VALIDATION REPORT
Reference Evapotranspiration
METREF (LSA-303)

EUMETSAT
LSA SAF
LAND SURFACE ANALYSIS

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Executive Summary

This report presents an assessment of the LSA SAF Reference Evapotranspiration, DMETRef, (LSA-303) product, by comparison with in situ measurements. Here we consider DMETRef to match the FAO definition, i.e. the evapotranspiration from a hypothetical extensive well-watered field covered with 12 cm high green grass having an albedo of 0.23 under given down-welling short-wave radiation (Allen et al., 1998). Hereafter this variable is referred to as ETo. The LSA SAF DMETRef product is estimated from daily solar radiation at the surface (i.e., LSA SAF DIDSSF product) via a methodology designed to be applicable to the reference surface referred above. In line with its definition, the LSA SAF DMETRef is based on estimates of the radiative energy available at the surface.

The difficulties of finding reliable in situ measurements that meet the definition of *ETo* are thoroughly discussed in this report. For the site that matches more closely the reference surface (Cabauw, The Netherlands), the LSA SAF product outperforms *ETo* derived from other commonly used methodologies, including the Penman-Monteith indicated by Allen et al (1998). For this station, it is shown that about 36% of LSA SAF *ETo* estimates meet the product target accuracy and 69% meet the threshold accuracy. However, if very low *ETo* observations are excluded (i.e., if only in situ *ETo* > 1mm/day are considered), the number of values that meet the target and threshold accuracies rise to 54% and 95%, respectively.

Other stations, located in areas that do not deviate greatly from the reference surface, put into evidence the high uncertainty in local measurements. Nevertheless, it is shown that LSA SAF DMETRef follows well in situ values, with differences largely within the threshold accuracy.

Local advection effects cannot be ignored in measurements performed in stations where summer conditions are mostly warm and dry (the case of Spanish sites near Cordoba and Albacete). In situ *ETo* measurements performed in those case with lysimeters within limited fields are higher than estimates due advection of warm dry air from the vicinity, acting as an extra source of energy. It is shown that this effect can be parameterized as a function of near surface air temperature. However, it is argued that those local advection effects should not occur in the idealized surface referred above. Nevertheless, LSA SAF DMETRef is mostly within the threshold accuracy in all cases analyzed in this report.

In contrast to the Penman-Monteith approach (see Allen et al., 1998, Annex 6), the LSA SAF DMETRef product is not influenced by local aridity or advection effects, and therefore it is particularly appropriate for large scale climate assessments, including drought monitoring (e.g. by considering the ratio of real and reference evapotranspiration). Additionally, it provides suitable estimates of irrigation requirements in support of water management.

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1 Introduction

This document describes the strategy followed to validate the LSA SAF Reference Evapotranspiration product derived from SEVIRI/MSG (METREF, LSA-303) and discusses the validation results.

It is recalled that reference evapotranspiration, denoted here as *ETo*, is the evapotranspiration rate from a clearly defined reference surface. According to FAO report by Allen et al. (1998), hereafter denoted as FAO56, *ETo* refers to evapotranspiration that a hypothetical extensive field covered with (0.12 m height) green grass with specified albedo, roughness length for heat and momentum and surface resistance, would experience under the given atmospheric conditions.

The concept was introduced to allow the estimation of the evaporative demand of the atmosphere independently of crop type, crop development or management practices. Since reference evapotranspiration is a hypothetical quantity that is defined ambiguously, and often used inappropriately, we revisit here different features around the concept of *ETo*, in order to explain the used validation procedure.

The LSA SAF DMETREF product (LSA-303) follows the algorithm described in ATBD_DMETREF and De Bruin et al. (2016), where it is shown that for an extensive surface with the characteristics defined above, evapotranspiration can be estimated fromdaily solar radiation, i.e., it can be estimated from the LSA SAF DIDSSF product and from temperature through the Claussius-Clapeyron equation. The requirements for LSA SAF DMETREF product are summarized in Table 1.

Table 1 Product Requirements for MSG Reference Evapotranspiration (DMETREF), in terms of area coverage, resolution and accuracy (Product Requirements Document version 2.9, SAF/LAND/PRD/2.9).

DSLF Product	Coverage	Resolution		Accuracy		
		Temporal	Spatial	Threshold	Target	Optimal
DMETREF (LSA-303)	MSG disk	Daily	MSG pixel resolution	30%	10%	5%

2 The LSA SAF Reference Evapotranspiration Product

2.1 Background and concepts

Due to the rapid growth of the world population the demand for agricultural products, either for direct necessaries of life or for luxury, is increasing rapidly. Agriculture is one of the main consumers of fresh water, whereas in many regions fresh water is scarce. There is a need of efficient water management in order to use the scarcely available water resources optimally. This implies that formal water legislation is needed leading to fair and effective use of available water resources. For this purpose, easily available information on crop water requirements is needed, i.e. on optimum water consumption of crops. In the last decade, the concept of the so-called water footprint has been introduced defined as the total volume of freshwater that is used to produce a particular agricultural crop or product. For obvious reasons crop water requirement is directly related to evapotranspiration ET. This quantity is determined by many parameters, such as crop factors, weather conditions, water availability, soil properties, plant diseases, management skill of the farmer etc. In order to provide guidelines for optimum water management, the Food and Agricultural Organization of the United Nations (FAO) have published a number of reports (Doorenbos and Pruitt, 1977 and Allen et al., 1998), hereafter denoted as FAO56. The FAO56 proposes reference (crop) evapotranspiration (*ETo*) to be estimated using the Penman-Monteith equation, and indicates the values of the respective parameters to be used (i.e., those considered valid for the reference surface), as well as a number of guidelines for the measurement of the respective inputs; we all refer hereafter this methodology as PMFAO.

This report is confined to the reference evapotranspiration, *ETo*, which is also used to calculate the aforementioned water footprint. The basic idea behind the crop factor approach is that meteorological factors are separated from crop factors, i.e. it is assumed that *ETo* depends on meteorological factors only. In most practical applications this concerns: incoming solar radiation (global radiation), mean air temperature at 2m (T_{air}) minimum temperature at 2m, maximum temperature at 2m, mean relative humidity at 2m, minimum relative humidity at 2m, maximum relative humidity at 2m, and wind speed at 2m, as detailed in Allen et al. (1998; in particular equations 4-39).

It is required that these meteorological data are measured over well-watered grass growing in 'extensive' fields resembling the hypothetical reference crop for which *ETo* is defined. In practice, high quality stations where the required input weather parameters are measured over well-watered reference grass are almost absent, particularly in semi-arid regions. In remote regions, the density of weather station networks is sparse or in poor conditions, and in many developing countries weather stations over well-watered grass are not present.

2.2 Objectives LSA SAF DMETRef product

For these practical reasons there is a need for an alternative approach to estimate *ETo* that is routinely available at low costs. The LSA SAF reference product aims to provide daily *ETo* on MSG pixel scale, virtually real-time. It should be stressed that this product is not meant to replace *ETo* calculated with input data of good weather stations covered with a vegetation closely resembling FAO reference grass (i.e., using the PMFAO equation).

Recently, the concept of the so-called water footprint has been introduced defined as the total volume of freshwater that is used to produce a particular agricultural crop or product. The water footprint is derived from *ETo*.

Note that often it is thought that the FAO56 approach is considered an international standard. This is not entirely true. For instance in California where agriculture highly depends on irrigation, the so-called CIMIS network of meteorological stations is installed and a different version of the Penman-Monteith equation (the "CIMIS Penman" equation is a version of the Pruitt and Doorenbos (1977) modified Penman equation) used in the calculations of *ETo* (http://www.cimis.water.ca.gov/, tab Resources). In the UK the MORECS -version is applied by the Met Office, while in the Netherlands KNMI publishes daily *ETo* estimates obtained with the revised Makkink- equation (de Bruin, 1987; de Bruin et al., 2010). Before discussing the validation results of the LSA SAF DMETRef product, as described in the Algorithm Theoretical Basis Document for Reference Evapotranspiration (sections 2 and 3), we present the concepts and definitions described in FAO56.

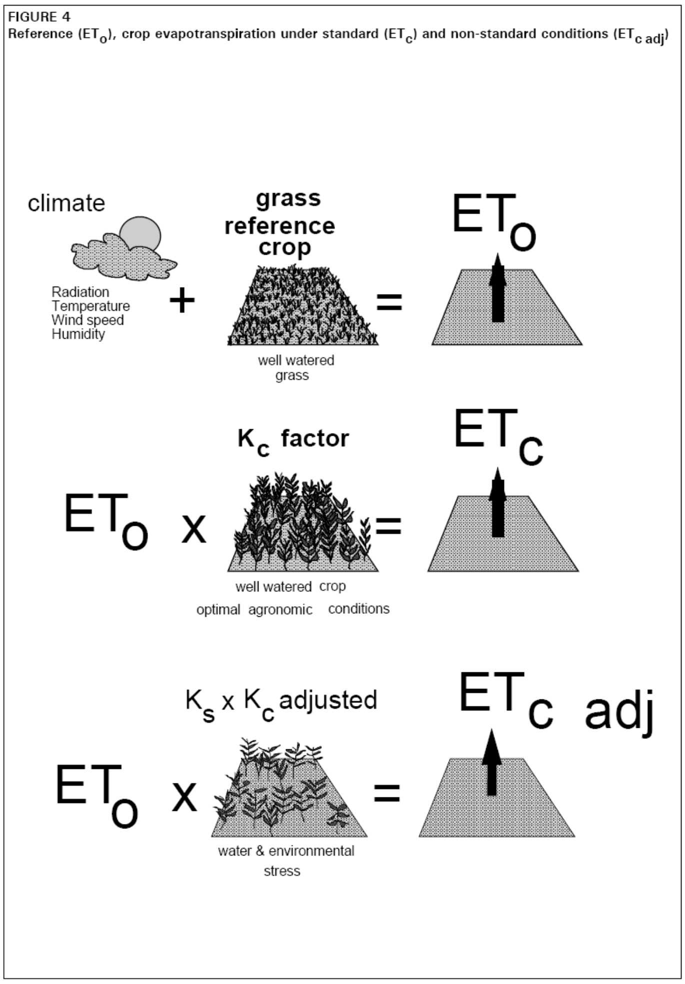

Figure 1 Semi-empirical method to evaluate ETc and ETc adj where field conditions differ from the standard conditions, correction factors are required to adjust ETc. The adjustment reflects the effect on crop evapotranspiration of the environmental and management conditions in the field. Source: Allen et al (1998).

Distinctions are made (Figure 1) between reference crop evapotranspiration (*ETo*), crop evapotranspiration under standard conditions (ET_c) and crop evapotranspiration under nonstandard conditions (ET_{c_adj}). *ETo* is a climatic parameter expressing the evaporation power of the atmosphere. ET_c refers to the evapotranspiration from excellently managed, large, well-watered fields that achieve full production under the given climatic conditions. Due to suboptimal crop management and environmental constraints that affect crop growth and limit evapotranspiration, ET_c under non-standard conditions generally requires a correction.

***ETo* corresponds to the evapotranspiration from a hypothetical extensive well-watered field covered with 12 cm high green grass having an albedo of 0.23 under given down-welling short-wave radiation (Allen et al., 1998).** The more precise definition of *Reference Surface* is given on page 15 in FAO56, where a fixed surface resistance of 70 s m^{-1} is also indicated. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s m^{-1} implies a moderately dry soil surface resulting from about a weekly irrigation frequency.

The crop evapotranspiration under standard conditions, denoted as ET_c, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement. Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration. The irrigation water requirement basically represents the difference between the crop water requirement and effective precipitation. The irrigation water requirement also includes additional water for leaching of salts and to compensate for non-uniformity of water application.

Crop evapotranspiration can be calculated from climatic data and by integrating directly the crop resistance, albedo and air resistance factors in the Penman-Monteith approach. As there is still a considerable lack of information for different crops, the Penman-Monteith method is used for the estimation of the standard reference crop to determine its evapotranspiration rate, i.e., *ETo*. Experimentally determined ratios of ET_c / *ETo*, called crop coefficients (K_c), are used to relate ET_c to *ETo* or $ET_c = K_c\, ETo$.

Differences in leaf anatomy, stomatal characteristics, aerodynamic properties and even albedo cause the crop evapotranspiration to differ from the reference crop evapotranspiration under the same climatic conditions. Due to variations in the crop characteristics throughout its growing season, K_c for a given crop changes from sowing till harvest. The calculation of crop evapotranspiration under standard conditions (ET_c) is discussed in Part B of FAO56.

The LSA SAF DMETref product is meant to present an estimate of reference crop evapotranspiration as defined above. The concept of reference crop evapotranspiration is that it is defined for a reference surface grass growing in an extensive field, although practical application of FAO guidelines partly disregard this definition. In one interpretation the adjective 'extensive' implies that edge effects can be neglected. But this contradicts the way the reference crop evapotranspiration concept is applied to cases where edge effects included. This concern the question whether or not effects of local advection must be accounted for. Validation of DMETRef estimates against independent observations will encounter this question, as discussed later in this report.

Recent studies have also demonstrated that *ETo* (or the ratio of *ETo* to actual evapotranspiration) is particular useful for drought monitoring (e.g., Otkin et al., 2016) and climate studies (e.g., Weedon et al., 2011). The use of the PMFAO for this purpose may however be affected by surface aridity. In the section below, we explain that the method described in the LSA SAF ATBD_DMETRef is not affected by local factors, such as surface aridity or local advection, since it makes use of experimental and theoretical evidence that the main driver of evapotranspiration over the extensive reference surface is global radiation.

2.2.1 Surface Aridity

As clearly explained in Annex 6 of FAO5 using input data collected over a dry surface instead of the prescribed well-watered grass, will lead to overestimation of *ETo* when calculated with PMFAO (e.g., Temesgen et al., 1999; Droogers and Allen, 2002, and recently alerted by the Californian irrigation advice facility CIMIS, 2015). Such overestimation associated to the use of observations taken over a dry instead of a well-watered surfaces is the so-called surface-aridity error: over dry warm surface the air temperature will be higher and air humidity will be lower compared to adjacent well-watered reference grass. As a result the water vapour deficit appearing in the second term of PMFAO will be overestimated when measured over dry surfaces. This is a relevant issue, which unfortunately, is ignored often in practice. An important advantage of the LSA SAF DMETRef product is that it is insensitive to the surface aridity errors, because it uses the external energy source that mainly drives ET, i.e., the global radiation.

Nevertheless, this feature is a further constraint for the validation of the LSA SAF DMETRef product. On one hand, end-users adapt PMFAO *ETo* estimates as the 'standard-truth', but on the other, the input data are usually not gathered over well-watered reference grass, whereas no correction for surface aridity errors are made.

For the purpose of climate studies at regional, continental or global scale, where *ETo* is assessed using reanalyses data, the aridity effect cannot be neglected and the use of PMFAO may lead to a significant overestimation of *ETo*. As an illustration of this, Figure 2 shows a global map of *ETo* calculated with PMFAO using ERA-Interim data (Weedon et al., 2011). Regions such as the Sahara present unrealistic high values (up to 3000 mm/year), which are a direct consequence of this effect.

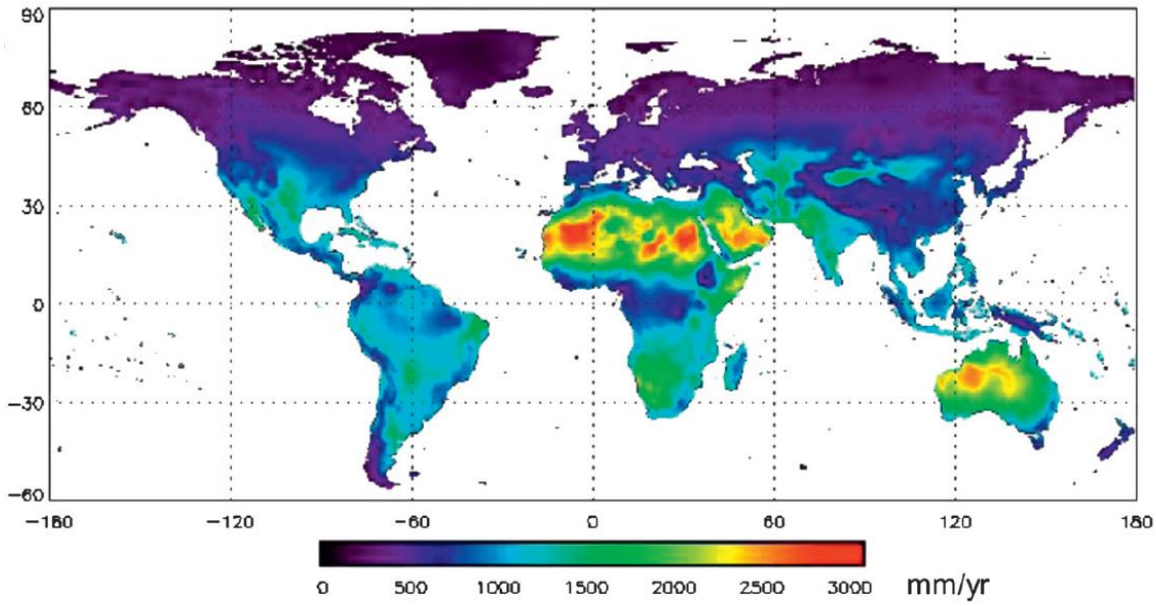

Figure 2 Reference evapotranspiration (mm/year) estimated using the PMFAO applied to ECMWF reanalyses (ERA-Int); source Weedon et al., (2011).

As another example, we refer the Clay Centre Station, Nebraska, USA (Figure 3; left). The site is in located in the semi-arid plains of the USA and is covered and surrounded with not irrigated grass. In Nebraska two 'standard' Penman-Monteith versions are adopted, namely the FAO56 version using well-watered grass as reference crop (i.e., the PMFAO), and a version using (taller) well-watered alfalfa as reference, both using local meteorological measurements as input. The estimated values are not corrected for the surface aridity effect. Figure 3 (right) shows values of net radiation estimated using the Slob-DeBruin methodology (see equation 5 in ATBD_DMETRef) for well-watered grass surfaces together with the two Penman-Moneith estimates of *ETo*; the data are shown for the dry year 1988. It is shown that estimates on various summer days often exceed net radiation twofold, which is highly questionable.

When PMFAO estimates are considered for comparison with the LSA SAF DMETRef product, cases affected by surface aridity are excluded. As such, and when applicable, cases where PMFAO (in energy flux units) is 30% or more above net radiation over the reference surface (Slob-DeBruin, equation 5 in ATBD_DMETRef) are excluded from the analysis, i.e., when the surface aridity index (Beregena and Gavilán, 2005) is higher than 1.3. It should be noted that this filter does not exclude local advection effects.

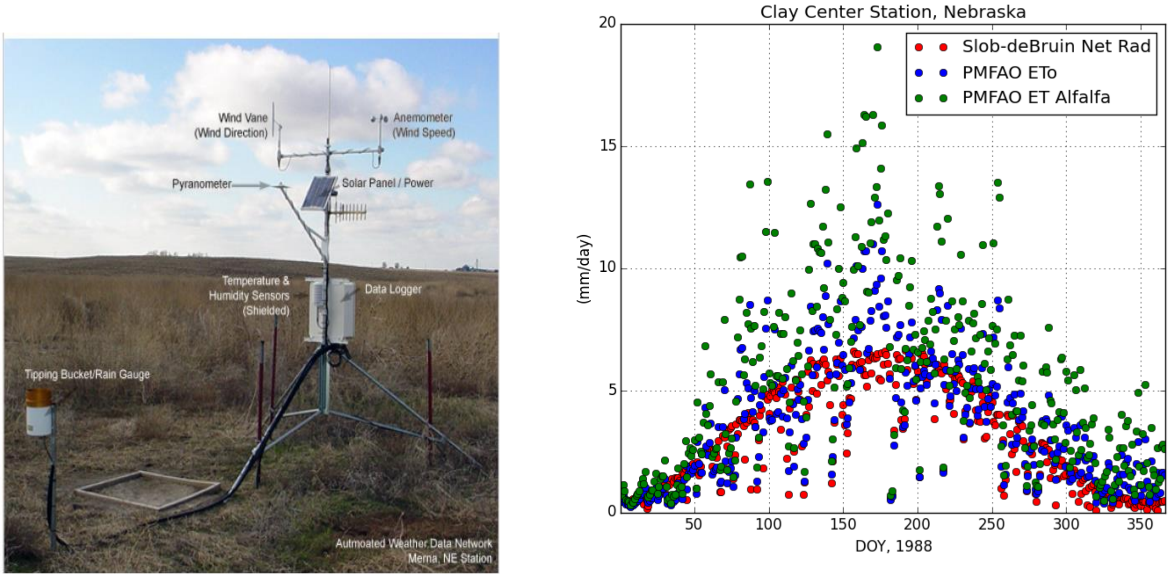

Figure 3 Left: Clay Centre Station, Nebraska, USA. Right: Daily values of the following variables for 1988: Net radiation estimated by the Slob-DeBruin equation for the reference surface (red; divided by the latent heat of vaporization to yield mm/day), PMFAO *ETo* (blue, mm/day); and alfalfa *ETo* using PM (grey; mm/day).

3 Validation Strategy and in situ measurements

The nature of the reference evapotranspiration, being the evapotranspiration that would be experienced by a reference surface consisting of an extensive field of well-watered short (12 cm) grass under the observed meteorological conditions, strongly limits the availability of observations that can be used as a sound ground reference, since direct measurements of actual ET as well as input data for PMFAO have a limited accuracy (see Allen et al. (2011) for an excellent review). There are many aspects of this problem beyond these technical and conceptual ones, including also features such as heterogeneity of the surface, terrain slopes, and vegetation cover. In general, the eddy-covariance (EC) method providing estimates of actual latent heat flux (or evapotranspiration) from fast response sensors for vertical wind speed and humidity was considered the most accurate, provided that one accounts for the so-called energy balance closure problem (e.g., Foken, 2008; Oncley et al., 2007; Mauder et al., 2007). Accuracy of ET measurements also depends on landscape as reported in a joint study of experimentalists in Large Eddy Simulation (LES-modelers) by Foken et al. (2006), where it is concluded that over heterogeneous terrain the EC method has a limited accuracy. Earlier studies over well-watered fields surrounded by dry terrain reveal the fact that the water vapour flux is not constant with height and that there is no horizontal homogeneity.

In this report we analyse in situ ET measurements with both EC and/or lysimetry gathered over sites with different characteristics (Table 2) in Europe. Although lysimeters are designed to measure evapotranspiration over a reference surface, their measures are often hampered by the size of the field, and therefore may be affected by advection effects. From all the in situ sites analysed here, Cabauw (The Netherlands) is the only one where local measurements of actual evapotranspiration can be considered identical to *ETo*: the site and surrounding area are dominated by grass, which only rarely is subject to water stress.

Table 2 Observation Sites. In the case of sites where EC estimates are available, the daily observations are a measurement of 30-min values. The observations considered in this report correspond to daily averages; all sites include standard meteorological observations.

Site	Measurements/ Period	Characteristics and references
Cabauw (The Netherlands) 51.91ºN; 4.93ºE	Eddy-covariance Radiation 2007-2012	- grass/ low vegetation, well-watered – similar to the reference surface - temperate climate mostly without dry season - Monna and Bosveld (2013)
Haarweg (The Netherlands) 51.91ºN; 4.93ºE	Radiation data only 2007-2011	- grass/ low vegetation, well-watered – similar to the reference surface - temperate climate mostly without dry season - Hartogensis (2015)
Falkenberg (Germany) 52.17ºN; 14.12ºE	Eddy-covariance Radiation 2007-2012	- non-irrigated grassland; water stress may occur - temperate climate; dry spells may occur in summer - Beyrich at al. (2002); Neisser et al. (2002)
Rollesbroich (Germany) 50.62ºN; 6.30ºE	Eddy-correlation Lysimeter (Oct 2013 – Nov 2015)	- managed grassland (ryegrass and smooth meadow grass) - temperate climate; dry spells may occur in summer
Cordoba (Spain) 37.83ºN; 4.85ºW	Lysimeter (2007-2009) Radiation (2009)	- Mediterranean semi-arid climate: annual precipitation is 536 mm; very dry and warm summers. - Berengena and Gavilán (2005)
Cordoba – RIA Stations	Standard meteorological observations only (2007-2012)	- Agroclimatic Information Network of Andalusia (RIA) - climate as above - Gavilán et al. (2006)
Albacete (Spain) 39.24ºN; 2.09ºW	Lysimeter Radiation (2007-2009; 2011-2012)	- Mediterranean climate with dry and warm Summers - López-Urrea et al. (2014)

3.1 Validation Strategy

The validation of LSA SAF DMETRef will be mostly performed by direct comparison with available in situ evapotranspiration measurements. For this purpose, the LSA SAF DMETRef product was processed to overlap with existing observations.

The set of sites listed above covers different types of climate regimes, but is limited by availability of observations which may considered close to the concept of reference evapotranspiration. In the case of Cordoba and Albacete sites (Spain), the effects of local advection affect significantly the observations.

For all sites considered here, we also provide comparisons with *ETo* estimates provided by other commonly used methods, namely:

- Priestley-Taylor (Priestley and Taylor, 1972; McMahon et al., 2013), where net radiation is derived from LSA SAF DIDSSF product, i.e., Priestley-Taylor *ETo* derived from SEVIRI/MSG data;

- Makkink (De Bruin, 1987; De Bruin et al., 2010) using as input the LSA SAF DIDSSF product. Makkink results are shown for Cabauw (The Netherlands), since this methodology is operationally used by KNMI (the Royal Netherlands Meteorological Institute) to derive *ETo*.
- Penman-Monteith following the guidelines in FAO (Allen et al., 1998), denoted by PMFAO. All PMFAO estimates presented in this report are obtained using uniquely in situ measurements, in contrast to the methods referred above.

Given the relevance of net radiation estimates in the LSA SAF DMETRef product, section 5 presents a validation the Slob-DeBruin equation (please see ATBD_DMETRef) fed with LSA SAF DIDSSF product against in situ measurements. The Slob-DeBruin equation used here was tuned to the reference surface and therefore we exclude from the comparison measurements obtained when the surface conditions strongly deviate from that reference, as further detailed in section 5.

4 Validation Results

4.1 Cabauw

Cabauw (The Netherlands) is located in an area dominated by non-irrigated grass (Figure 4). The ground water table is managed by a dense network of ditches, and only rarely droughts have reduced evapotranspiration. The terrain around the site also corresponds to grassland free from obstacles up to a few hundred meters in all directions. For further details about CESAR observatory see Monna and Bosveld (2013). Given its geographical location and local characteristics, the Cabauw test area resembles closely the hypothetical FAO reference grass for conditions without advection. The wide range of available local observations together with site characteristics make this a unique test base for studies of reference evapotranspiration: as discussed in de Bruin et al (2016), this is one of the rare cases where actual evapotranspiration over a large area actually corresponds to Reference Evapotranspiration, as defined by FAO56.

Figure 4 Cabauw site: eddy flux tower and surrounding landscape. The 10, 20, 40, 80, 140, and 200 m heights include observations of air temperature, dew point, relative humidity, specific humidity, wind speed, wind direction, U wind component, and V wind component.

Figure 5 presents estimates of the LSA SAF DMETRef product processed for the 2007-2012 period against in situ EC estimates. The data follow well the 1:1 line, with a bias of 0.1 mm/day and standard deviation of the differences of 0.3 mm/day, when compared with local observations. Most of the LSA SAF estimates are within the threshold accuracy of 30%. For comparison, we also show a verification of PMFAO estimates (using local observations), which in this case slightly overestimates local observations. For the sake of completeness, Figure 6 shows evaluation against EC measurements at Cabauw of: *ETo* estimations obtained using the Priestley-Taylor equation (Priestley and Taylor, 1972; McMahon et al., 2013); and *ETo* estimations obtained from the Makkink (De Bruin, 1987; De Bruin et al., 2010) methodology used by KNMI to derive this variable for The Netherlands. Net radiation used for the Priestley-Taylor equation was obtained via the Slob-DeBruin method (equation 5 in the ATBD_DMETRef) and the daily soil heat flux was assumed to be negligible. In both cases, we used LSA SAF daily solar radiation at the surface (DIDSSF) as main input. The results are similar to those obtained for the LSA SAF product, although Priestley-Taylor estimates show a conditional bias (underestimation/overestimation of low/high *ETo* in situ measurements). As expected, the outcome of Makkink *ETo* is remarkably similar to that of LSA SAF DMETRef, since in both cases it is assumed that available solar radiation determines net radiation over well-watered vegetated surfaces and therefore the rate of evapotranspiration.

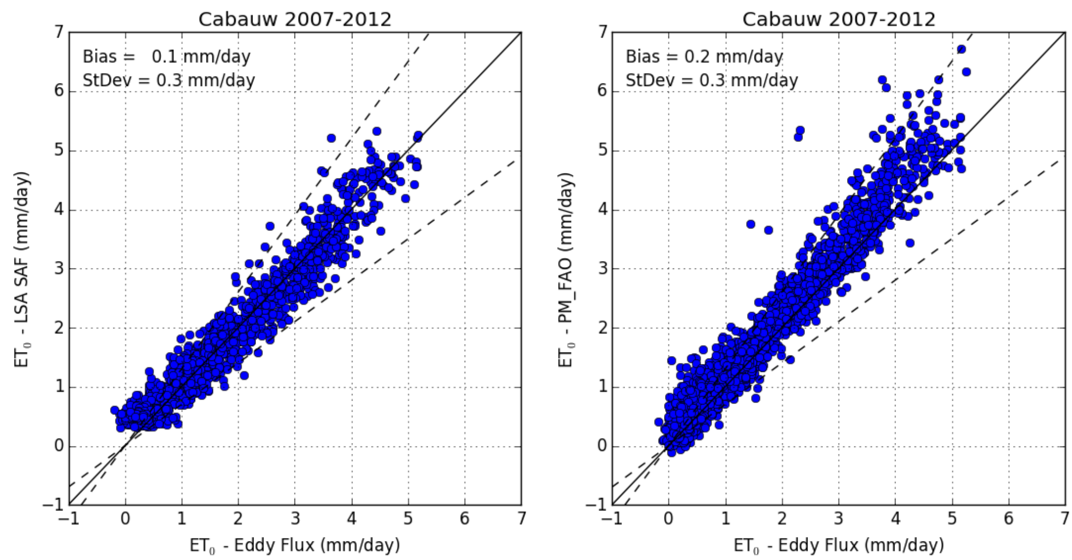

Figure 5 LSA SAF METRef product (left) and PMFAO *ETo* estimates using in situ data (right) versus EC estimates at Cabauw. Average and standard deviation of differences are also indicated; the dashed lines represent 30% deviation from the 1:1 line (solid black).

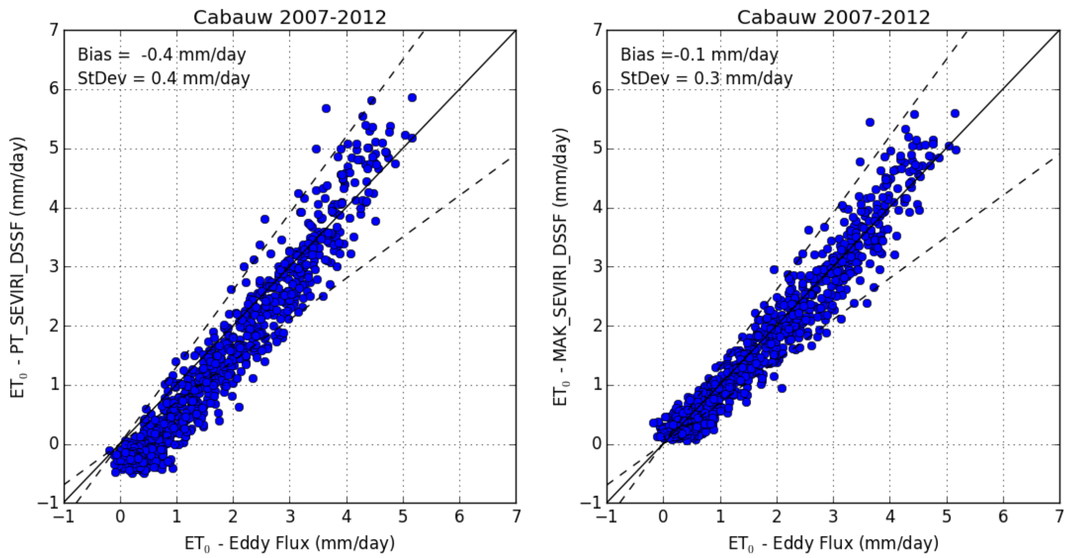

Figure 6 As in Figure 5, but for (left) Pristley-Taylor *ETo* estimates and (right) Makkink *ETo* estimates, using as input the LSA SAF daily DSSF (DIDSSF) values in both cases. The Makkink methodology is operationally used by the Dutch National Meteorological Service (KNMI).

In this station, 36% of the LSA SAF DMETRef product values processed for the 2007-2012 period meet the target accuracy, i.e., have a relative error of 10% or lower, and 69% meet the threshold accuracy (relative error of 30% or lower). The optimal accuracy is met by 18% of the DMETRef estimates. It should be noted, however, that the relative error is obviously very sensitive to the actual observed evapotranspiration and that higher relative errors are obtained in cases of low or very low evapotranspiration (Figure 7). Most of cases that do not meet the threshold accuracy of 30% correspond to observations below 1 mm/day and nearly all (see figure) to observations below 2 mm/day.

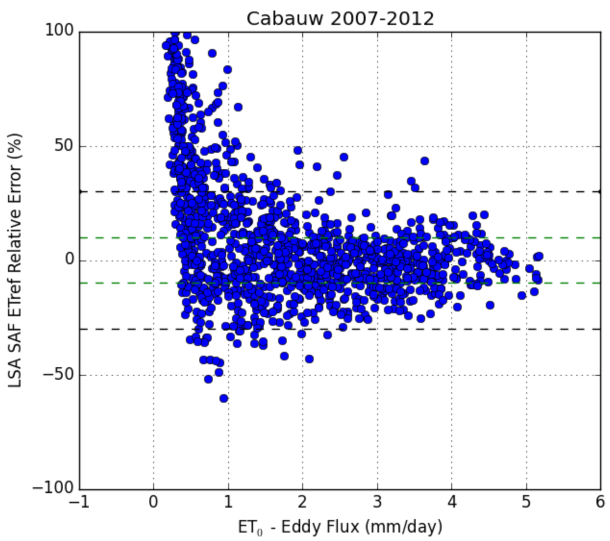

Figure 7 Relative error (%) of LSA SAF DMETRef product as a function of in situ measurements. The limits for target (green line) and threshold (black line) are also indicated.

4.2 Falkenberg

In this section we analyse comparisons of LSA SAF METREF product with data from Falkenberg, a site managed by the Meteorological Conservatorium Lindenberg /Richard-Aßmann (MOL) of the German Weather Service (Deutscher Wetterdienst, DWD; Figure 8a; Table 2). The site is located at about 5 km from the headquarters of MOL (Figure 8b). Flux measurements are performed using 2 omni-directional sonic anemometer-thermometers, providing flux data representative for the grassland of 150 x 250 m^2 both for westerly and easterly wind directions. The sonics are mounted on top of tall tube masts. Fast-response infrared hygrometers allow direct measurement of the latent heat flux using the eddy-covariance method. The site is covered by short grass (managed regularly so that the vegetation height is always less than 20 cm) and it is surrounded by grassland and agricultural fields in the immediate vicinity. A village is situated about 600 m to the SE and a small, but heterogeneous forest area lies to the west and north-west at about 1 to 1.5 km distance. The grass is not irrigated. Further information is provided by Beyrich at al. (2002) and Neisser et al. (2002), and https://www.eol.ucar.edu/projects/ceop/dm/insitu/sites/baltex/lindenberg/falkenberg/

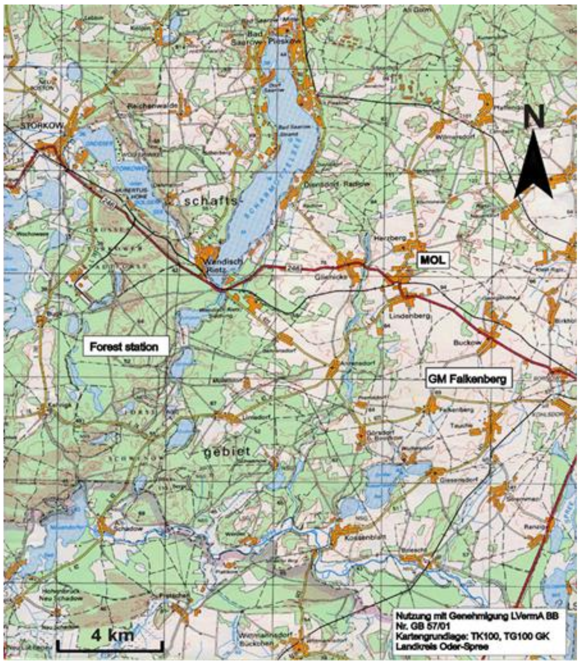

Figure 8 Falkenberg ground site: eddy flux tower (left) and map of the surrounding area (right). The station is identified in the map as “GM Falkenberg”. The tower is 99m height and includes standard meteorological profile measurements (wind speed, temperature, humidity) at levels 10 m, 20 m, 40 m, 60 m, 80 m, and 98 m.

LSA SAF DMETRef estimates are compared with daily averages of eddy-covariance (EC) latent heat, for the period between 2007 and 2012. However, EC daily averages could only be determined for a limited number of days due to poor quality EC data during night-time. It should also be mentioned that EC measurements suffer from the so-called energy balance closure problem (e.g., Wilson et al., 2002; Foken, 2008). Here we adopted the so-called Bowen ratio correction procedure in which both EC measurements of sensible (H) and latent heat fluxes (LE) are multiplied with the same correction factor, chosen such that the sum of H and LE equals the net radiation minus soil heat flux (all available at the Falkenberg site).

The comparison between LSA SAF *ETo* estimates and EC evapotranspiration is shown in Figure 9. As confirmed by the image of the site shown in Figure 8a, the results suggest that the Falkenberg grass does not resemble FAO reference grass. Nevertheless we use the Falkenberg dataset in this report because it is one of the few grass sites for which independent long term actual evapotranspiration data are available with additional high quality micrometrological measurements. Since Falkenberg grass suffers regularly from water stress LSA SAF *ETo* estimates are often greater than the measured EC values, which is in line with what would be expected. Here we use the difference between surface (*Tsfc*) and near surface air (*Ta*) temperature as a simple indicator for dry spells in the growing season, although there are other factors (e.g., near surface wind, atmospheric stability) controlling *Tsfc* - *Ta*. Figure 10 show the comparison between LSA SAF *ETo* and EC values, separating cases where -0.75K < (*Tsfc* - *Ta*) < 0.75K from those where (*Tsfc* - *Ta*) > 1K; here *Tsfc* was estimated from local measurements of downward and upward long-wave radiation assuming a surface emissivity of 0.98.

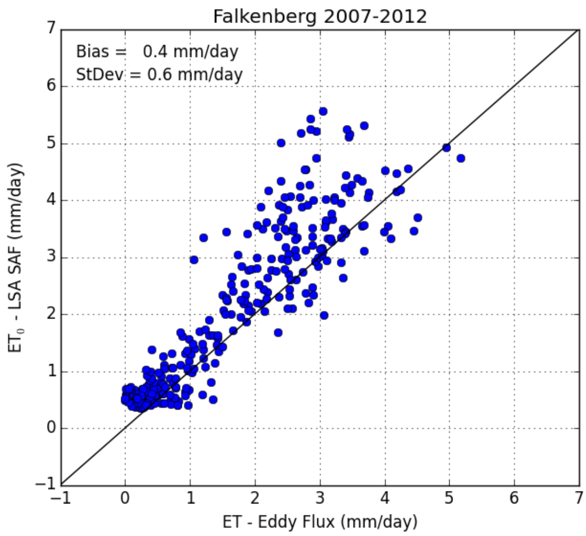

Figure 9 - LSA SAF estimates of *ETo* versus available daily averages of EC latent heat flux (converted into evapotranspiration) for all available data between 2007 and 2012. Mean differences (bias) and standard deviation of the differences between the two datasets are also indicated.

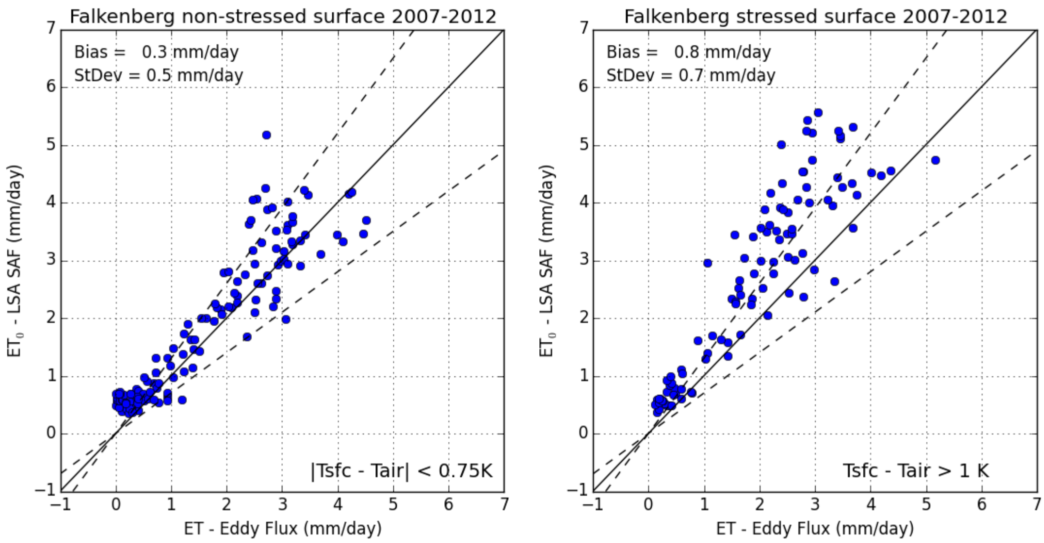

Figure 10 – Left: As in Figure 9, but for cases where the difference between the surface and 2m air temperature is below 0.75K; Right: As above, but for cases where the surface temperature is more than 1K warmer than air temperature. The dashed lines represent 30% deviation from the 1:1 line (solid black).

As indicated above, and in contrast to EC values taken from Cabauw, the observations at Falkenberg cannot be considered equivalent to *ETo*. As such, the statistics indicated in Figure 9 and Figure 10 are merely indicative. It is shown that in cases where differences between surface and air temperature are relatively low (the 0.75K threshold was chosen to ensure a reasonable number of points for analysis), i.e., when it is less likely that the surface is dry, then the points follow closely the 1:1 line, and most are within 30% of local observations. In contrast, LSA SAF ETo_0 becomes larger than local EC when temperature differences suggest surface water stress. These results also encourage the use of LSA SAF *ETo* (or the ratio between *ETo* and actual evapotranspiration) for drought monitoring.

4.3 Rollesbroich

The Rollesbroich study site is located in the Eifel low mountain range/Lower Rhine Valley Observatory (Germany). The vegetation of the extensively managed grassland site is dominated by ryegrass and smooth meadow grass (Figure 11). The site includes a set of six lysimeters arranged in a hexagonal design around the centrally placed service unit, which hosts the measurement equipment and data recording devices; here we will considered daily averages over the evapotranspiration measurements provided by all lysimeters. Each lysimeter contains silty-clay soil profiles from the Rollesbroich site and is covered with grass closely resembling the ones in the direct surroundings (Figure 11). Additionally, the spatial gap between lysimeter and surrounding soil was minimized to prevent thermal regimes which differ between the lysimeter and the surrounding field (i.e., the so-called oasis effect). Further information on the site and in situ measurements may be found in Gebler et al. (2015). The site also includes an EC tower providing latent and sensible heat flux measurements at a distance of about 30m from the lysimeters (Gebler et al., 2015).

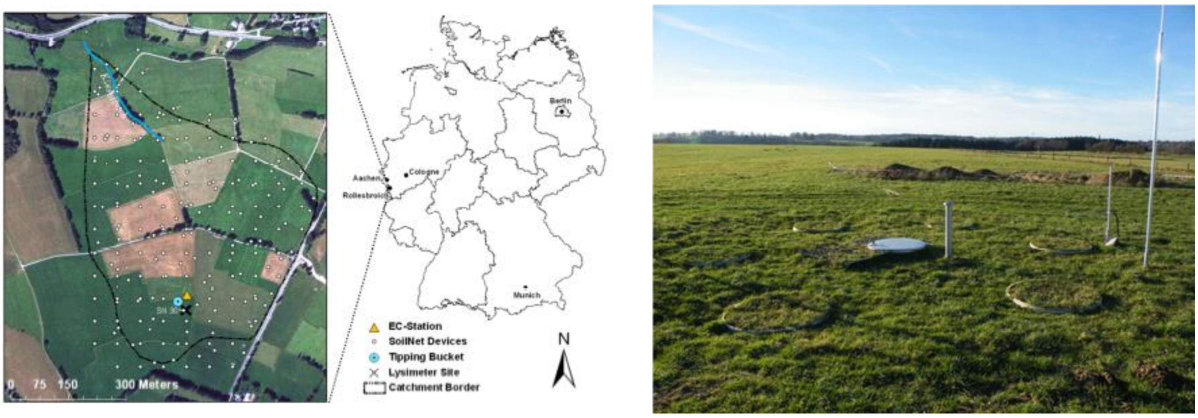

Figure 11 Left: overview of Rollesbroich site, including location of the EC tower (triangle) and lysimeters (x); Right: lysimeters set at the site. Source: Gebler et al. (2015).

When compared with lysimeter measurements, EC evapotranspiration values are lower, as shown in Figure 12. A comparison between the two datasets suggests that EC ET need to be corrected by a factor of 1.15. Gebler et al. (2015) indicate that this mismatch may be explained by instrumental or footprint differences, as EC measures a part of the upwind terrain. This implies that effects of local advection play a role. The scatter among lysimeter estimates is of the order of 14% of the overall mean values, which also provides an indication of significant uncertainties in local observations.

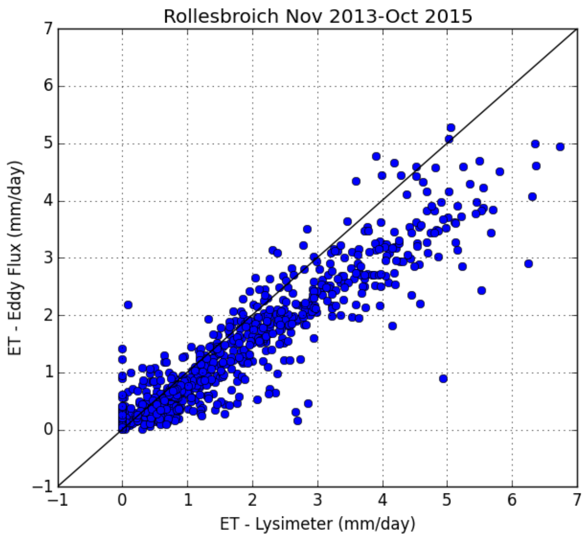

Figure 12 Eddy-covariance estimates of ET (mm/day) versus averages over the 6 lysimeters available in the Rollesbroich site, for the overlapping period between Nov 2013 and Oct 2015.

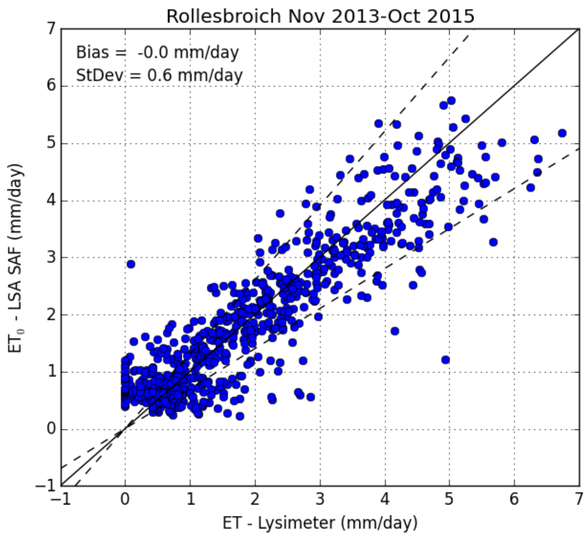

Figure 13 LSA SAF estimates of *ETo* versus available lysimeter measurements, averaged over the 6 lysimeters at the Rollesbroich site. Average and standard deviation of differences are also indicated; the dashed lines represent 30% deviation from the 1:1 line (solid black).

The LSA SAF DMETRef product was processed for 2013-2015 for the purpose of comparison with lysimeter observations at Rollesbroich (Figure 13). The average differences are negligible, and their standard deviation of 0.6 mm/day, is of the same order of that observed when the PMFAO is used with local meteorological observations (Figure 14). The use of Priestley-Taylor, applied as described above, i.e., using Slob-DeBruin estimates of net radiation from LSA SAF DIDSSF product, leads to statistics similar to those of PMFAO. The reason why PMFAO estimates are lower than lysimeter measurements (Figure 14, right panel) are not fully understood. Similar results were however, reported by Groh et al. (2015) for the end of the growing season in the same site.

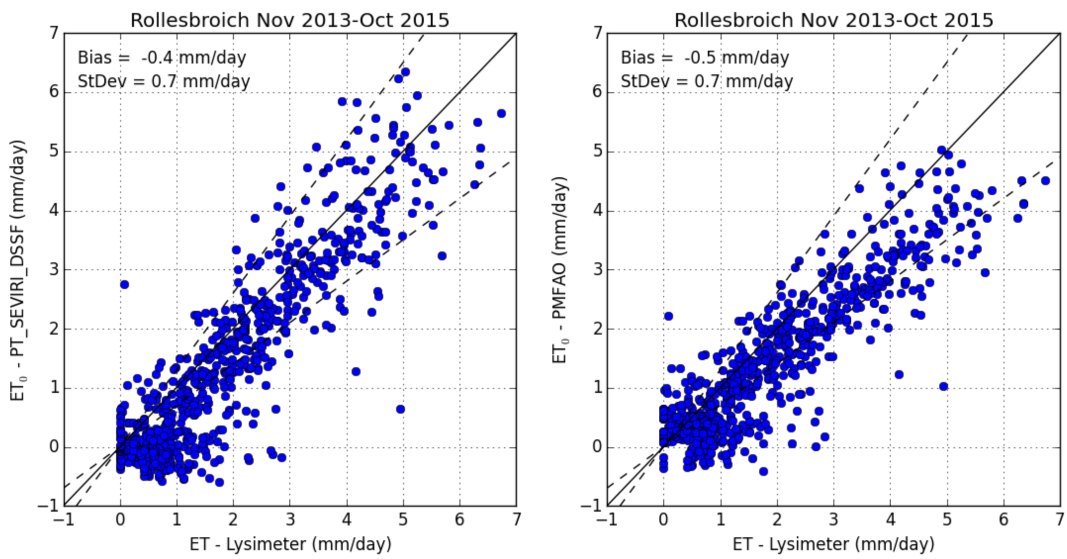

Figure 14 As in Figure 13, but for Priestley-Taylor *ETo* estimates using LSA SAF daily DSSF (DIDSSF) versus lysimeter measurements (left), and for PMFAO *ETo* estimates using in situ observations versus lysimeter values (right).

4.4 Cordoba

As stated in section 2.2, the LSA SAF crop reference evapotranspiration is designed such that effects of local advection effects are not accounted for. This hampers validation of LSA SAF DMETRef product in semi-arid regions, because test sites have limited sizes and are often surrounded by dry upwind terrain in the dry season. Moreover, it has been shown that under conditions of local advection it is very difficult to measure actual ET due to violation of basic assumptions such as horizontal homogeneity and the existence of a constant flux layer. As a result high quality datasets gathered in semi-arid regions within MSG disk are very rare. Here we will consider data gathered at the Experimental Station of the ‘‘Alameda del Obispo” located at the IFAPA Agricultural Training and Research Centre, near Cordoba, southern Spain, in the Guadalquivir Valley (Figure 15). A complete description of the site and observations may be found in Berengena and Gavilán (2005), and in Cruz et al., (2014a, 2014b). The climate in the experimental site is Mediterranean semiarid, with very dry summers (Table 2). The experimental data used here were collected in 2007- 2009 on a rectangular grass (Festuca arundinacea Schreb) plot of about 1.3 ha, which is used as a reference surface for *ETo* measurements. The plot was frequently mowed and sprinkler irrigated to meet the specifications of crop height and water status given for the reference crop. Prevailing winds during the irrigation season are westerly. The adjacent field on the west side was dry, flat, and fallow.

Although the grass field resembles as close as possible FAO reference grass, the size of the field is not “extensive”, but instead limited to 100 x 100 m^2, being often surrounded by dry terrain during summer months (see right panel in Figure 15). Berengena and Gavilán (2005) showed that ETo measured with a precision lysimeter in the centre of this field exceeds net radiation by the end of the dry season, meaning that under such conditions, sensible heat advected from upwind dry terrain is an additional energy source for evapotranspiration.

Figure 15 Left: Lysimeter site at IFAPA site; Right: overview of the area surrounding the measurement site.

Figure 16 shows the measured evapotranspiration obtained with the lysimeter plotted against the LSA SAF DMETRef product processed for the 2007-2009 period. Advection effects can be clearly identified: for higher *ETo* values, observed mostly during the dry warm season, the LSA

SAF estimates are lower than those local measurements; LSA SAF estimations are within the 30% threshold of in situ measurements. A similar behaviour may be observed in the case of estimates of *ETo* using the Priestley-Taylor equation and LSA SAF DIDSSF values (Figure 17; left panel), while PMFAO seems to simulate well advection effects over the site (Figure 17; right panel).

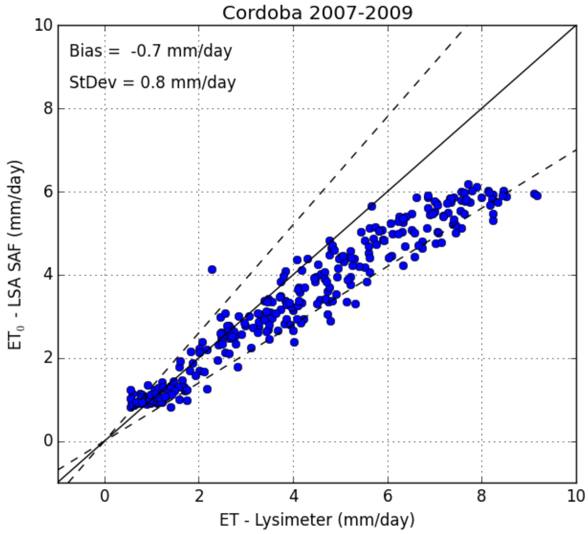

Figure 16 LSA SAF estimates of *ETo* versus available lysimeter measurements (mm/day); the dashed lines represent 30% deviation from the 1:1 line (solid black).

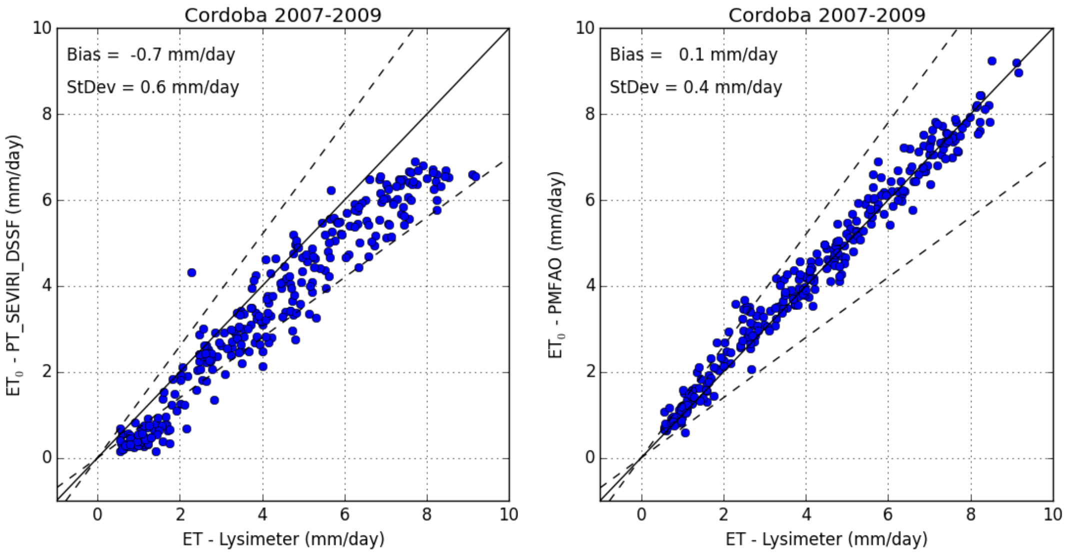

Figure 17 As in Figure 16, but for Priestley-Taylor *ETo* estimates using LSA SAF daily DSSF (DIDSSF) versus lysimeter measumrenets (left), and for PMFAO *ETo* estimates using in situ observations versus lysimeter values (right). Dashed lines represent 30% deviation from the 1:1 line (solid black).

We argue that method used to derive LSA SAF DMETRef is based on basic physical principles applied to the definition of reference evapotranspiration, i.e., assuming that for an unlimited grass surface, net radiation (most driven by available incoming solar energy) is the only source of energy for evapotranspiration. Estimations meeting this criteria should be therefore more appropriate for climate and drought monitoring, as well as for water management practices and providing advice for irrigation authorities. Nevertheless, users have long been using the PMFAO equation using local in situ measurements (as performed for Figure 17), and it is in the end up to users to decide which estimate for crop reference ET should be considered.

If advection effects are taken into account, then dry warm air advected into the area of interest is an extra source of energy, Q_{adv}, that can lead to increase evapotranspiration, on top of net radiation, Q^*, as indicated by equation 10 in the ATBD_DMETRef:

$$\lambda ET = \frac{\Delta}{\Delta+\gamma}(Q^* + Q_{adv}) + \beta \qquad (1)$$

Q_{adv} is the sensible heat horizontally advected from dry upwind terrain. This additional energy term will depend on meteorological screen variables as well as on the properties and dimensions of the upwind terrain. A universal parameterization of this extra energy source in terms of, e.g., available solar energy and T_{air}, is unrealistic. However, since Q_{adv} is expected to be a function of the air temperature of the upwind terrain (T_{air}), we consider

$$ETo\_{adv} = ETo + f(T_{air}) \qquad (2)$$

Where the function $f(T_{air})$ will vary with site. In the case of Cordoba lysimeter site, supported by observations in the nearby RIA station (Table 2) closer to the lysimeter site, $f(T_{air})=4(T_{air}-15)/\lambda$ (λ=latent heat of vaporization), if $T_{air} > 15$ ºC, and $f(T_{air})=0$, if $T_{air} \leq 15$ ºC. The adjusted LSA SAF estimates for advection effects for Cordoba is shown in Figure 18; the bias is brought down to 0.1 mm/day in this case.

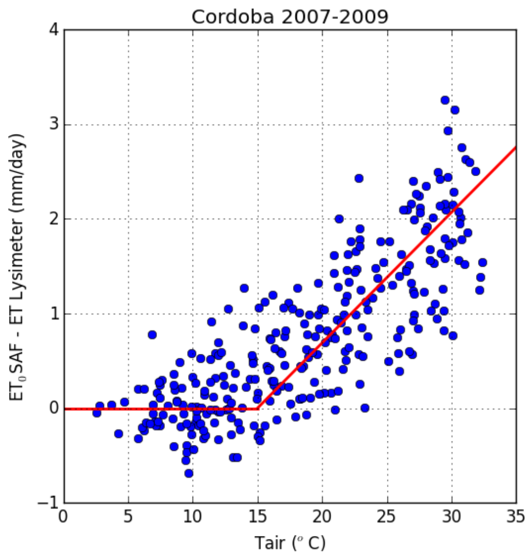

Figure 18 Left: Difference between LSA SAF DMETRef and lysimeter observations at Cordoba site (Q_{adv} as defined in equation 1) as a function of local measurements of upwind near surface air temperature (RIA *Tair* in ºC; see Table 2); the red line is an empirical adjustment of Q_{adv}^* as a function of Tair. Right: LSA SAF DMETRef product empirically adjusted for advection effects in Cordoba, versus lysimeter observations.

Below (Figure 19; left panel) we compare the LSA SAF DMETRef product against PMFAO estimates obtained from in situ data gathered at the RIA network station which is closer to the Cordoba lysimeter site (Table 2; Gavilán et al., 2006). In this case, the sensors are not located over well-watered grass, but cases of strong aridity effect are removed from the data where by ignoring all days with PMFAO (in energy units) 30% higher than net radiation estimated with the Slob-De Bruin method (PMFAO > 1.3 Q_{SdB}). The results do not differ significantly from the direct comparison of LSA SAF DMETRef against lysimeter estimates in Cordoba. Accordingly, when the same adjustment as a function of air temperature is applied, the mean differences become negligible (Figure 20). Although not shown here, Cruz et al. (2014, 2015) have found that a similar procedure, to account for advection effects as a function of local air temperature, using a revised Makkink equation as proposed by de Bruin et al. (2010), yield good results for 50 RIA stations in Andalucía.

The assessment of Priestley-Taylor estimates, using net radiation determined with the Slob-DeBruin formula fed with LSA SAF daily solar radiation (DIDSSF), and air temperature extracted from ECMWF ERA-Interim archive, is depicted in Figure 19 (right panel) for the same station.

The comparisons for the RIA station (Figure 19) are in line with the results shown in Figure 5 and Figure 6 for Cabauw, where the surface surrounding the measurements site does resemble the reference one as an extensive field of non-stressed grass. In that case, PMFAO appears to slightly overestimate local observations, while Priestley-Taylor *ETo* underestimate low and overestimate higher ones. The LSA SAF DMETRef, which present negligible bias at Cabauw, underestimate PMFAO when advection effects are present (i.e., higher *ETo* ranges in Figure 19 left panel), while Priestley-Taylor *ETo* shows a slight better agreement with PMFAO (Figure 19 right panel).

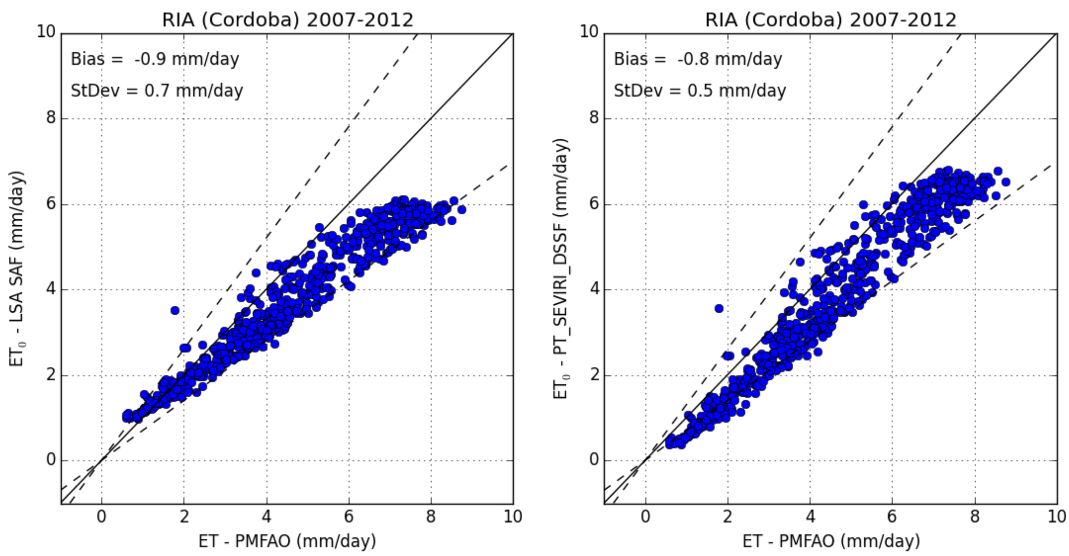

Figure 19 Left: LSA SAF DMETRef product versus PMFAO estimations using observations at the RIA station closest to Cordoba lysimeter site; Right: as above, but for Priestley-Taylor estimates, using as input LSA SAF daily solar radiation (DIDSSF). Dashed lines represent 30% deviation from the 1:1 line (solid black); mean and standard deviation of differences are also shown.

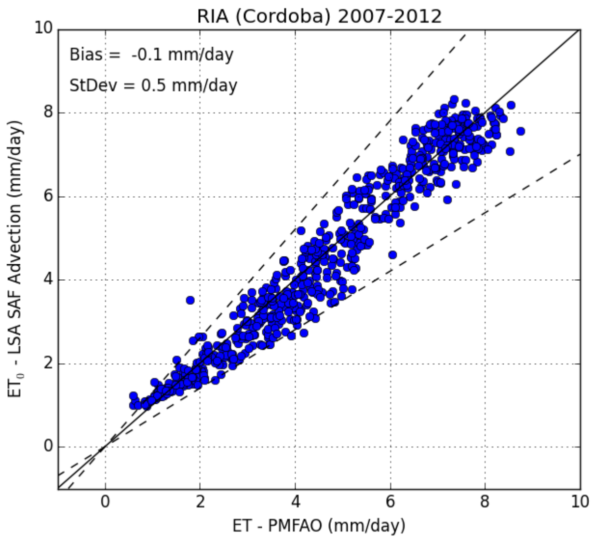

Figure 20 As in Figure 19 (left panel), but for the LSA SAF DMETRef adjusted to take into account advection effects, as observed over the Cordoba lysimeter site.

4.5 Albacete

As in Cordoba, Albacete is located in an area dominated by dry and warm Mediterranean summers. As such, measurements taken at the local lysimeter are subject to advection effects, which lead to higher evapotranspiration measurements than what you would expect over an unlimited field where advection would not be present. This is clearly visible in Figure 21 (left), in the case of high values. As referred above, it is up to users to choose crop reference evapotranspiration with or without local advection effects. PMFAO is calibrated for conditions with local advection, explaining the good agreement obtained with local lysimeter estimated in Cordoba (Figure 17) and Albacete (Figure 22).

As in the Cordoba case, the effect of extra sensible heat advected into the area may be parameterized as a function of air temperature (as in equation 2). It is stressed, however, that such corrections can only be inferred at ad hoc basis. For Albecete, we followed a similar procedure to that proposed for Cordoba lysimeter site, leading to $f(T_{air})=4(T_{air}-10)/\lambda$ (λ=latent heat of vaporization), if Tair > 10 ºC, and f(Tair)=0, if Tair $\leq$ 10 ºC. The comparison of this adjustment with in situ observations is shown in Figure 21 (right panel). Taking into account that the LSA SAF METRef product may be particularly useful in cases where weather station data gathered over well-watered grass are not available, adjustment to local advection as the one proposed here may useful for practical applications.

For completeness, we show the comparison between Priestley-Taylor and lysimeter measurements in Albacete (Figure 22; left panel), where the impact of advection is also visible. Althought not shown, the same effect is observed for *ETo* derived from Makkink equation; in this case, an adjustment, such as that fitting equation (2), where $f(T_{air})$ is a linear function of air temperature, leads to results similar to those in Figure 21 (right panel).

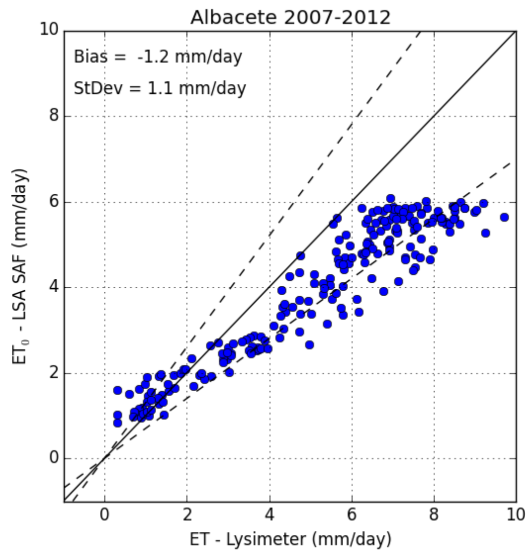

Figure 21 Left: LSA SAF DMETRef versus available lysimeter measurements (mm/day) at Albacete. Right: As before, but after adjusting DMETRef empirically to take into account advection effects. The dashed lines represent 30% deviation from the 1:1 line (solid black).

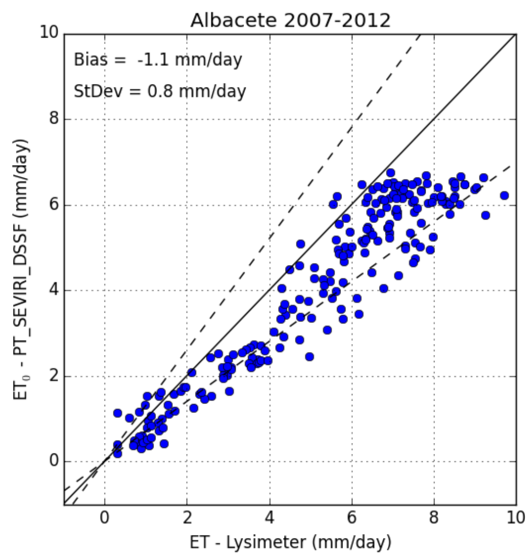

Figure 22 (Left) Priestley-Taylor ETo (using LSA SAF DIDSSF product) and (Right) PMFAO estimates versus lysimeter measurements at Albacete. The dashed lines represent 30% deviation from the 1:1 line (solid black).

5 On the Validation of Net Radiation over well-watered surfaces

One of the main assumptions of the method used to derive LSA SAF DMETRef product is that daily net radiation may be estimated from the daily global radiation (here provided by LSA SAF DIDSSF product) over well-watered vegetated surfaces. The underlying idea is that albedo is known for the reference surface (0.23) and therefore net short-wave radiation is easily determined. On the other hand, available solar radiation also seems to correlate well withnet long-wave radiation at the surface: its ratio to external radiation is strongly linked to cloud cover, which in turn control sky emissivity and down-welling long-wave fluxes; and it also controls average surface temperature (close to near surface air temperature for saturated surfaces), which in turn are linked to upwelling (down-welling) longwave radiation.

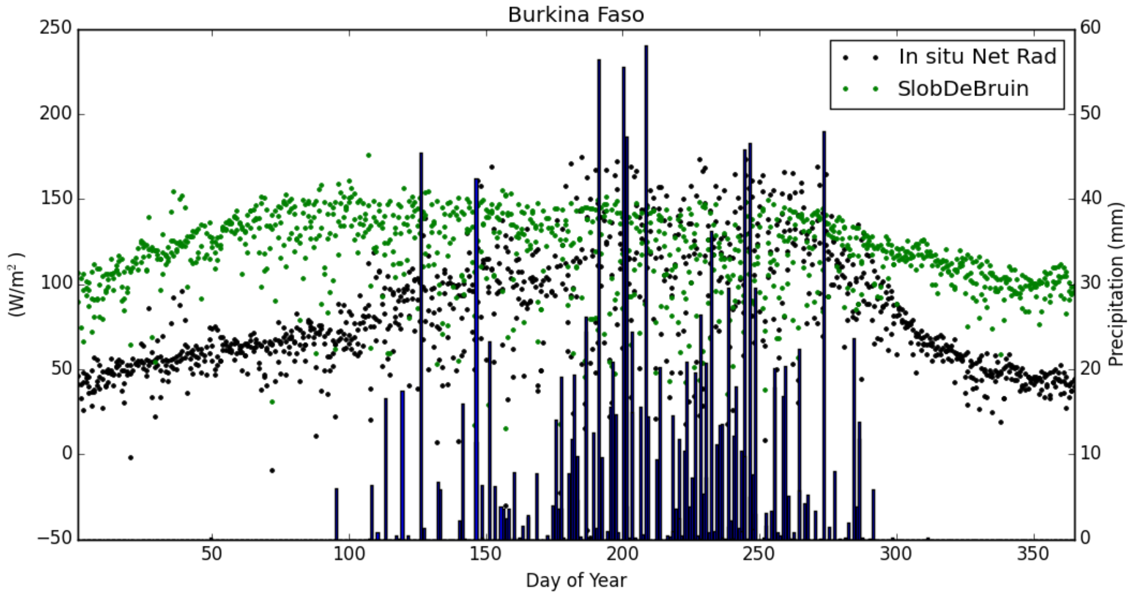

Figure 23 Net radiation (black dots) estimated from in situ measurements over bare ground soil (Burkina Faso), over a 3-year period; net radiation for the reference surface (Slob-deBruin equation) as estimated from in situ observations of solar radiation at the same site (green dots); daily precipitation (bars).

Surface aridity affects actual net radiation, and therefore net radiation measurements over surfaces that deviate from reference conditions are not suitable for *ETo* estimates. A clear example is presented for a bare soil site in Burkina Faso (de Bruin et al., 2012 a, b), shown in Figure 23. During the dry season the difference between actual net radiation (black dots) and that for hypothetic reference grass (green dots) may be over 50 w/m^2; the difference between the two greatly attenuates during the rainy season. A similar example is shown in Figure 24 for an Ameriflux (http://ameriflux.lbl.gov/) station, Vaira, covered with natural grass. It is seen that as soon as latent heat flux drops to zero in the dry season, the measured net radiation starts to become smaller than the estimated net radiation.

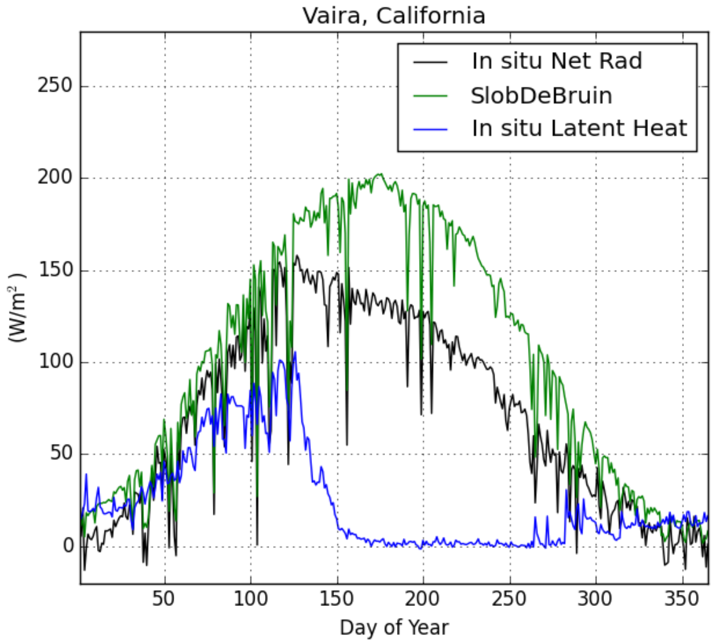

Figure 24 Net radiation (black line) estimated from in situ measurements over 2007 in Vaira (California); net radiation for the reference surface (Slob-deBruin equation) as estimated from in situ observations of solar radiation at the same site (green line); and in situ latent heat (blue line).

For a further brief validation of the Slob-DeBruin equation (equation 5 of the ATBD_DMETRef) we use measurements of the surface net radiation budget for the sites described in Table 2. In this validation exercise, we try to eliminate cases where the surface surrounding the in situ measurements strongly deviates from the reference. As such, in the case of Albacete we only considered cases where local albedo is 0.23 ± 0.05 and the difference between surface and air temperature ($T_{sfc} - T_{air}$) is below 1.5ºC.

Overall the results obtained with this simple parameterization are very good. The comparison with in situ observations in Cabauw (The Netherlands), Falkenberg (Germany), Rollesbroich (Germany), and Haarweg (The Netherlands) is shown in Figure 25. The data follow well the 1:1 line, with a few outliers, and average differences below 3 W/m^2. Standard deviation of the differences lies between 11 W/m^2 for Cabauw (the closest to the reference surface), and nearly 16 W/m^2 for the Rollesbroich site. The performance of net radiation estimates remains similar for the Spanish sites: the lowest scattering is obtained for Cordoba, with a standard deviation of differences of nearly 8 W/m^2 and a negative bias of 4 W/m^2; for Albacete the bias is negligible, but the standard deviation increases to about 15 W/m^2.

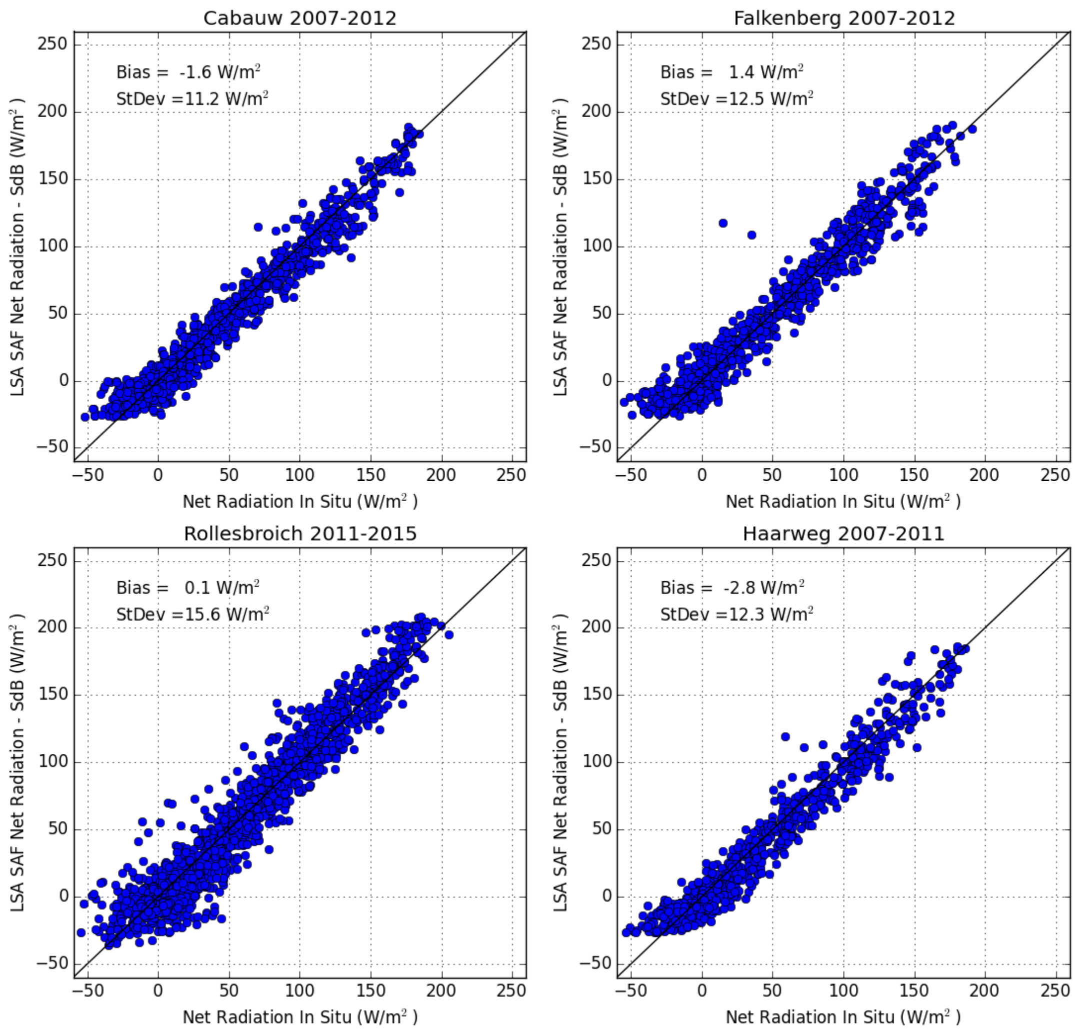

Figure 25 Comparison of LSA SAF estimations of net surface radiation (via the Slob-DeBruin equation) against in situ observations, for sites located in The Netherlands and Germany. Mean differences and standard deviation are also indicated.

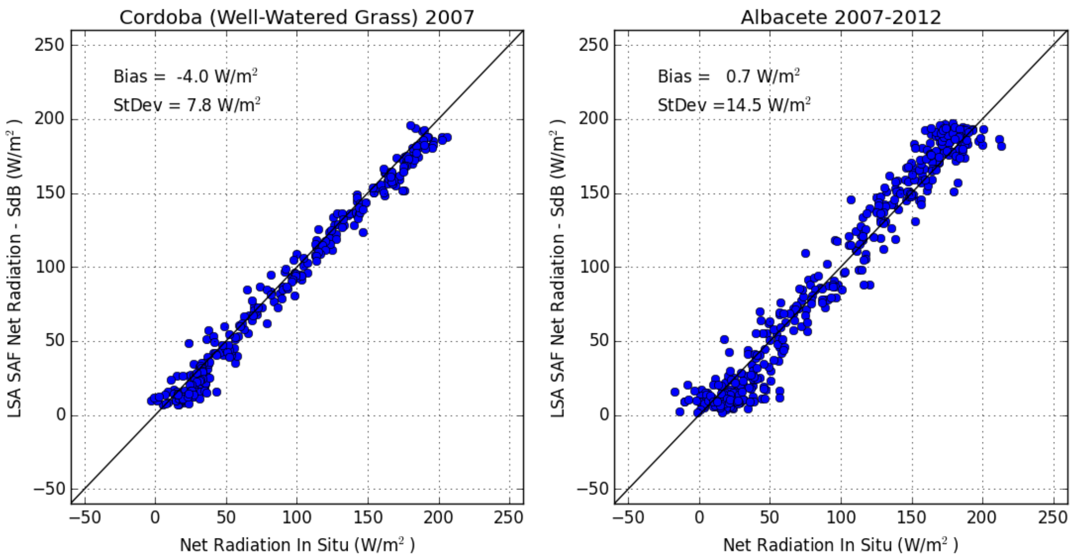

Figure 26 As in Figure 25, but for stations located in Spain (Mediterranean climate). Data from Cordoba site (left) were collected over a well maintained field of non-stressed grass; data collected over surface conditions that deviate significantly from the reference surface were removed from the Albacete dataset.

6 Concluding Remarks

This report presents an assessment of the LSA SAF DMETRef (LSA-303) product. The underlying algorithm is based on thermodynamical scaling ideas with observationally based coefficients for well-watered surfaces, where the main driver of evapotranspiration is available solar energy minus long wave cooling. The algorithm is valid for a reference grass surface, assuming we always have entrainment of dry warm air into the boundary layer as an additional source of energy, which may be interpreted as a kind of regional scale advection. The algorithm is therefore valid to the reference grass surface, assuming it covers an extensive field, as defined in the FAO report (Allen et al., 1998). Such method has the advantage of allowing estimates of reference evapotranspiration, *ETo*, from daily global radiation data, which can be derived from geostationary satellite data (as the LSA SAF DIDSSF product), and from daily averages of 2m air temperature (which are routinely obtained from ECMWF forecasts).

Validation of *ETo* estimates is a challenging task, since measurements of actual evapotranspiration over surfaces close to the FAO definition are extremely difficult to find. In this respect, Cabauw is an ideal test site. In semi-arid regions, however, measurements are strongly influenced by local advection which increases evapotranspiration during summer, when dry and very warm conditions prevail.

The uncertainty of in situ measurements also needs to be taken into account when assessing the LSA SAF DMETRef product. The variety of observations at the Rollesbroich site (1 eddy-covariance flux tower, EC, and 6 lysimeters) help putting this into perspective: differences among lysimeter are, on average, close to 14% of measured mean values and differences to EC estimates present an even higher scatter.

The LSA SAF DMETRef algorithm assumes that we may estimate the net radiation expected over a well-watered grass field from daily solar radiation. Validation against ground measurements of such net radiation derived from the LSA SAF DIDSSF product show a fairly good agreement. Despite the uncertainty of local measurements, which also need to correspond to a reference surface, root mean square differences range between less than 9 W/m^2 and less than 16 W/m^2.

As referred before, Cabauw (The Netherlands) is the only site that actual resembles the reference surface defined in the FAO report by Allen et al. (1998). Comparisons with local measurements show that the LSA SAF *ETo* product presents very similar results to those obtained with the Makkink algorithm (operationally used by KNMI, but forced with the LSA SAF DIDSSF product in this validation exercise). Both outperform estimates from Priestley-Taylor and PMFAO; the latter is applied to local observations. In the typical conditions where advection effects do not occur, PMFAO tends to overestimate the highest *ETo* observations. For this station, it is shown that about 36% of LSA SAF *ETo* estimates meet the product target accuracy and 69% meet the threshold accuracy. However, if very low *ETo* observations are excluded (i.e., if only in situ *ETo* > 1mm/day are considered), the number of values that meet the target and threshold accuracies rise to 54% and 95%, respectively.

Root mean square differences between LSA SAF DMETRef and observations at Falkenberg and Rollesbroich sites are close to those observed for Cabauw (0.7 mm/day, 0.6 mm/day and 0.4 mm/day, respectively), although scatter is higher. Such good results are only obtained for Falkenberg after disregarding those conditions which largely deviated from the reference surface. In both Falkenberg and Rollesbroich cases, *ETo* estimated with PMFAO or Priestley-Taylor led to even higher discrepancies with respect to local measurements (only shown for Rollesbroich due to the rather small sample gathered for Falkenberg).

The comparison with measurements performed at Spanish sites (Cordoba and Albacete) put into evidence the impact of local advection on the observations, not supposed to be included in *ETo*. In those cases, PMFAO estimates are much closer to the observations. The LSA SAF DMETRef product presents root mean square differences of 1.2 mm/day (Cordoba lysimeter site) and 1.6 mm/day (Albacete). It is shown that in those cases, the local advection effects may be parameterized with a function of local averaged air temperature, reducing comparisons with in situ to similar statistics to those obtained for the remaining European sites. Nevertheless, it is worth pointing that LSA SAF DMETRef is mostly within the threshold accuracy in all cases analyzed in this report.

In contrast to the Penmann-Monteith equation, which seems to somehow accommodate local advection, the LSA SAF DMETRef product is not influenced by aridity or advection effects. For these reasons, the LSA SAF DMETRef product is particularly appropriate for large scale climate assessments, including drought monitoring, on top of being a conservative approach to water management practices.

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