Modelling evapotranspiration by remote sensing parameters and agro-meteorological stations

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Abstract Field energy balances from irrigated and natural ecosystems, together with a net of agro-meteorological stations, were used to develop a model for actual evapotranspiration (ET) quantification, based on the ratio of actual to reference evapotranspiration and the relation of this ratio to remote sensing parameters. The model was applied in the Brazilian semi-arid region to analyse the regional ET, making use of Landsat images and a geographic information system. After comparison against field results, it showed good agreement, explaining 89% of the variances and a mean square error (RMSE) of 0.34 mm d^{-1}.

Key words satellite measurements; latent heat flux; water management

INTRODUCTION

Experimentally, the calculation of actual evapotranspiration (ET) can be made accurately using energy balance techniques, which in Brazil have been applied in agricultural crops and natural vegetation (*caatinga*) (Teixeira *et al.*, 2008). However, the spatial variability is significant and extrapolation of energy balance data directly from flux towers to the surrounding landscape environment can lead to inaccurate regional estimates.

Considering the simplicity of application, and its needing neither crop classification nor extreme conditions, a model based on the ratio ET/ET_0 and remote sensing parameters was developed with field data from four flux stations involving irrigated crops and *caatinga*, in the semi-arid conditions of the Low-Middle São Francisco River basin (Teixeira *et al.*, 2008).

MATERIALS AND METHODS

The remote sensing calculations were done from nine Landsat images together with seven agro-meteorological stations, while the field data were from irrigated fruit crops and *caatinga* (Teixeira *et al.*, 2008, 2009). Table 1 summarizes the regression equations for modelling.

Table 1 Summary ofthe regression equations.

Parameter	Equation	a	b	R^2
α_0	$\alpha_0 = a\alpha_p + b$	0.70	0.06	0.96
T_0	$T_0 = aT_{sat} + b$	1.11	−31.89	0.95
ET/ET_0	$ET/ET_0 = \exp\{a + [T_0/(\alpha_0 NDVI)]\}$	1.90	−0.008	0.91

The only remote sensing parameters are the surface albedo (α_0), the surface temperature (T_0) and the Normalized Difference Vegetation Index (NDVI). The instantaneous ratio ET/ET_0 is applied to grids of daily values of ET_0, considering instantaneous and 24-h values of this ratio to be similar.

Simple regression equations were used for atmospheric corrections to obtain the regional values of α_0 and T_0 by using field and satellite measurements. A simplified linear relationship between α_0 measured by pyranometers in the field and the planetary albedo by Landsat satellite (α_p) has been applied (Teixeira *et al.*, 2009). From the field energy balance experiments, the aerodynamic surface temperature (T_0) was calculated while the radiometric surface temperature was obtained from the Landsat band 6 (T_{sat}). The satellite thermal radiation was corrected for both atmospheric emission and the difference between radiometric and aerodynamic temperature by applying a regression equation with field and satellite values (Table 1).

The model is based on the modelling of ET/ET_0 at the satellite overpass time (subscript sat) at the regional scale (Fig. 1(a)). The instantaneous images of ET/ET_0 obtained are then multiplied by the grids of ET_0 for 24 hours. The satellite overpass time values of ET/ET_0, and those for 24 hours in irrigated mango orchards and caatinga (Teixeira *et al.*, 2008), were compared (Fig. 1(b)). The slope is close to one, supporting the assumption that instantaneous and daily ratios can be considered equal (Allen *et al.*, 2007).

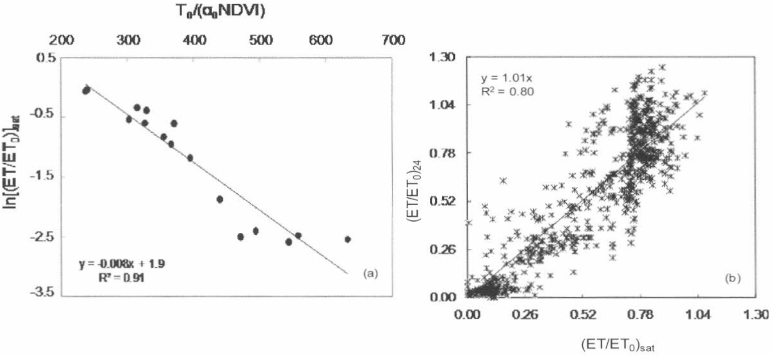

Fig. 1 Relations for ET/ET_0 ratio: (a) satellite overpass time values (subscript sat), (b) daily values (subscript 24). T_0: surface temperature; α_0: surface albedo; NDVI: Normalized Difference Vegetation Index.

RESULTS AND DISCUSSION

The ET results were validated with field measurements in the contrasting hydrological ecosystems of irrigated crops and caatinga in the Brazilian semi-arid conditions (Teixeira *et al.*, 2008). The results showed good agreement ($R^2 = 0.89$ and a root mean square error, RMSE, of 0.34 mm d^{-1}), explaining 89% of the variance.

The images of ET/ET_0 and of ET at daily time scales and for the dry period are presented in Fig. 2.

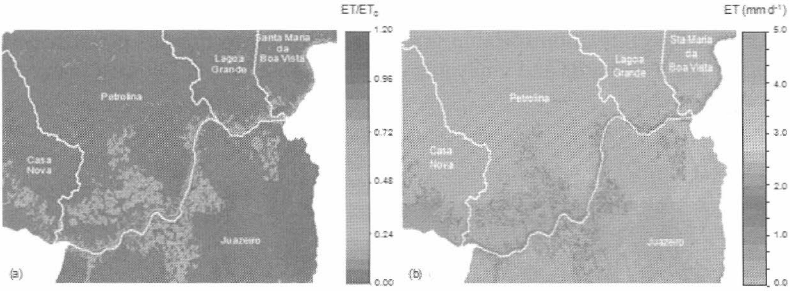

Fig. 2 Images of the satellite overpass ET/ET_0 (a) and daily ET (b) for the region comprised of the net of agro-meteorological stations in the Low-Middle São Francisco River basin on 15 October 2005.

The ET/ET_0 values (Fig. 2(a)) for irrigated crops are around 1.00 because the water supply reduces the heat losses to the atmosphere, while for the *caatinga* this ratio ranges from 0.00 to 0.20, as it converts the biggest part of the available energy into sensible heat flux during this period of the year. As a consequence, the *caatinga* presents low values of ET, while the irrigated fields show the highest ones (Fig. 2(b)). In general, irrigation intervals are short (daily irrigation), and the water supply is uniform, reducing the heat losses to the atmosphere. Pixels with values lower than 1.0 mm d^{-1} represent the *caatinga* species, while those from 1.0 to 5.0 mm d^{-1} coincide with irrigated crops, the highest ones being for table grapes.

In the wet period (Fig. 3), the moisture conditions are more homogeneous, making the values of ET/ET_0 for *caatinga* in some cases around 0.50, similar to those for irrigated crops (Fig. 3(a)).

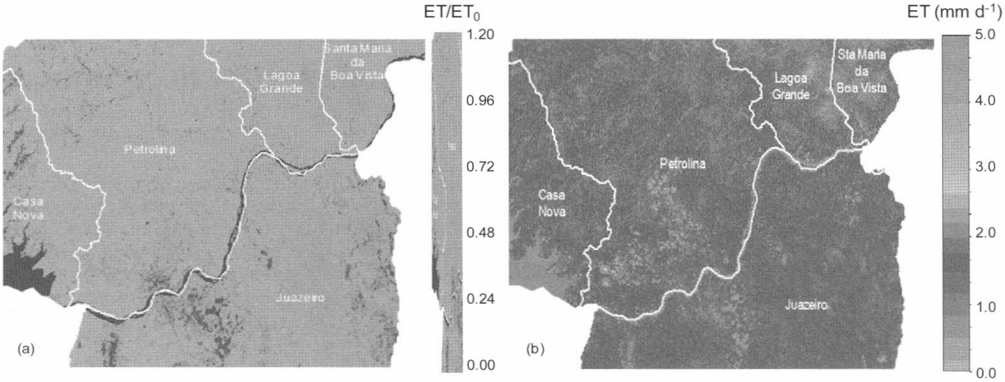

Fig. 3 Images of the satellite overpass ET/ET_0 (a), and daily ET (b), for the region comprised of the net of agro-meteorological stations in the Low-Middle São Francisco River basin on 22 January 2007.

A higher portion of the available energy in *caatinga* is converted into latent heat flux and, in most commercial farms, the irrigation is stopped while the rainfall keeps the soil uniformly wet for all ecosystems. A large area comprised of the net of agro-meteorological stations presents similar values of ET, with the exception of water bodies (Fig. 3(b)).

The ET/ET_0 maps for the dry period of 2005 (October) and for the wet period of 2007 (January) were calibrated with field data from irrigated mango orchards and *caatinga* for the same day of the year (DOY) of 2006 from the energy balance experiments described in Teixeira *et al.* (2008) to be used together with the image of July of 2006. The average ET/ET_0 values from these three images, representative of different soil moisture conditions were multiplied by the grid of the total ET_0 for 2006 giving the map of the annual ET (Fig. 4).

The highest accumulated regional ET values in 2006 (Fig. 4) are for mango orchards, being 500–1300 mm year^{-1}. Vineyards presented lower values, ranging 450–800 mm year^{-1}, while in *caatinga* they were between 200 and 400 mm year^{-1}. Considering that mango orchards are cultivated during the whole year and the cultivation of table grapes is restricted to the dry periods, it can be concluded that irrigated mango orchards and vineyards consumed more water per area than *caatinga* by factors of 3 and 2, respectively.

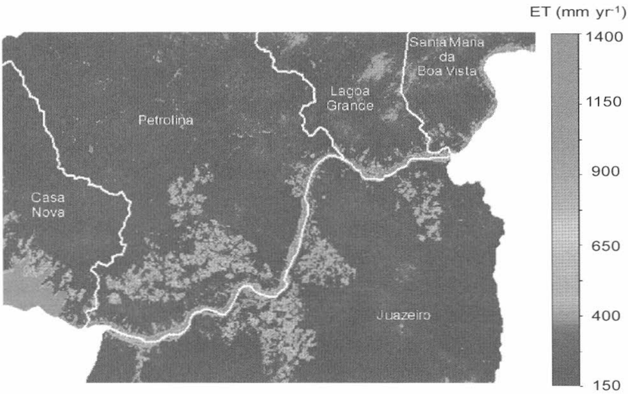

Fig. 4 Total annual actual evapotranspiration for 2006 for the region comprised of the net of agro-meteorological stations in the Low-Middle São Francisco River basin.

CONCLUSIONS

A model based on the Penman-Monteith equation for regional evapotranspiration acquirement in the Low-Middle São Francisco River basin, Brazil, presented a regression coefficient of 0.89 and a root mean square error of 0.34 mm d^{-1}. Considering the daily rates of the regional evapotranspiration, pixels with values lower than 1.0 mm d^{-1} outside the rainy period represent the *caatinga* species. Values from 1.0 to 5.0 mm d^{-1} during the driest conditions of the year coincided with irrigated crops, the highest ones being for table grapes. During the wet period, the moisture conditions are more homogeneous, making the *caatinga* ET/ET_0 values equivalent to those for irrigated crops with a large presentation of similar values for evapotranspiration. The highest accumulated ET values during 2006 were for mango orchards, 500–1300 mm $year^{-1}$. Vineyards presented lower values, 450–800 mm $year^{-1}$, while in the *caatinga* they were between 200 and 400 mm $year^{-1}$.

The results were encouraging given the complex mixture of the ecosystems in the semi-arid conditions, and considering that only maps of NDVI, surface albedo and surface temperature together with interpolated data of reference evapotranspiration are necessary, without the need for crop classification, which is not straightforward in fruit crops. Another advantage of the model is that it can be applied without the need to identify the extreme conditions, being also suitable for the rainy periods.

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