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Quality assurance procedures for validating meteorological input variables of reference evapotranspiration in mendoza province (Argentina)

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ABSTRACT

Validated meteorological data are required to make climate assessments, related decisions and to appropriately compute other important parameters such as reference evapotranspiration (ET_0), vital to accurately estimate crops water requirements. In addition, quality meteorological datasets will increase the reliability of the results obtained by scientific or technical models that use them. In semiarid regions, with a structural water deficit as province of Mendoza (Argentina), the integrity and quality of these data are crucial to improve ET_0 estimates, ensuring an adequate irrigation water management. In this work, several quality assurance procedures were applied to meteorological data—as a pre-requisite for ET_0 computations—in order to detect erroneous and invalid data of each parameter from automated weather stations located in the three irrigated areas of province of Mendoza (Northern oasis, Western oasis and Southern oasis). Due to the lack and poor quality of solar radiation data, calibration of new based temperature solar radiation prediction models for each of the station are proposed. Results show the data flagged for each variable by range/limits, step, internal consistency and persistence tests, providing guidance of great value to end users. Finally, a simple comparison of ET_0 estimations using original and validated meteorological datasets for each irrigated area in province of Mendoza is also reported.

1. Introduction

Ensuring accurate estimations of crop water requirements is crucial for a suitable planning and efficient use of water resources, especially in semiarid and arid regions as province of Mendoza (Western Argentina). The irrigated area in this province is currently almost 270,000 ha (FAO, 2015), with an amount of 52,792 irrigators. The agricultural consumptive uses in this province are relatively high and due to lack of precipitation (average annual precipitation around 200 mm) that limits crop growth and yield, optimizing and efficiently using of water resources represent a challenge for technicians and farmers to develop the regional economy. Although snow-melt supplies water to five rivers, the use of groundwater becomes important in periods with a shortage of surface water (Querner et al., 1997). In this sense, the annual water balance is in deficit and only 75% of the annual demand can be satisfied because of an annual deficit (DGI, 2010). Being an arid province located in Cuyo region—considered as a desert—, irrigated areas are located in three characteristics extensions similar to an oasis. The three oases are: (a) the Northern Oasis, formed by the basins of the Mendoza and Lower Tunuyán Rivers, where 50% of the provincial population lives; (b) to the south, the Western (or Central) Oasis, Valle de Uco, which coincides with the basin of the Upper Tunuyán River and (c) the Southern Oasis, formed by the basins of the Diamante and Atuel Rivers. The economic activity consuming most water is the production of high value temperate fruits and vegetables for both national and international markets (Díaz-Araujo and Bertranou, 2004). Nowadays, vineyards are still the principal crop, accounting for half cultivated area, followed by olive, fruit orchards (peaches, plums, apples and walnuts) and horticulture crops (tomatoes, potatoes, garlic and onions) (Morábito et al., 2007).

In terms of computing crop water requirements, the product of K_c (crop coefficient) and ET_0 (reference evapotranspiration) is the most widely used method, providing crop evapotranspiration

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estimations (ET_c). ET_0 is the evapotranspiration rate from a hypothetical grass reference surface, not short of water and with specific characteristics, initially introduced by Doorenbos and Pruitt (1977). Factors such as canopy cover, crop type or stage of growth affect the crop coefficient. However, reference evapotranspiration represents the evaporating rate of atmosphere and it is an important component of hydrological cycle that can be computed as a function of meteorological data (Allen et al., 1998). To avoid confusion about which ET_0 estimation method should be properly used, FAO proposed Penman-Monteith model in FAO Paper No. 56 (Allen et al., 1998) using reference crop parameters such as height of 0.12 m, albedo of 0.23 and surface resistance of 70 s m^{-1}. In addition, the Task Committee of ASCE (American Society of Civil Engineers) on 'Standardization of Reference Evapotranspiration' also recommended the use of this model (Allen et al., 2000; Itenfisu et al., 2003; Walter et al., 2001). This standardized method, incorporating thermodynamic and aerodynamic aspects, has received favourable acceptance and application over much of the world and different climatic conditions (Gavilán et al., 2008; Itenfisu et al., 2003; Pereira et al., 2015).

The accurate quantification and representativeness of ET_0 estimates depends on reliability of input meteorological variables involved and it is necessary to avoid biases in data (Allen, 2008), among other problems. In this sense, validation of these meteorological data applying several quality assurance procedures ensures that the information needed has been properly generated. It identifies incorrect values, detecting problems that require immediate maintenance attention (Estévez et al., 2011). In addition, proper interpretation of meteorological data requires knowledge of its context, including its metadata (Fiebrich et al., 2010). Various network managers reported in their works that an end-to-end quality assurance system (e.g., incorporating sensor calibrations, maintenance information, automated and manual quality control procedures) is essential for producing trusted, high-quality data (Hubbard et al., 2005; McPherson, 2007; Peppler et al., 2008). The World Meteorological Organization (WMO) reported that climate change models, agricultural and meteo-hydrological scientific applications and other technical activities require the improvement and strengthening of observation networks, in order to increase the availability of climate information resources and the quality of their applications (WMO, 2006). Since early 90's, for different purposes and due to the great development of automatic data acquisition systems, meteorological information from weather stations is recorded in large databases (Miller and Barth, 2003). However, in spite of the economic effort of installing these networks, questionable results may be due to poor data quality as a consequence of non-existing quality control methods as a pre-requisite for using meteorological data (Estévez et al., 2011). Thus, the WMO has recently introduced some basic characteristics of general principles of the data quality control (WMO, 2010a) and a deep discussion about them is also reported (WMO, 2010b). The main goals of the application of quality control procedures to meteorological data are to avoid inappropriate decision-making, identifying erroneous records, and to ensure that this information is suitably measured and stored. In addition, it is crucial to detect and solve problems related to sensors calibration and an adequate maintenance of the stations and their environment (Doraiswamy et al., 2000). In the literature there are several methods that can be applied to ensure the quality of meteorological information (Feng et al., 2004; Hubbard et al., 2005; Shafer et al., 2000; Sönmez, 2013). Some of the most recent works (Estévez et al., 2015; López-Lineros et al., 2014) use 30-min or 5-min observations to validate data for ensuring their quality, but the majority of the databases from meteorological networks contain records on a daily basis. Hubbard et al. (2005) outlined that validation procedures can be divided into two categories: those that use data from a single site and those that use data from multiple sites, comparing a station's data against neighbouring stations. The set of three computer-based rules introduced by O'Brien and Keefer (1985), were applied initially by Meek and Hatfield (1994) and they are based on: fixed or dynamic high/low limits, fixed or dynamic rate of change limits and a continual temporal no-observed-change. The main purpose of any validation method is to detect data of a doubtful quality and to properly flag them, incorporating valuable information to each record but not modifying it. Flags as "good", "suspect", "corrected" or "failure" show the level of confidence of data and information about the result of tests application (Fiebrich and Crawford, 2001). It is important to note that although occasionally algorithms can be applied to correct erroneous data or to fill the gaps, both original and corrected/estimated data should always be archived (Reek et al., 1992). Finally, there is a final step in the validation process where qualified personnel should verify and manually inspect meteorological data considered as potentially erroneous. This kind of verification allows ensuring that automatic procedures are flagging data correctly.

With the aim of providing ET_0 estimations and several related meteorological parameters to improve irrigation water management and other agronomic purposes such as frost protection, Direction of Agriculture and Climatic Contingencies (DACC) of Mendoza province has installed during the last decade an automated weather stations network covering the three main cultivated areas described above (Northern Oasis, Western Oasis, Southern Oasis). Currently, some of them are not operative due to lack of funds and there is no quality control system running for validating meteorological data before ET_0 estimations are calculated and provided on the website for different end users. This paper presents the results of the development and the application of several quality assurance procedures to all available meteorological measurements from DACC (2015) according to several tests and methods described in next sections. Moreover, due to the amount of solar radiation gaps and outliers, a new calibration for solar radiation model based on temperature data (Hargreaves, 1994; Hargreaves and Samani, 1982) has been carried out for each site. Several improper estimations of ET_0 were detected, mainly due to outliers and incorrect input meteorological data. The new developed system—as a pre-requisite for the ET_0 calculation—is capable of using solar radiation estimates instead of measured radiation if these observations are flagged as invalid. In this sense, Pereira et al. (2015) recently recommended still using standardized ET_0 equation (PM-FAO56) instead of other simple ET_0 computation methods, even existing missing data as solar radiation that can be estimated properly by different methods as the proposed in the present work.

The main goal of this work is to apply different procedures to compute quality ET_0 estimations before providing them to irrigators and farmers. In addition, the improvement of the integrity of long-term meteorological database, will ensure the reliability of technical and scientific models that use these records as input variables, generating screened quality hydro-meteorological datasets of great value. Finally, simple comparisons of ET_0 estimations using validated datasets instead original datasets are also reported, in order to quantify the effect of quality assurance procedures.

2. Materials and methods

2.1. Study area and weather data source

The present study was carried out in irrigated areas of Mendoza (western Argentina), located in Cuyo region—near the Andes mountains—, between the meridians 67° 50′ and 69° 50′W and the parallels 32° 30′ and 33° 50′S and occupying an extension of around 15 Mha. The region is characterized by an arid to semi-arid climate, with very dry summers and more humid winters. Its high variability, closely linked to El Niño/Southern Oscillation (ENSO) events in today's climate, and likely increases in extreme events such as heavy rainfall, hail and frost in tomorrow's climate, can reduce the availability of water, increasing the vulnerability of this agriculture area (Castex et al., 2015).

Datasets used in this work were obtained from all the available observations provided by Direction of Agriculture and Climatic Contingencies (DACC, 2015). Daily data of ET_0 estimations can be obtained at www.contingencias.mendoza.gov.ar. Automated weather stations of this network—some of them manufactured by Tecmes (Tecmes, 2015) and others by Micros (SiapMicros, 2015)—are controlled by a datalogger and are equipped with sensors for measuring temperature and relative humidity of the air, solar radiation, wind speed and direction, and precipitation. Technical specifications of the sensors are reported in Table 1. The measurements heights are those recommended by ASCE-EWRI (2005) and FAO-56 (Allen et al., 1998) with the exception of wind sensor, installed at 10 m. Daily values are stored for each meteorological variable. Variables validated were: daily solar radiation (Rs), daily mean, maximum and minimum air temperatures (T_m, T_x and T_n, respectively), daily mean, maximum and minimum relative humidity of the air (RH_m, RH_x, RH_n) and daily mean and maximum wind speed data (U and U_x, respectively). The geographical distribution of the stations is shown in Fig. 1. Site elevations range from 530 to 1074 m above mean sea level, longitude, from 67.9475W to 69.9877W and latitude, from 32.5952S to 34.7952S. Names, elevation, longitude, latitude and available data period of all the weather stations analysed in this study are reported in Table 2, as well as the manufacturer of each weather station that is also included.

Computations of ET_0 were carried out following standardized ASCE-Penman-Monteith equation:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_0 = standardized grass reference evapotranspiration (mm day^{-1} Δ =), slope of the saturation vapour pressure versus air temperature curve (kPa °C^{-1}), R_n = calculated net radiation at the crop surface (MJ m^{-2} d^{-1}), G = soil heat flux density at the soil surface (MJ m^{-2} day^{-1}) was assumed to be zero for daily values, T = mean daily air temperature (°C); U_2 = mean daily wind speed at 2 m height (m s^{-1}); e_s = saturation vapour pressure (kPa), e_a = mean actual vapour pressure (kPa) and γ = psychrometric constant (kPa °C^{-1}); units for the 0.408 coefficient were MJ^{-1} m^2 mm. Estimations of daily values of R_n, e_s, e_a and other constants and parameters were made following FAO-56 (Allen et al., 1998) and ASCE-EWRI (2005) and they are not repeated here, assuming albedo, grass height and bulk canopy resistance to be 0.23, 0.12 m and 70 m s^{-1}, respectively.

2.2. Quality control procedures

These methods are applied to identify erroneous and suspect data from sensor observations and to properly flag each meteorological record. Firstly, it is necessary the verification that all possible data have been collected and that the record structure is correct and complete, detecting gaps in data files and flagging them as erroneous, not using them as input variable for ET_0 estimations. In the present work, the quality control procedures applied are: range/limit (fixed or dynamic) test, step test, internal consistency test and persistence test. Each meteorological datum that does not satisfactorily pass the fixed range test is flagged as erroneous and data rejected by the other tests is flagged as suspect, being after validated by manual inspection. Thus, these records considered as potentially erroneous should be verified. This is the last step in the validation process and used to identify incorrect flagged records by automatic quality control algorithms, which it must be carried out by well-trained technicians (Shafer et al., 2000).

Range tests are based on the simple verification that any observation is within a predetermined range. There are two kinds of ranges: fixed (physics and instrumental) and dynamic ranges. Only measurements occurring inside this threshold are considered as valid, being properly flagged those outside this range (Feng et al., 2004; Meek and Hatfield, 1994; Reek et al., 1992; Shafer et al., 2000). Data occurring outside the acceptable fixed range are flagged as erroneous and they cannot be used for other computations. The fixed limits proposed for different variables are based on the sensors technical specifications (Table 1) and on ranges proposed by different authors (Table 3). Extreme values measured at each site and the theoretical possible extreme for each location and time period are used as dynamic range. High/low extreme values recorded for maximum, mean and minimum temperature variables and reported by Argentinian Meteorological Service (SMN, 2015)—long-term meteorological observations at closer observatories—have been used in this test. The records rejected by this dynamic range test are flagged as suspect and finally the verification by manual inspection is carried out. If these potential outliers are correctly verified, each one is stored for the corresponding location as a new extreme value. Regarding to solar radiation data (Rs), they can be validated following the dynamic tests described by Moradi (2007) and Geiger et al. (2002). In addition, the use of the comparison of measured solar radiation with solar radiation expected under clear sky conditions (R_{so}) is also recommended. This method was initially suggested by Allen (1996) and Geiger et al. (2002) proposed the same high bound incremented in 10%, allowing to avoid anomalies in the R_{so} estimations, mainly at sunset and sunrise or simply caused by the clean air assumption. Generally, the best estimates of R_{so} are obtained using equations that include the influence of sun angle, turbidity, atmospheric thickness and precipitable water (Allen, 2008). Following the procedure proposed by ASCE-EWRI (2005) that considers these effects and separating the components of beam and diffuse radiation, R_{so} can be computed as:

$$R_{so} = (K_B + K_D)R_a \quad (2)$$

where K_B is the clearness index for direct beam radiation (unitless), K_D is the transmissivity index for diffuse radiation (unitless) and R_a is the extraterrestrial solar radiation. The expressions to compute these parameters are outlined in ASCE-EWRI (2005) and they are not repeated here.

Secondly, step procedures are based on time consistency and they typically compare the change in magnitude between sequential observations. According to Shafer et al. (2000) two consecutive data are flagged as suspect when the difference exceeds an allowed value. Some recommendations of tolerance for temperature proposed by WMO (1993) can be applied to hourly or minute-interval values. Related to the daily step temperature (T_x-T_n), it was applied the verification of days with large daily temperature ranges (>30°) proposed by Robinson (1998). The test proposed by Meek and Hatfield (1994) for daily wind speed data is also recommended.

Methods based on the verification of physics or climatologic consistencies of each measured variable are called internal consistency tests (Grüter et al., 2001). In this section, simple verifications such as an average value must be lower than the maximum instantaneous value are included. Also, it should be verified several checks such as $T_x(d) > T_m(d) > T_n(d)$ or $T_x(d) > T_n(d\text{-}1)$ for a given day d (Feng et al., 2004; Reek et al., 1992). Comparisons between daily minimum temperature (T_n) and daily average dew point temperature (T_{dew})—computed following Jensen et al. (1990)—can also be included in this kind of methods, assessing the aridity conditions of the station and detecting humidity sensor problems. For example, if

Table 1
Specifications of the sensors installed on the automated weather stations and used to estimate ET_0 values.

Sensor	Variables	Accuracy	Range
TS251T (Tecmes)	Air Temperature & Relative Humidity	+/−0.25 °C +/−2%	−20/60 °C 0−100%
TS304 (Tecmes)	Solar Radiation	+/−5%	0–1400 W/m^{-2}
TS231 (Tecmes)TS232 (Tecmes)	Wind Speed Wind direction	+/−1% +/−3%	0–60 m/s^{-1} 0–360°
TTEPRH (Micros)	Air Temperature & Relative Humidity	+/−0.1 °C +/−2%	−30/60 °C 0−100%
TPIR (Micros)	Solar Radiation	+/−10 W/m^{-2}	0–1300 W/m^{-2}
TVDV (Micros)	Wind Speed Wind direction	+/−0.25 m/s^{-1} (0–20 $m\,s^{-1}$) +/−0.7 m/s^{-1} (>20 m/s^{-1}) +/−2°	0.25–50 m/s^{-1}0–360°

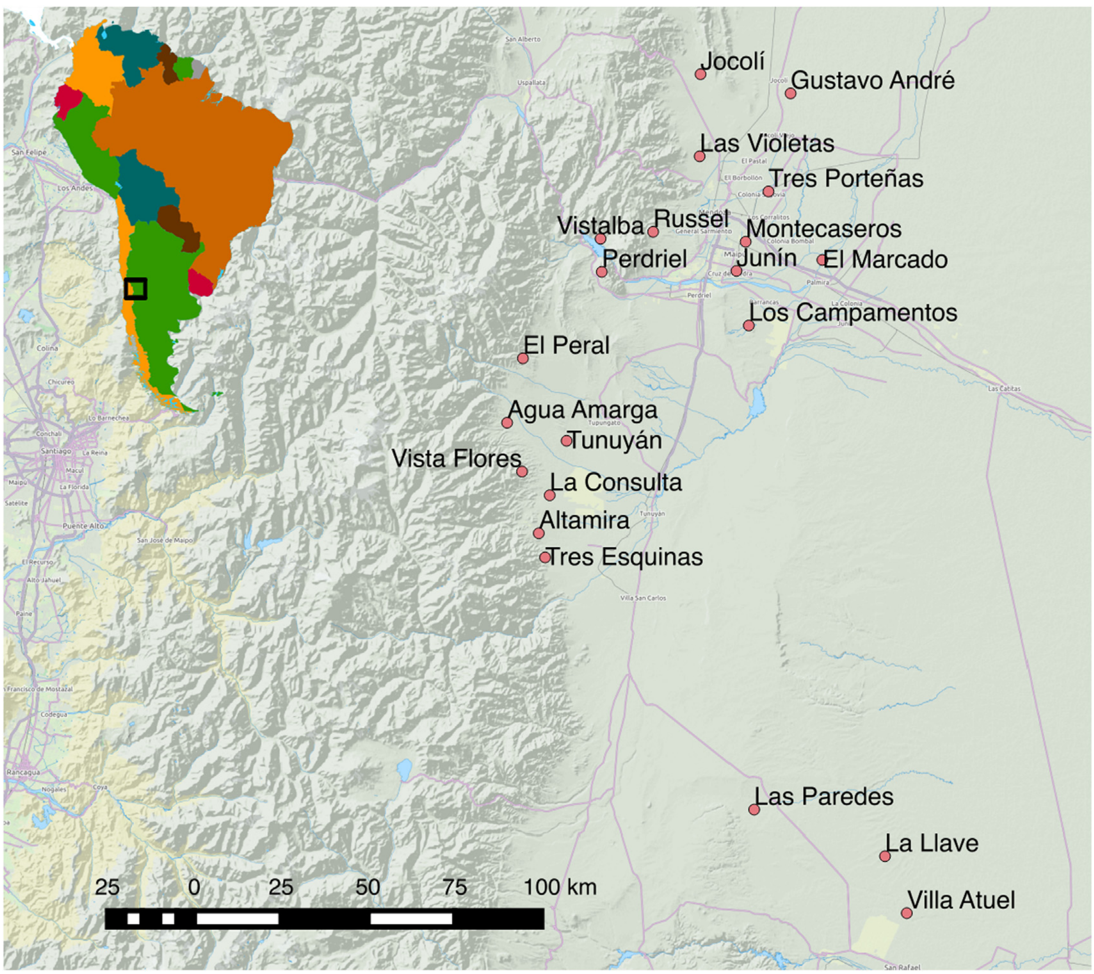

Fig. 1. Geographical distribution of the automated weather stations used in this study (province of Mendoza).

T_{dew} regularly and consistently exceeds T_n, then the humidity probe may be out of calibration (Allen, 2008). Fig. 2a and b show daily K_0 values ($K_0 = T_n - T_{dew}$) over the time for Perdriel and Villa Atuel stations, respectively. It can be observed periods where T_n is more than 5 °C above T_{dew}, revealing very dry and advective conditions (lack of well-watered vegetation) (Allen, 2008). In this sense, Villa Atuel (registering more days with high K_0 values) is subjected to higher local aridity than stations situated in Northern oasis as Perdriel. Limitations on the equation accuracy to estimate T_{dew} and frost conditions can cause some K_0 values below 0 °C, as it can be seen in both figures. However, the slight trend over the years observed in Villa Atuel station is not reflected in Perdriel, possibly caused by a little drift on sensor measurements.

To assess the plausibility of wind speed and direction data, some necessary conditions to check that anemometer is properly functioning can be verified (DeGaetano, 1997; Zahumensky, 2004). In addition, gust factor computation (ratio of maximum wind speed to mean daily wind speed) can be used as a suitable index for checking anemometers observations at different time periods (ASCE-EWRI, 2005). As an example, this factor is represented in Fig. 3a and b for two different locations: Altamira and Las Paredes, respectively. In Fig. 3a the gust factor values showed good behaviour in Altamira station over time, with the singularity of some gaps at the end of 2013. However, data from Las Paredes station showed some anomalies, especially at the end of time-period represented (2003). These periods of excessively great values suggest that the anemometer may be malfunctioning due to this factor frequently increases as

Table 2
Location, elevation and available data for the automated weather stations validated and used in this work. (T = manufactured by Tecmes and M = manufactured by Micros).

Name	Latitude(°S)	Longitude(°W)	Elevation (m)	Data period (available days)
Northern Oasis				
El Marcado (T)	33.0872	68.2136	600	2007–2015 (2859)
Gustavo André (M)	32.6461	68.3138	600	2007–2015 (2744)
Jocolí (M)	32.5952	68.5977	900	2007–2015 (3036)
Junín (M)	33.1161	68.4844	653	1998–2015 (6101)
Las Violetas (M)	32.8130	68.6005	960	2006–2015 (2924)
Los Campamentos (M)	33.2602	68.4455	600	2007–2015 (2850)
Montecaseros (M)	33.0391	68.4555	650	2007–2015 (2976)
Perdriel (M)	33.1187	68.9091	960	2006–2015 (3043)
Russel (M)	33.0128	68.7472	850	2006–2015 (3059)
Tres Porteñas (M)	32.9061	68.3836	650	1997–2015 (5840)
Vistalba (T)	33.0311	68.9130	1020	2012–2015 (798)
Western Oasis				
Agua Amarga (T)	33.5161	69.2075	970	1998–2012 (5936)
Altamira (T)	33.8058	69.1077	950	2004–2015 (3682)
El Peral (T)	33.3467	69.1577	1074	1997–2015 (6174)
La Consulta (M)	33.7066	69.0733	940	2003–2015 (4264)
Tres Esquinas (T)	33.8691	69.0877	850	1998–2015 (5942)
Tunuyán (T)	33.5636	69.0200	869	1996–2015 (6663)
Vista Flores (M)	33.6444	69.1605	975	1997–2015 (5783)
Southern Oasis				
La Llave (M)	34.6477	68.0161	555	1998–2015 (5453)
Las Paredes (M)	34.5266	68.4286	813	1997–2015 (5970)
Villa Atuel (T)	34.7952	67.9475	530	2008–2015 (2210)

Table 3
Quality control procedures applied to Direction of Climatic Contingencies database (province of Mendoza).

Validation Procedure	Air Temperature (°C)	Solar Radiation (W m^{-2})	Relative Humidity (%)	Wind Speed (m s^{-1})
Range test	$-20, -30 < T < 50$ (Shafer et al., 2000; Table 1) $T_{LOW} < T < T_{HIGH}$ (SMN, 2015)	$0 < Rs < 1400{,}1300$ (Table 1); $0.03R_a \leq Rs \leq R_a$; $Rs < 1.1R_{so}$ (Allen, 1996; Geiger et al., 2002; Moradi, 2007)	$0 < RH < 102$ (Table 1) (Shafer et al., 2000)	$0, 0.25 < U < 60, 50$ (Table 1) $0 < U_x < 100$ (Shafer et al., 2000)
Step test	$T_x - T_n < 30$ (Robinson, 1998)			$\lvert U(d)-U(d-1)\rvert < 10$ (Meek and Hatfield, 1994)
Internal consistency test	$T_x > T_m > T_n$; $T_x(d) > T_n(d-1)$; $T_n(d) \leq T_x(d-1)$ (Reek et al., 1992; Feng et al., 2004)		$RH_x > RH_m > RH_n$ (Reek et al., 1992; Feng et al., 2004)	Speed = 0 and direction = 0; speed $\neq 0$ and direction $\neq 0$ (DeGaetano, 1997; Zahumensky, 2004) $U_x(d) > U(d)$ (Vejen et al., 2002)
Persistence test	$T(d) \neq T(d-1) \neq T(d-2)$ (Meek and Hatfield, 1994)	$Rs(d) \neq Rs(d-1) \neq Rs(d-2)$ (Meek and Hatfield, 1994)	$RH(d) \neq RH(d-1) \neq RH(d-2)$ (Meek and Hatfield, 1994)	$U(d) \neq U(d-1) \neq U(d-2)$; $U_x(d) \neq U_x(d-1) \neq U_x(d-2)$ (Meek and Hatfield, 1994)

Table 4
Values of the empirical coefficients α and β (Eq. (4)) found in the calibration process and the total number of days of data used for each location.

Name	α	β	Time-period for calibration (days)	Time-period for evaluation (days)
Gustavo André	0.1282	0.0667	2005	770
Junín	0.1719	−0.0526	4398	1467
Montecaseros	0.1496	0.0249	2187	730
Russel	0.1503	−0.0096	2237	747
Tres Porteñas	0.1593	−0.0536	2971	991
Agua Amarga	0.1987	−0.2040	3861	1287
Altamira	0.1798	−0.1251	2378	794
El Peral	0.2062	−0.2130	4186	1395
La Consulta	0.1806	−0.0984	2456	820
Tres Esquinas	0.1888	−0.1703	2890	964
Tunuyán	0.1648	−0.1132	3213	1072
Vista Flores	0.1784	−0.1503	2656	886
La Llave	0.1706	−0.1135	2110	724
Las Paredes	0.1772	−0.1065	2291	765

contamination enhances the friction in the anemometer bearings, as it is reported by other authors (Allen, 2008; Estévez et al., 2011). In addition, with a failed anemometer, daily maximum and mean wind speeds can often have the same values, generally equal to any numerical offset in the calibration equation (Allen, 2008).

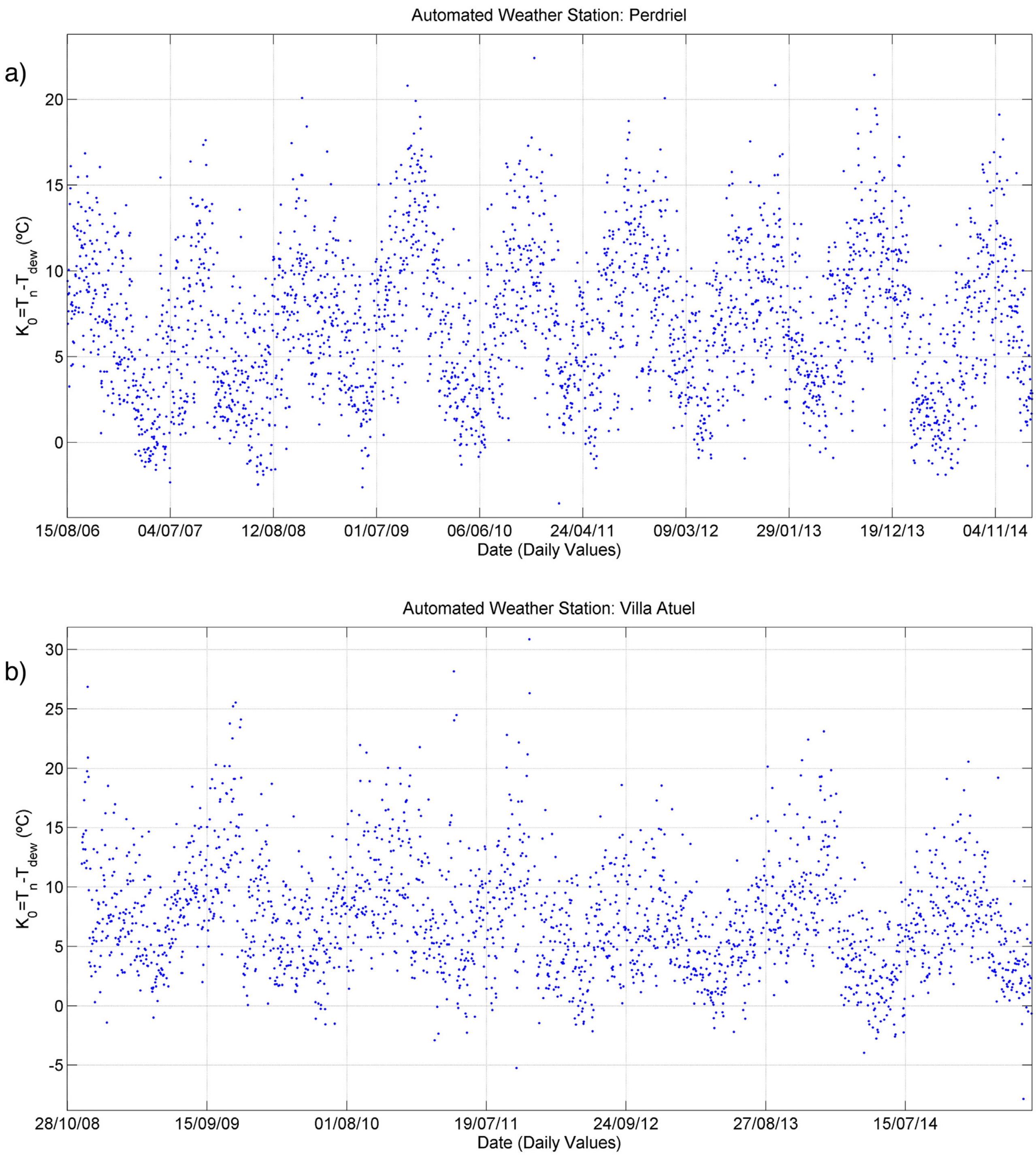

Fig. 2. Daily K_0 values (°C) estimated for Perdriel station (Northern oasis) (a) and for Villa Atuel station (Southern oasis) (b).

Finally, persistence method verifies whether observations vary minimally with time, possibly indicating a physical problem with either the sensor (e.g., bearing failure in or ice accumulation on a wind sensor) or its wiring (Fiebrich et al., 2010). Meek and Hatfield (1994) also assumed that a sensor that reports a constant value should be failing. Accuracy of sensors and the decimal precision of the corresponding variable in the database should be taken into account. For intra-daily values, the use of aggregate statistics for different time periods can be used (Shafer et al., 2000). In Table 3 it is summarized the persistence methods used in this work.

2.3. *Self-calibration of solar radiation model based on temperature*

Solar radiation is the major contributor to many simulation climate change, hydrology and ecology models (Rivington et al., 2005). In addition, it is a crucial input variable used in agricultural meteorology, especially for crop modelling and estimating evapotranspiration (Stöckle et al., 2003). The main problem related to this meteorological variable is that it is measured at a very limited number of weather stations. Even at stations where this variable is measured there are usually questionable quality data because of sensor failure or lack of calibration (Abraha and Savage, 2008). This

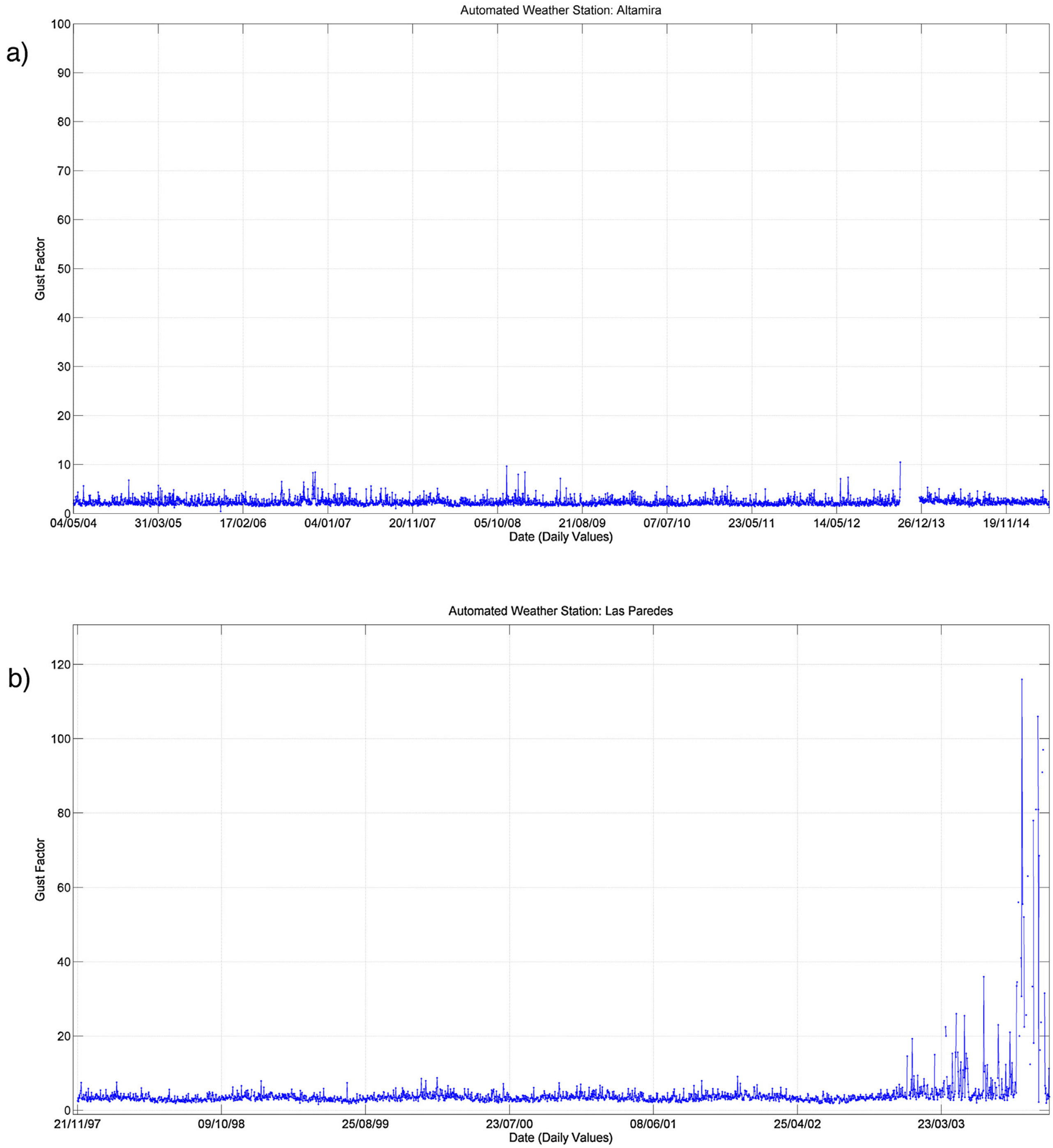

Fig. 3. Daily evolution of gust factor (ratio of daily maximum wind speed to daily mean wind speed) for Altamira station (a) and for Las Paredes station (b).

problem affects the majority of the stations validated in this work, revealing the need for applying quality assurance methods prior to ET_0 computations and substituting them by new reliable estimates of solar radiation values. Most empirical models for computing these estimations use the daily range between minimum and maximum air temperature ($\Delta T = T_x - T_n$). These approaches are based on the assumption that clear days show a greater air temperature range: daytime air temperatures are high because clouds do not absorb incoming solar radiation; on the other hand, night-time air temperatures are low because longwave radiation is emitted from the earth's surface to the atmosphere and not radiated back by cloudy sky. The coefficients of these models are site-dependent as many works have confirmed over the world (e.g., Bojanowski et al., 2013; Estévez et al., 2012; Grant et al., 2004; Martínez-Cob and Tejero-Juste, 2004; Trnka et al., 2005). Hargreaves et al. (1985) proposed the following simple linear equation between daily atmospheric transmissivity coefficient (τ_T) and daily air temperature range (ΔT (°C)):

$$\tau_T = \alpha\sqrt{\Delta T} + \beta \tag{3}$$

where α and β are site-specific empirical coefficients. As it is known, solar radiation at the earth's surface (Rs) is the product of τ_T and extra-terrestrial solar radiation (R_a). In the present study, a calibration method has been carried out using validated data for each site. Outliers and erroneous data have been discarded in this process. Only measured data of good quality have been used to derive the α and β coefficients for each individual weather station. Table 4 shows α and β values) and the number of days used in this process for each location. In order to carry out the subsequent statistical analysis for validating these models, the following parameters were calculated (Willmott, 1982): mean bias error (MBE), root mean square error (RMSE), relative error (RE) and the ratio between both average estimated and measured solar radiation values (R).

$$MBE = \frac{\sum_{i=1}^{n} (y_i - x_i)}{n} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - x_i)^2}{n}} \quad (5)$$

$$RE = \frac{RMSE}{x_{ave}} 100 \quad (6)$$

$$R = \frac{y_{ave}}{x_{ave}} \quad (7)$$

where n = number of days; y_i = estimated Rs; x_i = measured Rs; and x_{ave} and y_{ave} = averages of measured and estimated Rs, respectively.

3. Results and discussion

3.1. Application of quality control procedures

The results of running the validation procedures on the available datasets for each meteorological variable are summarized in Table 5. The application of the methods reported in Table 3 was carried out to all the weather stations studied (Table 2). For each variable, the maximum percentage of data flagged by each procedure is reported in Table 4 (corresponding to one station), as well as the average percentage and the standard deviation (corresponding to all the stations).

3.1.1. Air temperature

The dynamic range test applied to air temperature data did not flag any values (Table 4). However, results from the first test applied (fixed range) showed, on average, 0.02% of erroneous daily maximum data and 0.11% as the highest percentage of errors detected in Las Violetas station, with no errors identified in 13 stations. The average percentage of errors detected in daily mean and minimum air temperature data was 0.05% and 0.002%, with the maximum percentage obtained in El Marcado (0.91%) and Los Campamentos (0.04%) stations, respectively. No errors were detected in 18 stations for daily mean values and in 19 stations for minimum data. Related to daily temperature step test, only two stations had no data flagged and the maximum was obtained in El Marcado station (1.15%) for maximum and minimum temperature, obtaining 0.31% as the average percentage of flagged values for both variables. Results from internal consistency test showed, on average, 0.17%, 0.09% and 0.18% for maximum, mean and minimum data, respectively, obtaining the maximum percentages for daily maximum and mean values in El Marcado station. These results are slightly higher than those reported by Estévez et al. (2011), Feng et al. (2004) and Reek et al. (1992) in different climates. Finally, Altamira (0.24%), El Marcado (1.01%) and Russel (0.42%) stations showed the maximum percentages of flagged data by persistence test for daily maximum, mean and minimum values, respectively, and only one weather station (Villa Atuel) had no flagged data of these three variables. On average, all air temperature flagged data by this test were below 0.15%, being higher than results reported by Meek and Hatfield (1994) and Estévez et al. (2011).

3.1.2. Solar radiation

The results obtained after applying the fixed range test to solar radiation data showed that the fraction of errors caught by this procedure for all the stations were 0.26% on average, with the maximum percentage obtained in Los Campamentos station (2.60%) and 10 weather stations with no erroneous values. Nevertheless, dynamic range test was able to detect outliers in all the stations. The average percentage of flagged data by this procedure were 24.39%, ranging from 0.56% (Altamira) to 86.33% (Perdriel) where the quality of dataset was extremely poor, mainly due to a problem with wiring, data-acquisition system or sensor malfunctioning. In general, stations reporting some specific outliers as El Peral or Agua Amarga (Fig. 4a and b) indicate the accumulation or removal of contaminants on the sensor (dust, salt or bird droppings) as it is reported by Allen (2008). However, values continuously above or below the dynamic envelopes during a time-period as those detected in Junín station (Fig. 4c), reveal a change in sensor levels or improper calibration sensor.

Despite some limitations (Irmak et al., 2003; Yoder et al., 2005), this kind of method has been efficiently used to verify integrity of solar radiation before use them for other estimations (Allen, 2008; Estévez et al., 2011; Jensen et al., 1997). Finally, persistence test showed 24.39% of average percentage of data flagged, detecting the maximum fraction in Perdriel station (85.90%), mainly due to constant values reported when there is a continuous sensor failure. In general, the fraction of data flagged for solar radiation values was much higher than percentages reported by Estévez et al. (2011), Geiger et al. (2002) or Meek and Hatfield (1994).

3.1.3. Relative humidity

Fixed range test detected erroneous RH_x data only in four stations, with the maximum percentage obtained in Las Violetas (0.10%). No errors were detected for mean and RH_n values in all weather stations, except in El Marcado station (0.91%) for daily minimum data. These percentages were lower than those reported by Estévez et al. (2011) for daily maximum values and similar for the other variables (no errors detected), except the mentioned station. Related to internal consistency test, only RH_x values were flagged

Table 5
Percentage of flagged meteorological data by quality control tests (Max = maximum; Avg = average; St. Dev.=standard deviation of total network data). The percentages on each cell correspond to Max/Avg (St. Dev).

Variables		Range test (fixed limits)	Range test (dynamic limits)	Step test	Internal consistency test	Persistence test
Air Temperature	T_x	0.11/0.02 (0.03)	0/0 (0)	1.16/0.31 (0.35)	0.95/0.17 (0.20)	0.24/0.05 (0.20)
	T_m	0.91/0.05 (0.20)	0/0 (0)	1.15/0.31 (0.35)	0.94/0.09 (0.21)	1.01/0.14 (0.21)
	T_n	0.04/0.002 (0.01)	0/0 (0)		0.41/0.18 (0.12)	0.42/0.09 (0.12)
Solar Radiation	Rs	2.60/0.26 (0.58)	86.33/24.39 (26.04)			85.90/11.97 (21.83)
Relative Humidity	RH_x	0.10/0.01 (0.03)			0.91/0.05 (0.20)	29.07/8.12 (8.38)
	RH_m	0/0 (0)			1.43/0.13 (0.36)	19.72/1.88 (4.15)
	RH_n	0.91/0.04 (0.20)			1.43/0.08 (0.31)	15.89/6.54 (4.51)
Wind Speed	U	0.91/0.05 (0.20)		1.28/0.12 (0.27)	48.16/13.12 (11.90)	45.17/11.36 (10.76)
	U_x	0.11/0.02 (0.04)			0.19/0.01 (0.04)	38.85/7.47 (9.81)

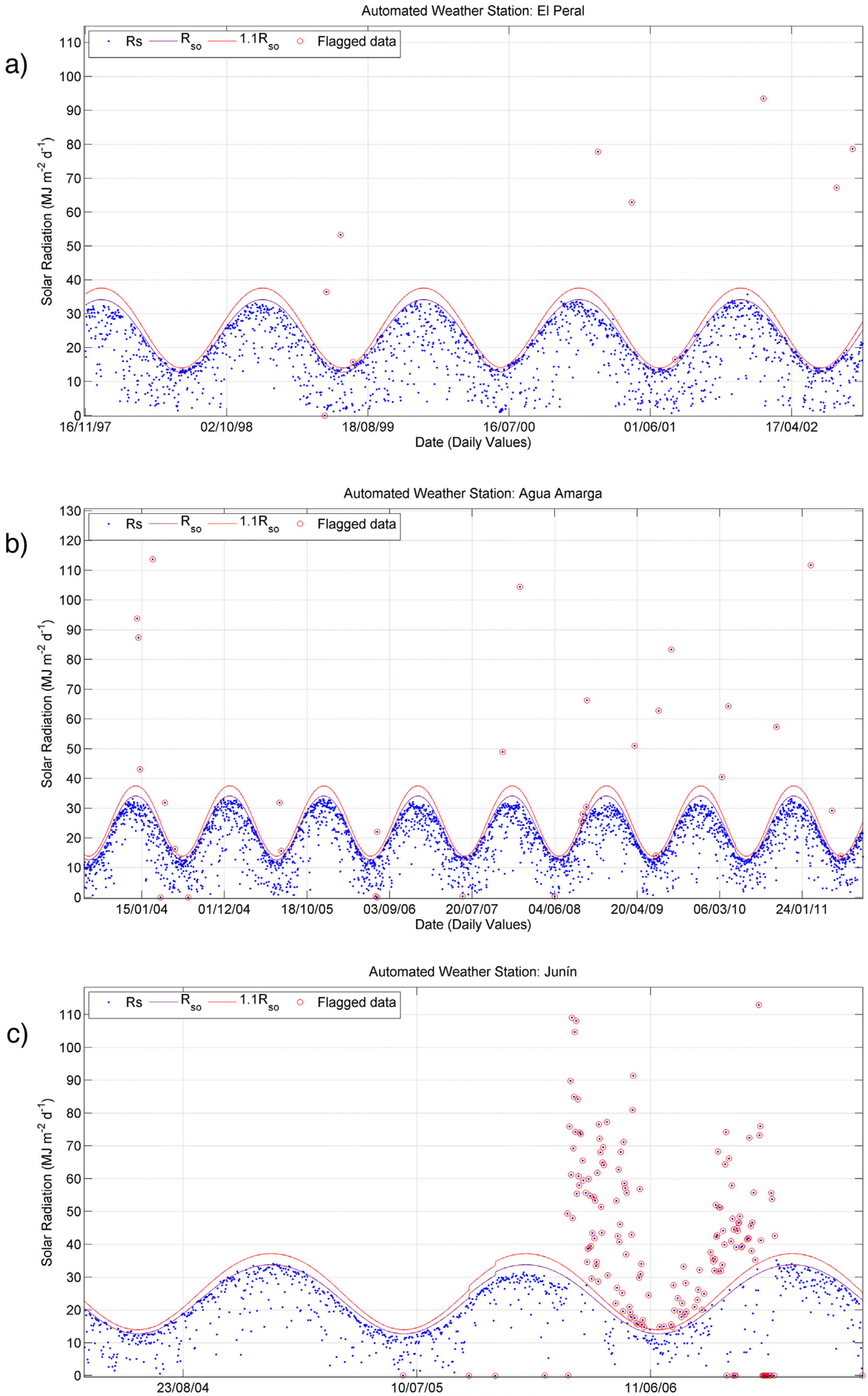

Fig. 4. Application of dynamic range test to daily solar radiation data for El Peral (a), Agua Amarga (b) and Junín (c) stations. Rs: Measured daily solar radiation; R_{so}: solar radiation expected under clear sky conditions. Note: The two abrupt changes observed in 2005 is due to the lack of data in all meteorological parameters for those dates (c).

in 5 stations, obtaining the maximum percentage in El Marcado station (0.91%), a lower fraction that the one reported by Estévez et al. (2011). The average percentages of RH_m and RH_n flagged data were 0.13% and 0.08%, respectively, with a maximum (1.43%) found in Gustavo André station for both variables. There were 11 locations without daily mean flagged data and 15 stations for minimum values. These fractions were higher than those reported by Feng et al. (2004) and lower than those reported by Estévez et al. (2011). The highest percentage of data flagged by persistence test was obtained for RH_x, with an average of 8.12% and the highest fraction detected in Vistalba station (29.07%). There were data flagged in all the stations for these three variables: RH_x, RH_m and RH_n. In general, these percentages were much higher than those reported by Estévez et al. (2011), Feng et al. (2004) and Graybeal et al. (2004), mainly due to the precision (no decimals) of the type of data from database in which relative humidity values are stored.

3.1.4. Wind speed

Only in three stations daily U data were flagged by the fixed range test, obtaining in El Marcado location the maximum percentage (0.91%). The same test applied to U_x values was able to flag data in only five stations, detecting the maximum fraction in Las Violetas station (0.11%). The results obtained for the step test, with an average of 0.12%, are similar to fractions reported by Estévez et al. (2011) and Meek and Hatfield (1994), being higher the maximum fraction detected in Las Paredes station (1.28%). For both variables U and U_x, the average percentages of flagged data by internal consistency test were 13.12% and 0.01%, respectively. The maximum fraction (48.16%) for U was detected in Las Violetas and for U_x in Villa Atuel (0.19%), noting that all the stations showed U flagged data and only five stations U_x flagged data. The percentages of U flagged data are, on average, higher than those reported by Estévez et al. (2011) and García-Marín et al. (2013), but lower those corresponding to U_x flagged data. Finally, the persistence test detected, in all the stations, higher percentages of anomalous data than those reported in literature, with an average of 11.36% and 7.47%, for U and U_x values, respectively. The highest fractions for both variables were obtained at the same station, Las Violetas, where after visual inspection, it was observed constant values for several and large time periods, indicating failed anemometer (Allen, 2008). In general, validation of wind speed measurements is difficult to carry out unless duplicate sensors are installed at the station (Allen, 2008). However, to improve ET_0 estimations, mean monthly wind speed data or limiting it $\geq$0.5 m/s can be used instead flagged data (Allen et al., 1998). Attending to the validation results obtained, it is important to note that the presence of ice with temperatures around 0 °C and dirty or worn anemometer bearings usually cause inconsistent wind speed values (ASCE-EWRI, 2005; Estévez et al., 2011).

In Fig. 5 it can be observed a simple comparison between ET_0 values in El Marcado station. In red colour are plotted ET_0 estimations using data flagged by fixed range test (original dataset) for T and U data, and ET_0 values using validated dataset are represented in blue colour. Erroneous U data were substituted by mean monthly values (from validated dataset) and T data were calculated as an average of T_x and T_n. For both variables, data were flagged by fixed range test as erroneous due to their values were above the upper limit, involving ET_0 overestimations in all cases, and up to 1 mm d^{-1} on many of them. These differences are due to the very high values of T and U initially used from original dataset, increasing ET_0 computations. The importance of these quality assurance methods is crucial because ET_0 estimations from original dataset are the values available on-line and used by irrigators, farmers and technicians, among others.

3.2. Evaluation of the self-calibrated solar radiation models

Due to the poor quality of some available datasets, six stations were discarded in this process. After the application of quality control methods and using only validated data of temperature and solar radiation, the coefficients for the self-calibration procedure for each location (Table 4) were computed. They ranged from 0.1282 (Gustavo André) to 0.2062 (El Peral) for α values and from −0.0096 to 0.0667 for β values. These coefficients are in accordance with those reported by Baigorria et al. (2004) in several stations around the Central Andes. The number of days used in the calibration process was approximately 2/3 of the validated dataset for each station, and 1/3 for evaluating the models, ensuring that at least, two years were used in this last step. Recently, Bojanowski et al. (2013) also used similar time-period to assess several solar radiation models performance.

In general, the models proposed had an adequate behaviour (Table 6). MBE values ranged from −1.80 MJ m^2 d^{-1} (Montecaseros station, Northern oasis) to 1.15 MJ m^2 d^{-1} (Agua Amarga, Western Oasis). These results are in accordance with those reported for several stations located in semiarid locations (Estévez et al., 2012) and they are better than those recently reported by Bojanowski et al. (2013) in Europe. The higher values for RMSE (5.41 MJ m^2 d^{-1}) and RE (27.56%) were obtained in Altamira station (Western oasis), whose comparison between measured and estimated solar radiation is represented in Fig. 6a. On the contrary, the minimum RMSE value (2.68%) was computed in Tres Porteñas station (Northern oasis), being similar to the range reported by Abraha and Savage (2008) and Bojanowski et al. (2013) for several models. In terms of RE, values achieved in this study, with the minimum obtained in El Peral station (16.83%) (Fig. 6b), are higher than the majority of the stations around the Central Andes (Baigorria et al., 2004) and similar to those reported by Estévez et al. (2012). Finally, the maximum overestimation (around 3%) was obtained in Russel station, and with the exception of Las Paredes location, the rest of stations tend to underestimate Rs values, registering the maximum underestimation (around 6%) in El Peral station. These values are better than those reported by Estévez et al. (2012) and similar to those summarized by Bojanowski et al. (2013). In general, the accuracy of air temperature based radiation prediction model can reduce its accuracy in some days due to the advection of cold or warm air masses (Winslow et al., 2001), phenomenon that can be observed during some days in both Fig. 6a and b.

3.3. Examples of the impact of flagged data on ET_0 estimations

To quantify the impact of validation procedures on ET_0 estimations, some examples are summarized in Table 7. Values of ET_0 using original datasets and values of ET_0 using validated datasets were analysed for one station of each oasis: Junín (Northern), Agua Amarga (Western) and La Llave (Southern). Outliers from the dynamic range test (upper envelope) detected in solar radiation data were substituted by estimated values from the new based-temperature models for each location (using Eq. (3), R_a and values from Table 4). Results showed, on average, deviations ranged from 5.17 mm d^{-1} (Junín) to 7.38 mm d^{-1} (Agua Amarga), and RMSE values from 6.66 mm d^{-1} (Junín) to 8.44 mm d^{-1} (La Llave). Finally, the maximum overestimation of ET_0 was found in Agua Amarga with a value of 20.75 mm d^{-1}. These overestimations are caused by solar radiation original values above the upper envelope of dynamic range test. The use of validated data from the new solar radiation estimation models based on temperature instead of using poor quality or in the absence of data, ensures the reliability of meteorological input variables that significantly affects the accuracy of ET_0 computations.

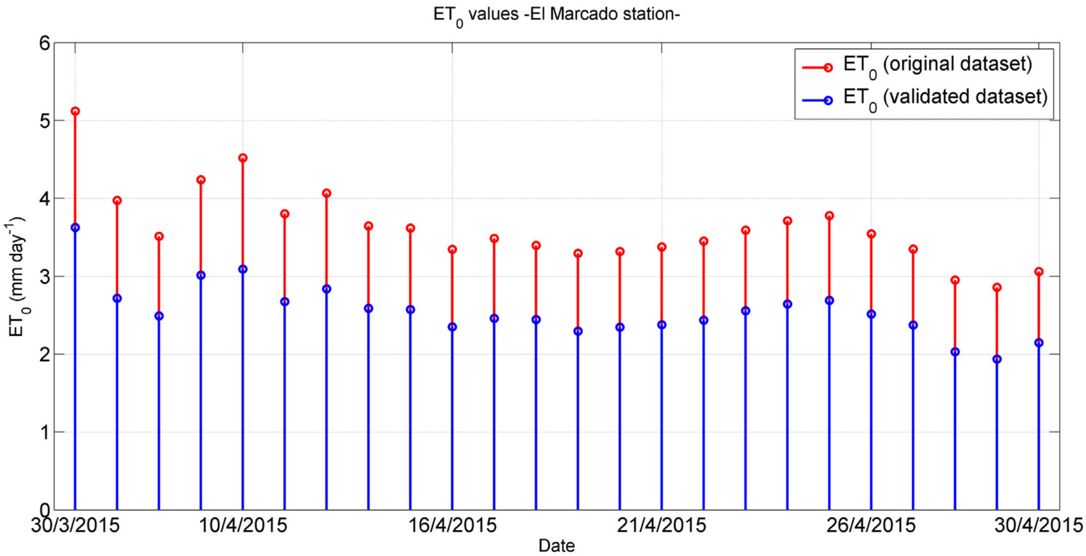

Fig. 5. ET_0 values in El Marcado station, using data flagged as erroneous by fixed range test (original dataset) and ET_0 values computed from validated dataset.

Table 6
Summary of Statistics of the evaluation of the Solar radiation models for each weather station (MBE: Mean Bias Error; RMSE: Root Mean Square Error; RE: Relative Error and R: ratio between both average estimated and measured Rs).

Name	MBE (MJ m^2 d^{-1})	RMSE (MJ m^2 d^{-1})	RE (%)	R
Gustavo André	−1.13	3.42	17.95	0.9749
Junín	−0.63	3.40	17.43	0.9761
Montecaseros	−1.80	3.32	17.47	0.9787
Russel	−0.32	2.74	21.74	1.0299
Tres Porteñas	−0.67	2.68	19.77	0.9995
Agua Amarga	1.15	3.59	20.23	0.9757
Altamira	0.07	5.41	27.56	0.9471
El Peral	−0.82	3.14	16.83	0.9392
La Consulta	0.39	5.02	24.51	0.9525
Tres Esquinas	−0.87	3.58	18.62	0.9749
Tunuyán	0.00	3.36	18.30	0.9882
Vista Flores	−0.53	4.40	24.63	0.9935
La Llave	−0.52	4.52	25.09	0.9704
Las Paredes	0.20	3.97	22.37	1.0282

Table 7
Effect of quality assurance procedures on ET_0 estimations. Example of outliers detected by dynamic range test (upper envelope) applied to Rs.

Stations	Average of ΔET_0 (mm d^{-1})	N° of days	RMSE ΔET_0 (mm d^{-1})	Maximum ΔET_0 (mm d^{-1})
Junín (Northern oasis)	5.17	183	6.66	19.83
Agua Amarga (Western oasis)	7.38	663	7.66	20.75
La Llave (Southern oasis)	6.81	39	8.44	17.18

$\Delta ET_0 = ET_{0orig}$-ET_{0valid}; ET_{0orig} = Reference Evapotranspiration computed using original dataset; ET_{0valid} = Reference Evapotranspiration computed using validated dataset.

4. Summary and conclusions

The requirement of high-quality ET_0 estimations is crucial to efficiently use of water resources, especially in arid and semiarid regions—as province of Mendoza—where the annual water balance is in deficit. The application of quality control procedures reveal the existence of several erroneous and potentially inaccurate data. In addition, the use of dynamically generated control charts allows making important decisions such as the replacement of sensors or their re-calibration, and detecting problems of field maintenance. In this sense, the present work has revealed the need of better conditioning the weather stations environment, tending towards the ideal conditions recommended. The quality assurance system described in this work will be able to properly flag all available records, being a prerequisite to their use (hydro-environmental parameters or models). The purpose of using quality assurance flags is to provide guidance to those who use data from the DACC network in Mendoza province. Since no data are altered, the user can make the final judgment depending on their quality. Many gaps and outliers of solar radiation data were found and due to its importance for many applications, self-calibration methods based on temperature have been proposed to predict this variable. These models were assessed revealing an adequate performance. Thus, they can be used instead of outliers or in the absence of data, providing consistent estimations for an important and major variable in agricultural meteorology.

Some examples showing the quantification of the impact of validation procedures on ET_0 estimations are also reported in this work. They reveal several improper values that should not be used to compute crops water requirements. To sum up, in the current climate change framework and its challenges, accurate computation of water needs using validated datasets is vital for an adequate use of natural resources, allowing to increase the agronomic effi-

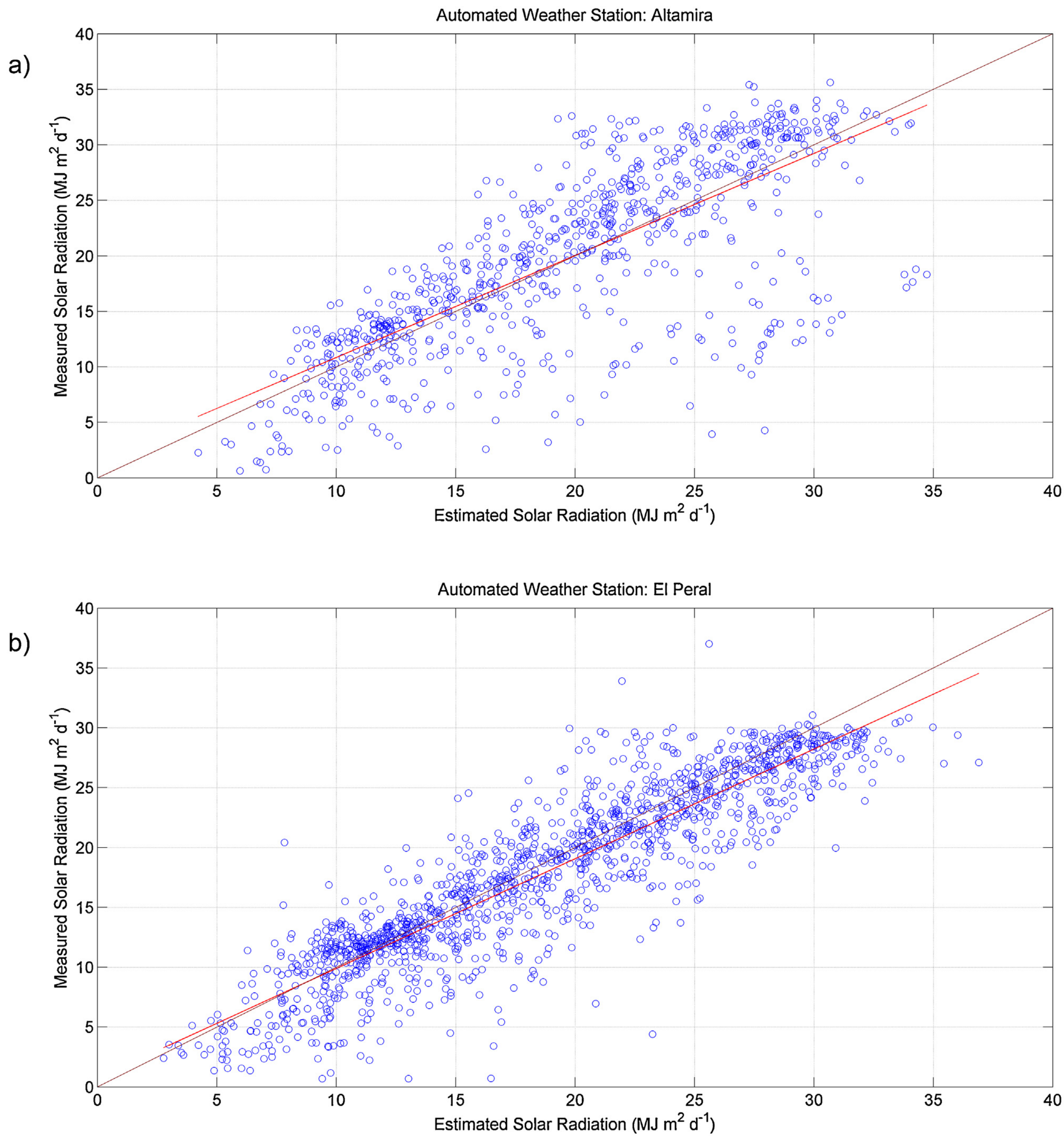

Fig. 6. Comparison between measured and estimated solar radiation for Altamira station (a) and El Peral (b) station.

ciency and productivity of this region as a source of socio-economic development.

Acknowledgments

We applied the "sequence-determines-credit" (SDC) approach for the sequence of authors. Javier Estévez acknowledges the support from the Spanish Banco Santander.

Appendix A.

In Table A1 is summarized the outline of quality control procedures applied to meteorological data. Daily solar radiation estimations using self-calibrated models developed in this work were computed as follows:

$$Rs\,(estimated) = \left(\alpha\sqrt{T_x - T_n} + \beta\right) R_a \tag{A1}$$

where T_x is the daily maximum air temperature, T_n is the daily minimum air temperature, α and β values are the empirical coefficients for each site (Table 4) and R_a is the extraterrestrial solar radiation, depending on solar constant (1367 W m^{-2}), day of year and location.

Table A1
Outline of quality control procedures applied to validate daily meteorological data prior to use them as input variables for ET_0 computations.

Variable	Procedures applied to validate data
Maximum Air Temperature: T_x	$-20°$ C < T_x, T_n, T_m < 50 °C (Tecmes stations)
Minimum Air Temperature: T_n	$-30°$ C < T_x, T_n, T_m < 50 °C (Micros stations)
Mean Air Temperature: T_m	T_{LOW} °C < T_x, T_n, T_m < T_{HIGH} °C
	T_{LOW}, T_{HIGH} = extreme values recorded (long-term series) by SMN
	T_x-T_n < 30 °C
	$T_x > T_m > T_n$
	T_x(d) > T_n(d-1)
	T_n(d) ≤ T_x(d-1)
	T_x, T_n, T_m (d) ≠ T_x, T_n, T_m (d-1) ≠ T_x, T_n, T_m (d-2)
	(d = day evaluated; d–1 = the day before; d–2 = two days before)
Solar Radiation: Rs	0 < Rs < 1400 W m^{-2} (Tecmes stations)
	0 < Rs < 1300 W m^{-2} (Micros stations)
	$0.03R_a \le Rs \le R_a$
	Rs < $1.1R_{so}$
	Rs (d) ≠ Rs (d-1) ≠ Rs (d-2)
	(d = day evaluated; d–1 = the day before; d–2 = two days before)
Maximum Relative Humidity: RH_x	0 < RH_x, RH_n, RH_m < 102%
Minimum Relative Humidity: RH_n	$RH_x > RH_m > RH_n$
Mean Relative Humidity: RH_m	RH_x, RH_n, RH_m (d) ≠ RH_x, RH_n, RH_m (d-1) ≠ RH_x, RH_n, RH_m (d-2)
	(d = day evaluated; d–1 = the day before; d–2 = two days before)
Mean wind speed: U	0 < U, U_x < 60 m s^{-1} (Tecmes stations)
Maximum wind speed: U_x	0.25 < U, U_x < 50 m s^{-1} (Micros stations)
	0 < U_x < 100 m s^{-1}
	U, U_x = 0 m s^{-1} and direction = 0
	U, U_x ≠ 0 m s^{-1} and direction ≠ 0
	U_x (d) > U (d)
	|U(d)-U(d-1)| < 10 m s^{-1}
	U, U_x (d) ≠ U, U_x (d-1) ≠ U, U_x (d-2)
	(d = day evaluated; d–1 = the day before; d–2 = two days before)

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