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Evapotranspiration in the Pampean Region using field measurements and satellite data

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ABSTRACT

Evapotranspiration (*LE*) is an important factor for monitoring crops, water requirements, and water consumption at local and regional scale. In this paper, we applied the semi-empirical model to estimate the daily latent heat flux ($LE_d = Rn_d + A - B(Ts - Ta)$). LE_d has been estimated using satellite images (Thematic Mapper sensor) and a local dataset (incoming and outgoing short- and long-wave radiation) measured during three years. We first estimated the daily net Radiation (Rn_d) from a linear equation derived from the instantaneous net Radiation ($Rn_d = CRn_i + D$). Subsequently, coefficients *A* and *B* have been estimated for two different cover vegetations (pasture and soybean). For each vegetation cover, an error analysis combining Rn_d, *A*, *B*, and surface and air temperatures has been calculated. Results showed that Rn_d had good performance (nonbias and low RMSE). LE_d errors for pasture and soybean were ±28 W m^{-2} and ±40 W m^{-2} respectively.

1. Introduction

Evapotranspiration (*ET*) is a primary process driving energy and water exchange among the hydrosphere, the atmosphere, and the biosphere (Priestley and Taylor, 1972; Brutsaert, 1984). *ET* is an important factor for monitoring water requirements of crops and water consumption at local and regional scale. Different methods have been proposed for measuring *ET* on various spatial scales from individual plants (i.e. porometer, sap-flow, lysimeter), fields (i.e. field water balance, Bowen ratio, scintillometer, eddy correlation) or landscape scales (i.e. energy balance, catchment water balance) (Soegaard and Boegh, 1995; Wang et al., 2006). Satellite Remote Sensing (*RS*) is a promising tool which has been used to provide reasonable estimates of the actual *ET* (also denoted as *LE*) at regional scales. Most *LE* estimations from *RS* can be calculated as a residual term of the available surface energy (*Rn*), the sensible heat flux (*H*), and the ground heat flux (*G*):

$$Rn = LE + G + H \tag{1}$$

Rn and *H* are calculated by a set of variables, some of which can be instantaneously estimated by *RS* (albedo, emissivity, and radiometric surface temperature). For most *RS*-based energy balance studies, it is assumed that *Rn* and *G* are known or they might be easily computed. The two remaining terms, *H* and *LE*, whose estimations are very difficult, are turbulent flux quantities. These terms are usually modeled using one-dimensional flux-gradient expressions based on a convection analogue to Ohm's law:

$$H = \frac{\rho C_p}{r_a}(T_0 - T_a) \tag{2}$$

$$LE = \frac{\rho C_p}{\gamma}\frac{(e_0 - e_a)}{(r_v + r_a)} \tag{3}$$

where ρ is the air density, C_p is the specific heat of the air, T_0 and e_0 are, respectively, the aerodynamic temperature and the vapor pressure of the surface at the effective level of heat and moisture exchange, T_a and e_a are the temperature and the vapor pressure of the overlying atmosphere, r_a and r_v are, respectively, the aerodynamic and physiological resistances to heat and moisture transport at the surface, and γ is the psychrometric constant.

Eqs. (1) and (2) form the basis of the alleged one-layer (*OL*) energy balance models. There is no distinction made in those models among vegetation canopy energy balance, temperature and vapor pressure regimes, and soil surface. To overcome the problem related to the lack of information on the surface resistance, *LE* (Eq. (3)) is estimated as the residual term (Eq. (1)). *RS* has been widely used with this type of framework to estimate the turbulent flux component of the surface energy balance. To do this, radiometric surface temperature (*Ts*) obtained from *RS* is used as a substitute for T_0 in Eq. (2) (Jackson et al., 1977; Seguin and Itier, 1983; Inoue and Moran, 1997; Sanchez et al., 2008a,b). The r_a is usually estimated using meteorological local data on wind speed, stability

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conditions, and roughness length, even though the average area of roughness lengths is highly nonlinear.

Over the last years, several regional experiments have tested *OL* models in detail and have provided significant progress (Gourturbe et al., 1997; Kustas and Norman, 1999). At the same time, results from these experiments have allowed to find feebleness in *OL* models and have pointed keys for future research. In fact, two alternative models including representations of different temperature and energy balance regimes for the vegetation canopy and the soil surface have been developed (Choudhury and Monteith, 1988; Kustas, 1990; Zhao-Liang et al., 2009). These models are considerably more complex, although recent investigations have shown them to be successful in overcoming some of the limitations of *OL* models. These models require in situ measurements (net Radiation, air temperature, air relative humidity, wind speed, crop height and leaf area index, canopy and soil temperatures, height and architecture of the plants, among others) and this information is not available in many situations. However, in many standard meteorological stations, there is not instrumentation to measure all these variables required by the models. The lack of specific instrumentation considerably limits the use of sophisticated models and operational applications. Moreover, these models are often limited due to the inherent complexity of those procedures. In most cases, however, regional values are estimated by semi-empirical models using as input local flux data measurement and *RS*. (Zhao-Liang et al., 2009; Reginato et al., 1985; Caselles and Delegido, 1987; Vidal and Perrier, 1989; Kustas et al., 1994). Jackson et al. (1977) were the first to demonstrate from field experiment that *LE* rates directly correlate with the temperature difference between canopy surface (*Ts*) and air (*Ta*). Seguin and Itier (1983) modified this method with the following semi-empirical model to calculate daily *LE* from:

$$LE_d - Rn_d = A - B(Ts - Ta) \tag{4}$$

where Rn_d is daily net Radiation, *A* is a simple partition into unstable case ($Ts - Ta > 0 \rightarrow A \neq 0$) and the advective case ($Ts - Ta < 0 \rightarrow A = 0$), and slope *B* is defined as a mean exchange coefficient which is weighted by the ratio between Rn_d and instantaneous net Radiation (Rn_i). *B* is indeed related to the instantaneous sensible heat flux (Eq. (2)) and can be defined as $B \cong Rn_d Rn_i^{-1} \rho C p r_a^{-1}$, where r_a depends on wind velocity and a roughness parameter (Seguin and Itier, 1983).

In Eq. (4), daily *G* is considered equal to zero (Jackson et al., 1977; Seguin and Itier, 1983), and *A* and *B* coefficients are considered to be constants at regional level for practical use (Seguin and Itier, 1983; Vidal and Perrier, 1989).

Semi-empirical models in flat areas are good tools for *LE* estimation (Brasa et al., 1998; Seguin et al., 1982) and good alternatives for regions with a lack of specific instrumentation. These models are also applicable in regions such as the Pampean Region of South America, where there can be seen homogeneous extended covers of soybean, maize, wheat, barley, oat, alfalfa, and others.

The objectives of this study are: (1) to obtain, from radiation measurement at local scale for the Pampean Region of Argentina, a relationship between daily net Radiation (Rn_d) and instantaneous net Radiation (Rn_i), (2) to validate the relationship Rn_d–Rn_i, (3) to estimate *A* and *B* coefficients (Eq. (4)) for soybean (*Glycine max* (L.) Merrill) and pasture (*Dactylis glomerata*, *Festuca arundinacea* and *Lolium multiflorum*), and (4) to apply the semi-empirical model with Landsat Thematic Mapper (TM) data.

2. Materials and methods

2.1. Experimental site and used datasets

The experiment was carried out in Argentina at a flat subhumid site (average slope of less than 1%) in the Salado River basin (37°5′ S, 59°7′ W, elevation 130 m) on 121 clear days between 2006 and 2009 in two plots of an homogeneous pasture and soybean stands with a full canopy cover (Fig. 1a). The average annual rainfall is about 950 mm (Tandil Station of the Argentinean National Meteorological Network, 37°14′ S and 59°15′ W, elevation 175 m), where the maximum monthly value is in March and the minimum is in August. Average values for annual temperature, wind speed, relative air humidity, and solar radiation are 14.2 °C, 2.6 m s^{-1}, 83% and 186 W m^{-2}, respectively. The average annual evapotranspiration is 1015 mm.

An energy balance station was located within a plot area of 5 ha of pasture and a 16 ha one of soybean. Short-wave (up and down) and long-wave radiation (up and down) were measured with a net radiometer (CNR1 Kipp & Zonnen through short-wave CM3 and long-wave CG3 radiation sensors). Air temperature/relative humidity and wind speed/direction were also measured (CS215-L16 Temperature and RH Probe Campbell Scientific, Met One 034B Windset Campbell Scientific). All data were obtained at 2 m high and recorded at 15 min intervals in a data logger (CR10X Campbell Scientific) (Fig. 1b).

Two TM images from the same area were acquired during the period of highest development of soybean and medium development of pasture. These had a 30 m resolution (band 6 is resampled to 30 m), seven band, 20 km × 20 km subsets of TM scenes acquired by the Landsat 5 satellite on March 3 and 19, 2007 (Fig. 1c). The full scene location reference was path 225 and row 86 on the Landsat World-wide Reference System. The images have been rectified by a reference image after atmospheric correction.

2.2. Estimation of the actual daily evapotranspiration

The actual daily evapotranspiration (LE_d) was calculated from the model proposed by Seguin and Itier (1983):

$$LE_d = Rn_d + A - B(Ts_i - Ta_i) \tag{5}$$

where Rn_d (W m^{-2}) is daily net Radiation, *A* (W m^{-2}) and *B* (W m^{-2} °C^{-1}) are empirical coefficients obtained for the study area, and Ts_i and Ta_i are, respectively, the instantaneous surface and the air temperature (°C).

The Rn_d can be obtained from the instantaneous net Radiation (Rn_i) estimated using satellite data. To obtain this information, it is necessary to know the relationship between the instantaneous and daily value of *Rn*. To estimate Rn_d, we assume that:

$$Rn_d = Rn_{10-11} C + D \tag{6}$$

where Rn_{10-11} is the average *Rn* registered between 10:00 am and 11:00 am, and *C* (dimensionless) and *D* (W m^{-2}) are coefficients obtained from a linear regression between the local measures registered of Rn_d and Rn_{10-11} through a CNR1 sensor in the pasture and soybean plots.

Rn_d and Rn_{10-11} have been determined according to the following expression through CM3 and CG3 sensors:

$$Rn = Rs_{\downarrow} - Rs_{\uparrow} + Rl_{\downarrow} - Rl_{\uparrow} \tag{7}$$

where $Rs_{\downarrow}$ is the incoming short-wave radiation (W m^{-2}), $Rs_{\uparrow}$ is the outgoing short-wave radiation (W m^{-2}), $Rl_{\downarrow}$ is the incoming long-wave radiation (W m^{-2}), and $Rl_{\uparrow}$ is the outgoing long-wave radiation (W m^{-2}).

A and *B* were statistically determined from a linear regression of LE_d–Rn_d values versus the corresponding Ts_i–Ta_i measurements at a local scale assuming homogeneous surface (Wassenaar et al., 2002). LE_d has been calculated from the Penman Monteith (PM) equation (Allen et al., 1998) using meteorological data recorded by an energy balance station.