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Measurement and modelling of evaporation from a coastal wetland in Maputaland, South Africa

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Abstract

The contribution of freshwater supply from the Mfabeni Mire to Lake St. Lucia during dry periods is important to the survival of certain plant and animal species in the iSimangaliso Wetland Park. This freshwater supply is mainly dependent on the variability of the major components of the water balance, namely rainfall and total evaporation (ET). Attempts to quantify the water balance have been limited through uncertainties in quantifying ET from the Mfabeni Mire. Despite advances in evaporation measurement and modelling from wetlands, there still exists some doubt as to which methods are best suited to characterise wetland ET with most authors suggesting a combination of methods.

In this study, the surface renewal (SR) method was successfully used to determine the long-term ET (12 months) from the Mfabeni Mire with calibration using eddy covariance during two window periods of approximately one week each. The SR method was found to be inexpensive, reliable and with low power requirements for unattended operation. The annual ET was lower (900 mm yr^{-1}) than expected, due to cloud cover in summer and low atmospheric demand throughout the year, despite the available water and high windspeeds. Daily ET estimates were compared to the Priestley-Taylor results and a site specific calibration $\alpha = 1.0$ was obtained for the site. The Priestley-Taylor results agreed well with the actual ET from the surface renewal technique ($R^2 = 0.96$) throughout the 12 month period. A monthly crop factor (K_c) was determined for the standardised FAO-56 Penman-Monteith. However, K_c was variable in some months and should be used with caution for daily ET modelling.

These results represent not only some of the first long-term measurements of ET from a wetland in Southern Africa, but also one of the few studies of actual ET in a subtropical peatland in the Southern Hemisphere. The study provides wetland ecologists and hydrologists with guidelines for the use of two internationally applied models for the estimation of wetland ET within a coastal, subtropical environment.

1 Introduction

The Maputaland coastal plain is an ecologically sensitive area on the east coast of South Africa prone to prolonged droughts and floods (Mucina and Rutherford, 2006; Taylor et al., 2006b). It is essential in such areas to accurately determine the water balance for the effective management of the water resource. Accurate estimates of the water resource are however highly dependent on evaporation losses. The Mfabeni Mire is one of the wetlands of the Maputaland coastal plain (Grundling et al., 1998) with a high water availability creating the potential for high evaporative losses. However, total evaporation (ET) estimates from wetlands have frequently relied on indirect methods based on estimates of potential evaporation and its calculation as a residual in the water-balance (LaBaugh, 2002). This work in Maputaland represents one of the few ET studies in a subtropical peatland of the Southern Hemisphere in which actual ET was measured and forms part of a research programme funded by the South African Water Research Commission under KSA 2 (Water Linked Ecosystems). It therefore provides critical new insights into the partitioning of the energy balance and to the processes and limitations to ET that may differ from the commonly studied Northern Hemisphere boreal and arctic tundra peatlands.

Despite improvements to measurement techniques and the dominant role of ET in wetland water-balances, there are few studies in Southern Africa with actual measurements of ET from wetlands. Wetland ET has been estimated in the Ntabamhlope research catchment of the Drakensberg using diurnal fluctuations in the water table levels (Smithers et al., 1995) with significant residuals and deficiencies identified in the technique. Also at Ntabamhlope, an evaporimeter was used together with the Penman (1948) method and the complementary relationship concept of Bouchet (1963) but problems with instrumentation drift compromised the results (Chapman, 1990). At the Nylsvlei wetland, ET was estimated using a combination of meteorological models, pan evaporation and a few days of energy balance measurements (ignoring sensible heat flux) to derive monthly means of ET (Birkhead et al., 2007). The most comprehensive wetland ET study in South Africa was performed by Dye et al. (2008) in which the Bowen ratio technique was used together with a sonic anemometer to verify the WAVES model results over a *Phragmites communis* dominated wetland over one year. The Bowen ratio technique however has drawbacks (Savage et al., 1997) and due to high power requirements the data collected was intermittent. These studies all contributed to an improved understanding of wetland ET but were limited by the techniques available at the time and focused only on inland areas.

Meteorological models that calculate estimates of ET such as the Penman-Monteith model have gained popularity due to their relatively low data requirements and have been incorporated into numerous hydrological and crop-growth models such as CANEGRO (Inman-Bamber, 1991), ACRU (Schulze et al., 1995), SWB (Annandale et al., 2003) and SAPWAT (van Heerden et al., 2009) amongst others. These formulations are most suitable for uniform agricultural crops and have not been tested for many natural vegetation types and in particular wetlands with heterogeneous vegetation including sedges and reeds often growing in open water. For instance, the way some ET models have been applied (e.g. Penman-Monteith) has resulted in some doubt in the use of published vegetation specific parameters such as the crop factor (Drexler, et al., 2004). Much of this doubt has been removed since the standardization of the Penman-Monteith formulation by the Food and Agriculture Organization (Allen et al., 1998). Despite the value in meteorological models in estimating ET, it has long been accepted that they require vegetation or location specific parameters that change seasonally (Monteith, 1981; Ingram, 1983; Mao et al., 2002).

Numerous studies have addressed the hydrology of Maputaland (Taylor et al., 2006b; Vaeret et al., 2009; Kelbe and Germishuyse, 2010). Where ET estimates have been required for modelling or water balance studies, the best information has been obtained from the Water Resources of South Africa study by Midgley et al. (1994) or the published maps of the region by Schulze et al. (1997). However, this information was based on regional estimates of potential evaporation and is inadequate for detailed studies addressing water-balance, land management, environmental reserve and climate change studies.

Internationally, Souch et al. (1996) concluded that our understanding of ET and the related physical processes are not well characterized for many wetland types. Dexler et al. (2004) state that despite the numerous methods available to quantify wetland ET, it remains insufficiently characterized due to the diversity and complexity of wetland types and that no single model or measurement technique can be universally applied. This leaves wetland ecologists and hydrologists with some uncertainty regarding the most appropriate methods for estimating wetland ET in water-balance studies or environmental water requirement assessments.

There was therefore a significant need to apply the most appropriate and up-to-date methods to determine the long-term ET for key strategic wetlands and to use these results to verify existing meteorologically based models. This will not only reduce uncertainty, but will also provide some guidance in terms of wetland ET rates and thus, lead to a better understanding of the processes that define the partitioning of the surface energy balance in wetlands. With calibration periods using eddy covariance, Drexler et al. (2004) suggested that surface renewal (SR) holds promise as a suitable technique for the measurement of wetland ET. Further studies have confirmed that SR now provides a relatively low maintenance and cost effective solution for the long-term measurement of the sensible heat flux over wetlands (Mengistu and Savage, 2010). In this study the SR method was therefore applied over a period of one year (September 2009–August 2010) to determine the ET from the Mfabeni Mire in the iSimangaliso Wetland Park. These results were compared to ET estimates from two well known meteorological models, namely, the Priestley-Taylor and FAO-56 Penman-Monteith models to provide wetland ecologists and hydrologists with an indication of their suitability to ET estimation in subtropical coastal wetlands of the Maputaland coastal plain.

2 Study sites

The study area was located in the Eastern Shores section of the iSimangaliso Wetland Park which was declared South Africa's first UNESCO World Heritage Site in 1999.

It lies adjacent to Lake St. Lucia and within the St. Lucia Ramsar Site designated in 1986. It is a premier tourist destination contributing to the economy of the surrounding communities and the town of St. Lucia (Fig. 1).

The health and future conservation of Lake St. Lucia is, however, strongly dependent on the water level and the salinity of the water within the Lake, which is controlled in part by freshwater inflows (Whitfield and Taylor, 2009). During droughts, the rivers to the west (Mkuze, Mzinene, Hluhluwe and Nyalazi) provide limited inflow into the lake (Taylor et al., 2006a). Freshwater seepage from the groundwater mound of the Embomveni ridge on the Eastern Shores area into the Nkanzana and Tewate Rivers and other seepage zones along the shoreline become the most important contribution to the lake (Rawlings and Kelbe, 1991; Bjørkenes et al., 2006). This groundwater seepage from the Eastern Shores area has significant ecological importance and provides refuge sites where localised freshwater inflows enable many species to survive during periods of high salinity, preventing extinction and loss of biodiversity (Taylor et al., 2006b).

The Eastern Shores is bordered by the Indian Ocean to the east and Lake St. Lucia to the west (Fig. 1). High coastal dunes form a barrier to the east, and to the west the slightly lower, undulating Embomveni Dunes flank Lake St. Lucia. Between these dunes lies an interdunal ancient drainage line that forms the Mfabeni Mire. The Mire is drained by the Nkazana Stream which feeds Lake St. Lucia and is a critical freshwater source during severe drought periods. Peat has accumulated in the Mfabeni Mire over the past 45 000 yr, forming one of the largest peatlands in South Africa and one of the oldest active peatlands in the world (Grundling et al., 1998). The Mire is 8 km long in a north-south direction and 3 km at it's widest point. It has an overall extent of 1047 ha providing more than adequate fetch for the micrometeorological techniques used. Detailed vegetation studies have been completed in and around the Mfabeni Mire by Lubke et al. (1992), Sokolic (2006) and Vaeret and Sokolic (2008). The dominant species in the immediate vicinity of the Mfabeni Mire study site (28°9.007′ S, 32°31.492′ E) are the sedges *Rhynchospora holoschoenoide* and *Fimbristylis bivalvis*, and the grasses *Panicum glandulopaniculatum* and *Ischaemum fasciculatum*. The vegetation height was typically 0.76 m and the leaf area index (LAI) was between ∼1.7 in winter and ∼2.8 in summer. The plant roots have permanent access to the water table at this site.

The Mfabeni Mire is a subtropical freshwater wetland surrounded by Maputaland Coastal Belt vegetation which is a mixed, seasonal grassland community (Mucina and Rutherford, 2006). Therefore, for purposes of comparison, ET was also measured over dry grassland on the western Embomveni Dunes, over the same period as the Mfabeni Mire, using the same techniques. The Embomveni Dune site was 6 km from the measurement station in the Mfabeni Mire and therefore experienced similar climatic conditions but represented a significantly different landscape position (28°11.549′ S, 32°28.807′ E). The dunes have an elevation of approximately 30 m above mean sea level. The grass roots were confined to the upper 1 m of the sandy soil profile and were not in contact with the watertable. During the summer growing season the grassland vegetation was therefore dependent on soil water stores and rainfall. The vegetation was mixed but the dominant plants were the grasses *Trachypogon spicatus*, *Imperata cylindrica*, the herb *Helichrysum kraussii*, the sedge *Cyperus obtusiflorus*, the succulent *Crassula alba*, and the tree *Parinari capensis*. The average vegetation height was typically 0.34 m and the LAI between ∼0.85 in winter and ∼1.2 in summer.

The iSimangaliso Wetland Park is situated in the Indian Ocean Coastal Belt Biome (Mucina and Rutherford, 2006). It has a subtropical climate and lies in a summer rainfall area. There is a steep rainfall gradient from east to west and at the coastline, the mean annual precipitation exceeds 1200 mm yr^{-1} but only 900 mm yr^{-1} to the west (10 km) at Fanies Island. Taylor et al. (2006b) indicated that the temporal variability of the rainfall gives rise to severe wet and dry periods in Maputaland and during this study there was a well reported drought in the region.

3 Materials and methods

The shortened energy balance equation is used in evaporation studies to describe energy partitioning at the earth's surface (Eq. 1). The "shortened" version ignores the energy associated with photosynthesis, respiration and energy stored in plant canopies which are small when compared with the other terms (Thom, 1975). The net irradiance (R_n) equates to the sum of the sensible heat flux (H), the ground heat flux (G) and the latent energy flux (LE) which represents evaporation:

$$R_\mathrm{n} = \mathrm{LE} + H + G \tag{1}$$

where, all components except LE are measured, the energy balance equation may be used to determine LE as the residual term in Eq. (1) which is then converted into ET (Savage et al., 2004).

Net irradiance and ground heat flux were measured at both the Mfabeni Mire and Embomveni Dune sites from October 2009 to September 2010. A net radiometer (NR-Lite, Kipp and Zonen, Delft, The Netherlands) was used to measure R_n at 2.0 m above the canopy and G was measured using two soil heat flux plates (HFT-3, REBS, Seattle, WA, USA). The plates were placed at a depth of 80 mm below the soil surface. A system of parallel thermocouples at depths of 20 and 60 mm were used for measuring the soil heat stored above the soil heat flux plates and volumetric soil water content (CS615, Campbell Scientific Inc., Logan, Utah, USA) was measured in the upper 60 mm. At the Mfabeni Mire, the groundwater level at its highest was 0.1 m below the surface and therefore, the total G was determined using the methodology described by Tanner (1960) at both sites. The measurements were sampled every 10 s with a CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) and 30-min averages were computed.

Over the corresponding time period, H was calculated using the SR technique at both the Mfabeni Mire and Embomveni Dunes. Air temperature was measured using two unshielded type-E (chromel/constantan) fine-wire thermocouples (76 µm diameter) placed at heights of 1.00 m and 1.40 m above the ground surface. Results were recorded with a datalogger (CR3000, Campbell Scientific Inc., Logan, Utah, USA) powered by two 100 Ah batteries and two 20 W solar panels. Data was saved onto a 2 GB compact flash card able to store up to six weeks of high frequency (10 Hz) data. The SR technique is based on the principle that an air parcel near the surface is renewed by an air parcel from above (Paw U et al., 1995). This process involves ramp like structures (rapid increase and decrease of a scalar), which are the result of turbulent coherent structures that are known to exhibit ejections and sweeps under shear conditions (Gao et al., 1989; Raupach et al., 1996; Paw U et al., 1992). The theory of heat exchange between a surface and the atmosphere using the SR method is described in detail by Paw U et al. (1995, 2005), Snyder et al. (1996) and Mengistu and Savage (2010). The exchange of heat energy between a surface and the atmosphere is expressed as:

$$H = \alpha \rho_\mathrm{a} c_p z \frac{a}{\tau} \tag{2}$$

where, α is a weighting factor, ρ_a is the density of air, c_p is the specific heat capacity of air, z is the measurement height, a is amplitude of the air temperature ramps and τ is the total ramping period. The amplitude and the ramping period were deduced using analytical solutions of Van Atta (1977) for air temperature structure function:

$$S^n(r) = \frac{1}{m-j} \sum_{i=1+j}^{m} \left(T_i - T_{i-j}\right)^n \tag{3}$$

where, n is the power of the function, m is the number of data points in the time interval measured at frequency f (Hz), and j is the sample lag between data points corresponding to a time lag $r = j/f$, T_i is the ith temperature sample. Time lags of 0.4 and 0.8 s were used in this study. Second, third and fifth orders of the air temperature structure parameter are required to solve for a and τ.

The weighting factor (α) is required to determine H (Eq. 2). It depends on the measurement height, canopy architecture and thermocouple size (Snyder et al., 1996; Spano et al., 1997, 2000). Once determined by calibration, it is fairly stable and does not change regardless of weather conditions unless the surface roughness changes (Snyder et al., 1996; Spano et al., 2000; Paw U et al., 2005). An extended Campbell Scientific Open Path Eddy Covariance system (Campbell Scientific Inc., Logan, Utah, USA) was therefore deployed at the Mfabeni Mire to determine the weighting factor during two window periods of measurement in November 2009 and March 2010. A "Sx" style Applied Technologies, Inc. sonic anemometer (Longmont, Colorado, USA) was used at the Embomveni Dune site during the same window periods. The sensors were mounted on 3 m lattice towers at a height of 2.5 to 3.0 m above the ground level or 2.0 to 2.5 m above the vegetation cover. They were orientated into the direction of the mean wind on the upwind side of the tower to minimize flow distortion effects. At both sites, water vapour corrections as proposed by Webb et al. (1980) and coordinate rotation following Kaimal and Finnigan (1994) and Tanner and Thurtell (1969) were performed using EdiRe software (R. Clement, University of Edinburgh, UK) to determine the eddy covariance derived H. By substituting this H into Eq. (2), the weighting factor (α) for the Mfabeni Mire ($\alpha = 0.8$ at a measurement height of 1.0 m above ground surface) and Embomveni Dunes ($\alpha = 1.0$ at a height of 1.0 m above ground surface) was determined.

Finally, ET using the SR technique ($\mathrm{ET_{SR}}$) was determined every 30 min as a residual in Eq. (1). At night, $\mathrm{ET_{SR}}$ was negligible during the calibration periods and was therefore only calculated during daytime (unstable) conditions when ($R_n > 0$). The direction of H was determined by comparing the air temperature at two different heights using the fine-wire thermocouples of the SR system and found to be positive when $R_n > 0$. Daily $\mathrm{ET_{SR}}$ was then used to verify the Priestley-Taylor and FAO-56 Penman-Monteith models described in the results and simple linear regression was used to assess whether ET could be accurately predicted from these models. Polynomial regression quantiles (95th quantile) were fitted in GenStat (VSN International, 2011) to determine the general seasonal course of the modelled results in the Mfabeni Mire and Embomveni Dunes. Regression quantiles are useful for describing the upper "edge" of a cloud of heterogeneous data to identify the pattern of constraint imposed by the independent on the dependent variable (Cade et al., 1999). Net irradiance was used in the derivation of measured and modelled results and therefore auto self-correlation was minimized by using independently collocated measurements.

An automatic weather station providing supporting climatic data in the Mfabeni Mire measured rainfall, air temperature and relative humidity, solar irradiance, windspeed and direction. Solar irradiance was measured using an LI-200X pyranometer (LI-COR, Lincoln, Nebraska, USA). Wind speed and direction were measured using a wind sentry (Model 03002, R. M. Young, Traverse city, Michigan, USA). The raingauge (TE525, Texas Electronics Inc., Dallas, Texas, USA) was mounted at 1.2 m and the remaining sensors 2 m above the ground. Vapour pressure deficit (VPD) was calculated from the air temperature and relative humidity sensor (HMP45C, Vaisala Inc., Helsinki, Finland) according to Savage et al. (1997). The climatic data were averaged over 30-min intervals from observations made every 10 s and stored on a data logger (CR3000, Campbell Scientific Inc., Logan, Utah, USA).

To understand potential constraints to ET, volumetric soil water content was determined using CS615 time domain reflectometers (Campbell Scientific Inc., Logan, Utah, USA) at the Mfabeni Mire (0.100 m, 0.200 m, 0.400 m) and at the Embomveni Dunes (0.025 m, 0.075 m, 0.125 m, 0.250 m, 0.500 m, 1.000 m). At the Dune site, soil water potential was measured using Watermark 200 sensors (Irrometer Company, Riverside, California, USA) at the same depths. Soil water data was measured hourly and stored on a data logger (CR10X, Campbell Scientific Inc., Logan, Utah, USA).

LAI is the surface area on one side of the leaf material (m^2) per unit area of ground (m^2). It is a biophysical property closely linked to plant ET (Allen et al., 1998). The average LAI of the vegetation at the Mfabeni Mire and Embomveni Dunes was measured at monthly intervals across each site using an LAI-2000 (LI-COR Inc., Lincoln, Nebraska, USA).

4 Results

4.1 Weather conditions during the study period

Over the study period most of the rainfall occurred during the summer months from October through to March, although there was some rainfall experienced in winter (May to August) associated with frontal conditions (Fig. 2). At the research site in the Mfabeni Mire the precipitation over the 12-month measurement period was 650 mm (Fig. 2). This was significantly below the annual average (1200 mm) but in agreement with the well-reported drought in the region. The groundwater level at the beginning (October 2009) of the study period at Mfabeni was 0.1 m below the surface and by the end of August 2010 was 0.3 m below the surface, confirming the prevailing drought conditions. In normal rainfall years, Mfabeni Mire is often flooded in summer with water depths of ~0.3 m above the peat surface.

Daily solar radiant density fluctuated seasonally, peaking at 12 MJ m^{-2} in winter and 27 MJ m^{-2} in summer (Fig. 2), but was more variable in summer due to cloud cover, which was particularly prevalent in the mornings until 11:00 a.m. LT. Maximum temperatures in the Mfabeni Mire were frequently above 30 °C in summer and generally below 30 °C in winter. The average daily minimum temperature was 20 °C in summer and rarely below 5 °C in winter, although on 17 June 2010 the temperature dropped to −1.2 °C. The humid coastal conditions are best described by the average daytime ($R_n > 0$) VPD of 0.79 kPa indicating a low atmospheric evaporative demand generally. The monthly average daytime VPD fell between 0.56 kPa and 0.96 kPa (Fig. 3) with October experiencing the lowest and February the highest VPD. The average daytime ($R_n > 0$) windspeed was 4 m s^{-1} (Fig. 3). The highest monthly average was measured in October (5.4 m s^{-1}) and the lowest in May (3.2 m s^{-1}). Both VPD and windspeed have an important influence on ET (Anderson, 1936; Allen et al., 1998).

Fires are a common occurrence in South African wetlands (Cowan, 1995). A runaway fire burned through the Mfabeni Mire just before measurements commenced in September 2009. It spread from dry peat that smoldered for weeks in the northeast corner of the Mfabeni Mire and was rekindled by a change in wind direction. Despite high windspeeds during the fire, the burn was patchy due to low fuel load densities and some of the actively growing vegetation such as the reeds and sedges were undamaged. The burn however, provided an opportunity to investigate the ET directly after a fire, followed by natural spring re-growth.

Albedo (ratio of reflected irradiance from the surface to incident irradiance upon it) increased after the fire in September 2009 from 0.10 to 0.22 in April 2010 due to vegetative re-growth (Fig. 4) and then gradually decreased again to approximately 0.17 due to plant senescence and winter conditions. These data are useful for future solar irradiance modelling studies and for remote sensing energy balance models such as the Surface Energy Balance Algorithm for Land model SEBAL which has been used successfully in wetland areas (Bastiaanssen et al., 1998; Mohamed et al., 2006).

4.2 Measured energy balance and total evaporation

Net irradiance at the Mfabeni Mire in summer (up to 800 $\mathrm{W\,m^{-2}}$) was variable due to intermittent cloud cover (Fig. 5a). Cloudy mornings, with some clearing between 10:00 and 11:00 were common. During winter, there was noticeably less variation in R_n due to the dominance of clear skies (Fig. 5b). For example, in August 2010, four of the days (18, 21, 22 and 23) showed complete cloudless conditions which were never observed during the summer period.

At the Embomveni Dunes, the peak daily R_n in summer (Fig. 5c) was $\sim$100 $\mathrm{W\,m^{-2}}$ lower than at the Mfabeni Mire. This is a function of the albedo and indicated that there was more irradiance reflected from the grassland surface than at the wetland in summer. Where exposed, the dark surface of the peat at the Mfabeni Mire was in contrast to the white sand of the Embomveni Dunes. This is important as it determines the amount of available energy ($R_\mathrm{n} - G$) in summer. Plant senescence in winter reduced the difference in the reflected irradiance between the sites (Fig. 5b and d).

There was a marked dominance of H over LE at the Embomveni Dunes ($\beta > 1$) in summer and winter (Table 1; Fig. 5c and d). The exception was when rainfall increased the soil water content. For example, 12 mm of rain on 19 and 20 August 2010 increased the near surface volumetric soil water content from 6.2 % to 8.7 %. On the 21 and 22 August the LE was similar to the H but by 23 August, ET had depleted the soil water to 7.0 % and H dominated the energy balance again. This showed the dependence of the grassland $\mathrm{ET_{SR}}$ on soil water and identified it as a limiting factor for growth.

There was a shift in the distribution of the energy balance at the Mfabeni Mire between summer and winter (Table 1). At the Mfabeni Mire, in summer, the ratio LE:R_n (0.61) was almost twice H:R_n (0.31), while G:R_n made up the remainder (0.08). The pattern shifted in winter to an equal split between LE:R_n and H:R_n (0.46) while G:R_n was again 0.08. The reduced dominance of LE:R_n was likely due to plant senescence in winter and was typical of a surface with full canopy cover. At the Embomveni Dunes there was little change in the energy partitioning between seasons. This indicated that the limiting factors controlling the partitioning of the energy balance remained consistent between seasons. The exception was after rainfall at the Embomveni Dunes where a change in water availability altered the partitioning of the energy balance as discussed above. At both sites there was little change in the ratio G:R_n between seasons as the reduced LAI in winter (described above) was likely offset by an increased sun angle.

The $\mathrm{ET_{SR}}$ at the Mfabeni Mire varied seasonally (Fig. 6). Intermittent cloud during the summer period (October to March) resulted in large daily fluctuations in $\mathrm{ET_{SR}}$. This was also evident in the high variability of R_n in summer in comparison to the winter period, which the meteorological data (Fig. 2) showed to be characteristic of the coastal weather patterns for the area. In the Mfabeni Mire, the average summer $\mathrm{ET_{SR}}$ was 3.2 mm day^{-1} ($\sigma = 1.4$ mm day^{-1}). The fitted 95 % regression quantile ($p < 0.001$) indicated potential maximum daily rates in summer to be approximately 6.0 mm day^{-1}. During the winter months (April to September) the average daily $\mathrm{ET_{SR}}$ was 1.8 mm day^{-1} ($\sigma = 0.8$ mm day^{-1}) with an estimated potential maximum around the winter solstice of 1.3 mm day^{-1}. The accumulated $\mathrm{ET_{SR}}$ over 12 months was 900 mm (Table 2) of which 64 % occurred in the summer months (October to March).

At the Embomveni Dune site (Fig. 6), as with the Mfabeni Mire, there were many cloudy days in summer. The average summer ET_{SR} (October to March) was 1.7 mm day^{-1} ($\sigma = 0.8$ mm day^{-1}) with the potential maximum rate estimated by the 95 % regression quantile of approximately 3.0 mm day^{-1}. The average daily ET_{SR} during the winter months (April to August) was 1.0 mm day^{-1} ($\sigma = 0.8$ mm day^{-1}) with an estimated maximum around the winter solstice of 1.2 mm day^{-1}. The accumulated ET_{SR} over 12 months was 478 mm (Table 2) of which approximately 63 % occurred in the summer months (October to March).

Despite the close proximity of the two sites (6 km), ET_{SR} at the Mfabeni Mire (900 mm) was almost double the ET_{SR} at the Embomveni Dune site (478 mm). This difference was due to the freely available water at the Mfabeni Mire. The dominant limitations to transpiration and surface evaporation at the Mfabeni Mire were therefore likely to have been available energy, low atmospheric demand (noted above) and stomatal control due to plant senescence in winter. The lower ET_{SR} at the Embomveni Dunes was however due to limited soil water availability exacerbated by low rainfall (650 mm in 12 months) experienced during the measurement period. Soil water availability was generally low with volumetric water content of ~6 % and frequently below −150 kPa at a depth of 0.075 m (measured continuously but not shown).

During the research, the SR method was found to be reliable, easy to operate in the field and suitable for long-term, unattended use over wetlands with calibration using eddy covariance. However, the fine-wire thermocouples are fragile and easily broken by animals, hail or contact with fast growing vegetation, and at least one backup thermocouple was used.

4.3 Modelling of total evaporation

Evaporation measurement is complex and in most studies of wetland hydrology is modelled using weather data collected from a nearby automatic weather station. Two methods used widely for wetland applications are the FAO-56 Penman-Monteith method

(Allen et al., 1998) and the Priestley-Taylor method (Priestley and Taylor, 1972). These models are relatively simple and suitable for use by hydrologists or wetland ecologists to determine wetland ET. They are also well suited to wetland applications as water availability does not limit transpiration.

FAO-56 Penman-Monteith: the original Penman model (Penman, 1948) is frequently cited and was a significant contribution to evaporation modelling. It was improved by Monteith (1965) by incorporating surface and aerodynamic resistance functions and was widely used in this form as the Penman-Monteith equation. It is still commonly applied but is highly data intensive (Moa et al., 2002; Drexler et al., 2004). The equation was later standardised by the Food and Agriculture Organisation (Allen et al., 1998) into a form known as the FAO-56 Penman-Monteith model. The standardisation includes the definition of a reference crop as "a hypothetical crop with an assumed height of 0.12 m having a surface resistance of $70\,\mathrm{m\,s^{-1}}$ and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered" (Allen et al., 1998). By further assuming a constant for γ (the psychometric constant), simplifying the air density (ρ_a) and estimating aerodynamic resistance from an inverse function of wind speed, the FAO-56 Penman-Monteith equation can be expressed as:

$$\mathrm{LE} = \frac{0.48\Delta(R_\mathrm{n}-G)+\gamma\frac{900}{T+273}U_2(e_\mathrm{s}-e_\mathrm{a})}{\Delta+\gamma(1+0.34U_2)} \tag{4}$$

where, Δ is the rate of change of saturated vapour pressure with temperature ($\mathrm{kPa\,^\circ C^{-1}}$), γ is the psychometric constant ($\mathrm{kPa\,^\circ C^{-1}}$), T is the mean air temperature (°C) at a height of 2 m, U_2 is the mean wind speed ($\mathrm{m\,s^{-1}}$) at a height of 2 m, e_s is the saturated water vapour pressure (kPa) at T and e_a is the mean ambient water vapour pressure (kPa) at 2 m above the ground.

Thus, the FAO-56 Penman-Monteith model provides an estimate of ET from a hypothetical grass reference surface ($\mathrm{ET_r}$). It can be universally applied as it provides a standard to which ET at different times of the year or in other regions can be compared and to which the ET from other crops can be related. It is used internationally to estimate crop ET using the crop factor (K_c) approach in the form:

$$K_c = \frac{\text{ET}}{\text{ET}_r} \tag{5}$$

where the crop is not water stressed. In Allen et al. (1998) numerous values of K_c have been compiled for different vegetation types and the different stages in crop development.

The ET_r was calculated hourly and summed each day. The daily results of ET_r (Fig. 7) reflected a similar seasonal trend to that shown by the ET_{SR} (Fig. 6) at the Mfabeni Mire. The standard deviation in summer (σ) was higher (1.3 mm) than in winter (0.7 mm). Monthly K_c averages (Fig. 8) reflect the need to accommodate seasonal changes in K_c at times. The monthly 95 % confidence intervals indicate a higher variability of daily K_c from June to January. In contrast, K_c was less variable from February to May. From October to January there was no significant difference between mean monthly K_c and a single mean over this period would be suitable. However, from February to September all but two of the monthly K_c's are significantly different and a monthly K_c should be used over these months. Over the 12 months of measurement the average K_c was 0.80 indicating that the ET_{SR} was on average 20 % less than ET_r. This K_c result was low for a wetland, particularly considering the freely available water in the Mfabeni Mire. Although the linear regression of ET_{SR} on ET_r was significant ($F_{1,355} = 1640$, $p < 0.001$) and accounted for 82 % of the variation in ET_{SR}, residual variation about the regression was not constant (hetroscedastic), even under various data transformations. This suggests that the crop factor approach was not suited to estimating ET for the Mfabeni Mire.

Priestley-Taylor: the Priestley-Taylor model (Priestley and Taylor, 1972) is a simplified version of the more theoretical Penman model. The aerodynamic terms of the Penman model are replaced by an empirical α term. It is reasoned that as an air mass moves over an expansive, short, well-watered canopy, ET would eventually reach a rate of equilibrium when the air is saturated and the actual rate of ET would be equal to the Penman rate of potential evapotranspiration. This is referred to as equilibrium evaporation (ET_{EQ}). Under these conditions the aerodynamic term of the Penman equation approaches zero and irradiance dominates. The Priestley-Taylor model is therefore commonly used to estimate evaporation from wetlands (Price, 1992; Souch et al., 1996; Mao et al., 2002):

$$LE_{(P\text{-}T)} = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G) \tag{6}$$

where,

$$\frac{\Delta}{\Delta + \gamma} = 0.4132 + 0.0158 T_z - 0.000115 T_z^2 \tag{7}$$

and

$$T_z = \frac{T_{max} + T_{min}}{2} \tag{8}$$

where, $LE_{(P\text{-}T)}$ is the Priestley-Taylor total daily latent energy flux ($MJ\,m^{-2}$), α is the advective term (representing Penman's aerodynamic term as a constant fraction), T_{max} is the maximum daily air temperature (°C) and T_{min} is the minimum daily air temperature (°C).

At the Mfabeni Mire, ET_{EQ} ($\alpha = 1$) reflected the seasonality observed in ET_{SR} (Fig. 6). The fitted 95 % regression quantile ($p < 0.0001$) indicates maximum rates on clear days. In summer the rates were higher (6.0 mm day^{-1}) but variable ($\sigma = 1.5$ mm day^{-1}) and in winter, lower (1.7 mm day^{-1}) and less variable (0.8 mm day^{-1}). A linear regression of ET_{SR} on ET_{EQ} ($F_{1,355} = 7553$, $p < 0.001$) over the 12 months of measurement indicated that ET can be accurately predicted ($R^2 = 0.96$) by the Priestley-Taylor equilibrium model at the Mfabeni Mire (Fig. 9). The Priestley-Taylor α represented by the slope of the linear regression in Fig. 10 and is equal to 1 (intercept of −0.3).

At the Embomveni Dune site, ET_{EQ} again reflected the seasonality of ET_{SR} with summertime highs of 5 mm day^{-1} ($\sigma = 0.8$ mm day^{-1}) and wintertime lows of 1.8 mm day^{-1}

($\sigma = 0.4\,\text{mm day}^{-1}$). An acceptable linear regression of ET_{SR} on ET_{EQ} was found with square-root transformed data to ensure a constant and approximately normally distributed residual. However, the confidence with which ET_{EQ} can be used to estimate ET_{SR} was lower ($R^2 = 0.71$) than at the Mfabeni Mire ($R^2 = 0.96$). In summer for example, the 95 % regression quantile of ET_{SR} was only $3.0\,\text{mm day}^{-1}$ whereas ET_{EQ} was $5\,\text{mm day}^{-1}$. This indicates that a severe constraint was imposed by low soil water availability (measured but not shown) and only on occasions after rainfall, was ET_{SR} similar to ET_{EQ} as noted in Fig. 5c and d. The Priestley-Taylor α represented by the slope of the linear regression was equal to 0.54.

5 Discussion

The seasonal fluctuation of daily ET_{SR} at the Mfabeni Mire compared well with the limited work undertaken on wetland evaporation in South Africa. Dye et al. (2008) measured ET with eddy covariance and Bowen ratio intermittently over a Phragmites communis reedbed in the Orkney district (27.02° S, 26.68° E). The ET in summer in the reedbed peaked at $6.0\,\text{mm day}^{-1}$ (Mfabeni = $6.0\,\text{mm day}^{-1}$) and averaged approximately $3\,\text{mm day}^{-1}$ (Mfabeni = $3.2\,\text{mm day}^{-1}$). Around the winter solstice, peak rates of $1.6\,\text{mm day}^{-1}$ (Mfabeni = $1.3\,\text{mm day}^{-1}$) were measured. Dye et al. (2008) also noted the summertime variation in daily ET rates depending on cloud and humidity. These results from Orkney compared favourably with the results from Mfabeni and indicated that despite the geographically distinct location and altitude the ET estimates were similar.

Also inland but further to the north, ET was measured in a riparian area of the Sabie River in the Kruger National Park, South Africa (Everson et al., 2001). The Bowen ratio technique was applied over a *Phragmites mauritianus* reedbed in a riparian wetland. Maximum ET rates were $9\,\text{mm day}^{-1}$ in summer and $4\,\text{mm day}^{-1}$ in winter. These rates are higher than at the Mfabeni Mire due to the higher available energy but most significantly the daily average VDP's were higher (mostly between 1 and 3 kPa) and therefore the sites are not comparable.

The ET_{SR} results from the Embomveni Dunes (dry grassland) serve as an interesting contrast to the wetland ET_{SR}. The 12 month accumulated ET_{SR} at the Mfabeni Mire was 900 mm in contrast to 478 mm at the Embomveni Dune site. The soil water content at the grassland was low (~6 % volumetric and frequently below −150 kPa at a depth of 0.075 m) during the measurement period due to the prevailing drought conditions. The ET_{SR} at the Embomveni Dunes was therefore limited by soil water availability rather than energy. A similar result was observed by Jacobs et al. (2003) in a wetland under drought conditions in Central Florida, USA. They found that the fraction of available energy used in the evaporation and transpiration of water depended on soil water content and that a two-stage model with a reduction coefficient under dry conditions was appropriate. The soil water content in the Mire was by comparison much higher (>85 %) and the ET_{SR} was energy limited.

In South Africa, two comparative long-term studies of ET over grasslands have been performed. Everson et al. (1998) estimated ET over *Themeda triandra* grasslands of the Drakensberg escarpment near Cathedral Peak (28.95° S, 29.20° E). Cathedral Peak lies approximately 250 km inland of the coast with altitudes of 2000 m and falls within the Grassland Biome. They found maximum daily ET to be as high as 7 mm day^{-1} in summer (Embomveni = 3.0 mm day^{-1}) and <1 mm day^{-1} in winter (Embomveni <1.2 mm day^{-1}). The high summer rates of the Drakensberg contrast with the Embomveni Dunes and were higher due to the high summer rainfall in the Drakensberg area which sustains an adequate soil water content for transpiration. At the Embomveni Dunes the deep sandy soil profile drained rapidly after rain (data not shown), returning the system to a water limited environment. The second study was performed by Savage et al. (2004) in the KwaZulu-Natal Midlands near Pietermaritzburg (24.63° S, 30.43° E) approximately 100 km from the coast in a mixed grassland community during a dry period. They reported average daily summer ET rates to be approximately 3 mm day^{-1} and daily winter ET, 1 mm day^{-1}. These results are closer to the ET_{SR} in the Embomveni Dune site possibly due to the similar drought conditions and a water limiting environment reported during their study.

The Priestley-Taylor model (Eq. 6) was originally derived for use over extensive, saturated surfaces. When $\alpha = 1$, the equation represents the equilibrium model which occurs when the gradient of VPD approaches zero and $\mathrm{ET}_{\mathrm{EQ}}$ equals potential evaporation. During unstable daytime conditions, this is mostly not the case. Priestley and Taylor (1972) found an average α over oceans and saturated land of 1.26. This implies that additional energy increases the ET by a factor of 1.26 over $\mathrm{ET}_{\mathrm{EQ}}$. This has been explained by some as a result of entrainment of warm, dry air, down through the convective boundary layer (Lhomme, 1997). Numerous studies have determined other values for α (Monteith, 1981; Paw U and Gao, 1988; Clulow et al., 2012). Ingram (1983) found the value of α to be dependent on vegetation cover and that for treeless bogs α lay between 1 and 1.1 and for fens approximately 1.4. Moa et al. (2002) derived values for α in a subtropical region of Florida (USA) over sawgrass and cattail communities interspersed with open water areas of between 0.65 and 0.99. Most available literature regarding suitable α values, are however derived from studies in subarctic regions (Eaton et al., 2001), arid areas (Bidlake, 2000), over lakes (Rosenberry et al., 2007) or boreal aspen forest (Krishnan et al., 2006). The Priestley-Taylor α is site specific and these estimates from the Mfabeni Mire for Southern African vegetation and climatic conditions are valuable.

The α estimate of 1.0 (with an offset of $-0.3\,\mathrm{mm}$) calculated for the Mfabeni Mire is low in comparison with results from much of the international literature. However, it agrees well with those of Moa et al. (2002) derived from a similar wetland region with a similar subtropical climate. The result shows that the rate of evaporation was at equilibrium ($\mathrm{ET}_{\mathrm{SR}} = \mathrm{ET}_{\mathrm{EQ}}$) and the linear regression suggests that the ET can confidently be predicted using the Priestley-Taylor model.

The standardized FAO-56 Penman-Monteith model together with a K_{c} was developed to be applied internationally allowing comparison between different sites in different locations (Allen et al., 1998, 2006). It has, in some respects, become the industry standard in terms of ET estimation from different land-uses and is incorporated into numerous hydrological models (ACRU, SWAT, SWAP) and would be a popular solution for a wetland ecologist or hydrologist seeking to characterize the ET from a wetland using meteorological inputs. The report by Allen et al. (1998) is comprehensive and provides solutions for different time steps and levels of data increasing the accessibility of the method. The relatively poor relationship between $\mathrm{ET_{SR}}$ and $\mathrm{ET_r}$ ($R^2 = 0.82$), for the Mfabeni Mire, showed that despite attempts to create a universal solution, it should be used with caution when applied to natural vegetation. An alternative to the K_c method is to estimate the ET using the Penman-Monteith method but Drexel et al. (2004) found the lack of information on aerodynamic and surface resistances limiting.

The Priestley-Taylor model is a simplification of the FAO-56 Penman-Monteith model in which the mass transfer term is reasoned to be close to zero over a wet expansive surface and is ignored. The residual variation around the regression between $\mathrm{ET_{SR}}$ on $\mathrm{ET_r}$ ($R^2 = 0.82$) was higher than between $\mathrm{ET_{SR}}$ and $\mathrm{ET_{EQ}}$ ($R^2 = 0.94$). This difference must therefore be introduced from within the mass transfer term of the FAO-56 Penman-Monteith model (Eq. 7) which is a function of windspeed and VPD (or air temperature and relative humidity). This relationship between $\mathrm{ET_{SR}}$ and $\mathrm{ET_r}$ is described by K_c (Eq. 8) which was most variable in October when the highest daily average windspeeds and lowest daily average VPD's were measured (Fig. 3). In contrast, the daily variability of K_c was lowest in February which corresponded to the month with the lowest windspeed and highest VPD. The high windspeeds, possibly combined with low VPD's, reduced the confidence with which the FAO-56 Penman-Monteith model can be used to predict $\mathrm{ET_{SR}}$ at the Mfabeni Mire.

Leaf area index was measured at both sites at monthly intervals. Anser et al. (2003), in their global synthesis of LAI observations conclude that the leaf area index of the wetland biome is not well represented internationally but that it is a key descriptor of vegetation. They document the results from six wetland studies resulting in a mean wetland LAI of 6.3 with a minimum of 2.5 and a maximum of 8.4. In comparison, the LAI of the Mfabeni Mire was lower, between ~1.7 in winter and ~2.8 in summer. This result is of importance where site specific parameters (such as the Priestley-Taylor α

factor) are transferred to similar or nearby wetlands. Allen et al. (1998) for example, applied a correction to K_c based on an LAI that is lower than full cover. The relatively low $\mathrm{ET_{SR}}$ in contrast to the $\mathrm{ET_r}$ of the Mfabeni Mire could partly be explained by the low wetland LAI that was measured.

6 Conclusions

Despite maximum ET rates of up to 6.0 mm day^{-1}, the average summer (October to March) $\mathrm{ET_{SR}}$ was lower (3.2 mm day^{-1}) due to intermittent cloud cover which reduced the available energy. In winter (May to September), there was less cloud but the average $\mathrm{ET_{SR}}$ was only 1.8 mm day^{-1} due to plant senescence and the accumulated $\mathrm{ET_{SR}}$ over 12 months was 900 mm. Despite plentiful water and a subtropical environment, wetlands are not necessarily the high water users they are frequently perceived to be (Bullock and Acreman, 2003). Even high windspeeds characteristic of the site did not raise the ET due to the low evaporative demand (or VPD) of the air.

The Embomveni Dune (dry grassland) measurements of $\mathrm{ET_{SR}}$ provided a useful contrast to the Mfabeni Mire (wetland). The $\mathrm{ET_{SR}}$ was seasonal at both sites yet the total $\mathrm{ET_{SR}}$ at the Embomveni Dunes was limited by soil water availability and was only 478 mm over 12 months. The drought conditions (650 mm of rainfall versus a mean annual precipitation of 1200 mm yr^{-1}) therefore contributed to the low summer $\mathrm{ET_{SR}}$ at the Embomveni Dunes which are expected to be higher in a normal to high rainfall year.

A linear regression of $\mathrm{ET_{SR}}$ on $\mathrm{ET_r}$ was significant and accounted for 82 % of the variation in $\mathrm{ET_{SR}}$, however, the residual variation about the regression was not constant (hetroscedastic), even under various data transformations suggesting that the crop factor approach was not suited to estimating $\mathrm{ET_{SR}}$ for the Mfabeni Mire. The Priestley-Taylor model however, closely reflected the daily changes in $\mathrm{ET_{SR}}$ at the Mfabeni Mire and $\alpha = 1$ (intercept of -0.3) can be used with confidence to estimate daily ET ($R^2 = 0.96$) throughout the year. This relationship between $\mathrm{ET_{SR}}$ and $\mathrm{ET_{EQ}}$ showed that ET from the Mfabeni Mire was largely dependent on energy and was at the equilibrium (or potential) rate. Including the mass transfer term, as is the case in the FAO-56 Penman-Monteith model, was of no benefit due to the complexity of the high windspeed and low VPD at the site.

At the Embomveni Dunes, a Priestley-Taylor α of 0.54 reflected the drier conditions and lower dependence of ET on energy. The linear regression of $\mathrm{ET_{SR}}$ on $\mathrm{ET_{EQ}}$ showed more variation at the Embomveni Dune site ($R^2 = 0.71$) than at the Mfabeni Mire ($R^2 = 0.96$) and a more complex model that takes antecedent rainfall into account by including the soil water content is required for the Embomveni Dune site.

The significant advantage of the Priestley-Taylor method for use by wetland hydrologists and ecologists is the low data requirement. If R_n and G are measured or estimated (Drexler et al., 2004) from a nearby weather station then only T_max and T_min are required to estimate the wetland daily ET. In addition, the Priestley-Taylor model has been internationally accepted and tested since 1972 although the extent to which it can be applied beyond the Mfabeni Mire to other South African wetlands under equilibrium conditions requires further investigation.

The SR method was used to estimate the H and was found to be suitable for long-term, unattended use over wetlands with periodic calibration using eddy covariance. The fine-wire thermocouples (76 µm diameter) are however fragile and backup thermocouples should be installed to avoid data loss.

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Table 1. Distribution of the average daily energy balance as fractions of R_n, as well as the Bowen ratio (β), at the Mfabeni Mire and Embomveni Dune sites.

Site	Summer				Winter			
	LE:R_n	H:R_n	G:R_n	β	LE:R_n	H:R_n	G:R_n	β
Mfabeni Mire	0.61	0.31	0.08	0.51	0.46	0.46	0.08	1.00
Embomveni Dunes	0.36	0.55	0.09	1.53	0.37	0.53	0.10	1.43

Table 2. Summary of seasonal and annual total evaporation derived using a surface renewal system to calculate the sensible heat flux.

Site	Summer (mm)	Winter (mm)	Total (mm)
Mfabeni Mire	575 ($\sigma = 1.4$)	325 ($\sigma = 0.8$)	900 ($\sigma = 1.4$)
Embomveni Dunes	303 ($\sigma = 0.8$)	175 ($\sigma = 0.4$)	478 ($\sigma = 0.7$)

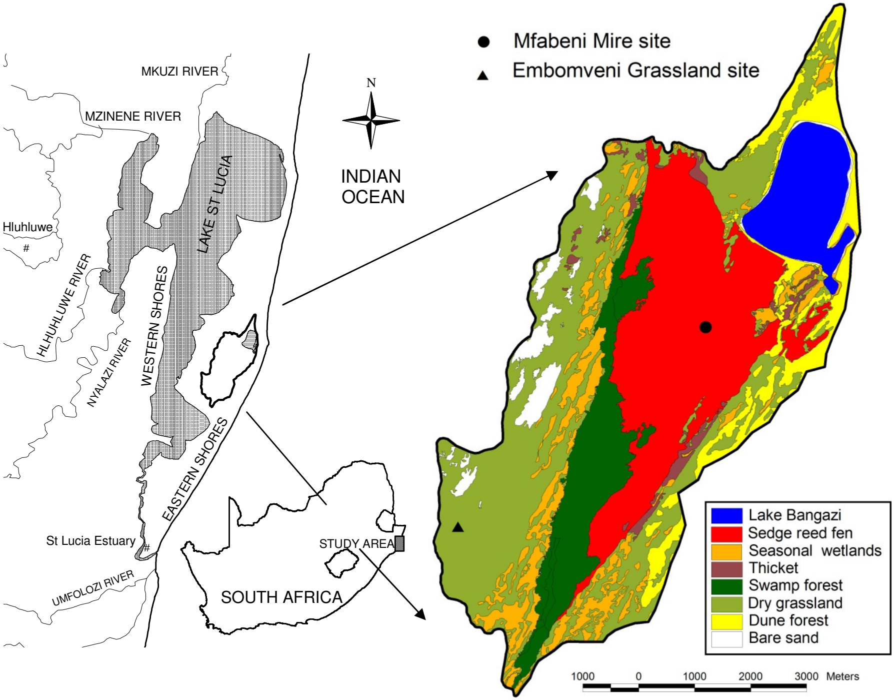

Fig. 1. The location of the Mfabeni Mire and Embomveni Dune sites. The Mfabeni Mire is represented by the Sedge Reed Fen vegetation unit.

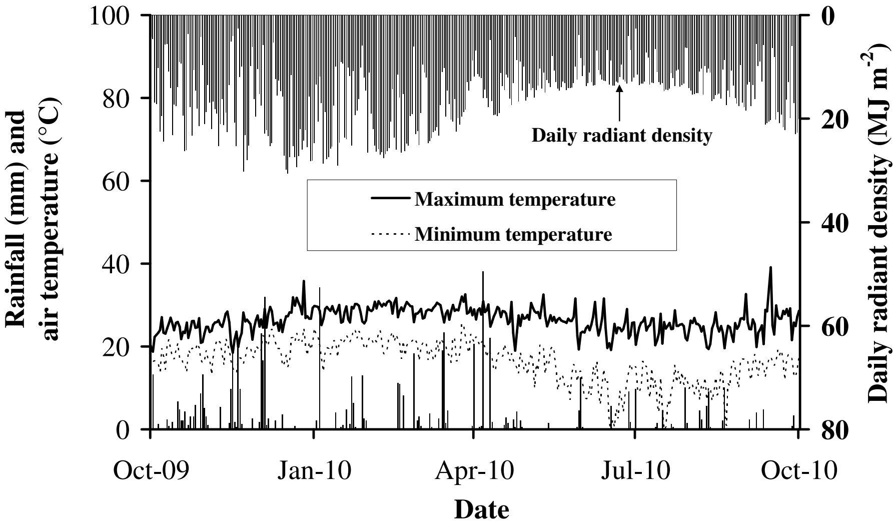

Fig. 2. Climatic conditions at the Mfabeni Mire including maximum and minimum air temperature (°C), rainfall (mm) and daily solar radiant density (MJ m^{-2}) from October 2009 to September 2010.

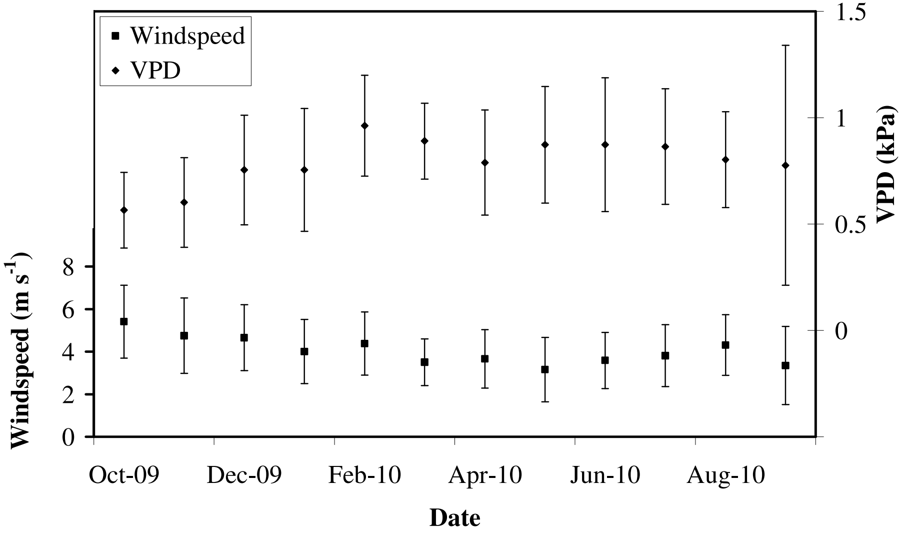

Fig. 3. Monthly average windspeed and VPD (with standard deviation error bars) at the Mfabeni Mire from October 2009 to September 2010.

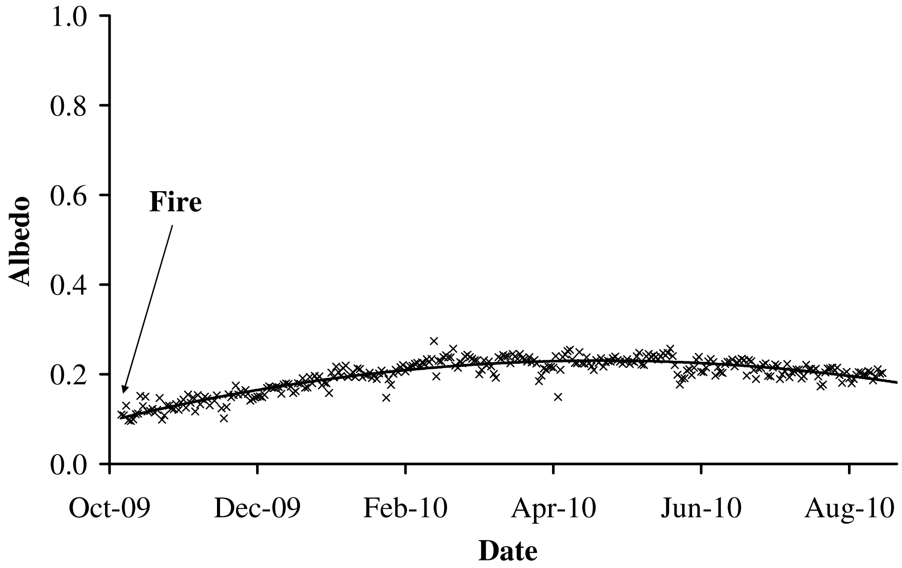

Fig. 4. The change in albedo of the Mfabeni Mire following the recovery of vegetation after a fire in September 2009, regrowth (summer) and senescence (winter).

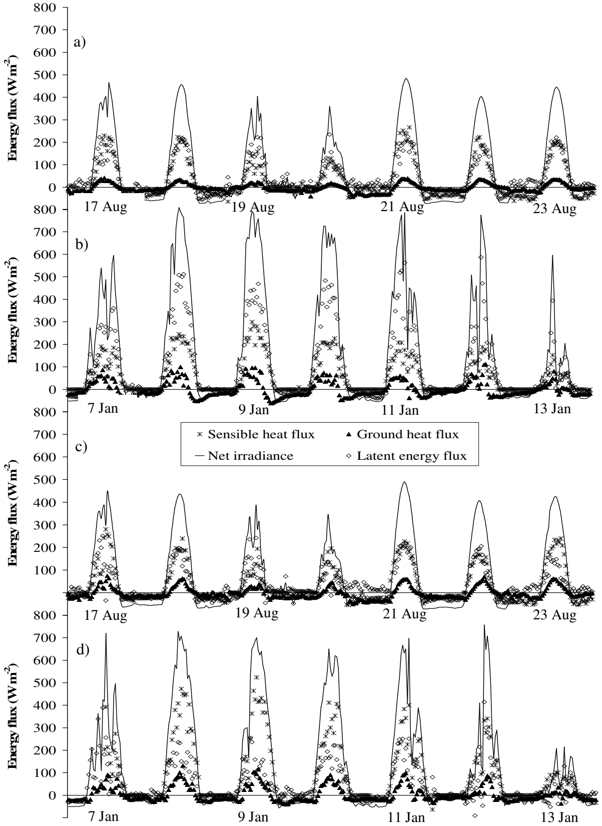

Fig. 5. Diurnal energy fluxes at Mfabeni Mire on **(a)** 17 to 23 August 2009 and **(b)** 7 to 13 January 2010 and on corresponding days at the Embomveni Dunes in **(c)** August 2009 and **(d)** January 2010.

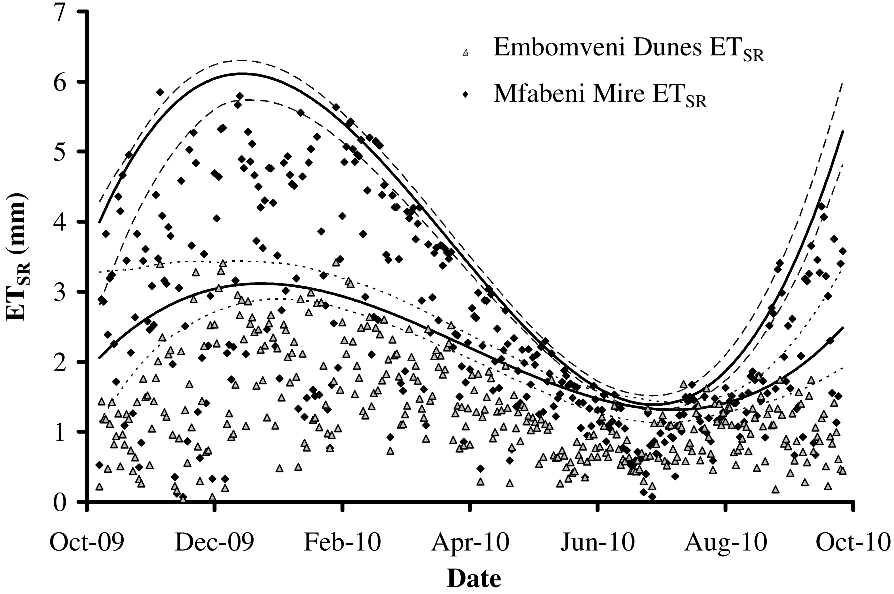

Fig. 6. Daily total evaporation at the Mfabeni Mire (upper line) and Embomveni Dunes (lower line) from October 2009 to September 2010 using the surface renewal technique. Solid lines represent fitted 95 % regression quantiles and dashed lines their 95 % confidence intervals.

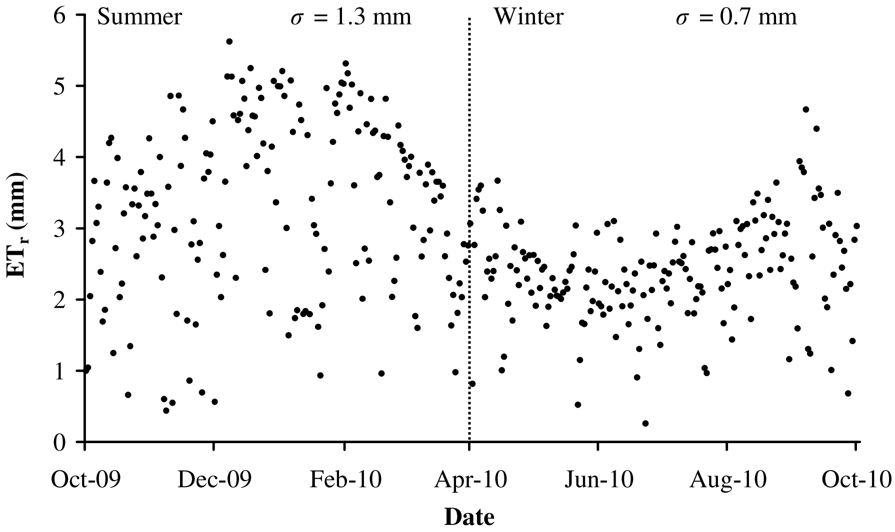

Fig. 7. The short grass reference evaporation (ET_r) from October 2009 to September 2010 in the Mfabeni Mire reflected the seasonal trend of the measured ET_{SR} with higher but more variable summer values ($\sigma = 1.3$) and lower less variable winter values ($\sigma = 0.7$).

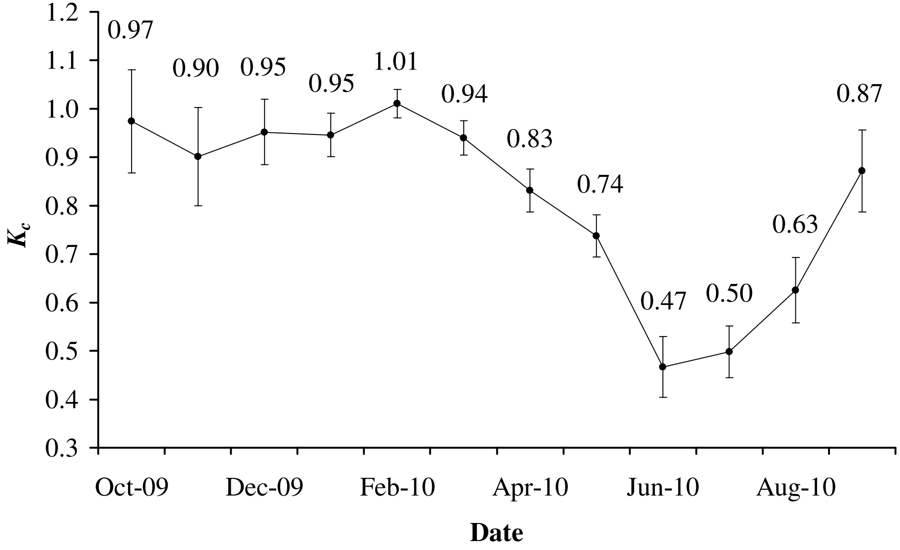

Fig. 8. Mean monthly crop factor (K_c) for the Mfabeni Mire from October 2009 to September 2010 with 95 % confidence intervals.

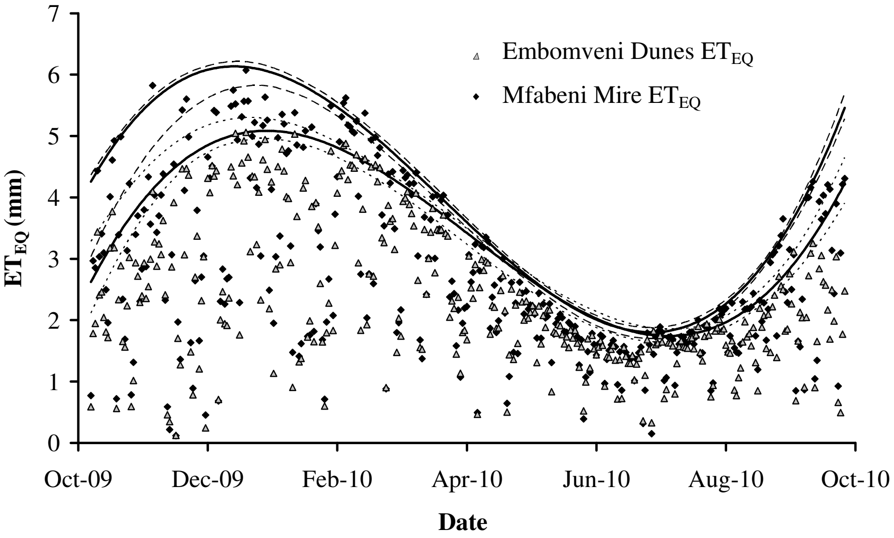

Fig. 9. The equilibrium evaporation (ET_{EQ}) from October 2009 to September 2010 at the Mfabeni Mire (upper line) and Embomveni Dunes (lower line) reflected the seasonal trend of the measured ET_{SR} with higher but more variable summer results and lower less variable winter values. Solid lines represent fitted 95 % regression quantiles and dashed lines their 95 % confidence intervals.

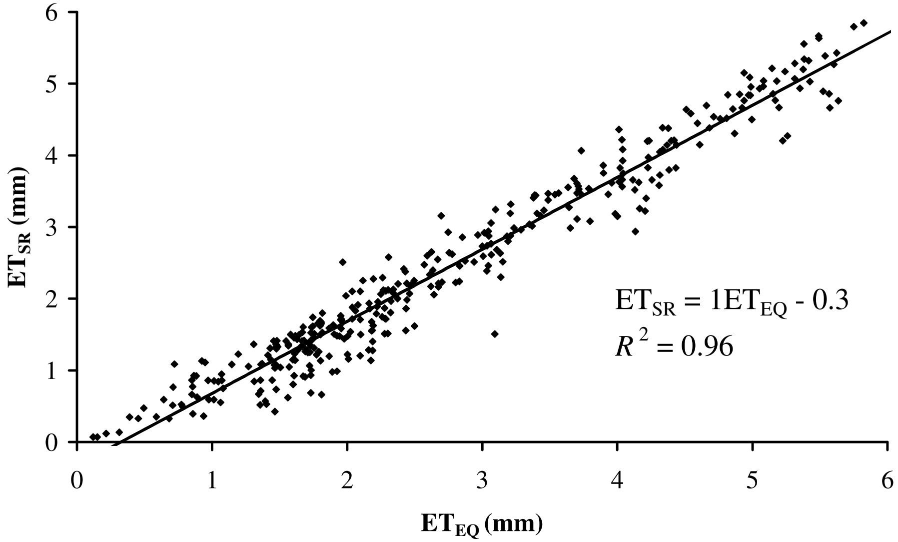

Fig. 10. The advective term (α) at the Mfabeni Mire determined as the slope of the linear regression of ET_{EQ} vs. ET_{SR} from October 2009 to September 2010.