of the ET flux is relatively smaller than in wetter regions. In these areas, plants are prone to water stress and are adapted accordingly to prolonged dry conditions. ET is highly variable over space and time, depending on landscape heterogeneity, topography, climate, vegetation type, soil properties, management and environmental constraints [7,9]. The conventional point-based ET estimation methods do not capture large spatial scale variability of ET and are very difficult to obtain due to time and cost constraints. These methods include (i) direct measurements with porometry and lysimeters [10]; (ii) atmospheric measurements, including energy balance and micrometeorological techniques like

Bowen ratio [11], eddy covariance [12], scintillometry [13], as well as methods based on weather data, for example; used for the calculation of the Penman-Monteith reference grass evapotranspiration (ET<sub>o</sub>) and crop coefficient [9]; (iii) soil measurements [14] and the application of the soil water balance. The *in situ* estimation of ET using the above techniques was successful in a number of agricultural and natural environments within South Africa, e.g., natural vegetation [15], wetlands [13] and crops [16].

Remote sensing-based techniques have the capability to estimate spatial and temporal variation of ET from catchment to global scales. Several studies reviewed different remote sensing techniques used to estimate ET [17–19]. They are classified into;

- empirical methods that involve the use of statistically-derived relationships between ET and vegetation indices such as the normalized difference vegetation index (NDVI) or the enhanced vegetation index (EVI) [20–25],
- residual methods of surface energy balance (single- and dual-source models) [8,26] which include the Surface Energy Balance Algorithm over Land (SEBAL) [27,28], Surface Energy Balance System (SEBS) [8,29,30] and Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) [6,31,32],
- physically-based methods that involve the application of the combination of Penman-Monteith [7,33,34] and Priestley-Taylor types of equations [35–39], and
- Data assimilation methods adjoined to the heat diffusion equation [40] and through the radiometric surface temperature sequences [41].

Various remote sensing-based ET estimation algorithms (e.g., SEBS, SEBAL and METRIC) have been partially evaluated in South Africa [42]. Although estimates of net radiation and ET were accurate, the soil and sensible heat fluxes were more complex and challenging to determine. Furthermore, Sun *et al.* [43] used local flux tower data (Skukuza) to evaluate a remote sensing-based continental ET product at 3 km resolution, which was developed by combining data from the MODIS sensor and SEVIRI sensor onboard the geostationary-orbiting MSG satellite. Although the results were reasonable during the wet season, low correlations were observed during the dry season, due to factors such as, the spatial scale differences between the satellite sensor and flux tower observations. In South Africa, SEBAL was used to provide information on water use efficiency of irrigated crops, including grapes, deciduous fruits, sugarcane, and grain crops [29]. A recent study by Gibson *et al.* [29], discussed the use of SEBS in South Africa for various agricultural and natural systems, and finally recommended the validation of existing global ET products in South Africa to encourage their use.

Remote sensing-based global estimates of ET have been produced by different algorithms. For example, the MODerate Resolution Imaging Spectroradiometer (MODIS) MOD16 [7,34], and the EUMETSAT MSG ET product [43]. The MOD16 ET product has a spatial resolution of 1 km and is available on an eight-day, monthly and yearly basis. The EUMETSAT MSG ET product is available at 3 km spatial resolution every 30 min or daily. These products have been calibrated and validated mainly in the Northern hemisphere, with sites located in North and South America, Europe, Asia and sometimes Australia. For instance, Cleugh *et al.* [33] applied the Penman-Monteith algorithm and MODIS data to estimate ET for the Australian continent. Mu *et al.* [7,34] modified this algorithm and used flux tower data from Ameriflux stations to validate the global MOD16 product. Kim *et al.* [44] later validated the global product using Asiaflux stations. Jia *et al.* [36] evaluated spatiotemporal

MODIS ET product in the Hai river basin. Inaccuracies, such as over- or underestimation, and no relationship were observed between the flux tower and MOD16 ET estimates in the above publications. Errors or uncertainties are assumed to be caused by misclassification of landcover types from the global MODIS land cover product, scaling from flux tower to landscape, and algorithm limitations. Accurate classification of land cover type is critical for ET estimation. In South Africa, the first attempt to evaluate the MOD16 ET was done by Jovanovic *et al.* [45], using historical *in situ* ET measurements. Jovanovic *et al.* [45] found that the MOD16 method underestimated ET, but the *in situ* data collected was not sufficient to evaluate remote sensing based products. Most of this *in situ* ET data were for small fields, not sufficient to cover a 1 km × 1 km pixel. There is a need to evaluate global remote sensing products again at long term monitoring sites in South Africa.

The main objective of this study is to evaluate the MOD16 global ET product using eddy covariance flux tower-derived ET in the savanna and woodland biome in the Kruger National Park, South Africa. Thirty-minute latent heat fluxes (LE) were acquired from the CARBOAFRICA project for Skukuza and Malopeni towers, and converted to daily ET. The flux tower-derived ET was then summed to an eight-day ET corresponding to the MOD16 ET values for comparison.

## 2. Materials and Methods

The historical flux tower data records from two sites in the Kruger National Park were used. The flux tower data were preprocessed to acquire daily, eight-day and monthly ET. The measured ET from the flux tower was then compared to the modelled MOD16 global ET product. We used basic statistical metrics, including the coefficient of determination, root mean square error and bias, to assess MOD16 ET against measured ET.

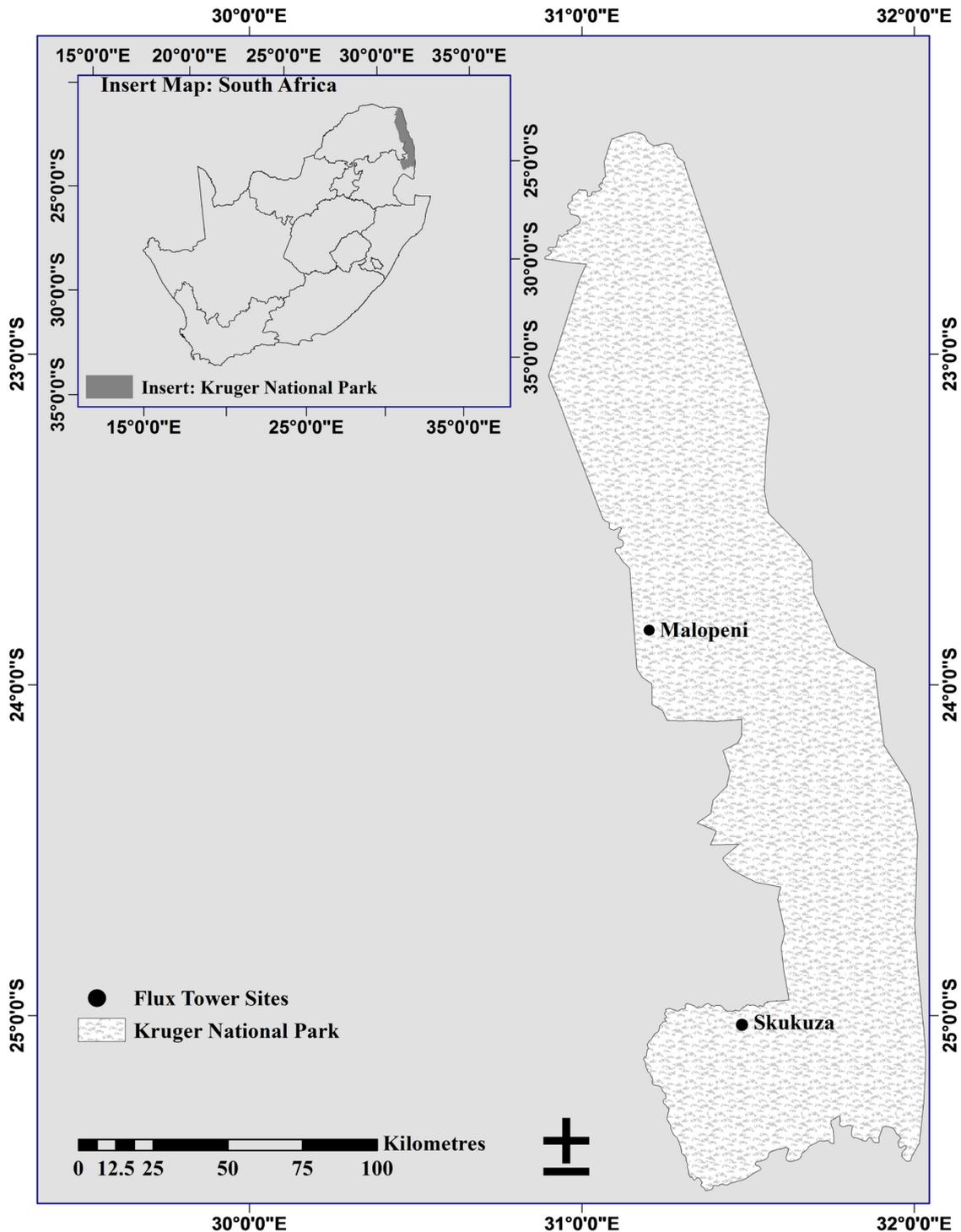
### 2.1. Study Area and Flux Tower Instrument

Two eddy covariance flux tower sites, Skukuza and Malopeni, were selected (Figure 1). From 2000 to 2005, the Skukuza flux tower was equipped with a closed path gas analyser for carbon dioxide and water, but from 2006 this changed to a Licor Li7500 open path gas analyser with a Campbell Scientific CSAT sonic anemometer. The Malopeni flux tower is equipped with a Licor Li7500 gas analyser and a Gill WindMaster Pro sonic anemometer. These flux towers contributed to the CARBOAFRICA network, a project which ran from 2007 to 2010, and was designed to contribute to the quantification, understanding and prediction of the carbon cycle and energy fluxes in Sub-Saharan Africa. Though these two sites are located in Kruger National Park, their localities present an interesting contrast in weather, soil, geology and vegetation types.

Established in 2000, the Skukuza flux tower (25.0197°S, 31.4969°E), lies at 365 m above the sea level, in an area with 547 mm/year of mean annual rainfall, which falls between November and April [46]. The annual temperature ranges between 14.5 and 29.5 °C. This site lies at the boundary of two distinct savanna vegetation types which include broad-leafed *Combretum* savanna and fine-leafed *Acacia* savanna. These contrasting savanna types occur on soils of differing texture, water holding capacity and nutrient levels, and are characterized by different physical structure, physiology and phenology [46]. These two savanna types are typical of the southern Kruger National Park, and placing the flux tower on the ecotone allows for an integrated measurement of the fluxes over these different savanna types.

The Malopeni flux tower (23.8325°S, 31.2145°E) is located in the northern part of KNP approximately 130 km north-west of Skukuza and 12 km from the town of Phalaborwa. The tower was established in 2009 on a site dominated by the broad-leaf *Colophospermum mopane* characteristic of a hot and dry savanna, 384 m above the sea level, with a mean annual rainfall of 472 mm/year [47]. Temperature ranges between 12.4 and 30.5 °C.

**Figure 1.** Study area map showing an insert of South African and Kruger National Park boundaries, with projected coordinates.



## 2.2. Flux Tower Data

To evaluate the global 1 km, eight-day MOD16 ET product, eddy covariance LE data from the Skukuza (2000–2010) excluding 2002 and 2006, and Malopeni (2009) flux towers were used. LE for 2002 and 2006 were excluded from the analysis, since the measurement years were incomplete. The 16 m and 7 m measurement height of Skukuza and Malopeni towers, respectively, are adequate to validate the 1 km pixel of MOD16. The size of eddy covariance source area or footprint does not only depend on instrument height [48], but also on the wind direction and velocity, atmospheric stability and the underlying surface conditions [49]. The source area or footprint modelling was not carried out because the location of the flux tower was homogeneous. The LE data observed every 30 min were MODIS-driven estimation of terrestrial latent heat flux in China based on a modified Priestley-Taylor algorithm converted to daily ET using equations presented in Mu *et al.* [34]. In addition, only reliable 30 min measurements were prioritized, exceeding 40 per day. The derived daily ET was further summed over eight days for each year to match the MOD16 ET product. Some of the data were excluded from analysis because of insufficient ET measurements. The number of the 30 min ET measurements per day (over 40) was prioritized in the validation process, to avoid compromising the completeness and reliability of the flux tower data. For further analysis, eight day summations were done to create monthly ET for Malopeni and Skukuza.

## 2.3. MOD16 Global ET Data

The MOD16 ET product with temporal resolution of eight days and spatial resolution of 1 km, were acquired for free from the University of Montana's Numerical Terradynamic Simulation group ([ftp://ftp.nts.g.umt.edu/pub/MODIS/NTSG\\_Products/MOD16/MOD16A2.105\\_MERRAGMAO/](ftp://ftp.nts.g.umt.edu/pub/MODIS/NTSG_Products/MOD16/MOD16A2.105_MERRAGMAO/)). The ET values corresponding to Skukuza from 2000–2010 and 2009 for the Malopeni sites were extracted from each pixel of the MOD16 ET images using ArcGIS 10×. The algorithm used to derive the MOD16 ET product was modified by Mu *et al.* [7,34], from Cleugh *et al.* [33]'s Penman-Monteith derived model.

## 2.4. Rainfall Data

The rainfall data sets were collected from the South African Weather Service (SAWS) for Skukuza and Phalaborwa rainfall stations, for the dates corresponding to the ET data. Skukuza station is approximately 20 km away from the flux tower, while Phalaborwa rainfall station is located approximately 10 km away from the Malopeni flux tower. We used rainfall data to interpret variability in ET in relation with the wetness conditions in the landscape and the response of vegetation to drought and water stress.

## 2.5. Data Analysis

For assessing the relationship between the MOD16 ET and flux tower derived ET, the coefficient of determination ( $R^2$ ), root mean square error ( $RMSE$ ) (Equation (1)), bias (Equation (2)) and percent bias (PBias) (Equation (3)) were used. These statistical techniques were commonly used for comparing pairs of variables, e.g., Sun *et al.* [43]. The  $R^2$  was used to determine the strength of the relationship

between the flux tower measured and the MOD16 modelled ET. Bias, on the other hand, is a measure of how a modelled value deviates from the true value, and indicates whether there is under- or overestimation, while the percent bias is a percentage of bias relative to the observed mean.

The *RMSE*, *Bias* and *PBias* were computed using the following equations:

$$RMSE = \sqrt{\frac{\sum (FET - MET)^2}{N}} \quad (1)$$

$$Bias = \frac{\sum (MET - FET)}{N} \quad (2)$$

$$PBias = \frac{Bias}{\left(\frac{1}{N}\right) \sum FET} \times 100 \quad (3)$$

where *FET* is flux tower ET, *MET* is MOD16 ET and *N* number of measurements. *Bias* and *RMSE* values close to zero signify that the MOD16 ET does not deviate from the true ET value (flux tower), indicating that the MOD16 is deemed accurate, while higher values of these statistic metrics indicate a high level of inaccuracy. A negative value of bias signifies underestimation, while a positive value shows overestimation by the modelled value or MOD16.

### 3. Results

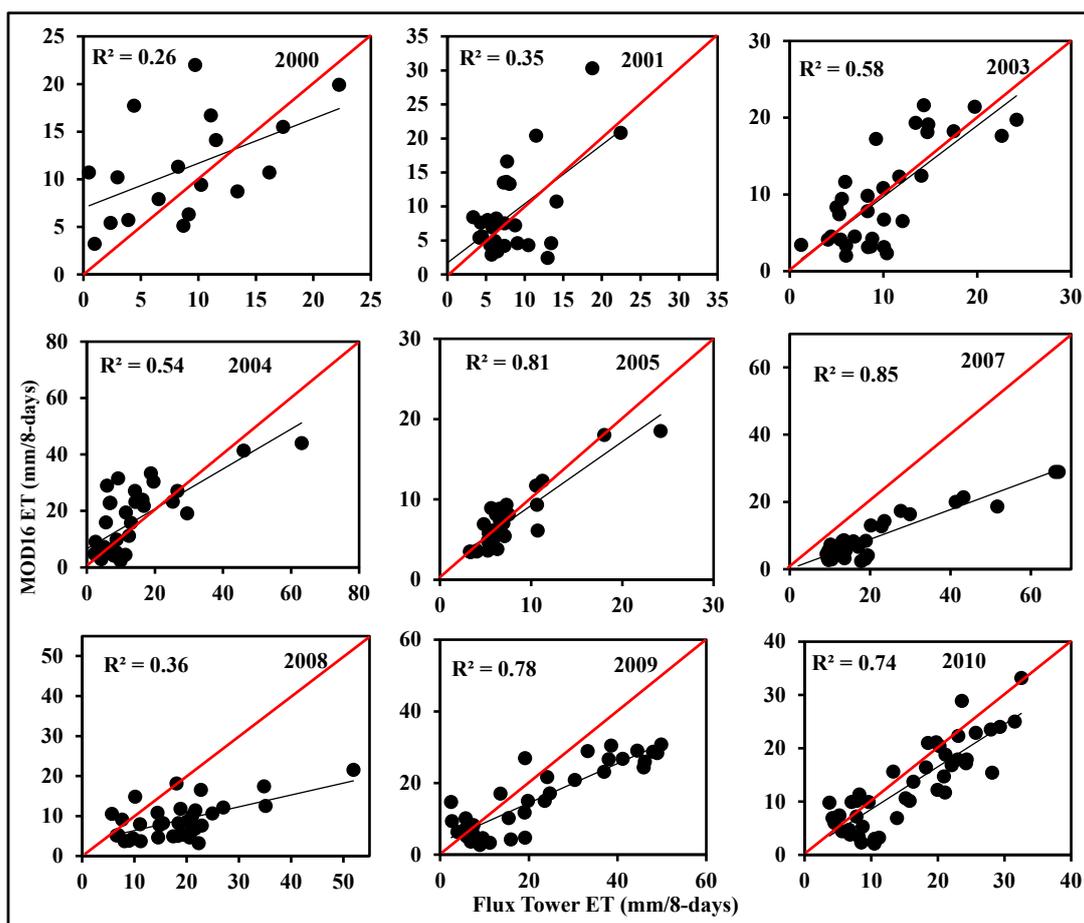
For the Skukuza site, the results show an inconsistent comparison of the flux tower and MOD16 ET values over a period of time (Table 1; Figure 2). From 2000–2010, excluding 2002 and 2006, the highest correlations were obtained in 2005 and 2007 achieving  $R^2$  of 0.81 and 0.85, respectively. According to the *RMSE*, 2003 ( $R^2 = 0.58$ , *RMSE* = 3.4 mm/8-days) and 2005 ( $R^2 = 0.81$ , *RMSE* = 2 mm/8-days) achieved the lowest values which indicate reasonable accuracy of the MOD16 ET product. In the years 2003 and 2005, the relationship is almost 1:1, with 2005 yielding the lowest *RMSE*, with the second highest  $R^2$ . In 2009 and 2010, there is almost a complete set of measurements from the flux tower measurements (36 and 44 out of 45 eight-day periods, respectively). In 2009 and 2010, the validation results ( $R^2 = 0.78$  and 0.74, respectively) are poorer compared to 2005 and 2007 based on the lower coefficient of determination, as well as the higher *RMSE* (7.39 and 4.3 mm/8-days). In general, Skukuza results showed that there is an overestimation of MOD16 ET in 2000 and 2004, with a *Bias* ranging from 2.80 to 3.08 mm/8-days (22.4–33.33% of the observed mean) (Table 1). Whilst, there was evidence of high underestimation of MOD16 ET in 2007, 2008, 2009 and 2010 with *Bias* ranging from –12.1 to –2.6 mm/eight-days (–55.7 to –16.44% of the observed mean). The 2003 and 2005 results, specifically, yielded low *Bias* and *PBias* which confirms the reasonable prediction of MOD16 during these years.

**Table 1.** Validation of MOD16 products using flux tower based evapotranspiration (ET) from Skukuza and Malopeni site.

Flux Tower	Year	R <sup>2</sup>	RMSE (mm/8-days)	Bias (mm/8 day)	PBias (%)	No. of Measurements *
Skukuza	2000	0.26	5.22	3.08	33.33	18
	2001	0.35	3.60	0.58	6.63	26
	2003	0.58	3.40	-0.31	-3.02	32
	2004	0.54	8.00	2.85	22.38	37
	2005	0.81	2.00	-0.24	-3.20	26
	2007	0.85	6.00	-12.11	-55.71	32
	2008	0.36	7.40	-9.47	-51.68	34
	2009	0.78	7.39	-6.46	-29.50	36
	2010	0.74	4.30	-2.57	-16.44	44
Malopeni	2009	0.23	3.00	1.18	21.20	35

\* A complete yearly eight days measurements should be 45, as per MOD16 dates.

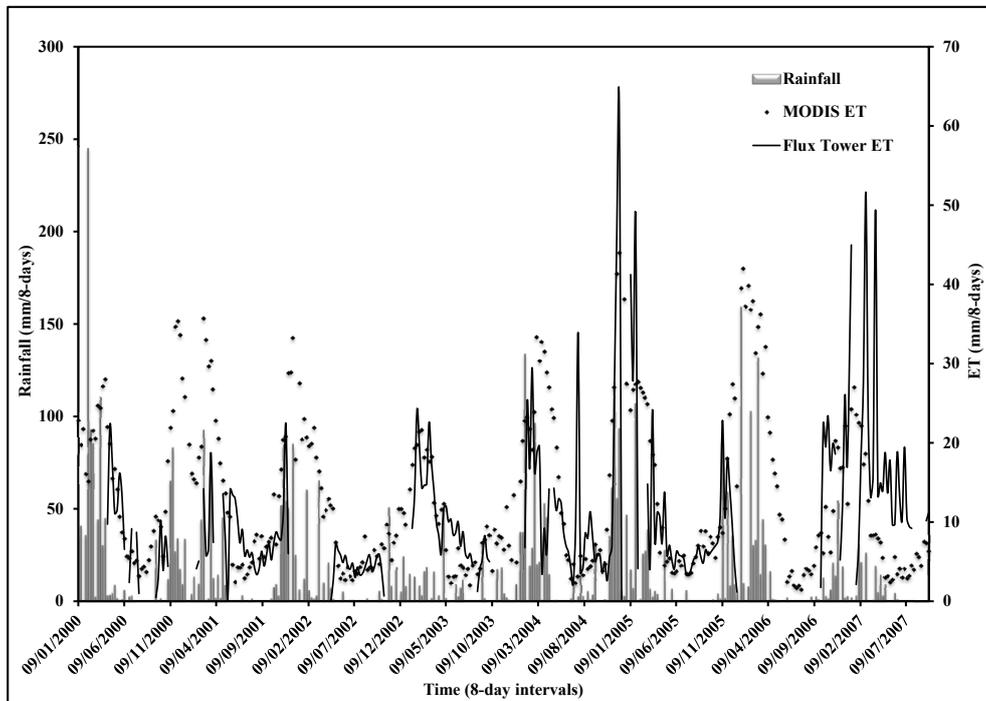
**Figure 2.** Eight day validation results of MOD16 ET using Flux tower data (mm/eight-days) in Skukuza (2000–2010). The 1:1 line is depicted by a red color.



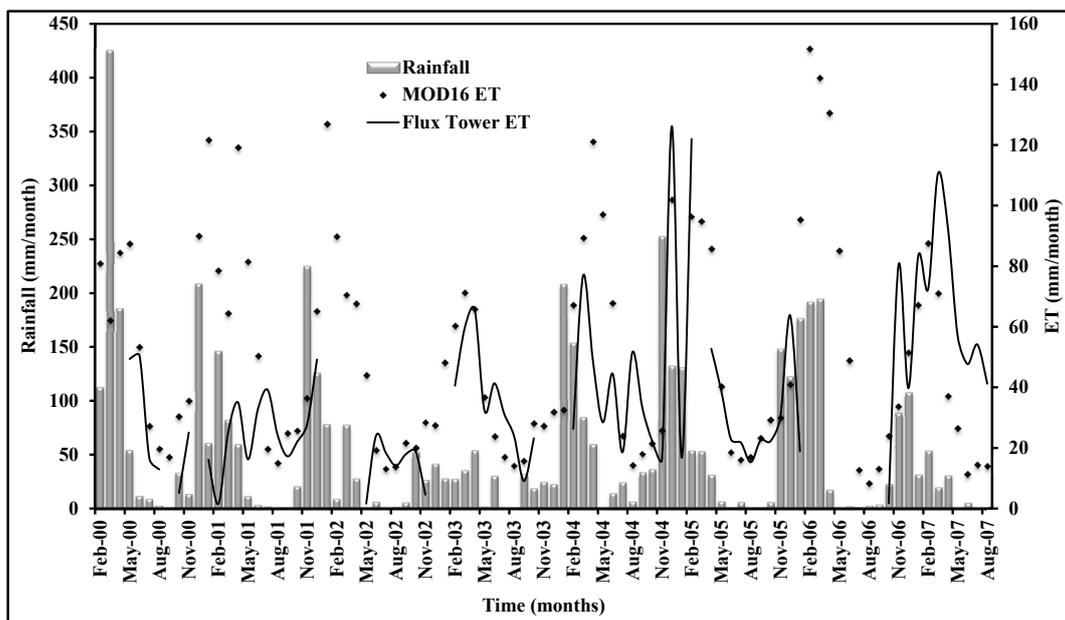
The eight-day and monthly comparison of the ET in Skukuza between January 2000 and December 2010 are shown in Figures 3 and 4. Flux tower ET values are generally higher than MOD16, especially during summer months (December–February), when most of the data gaps occur. During

winter season (June–August), when the flux record is more complete, MOD16 and flux tower ET are closely related. This is a confirmation of the results for *Bias* and *PBias* showing systematic underestimation of ET by MODIS ET.

**Figure 3.** Eight-day time series comparison of MOD16, rainfall and Skukuza flux tower derived ET.



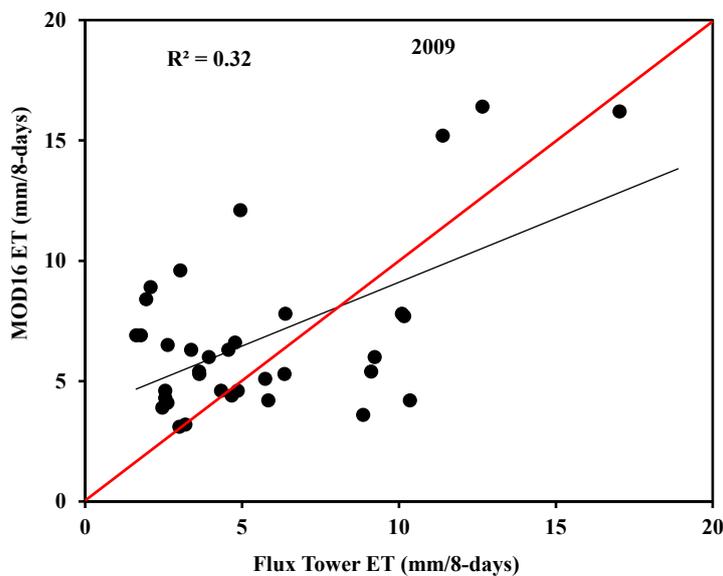
**Figure 4.** Monthly time series comparison of MOD16 and Skukuza flux tower derived ET.



For the Malopeni site, the results show a relatively good *RMSE* (3 mm/8-days) with 35 out of 45 eight-day flux tower measurements (Table 1; Figure 5). Malopeni’s validations are similar to those of Skukuza in 2001, 2003 and 2005 in terms of *RMSE*. In terms of the *R<sup>2</sup>-value* (0.23), Malopeni

validation is the lowest. Generally, the results of Malopeni show that MOD16 ET is overestimated ( $Bias = 1.18$ ,  $PBias = 21\%$  of the observed mean). Figures 6 and 7 show the time series visualization of eight-day and monthly ET. In both the eight-day and monthly time series, MOD16 ET started to increase around August–September while flux tower ET continues to drop.

**Figure 5.** Validation of MOD16 ET using flux tower data (mm/8-days) in Malopeni (2009). The 1:1 line is depicted by a red color.



**Figure 6.** Eight-day time series comparison of MOD16 ET, rainfall and Malopeni flux tower derived ET.

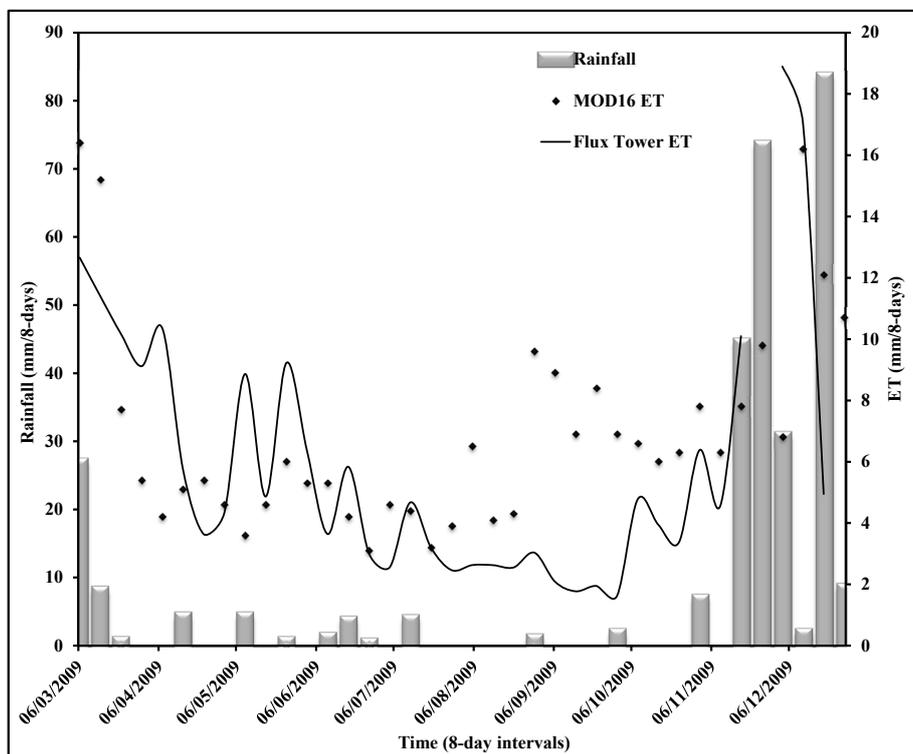


Figure 7. Monthly time series comparison of MOD16, rainfall and Malopeni flux tower derived ET.

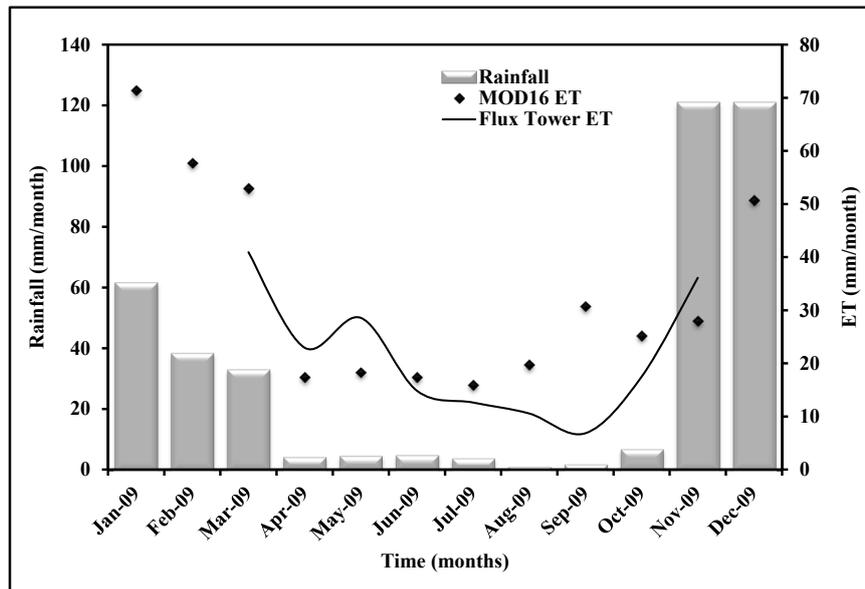


Figure 8 shows all-period data (2000–2010) comparison of eight day and monthly modelled MOD16 and measured flux tower ET for Skukuza as well as monthly for Malopeni in 2009. Results indicate a poor relationship between modelled MOD16 and measured flux tower ET. Eight-day and monthly comparisons yielded  $R^2$  of 0.20 and 0.16, respectively. Monthly comparison for Malopeni obtained  $R^2$  of 0.33, which is relatively higher than the correlation achieved in Skukuza site. This could be a consequence of the number of data points used, only one year for Malopeni and several years for Skukuza used. Generally, the results show that there is a poor relationship between MOD16 and flux tower ET when using all data sets from various dates in each site.

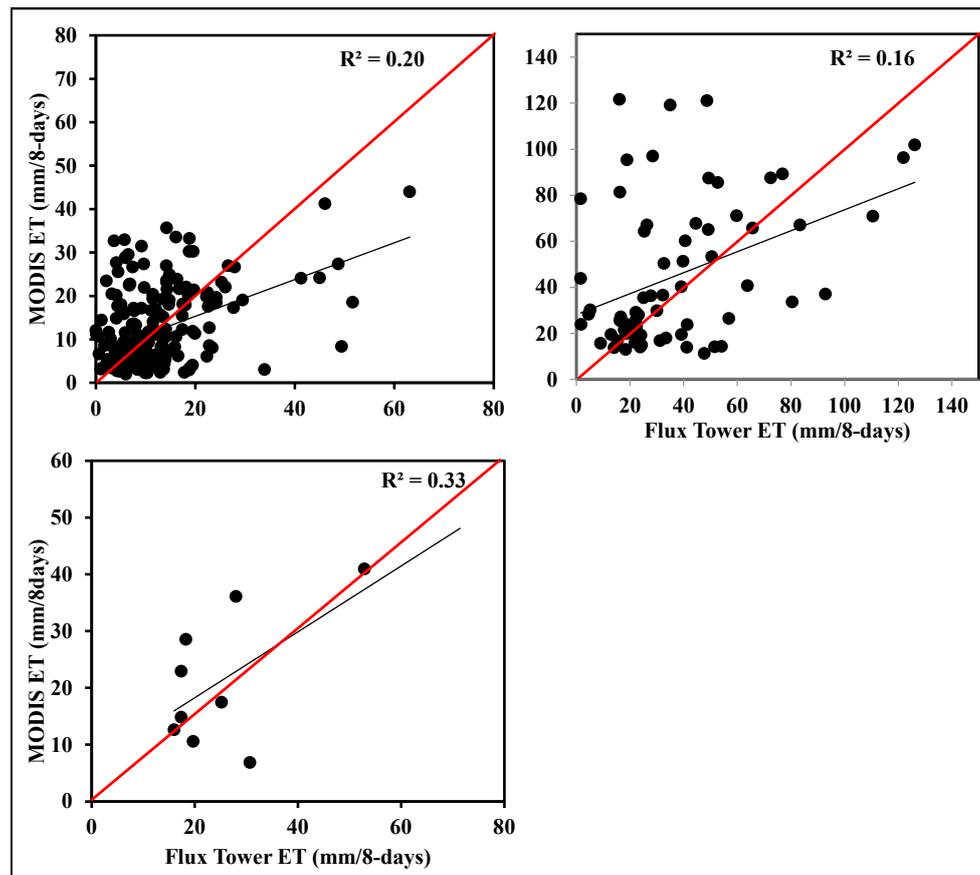
General trends as depicted by Figures 3 and 4 for Skukuza as well as Figures 6 and 7 for Malopeni show that both the flux tower and MODIS ET are to some extent related to rainfall variability (see Table 2). Table 2 shows further analysis of the relationship between rainfall and flux tower measured as well as MOD16 modelled ET for eight days and monthly data. Generally, there is a significant relationship between rainfall and ET. High rainfall peaks are associated with high ET values. In addition, missing flux tower ET values are associated with high rainfall or towards the end of the rainy season, since the measurements from the flux instruments become unreliable when wet.

Table 2. Analysis for the comparison between ET and rainfall.

Sites	Types	Duration	$R^2$	RMSE(mm/8-days)	* $P < 0.05$
Skukuza	Flux Tower	8day	0.14	8.85	Yes
		Mon	0.01	28.1	No
	MOD16	8day	0.15	9.41	Yes
		Mon	0.16	33.9	Yes
Malopeni	Flux Tower	8day	0.01	5.02	No
		Mon	0.41	8.99	Yes
	MOD16	8day	0.11	4.60	Yes
		Mon	0.32	13.77	Yes

\* 95% confidence level, where YES indicates significance; Mon = Monthly.

**Figure 8.** (Top left) indicates all eight day comparisons between MODIS and Flux tower ET from 2000 to 2010, (top right) is a monthly comparison for Skukuza from 2000 to 2010 and (bottom) is a monthly comparison for Malopeni in 2009.



#### 4. Discussion

The paper focused on the evaluation of the MOD16 modelled ET product in South African savannas using flux tower measured ET. Discrepancies between MOD16 ET and flux tower ET can originate from a number of factors, including the parameterization (input data) of the Penman-Monteith model, flux tower measurement error, flux tower footprint *vs.* MODIS pixel size as well as the limitations of the algorithm, most of which were identified by Mu *et al.* [7,34]. The main input data for the MODIS ET modelling include MODIS derived global products such as land cover [50], albedo, leaf area index (LAI), fraction of photosynthetic absorbed radiation (FPAR) as well as meteorological data. These input parameters are coarse scale products, generally poorly or not validated in the semi-arid conditions of South Africa, which are likely to generate significant ET prediction errors. For instance, MODIS global land cover (MOD12Q1) is a relatively coarse product (500 m) which inadequately captures the heterogeneity of savanna ecosystems. Further, the global MODIS based LAI or FPAR products have not been validated in Southern Africa. For generating the LAI product, an inversion of the physically-based model such as PROSAIL is used [51]. However, a backup algorithm based on LAI *vs.* NDVI relationship is used, when the inversion of the physically based model does not provide a solution [51]. In the semi-arid environments like South Africa, it is likely that the LAI is based on the latter approach because of the global parameterization. Therefore,

it is crucial that the input data such as land cover, FPAR and LAI are also assessed and validated in the local context, and improved when needed. This exercise will help determine and document error propagation within the MOD16 algorithm and support the development of local parameterization of models for an integrated water management system. Sensitivity analyses are required to identify the variables which influence the ET output the most, and to document the level of agreement between input and output errors.

Uncertainties associated with the flux tower measurements could have also influenced the results. The flux towers have an energy balance closure problem due to the fact that the sum of the net radiation and the ground heat flux is sometimes larger than the sum of the turbulent fluxes of latent and sensible heat [52]. The energy balance closure problem was not corrected in this paper due to the lack of reliable ground heat flux measurement. Flux tower measurements are largely influenced by weather conditions. During rainy and stormy days, flux tower sensors either record abnormal values or simply do not record any data. The missing flux tower measurements affected the cumulative eight-day ET. The advantage of having full eight-day measurements was evident in the 2010 datasets, which provided the best overall relationship between the flux tower and MOD16 ET measurements. The low correlations obtained during the dry season are similarly observed in other regions and probably related to a lag in detecting the plant water stress using remote sensing techniques [53]. The relationship between rainfall with flux tower and MOD16 ET (Table 2) demonstrated that rainfall has a significant influence in the variability of ET, and hence the estimation of ET.

Spatial discrepancy may still exist between the footprint of the flux tower measurements and the MODIS pixel. The height of the sensors on a flux tower [48], wind direction or velocity, atmospheric stability and underlying surface conditions influence the size of the eddy covariance source area [49]. The measurement heights of Skukuza and Malopeni are 16 m and 7 m, respectively, thus the footprints of these towers are 1.6 km and 0.7 km, respectively. The Skukuza flux tower footprint provides a better match to the MODIS pixel size compared to the Malopeni flux tower. In addition, the layout of a single 1 km pixel may not directly match the flux tower footprints and may add further spatial discrepancy between the two. Footprint modelling is a means to reduce the spatial discrepancy between flux tower measurements and MODIS pixel [36], but this was beyond the scope of this study.

Shortcomings associated with the algorithm itself could have influenced the differences between flux tower and MOD16 ET. Mu *et al.* [34] argued that several physical factors such as micro-climate, plant biophysics for site specific species and landscape heterogeneity influence the soil surface evaporation and plant transpiration processes, which likely affect MOD16 ET estimation accuracy. The MOD16 ET does not account for disturbance history or species composition and stand age [7,34], which could also add further uncertainty. The algorithm makes the assumption that the stomata close during the night, while studies such as Musselman and Minnick [54] have reported stomata opening during the night. This induces underestimation of daily ET because of the bias imposed by night time vegetation transpiration [34].

## 5. Conclusions

The study evaluated the quality of the MOD16 ET global products. Generally, MOD16 is poor and the accuracy is not consistent over a period of time in selected savanna ecosystem sites.

The quantification of errors associated with the MOD16 ET product in the savanna ecosystem presents new findings. The MOD16 product underestimated ET with errors ranging from 2–7 mm/8 days in the Skukuza site and 3 mm/8 days in the Malopeni site. The evaluation of this product and quantified errors has been undertaken exhaustively for the first time in the dry savanna ecosystem, especially in South Africa. Rainfall was found to significantly ( $p < 0.05$ ) influence ET distribution and is associated with the missing data. Several factors could have influenced the inconsistency between MOD16 and flux tower derived ET, including parameterization of the model, scaling from flux tower measurement to a pixel as well as limitations associated with the algorithm used. For further evaluation of MOD16, footprint modelling for the eddy covariance source area should be done to ensure spatial representativeness or to reduce errors associated with scaling from flux tower measurements to a pixel. In addition, the energy balance closure problem should be analyzed, provided that there is reliable soil heat flux data. In future, there is a need to develop locally parameterized models for consistent estimation and mapping of ET in South Africa. It is important to understand existing ET estimation methods in order to improve ET estimation for the South African environment. In addition, future activities should also focus on the improvement of the estimation accuracy of other remote sensing derived input variables such as LAI, albedo and land cover. Accurate and consistent estimation and mapping of ET is crucial for understanding plant or crop water use which is an important component of integrated water resource management.

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### **Author Contributions**

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### **Conflicts of Interest**

The authors declare no conflict of interest.

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