A Thermodynamically Based Model for Actual Evapotranspiration of an Extensive Grass Field Close to FAO Reference, Suitable for Remote Sensing Application

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ABSTRACT

A thermodynamically based model is presented to estimate daily actual evapotranspiration (ET) of a grass site closely resembling reference grass as defined by the Food and Agriculture Organization of the United Nations (FAO) under nonadvective conditions, from Meteosat Second Generation (MSG) imagery. The model presented here is derived from the thermodynamic theory by Schmidt combined with an atmospheric boundary layer model. Daily net radiation over the (reference) grass surface is parameterized as a function of global radiation, which can be estimated from MSG observations. It is then shown that ET over the grass area can be estimated using remotely sensed daily global radiation and air temperature as input only. The validation relied on observations gathered in Cabauw, a site closely resembling the reference grass, as defined by the FAO. The comparison with in situ data indicated a bias of 2.8 W m^{-2} and an RMSE of 7.7 W m^{-2}. The possibility of using the approach developed here to provide reference crop evapotranspiration ET$_o$ is discussed. Because of the ambiguousness of ET$_o$ definition regarding local advection effects, it should be noted that explicitly advection-free conditions are dealt with. It is pointed out that in semiarid regions local advection cannot be ignored.

1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) published a number of reports (Doorenbos and Pruitt 1975; Allen et al. 1998) with guidelines for optimum water management. In this work, we will refer to the concepts and approaches defined in FAO Irrigation and Drainage Paper 56 (FAO-56) by Allen et al. (1998). The first step in the FAO methodology is the calculation of the so-called reference (crop) evapotranspiration, denoted by ET$_o$. It corresponds to the 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. It is assumed that ET$_o$ depends on the prevailing weather conditions only and therefore provides a characterization of the "evaporative power of the atmosphere." The water requirements of a particular crop E_c within a given stage in the growing season, and under the same atmospheric conditions, are assumed to be linearly related with ET$_o$ via a crop coefficient K_c:

$$E_c = K_c \text{ET}_o. \tag{1}$$

The crop coefficients are tabulated values (e.g., Allen et al. 1998), depending on the crop type and growing stage. Variable E_c would then correspond to the expected

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evapotranspiration of crop c, assuming disease-free plants and optimum soil conditions.

The FAO definition of ET_o for an extensive, well-irrigated grass field and its evaluation through the Penman–Monteith equation, which is derived for idealized horizontally homogeneous and uniform flat terrain, leads to an ambiguity (McMahon et al. 2013; Katerji and Rana 2011, 2014). In practice, irrigation is most relevant in semiarid regions where such idealized fields do not exist. Usually, weather stations are located at fields smaller than $10^4 m^2$ and are often surrounded by dry terrain. Under such conditions, processes that can be denoted with the generic name advection will lead to significant inconsistencies between idealized ET_o and ET_o estimates using ground data (Dingman 1992).

Another, more fundamental drawback of the ET_o concept is that it concerns a purely hypothetical grass surface that does not exist in reality, by which experimental validation of any estimation formula for ET_o is not really possible. Note that in Allen et al. (1998) there is no chapter dealing with experimental validation of the recommended methodology to calculate ET_o, being a version of the Penman–Monteith equation (hereafter PMFAO). Nonetheless, PMFAO is widely used even far outside the goals for which it is developed (irrigation practice). The experimental validations of PMFAO we could find in literature concern (lysimeter) studies mainly in semiarid regions installed in small fields (e.g., Allen et al. 2006). But then local advection cannot be ignored, which contradicts the definition of ET_o that refers to extensive grass, therefore suggesting that local advection should be ignored. This has created an ambiguous situation. Moreover, because of the fact that in hydrology and hydrometeorology PMFAO is generally accepted as "the best" to estimate ET_o, interest in the physical background has faded. In the last decade, PMFAO has been applied, without further discussion about its validity, outside the field of irrigation, for instance, in climate change studies in which long-term weather records gathered under nonreference conditions are analyzed. We conclude that there is a need to pay attention to actual evapotranspiration of an actual grass field that closely resembles the FAO reference surface.

With this in mind, a model will be presented for actual ET of an existing grass field derived from first physical principles. Our derivation is based on the thermodynamic model by Schmidt (1915) combined with a model for the atmospheric boundary layer. The latter has been used and tested by de Bruin (1983), McNaughton and Spriggs (1986), Jacobs and de Bruin (1992), and, more recently, by van Heerwaarden et al. (2010).

To increase practical applicability, we will deal also with a simple method to estimate net radiation from the incoming solar radiation at the surface (hereafter denoted as global radiation) with the empirical formula of Slob–de Bruin (hereafter SdB; de Bruin 1987; de Bruin and Stricker 2000). And, in a final step, we will apply remotely sensed global radiation as provided by the EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA SAF; Trigo et al. 2011) and by the Surface Insolation under Clear and Cloudy Skies (SICCS) derived from the SEVIRI [a platform on Meteosat Second Generation (MSG)] imagery system of the Royal Netherlands Meteorological Office (Koninklijk Nederlands Meteorologisch Instituut; KNMI) by Greuell at al. (2013) to obtain estimates of ET.

Using the Cabauw Experimental Site for Atmospheric Research (CESAR) database of micrometeorological observations gathered at Cabauw (the Netherlands) over a grass surface that closely resembles the FAO hypothetical reference grass, we will validate our models for actual ET, net radiation, and MSG global radiation against independent measurements.

Finally, we will discuss the operational applicability of our findings in, for example, irrigation practice or in other disciplines, such a climate change studies.

2. Data and material

a. In situ measurements: Cabauw

Here, we consider data gathered at CESAR for the period 2007–12. The site is located in the western part of the Netherlands (51.971°N, 4.927°E). We used the data collected at the experimental field near the 200-m tower covered with short grass. The soil consists of a 0.7-m-thick clay layer on top of a thick peat layer. The 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, which was free from obstacles up to a few hundred meters in all directions during the whole 2007–12 period. For further details about the CESAR observatory, see Monna and Bosveld (2013). Given its geographical location and local characteristics, the Cabauw resembles closely the hypothetical FAO reference grass for conditions without advection. We extracted the so-called validated and gap-filled meteorological surface data and surface flux files (CESAR Consortium 2013). This concerns 10-min values from which we calculated 24-hourly averages. In particular, we used the actual evaporation that is obtained from the energy budget residual method (Beljaars and Bosveld 1997). Cabauw is located in the midlatitude climate zone where droughts

are rare. In the period 2007–12, a limited number of dry spells were detected in the growing season. These were found by comparing measured ET with the reference crop ET evaluated with the formula of Makkink (ET$_{makkink}$, see section 5; de Bruin 1987). We ignored days for which the actual ET is less than 0.80 ET$_{makkink}$.

The database included net radiometer data as well as separate observations of the four components of net radiation, that is, incoming and reflected shortwave radiation ($K^{\downarrow}$ and $K^{\uparrow}$) and incoming and outgoing longwave radiation. We excluded days for which directly measured net radiation differs more than $15\,\mathrm{W\,m^{-2}}$ from that calculated from the four components.

The grass site is not irrigated and is surrounded by similar grass. Consequently, under normal conditions advection will be absent. Cabauw evapotranspiration might be affected by advection only when rainfall is distributed in such a way that the site becomes wetter than the surrounding terrain. We found that such rare situations occurred on 27–30 July 2007, 14–15 August 2007, and 24–28 May 2012. Data on these days were also excluded from the main results discussed in this study. On these days the sensible heat flux given by the Extra Large Aperture Scintillometer (XLAS; see Kohsiek et al. 2002), representative for the surrounding area, provides much higher estimates than the locally measured value.

For the selected days, we determined the albedo of the Cabauw site from the ratio of daily mean outgoing and incoming shortwave radiation. The results are plotted in Fig. 1. It appears that the albedo varies from day to day with a standard deviation of 0.018 around the average of 0.23. This is the albedo of the reference grass surface as defined by Allen at al. (1998). Considering the environmental conditions of the Cabauw site regarding, for example, albedo, water stress, and advection, we are confident to state that the Cabauw site resembles fairly closely the hypothetical idealized reference FAO grass surface.

b. Remote sensing observations: MSG

The SEVIRI instrument on board the geostationary platform MSG provides top-of-the-atmosphere optical measurements every 15 min and with a spatial resolution of up to 3 km.

Several methodologies have been proposed to derive incoming solar radiation at the surface from remote sensing observations. Most rely on the identification of clouds and/or characterization of cloud properties from visible and infrared observations. Moreover, these methods take into account that under cloudy conditions there is a clear link (anticorrelation) between top of the atmosphere reflectances and solar radiation at the surface.

Here we will consider two different remote sensing products, both retrieved from SEVIRI on board MSG and available in near–real time from the LSA SAF (Trigo et al. 2011; Geiger et al. 2008) and from the KNMI SICCS algorithm (Greuell et al. 2013; Deneke et al. 2008). Both LSA SAF and SICCS products are aggregated to daily averages of global radiation. The high temporal frequency of SEVIRI observations (15 min) allows characterizing the diurnal cycle of incoming solar radiation and therefore producing robust daily estimates. The LSA SAF product has been validated against a wide number of in situ observations [including the Baseline Surface Radiation Network (BSRN)], most of which are in Europe, revealing mean errors ranging between around -4 and $-7\,\mathrm{W\,m^{-2}}$ (Ineichen et al. 2009; Carrer et al. 2012). The SICCS product has also been validated against European BSRN measurements, revealing a similar performance with biases between -1 and $13\,\mathrm{W\,m^{-2}}$ (Greuell et al. 2013).

3. Theory

a. The Schmidt thermodynamic model

In this section, we reformulate the arguments used by Schmidt (1915) to estimate the evaporation of the oceans. We introduce a hypothetical flat box at the grass surface, which contains, besides the vegetation and a soil layer, the lowest layer of the atmosphere with height h. Thus, the volume of the box equals hO, where O is the area of the bottom of the box. Because we consider well-watered grass surface, we assumed that water vapor in the box is saturated at surface temperature. Next, we consider a thermodynamic process in which during a short time interval dt an amount of energy dQ is added corresponding to an available energy flux density $(\mathrm{W\,m^{-2}})$ of A. As a result the temperature in the box will increase by dT and a part of the added energy is used to increase the enthalpy of the air in the box by $m_a c_p dT$, where m_a is the mass of air in the box and c_p is the specific heat of air at constant pressure. Obviously, $m_a = \rho hO$ and with the equation of state for air this can be written as $m_a = (p/RT)hO$ with p the air pressure and R the specific gas constant of air. By dividing the increase of enthalpy in the box by Odt, the mean sensible heat flux density $H = (p/RT)c_p h\, dT/dt$ is obtained. Assuming, as Schmidt did, that the air in the box remains saturated, the water vapor pressure in the box will increase by $e_s(T + dT) - e_s(T) \approx \Delta dT$, with $e_s(T)$ representing the saturated water vapor pressure at temperature T and $\Delta = de_s/dT$, also at T. As a result, the mass of water vapor
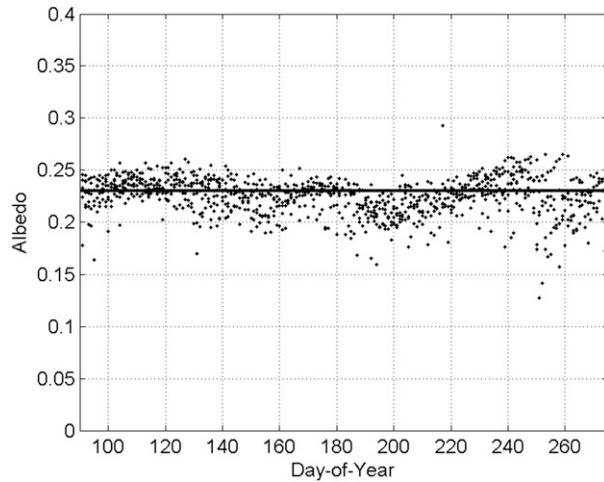
FIG. 1. Measured albedo for days of the year 90–275 at Cabauw during 2007–12.

will increase by dm_v. With the equation of state for water vapor we find that $m_v = (\Delta dT/R_v T)hO$. The energy required to evaporate this amount of water is λdm_v. By dividing by Odt we obtain the latent flux density $\lambda \mathrm{ET} = \lambda \Delta/(R_v T)h\, dT/dt$. With $\gamma = (R_v/R)(c_p p/\lambda)$ we find that the ratio B of the increase of the enthalpy of the air in the box and the energy required for evaporation to keep the water vapor pressure saturated is given by

$$B = \frac{\gamma}{\Delta}. \qquad (2)$$

Note that B can be identified as the Bowen ratio $B = H/\lambda \mathrm{ET}$, and that $A = H + \lambda \mathrm{ET}$. This result is obtained for time step dt. As an extension of Schmidt's approach, we introduce a hypothetical valve in the top of the box, so that at the end of time step dt the increase of enthalpy and water vapor formed in the box during dt can be released into the atmosphere. It is assumed that no energy is required for this release. At the end of each time step the temperature and water vapor content will be reset at their initial values. In the next time interval dt the process is repeated. For a number of time steps this is repeated, covering a total of about 10 min. In the next 10-min period we start with the new actual surface temperature. In this way a quasi-stationary process is simulated for the vertical transfer of heat and water vapor from the surface into the atmosphere.

In our case, where local advection has been excluded, $A = Q^* - G$, where Q^* is the net radiation, and G is the amount of heat stored in the vegetation–soil part in our box. Because we consider 24-hourly averages, G can be ignored. In this way, we arrive at

$$\lambda \mathrm{ET} = \frac{\Delta}{\Delta + \gamma} Q^* = \lambda \mathrm{ET}_{\mathrm{eq}}. \qquad (3)$$

The quantity $\mathrm{ET}_{\mathrm{eq}}$ is the so-called equilibrium evaporation (see, e.g., Raupach 2001). The only assumption made so far is that air over well-watered surfaces close to the ground is saturated and local advection is absent.

With Schmidt (1915), we recognize that in real life air is not saturated and that corrections should be made. Following de Bruin and Holtslag (1982), our correction consists of adding to $\lambda \mathrm{ET}_{\mathrm{eq}}$ a constant β, which leads to

$$\lambda \mathrm{ET} = \lambda \mathrm{ET}_{\mathrm{eq}} + \beta \, (\mathrm{W\,m^{-2}}). \qquad (4)$$

A physical explanation is the entrainment of relatively warm and dry air present aloft in the atmospheric boundary layer (ABL) into the well-mixed ABL during daytime. Consequently, relative humidity in the ABL is less than 100% in spite of a high surface evaporation rate. This explains why a correction factor should be used. It is outside the scope of this paper to discuss the entrainment process in detail. For this the reader is referred to, for example, McNaughton and Spriggs (1986), Jacobs and de Bruin (1992), van Heerwaarden et al. (2010), and Ouwersloot and J. Vilà-Guerau de Arellano (2013). The remaining question is why the parameter β can be considered constant. This will be discussed later.

b. Parameterization of net radiation

For practical and more fundamental reasons, we will apply the SdB formula for net radiation of well-watered grass reported by de Bruin [1987; see also de Bruin and Stricker (2000)]:

$$Q_r^* = (1 - 0.23)K^{\downarrow} - C_S \frac{K^{\downarrow}}{K^{\downarrow}_{\mathrm{ext}}}, \qquad (5)$$

where Q_r^* is net radiation of grass under reference conditions, $K_r = (K^{\downarrow}/K^{\downarrow}_{\mathrm{ext}})$, $K^{\downarrow}$ is the downwelling shortwave radiation at the surface, $K^{\downarrow}_{\mathrm{ext}}$ is downwelling shortwave radiation constant at the top of the atmosphere, and C_S is an empirical constant. De Bruin (1987) reported for unstressed grass of Cabauw $C_S = 110 \, \mathrm{W\,m^{-2}}$. The "universality" of SdB will be discussed later.

This yields

$$\lambda \mathrm{ET} = \frac{\Delta}{\Delta + \gamma} \left[(1 - 0.23)K^{\downarrow} - C_S \frac{K^{\downarrow}}{K^{\downarrow}_{\mathrm{ext}}} \right] + \beta. \qquad (6)$$

Evapotranspiration over the reference surface can be inferred through the application of Eq. (6) to estimations of $K^{\downarrow}$ obtained from remote sensing data, such as MSG.
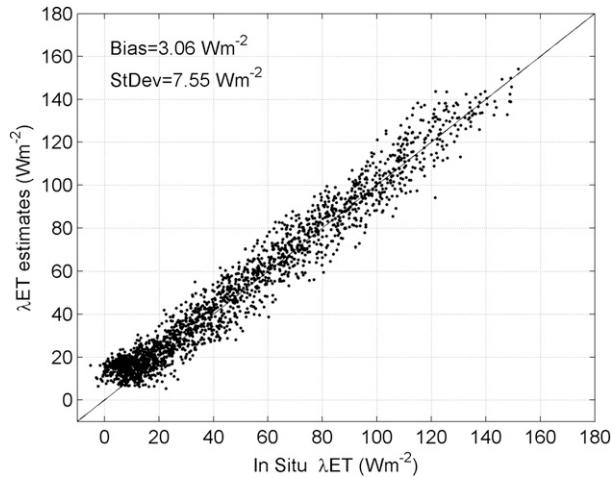
FIG. 2. Latent heat flux estimated according to Eq. (6), that is, using the SdB net radiation formula, plotted against in situ measured values: daily values at Cabauw during 2007–12 except for a limited number of dry and advective days (see text).

FIG. 3. Test net radiation formula of SdB at Cabauw during 2007–12.

Equation (6) requires as input global radiation and air temperature as input only. This applies also for the revised Makkink equation introduced by de Bruin (1987):

$$\lambda \mathrm{ET} = 0.65 \frac{\Delta}{\Delta + \gamma} K^{\downarrow}. \qquad (7)$$

We will provide a separate test of this revised Makkink formula because it is applied in practice quite often in the Netherlands.

4. Experimental validation

a. Validation using ground observations

A test of Eq. (6) applied to ground measurements taken at Cabauw is depicted in Fig. 2. We recall that this concerns daily values for 2007–12, and $\beta \approx 20\,\mathrm{W\,m}^{-2}$, $C_S = 110\,\mathrm{W\,m}^{-2}$. The bias (mean of estimated minus measured values) is $3\,\mathrm{W\,m}^{-2}$ and the standard deviation of this difference is $7.6\,\mathrm{W\,m}^{-2}$.

For the same selected days, a separate test of the SdB formula for daily net radiation applied to ground data is given in Fig. 3, using $C_S = 110\,\mathrm{W\,m}^{-2}$, the value that applies to well-watered "reference" conditions (de Bruin 1987). Linear regression yields a bias of $1.4\,\mathrm{W\,m}^{-2}$ and the standard deviation of this difference is $9.6\,\mathrm{W\,m}^{-2}$.

b. MSG-derived solar and net radiation

Figure 4 shows scatterplots of LSA SAF and SICCS global radiation estimated from MSG SEVIRI satellite observations against in situ observations at Cabauw, for the 2010–12 period. The points in Fig. 4 assume the following conditions concerning the quality indicators
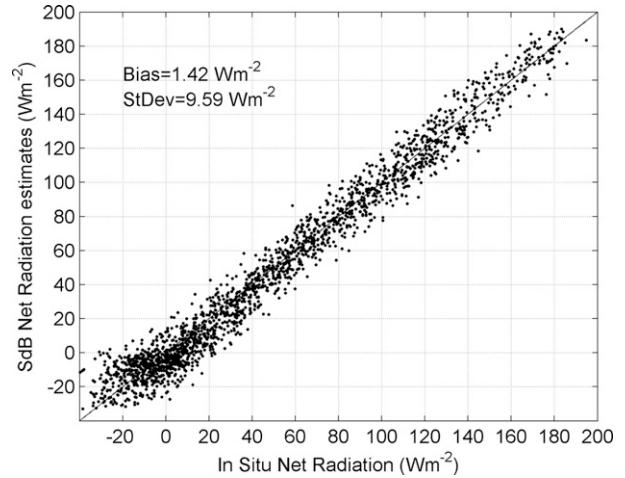
provided when both products are verified simultaneously: (i) the missing SEVIRI observations in the case of the LSA SAF are less than 5% and (ii) quality flag above 0.5 in the case of SICCS. The two solar radiation products reveal comparable behavior, with nearly the same scatter around the observations (the standard deviation of this difference is about $12\,\mathrm{W\,m}^{-2}$). In this case, SICCS has a negligible bias, while the LSA SAF underestimates the observations by $6\,\mathrm{W\,m}^{-2}$. These results are fairly in line with the other validation exercises mentioned above and suggest the two products are of similar quality.

The SICCS product has also been validated against European BSRN measurements, revealing a similar performance with biases between -1 and $13\,\mathrm{W\,m}^{-2}$ (Greuell et al. 2013). Differences between the LSA SAF and SICCS solar radiation products are intrinsically linked to the respective algorithms and underlying assumptions. Estimates are particularly sensitive under cloudy conditions. In this case SICCS relies on the retrieval of cloud properties (optical thickness, effective radius), while the LSA SAF assumes the pixel to be covered by a homogeneous cloud layer, where cloud transmittance is inferred from cloud albedo.

To demonstrate the skill of using remotely sensed estimations of solar fluxes to model net radiation, we compare the output of the SdB formula using the MSG SICCS global radiation with ground measurements (Fig. 5). These results reveal the suitability of the MSG-derived products for practical application. The bias ($1.6\,\mathrm{W\,m}^{-2}$) is small and the standard deviation of this difference ($11.7\,\mathrm{W\,m}^{-2}$) is slightly greater than that found for global solar radiation.

When the net radiation estimates are used to obtain evapotranspiration, that is, through the use of Eq. (6), we
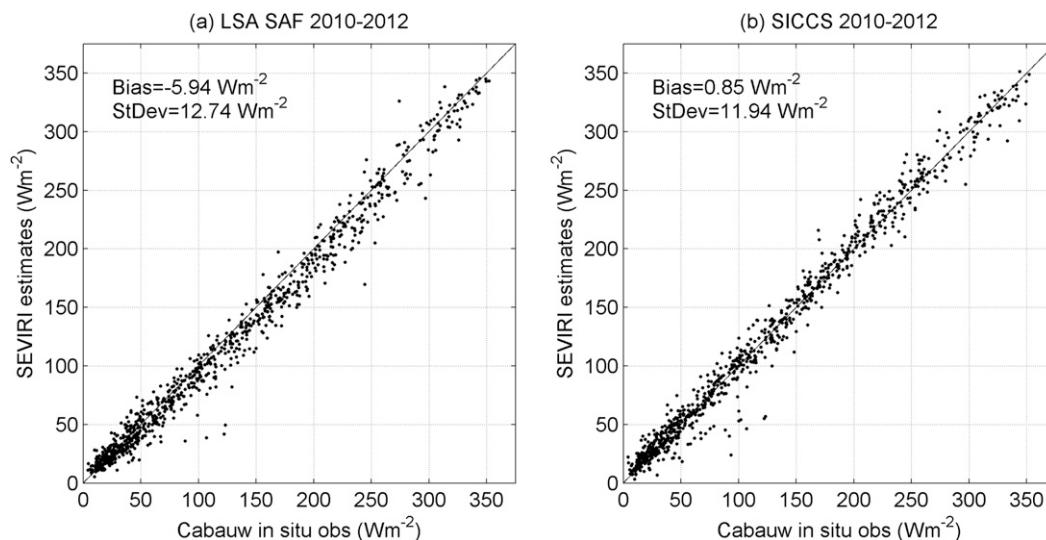
FIG. 4. Scatterplots of daily solar radiation estimates from SEVIRI MSG ($W m^{-2}$) against in situ observations in Cabauw considering (a) LSA SAF and (b) SICCS products. The mean (bias) and standard deviation of differences are also displayed.

do not get any significant degradation of the results obtained from Eq. (6) fed with in situ measurements only (shown in Fig. 2). The comparison with daily evapotranspiration values corresponding to eddy covariance observations (Fig. 6) reveals a bias of 2.8 $W m^{-2}$ and the standard deviation of this difference is 7.7 $W m^{-2}$.

5. Discussion

This work is focused on a model for actual ET of actual grass that is close to hypothetical FAO grass, accepting that the interpretation of the FAO definition "extensive field" excludes advection. The methodology is based on the thermodynamic model by Schmidt (1915), published 100 years ago. Furthermore, we argue that air above well-watered grass is never saturated because after sunrise warm and dry air is entrained into the ABL, explaining the need for a correction factor β [Eq. (3)]. Because of weather variability that characterizes the climate conditions at Cabauw, β is expected to show a day-to-day variation. To get an impression of this variability, we plotted $\beta = \lambda ET_{measured} - [\Delta/(\Delta + \gamma)] [(1 - 0.23)K^{\downarrow} - C_S(K^{\downarrow}/K_{ext}^{\downarrow})]$ in Fig. 7, obtained from in situ ET estimates and MSG and computing β from Eq. (6). It is seen that, strictly speaking, β is indeed not constant, but the random scatter around its mean value of about 20 $W m^{-2}$ is relatively small. This scatter results in a random error in ET of about 10 $W m^{-2}$, which corresponds to about 0.3 mm day^{-1}.

When the measured β is plotted against the wind speed, or the vapor pressure deficit vpd $= e_s(T) - e_a$,

where e_a is the daily mean of the measured vapor pressure and T the daily mean air temperature at 2 m, or against their product, we do not find a clear correlation. This implies that vpd and wind speed have a second-order influence on actual ET of well-watered grass.

The use of a single site for validating the approach described here may be a limiting factor. However, the analysis of other sites, such as those within the well-known EUROFLUX network (e.g., Hu et al. 2015; see also Valentini 2003), did not reveal any other with the characteristics of Cabauw, where measurements are provided within a wide green nonstresses grass area. Nevertheless, we argue that, since the formulation described above is fairly based on fundamental physical principles, our model is applicable for all similar grass sites. The readers are invited to test our models against other independent data. For the time being, we conclude that, because our formulas are based on first physical principles, our model is applicable for all similar grass sites.

Furthermore, the fact that for Cabauw site actual ET appears to be determined primarily by global radiation and air temperature was found earlier by de Bruin (1987), who tested the revised Makkink Eq. (7) for an older dataset. A test of this approach is shown in Fig. 8. It is seen that the revised Makkink tends to overestimate slightly at high values, but the overall performance is very suitable for most practical applications.

Is the model given by Eq. (6) suitable for estimating the crop reference evapotranspiration (i.e., ET$_o$) in
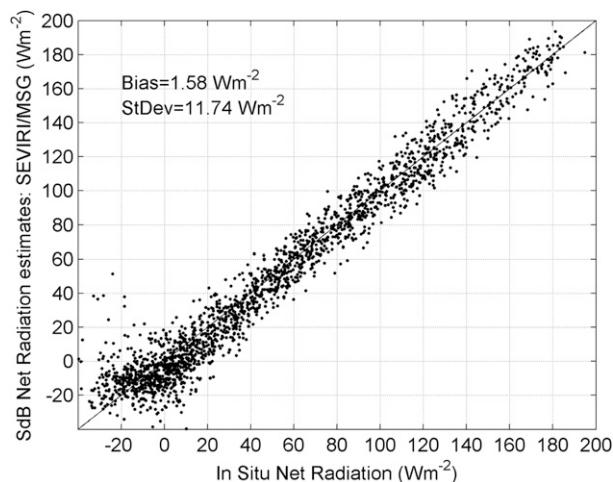
FIG. 5. As in Fig. 3, but for SEVIRI MSG global radiation according
the SICCS algorithm.

FIG. 6. As in Fig. 2, but for SEVIRI MSG global radiation (SICCS)
as input.

irrigation practice? We cannot answer this question because of the ambiguity in the FAO definition concerning effects of local advection. All we can conclude here is that, if in irrigation water management the FAO definition of ET_o is interpreted such that local advection should be excluded, then our model can be applied to estimate ET_o. However, if, local advection is to be included, then our model will lead to underestimations. In a future study we will consider actual ET of an actual grass field near Córdoba, Spain, in a semiarid climate. This experimental field is designed to resemble as close as possible FAO reference grass, except that the size of the field is not extensive, but limited to $100 \times 100 \, m^2$. In the dry season the surrounding area is often dry. Berengena and Gavilán (2005) showed that actual ET measured with a precision lysimeter in the center of this field exceeds net radiation by the end of the dry season. They tested, among others, the Makkink equation and found that this formula indeed underestimates actual ET. The deviation between measured and estimated values is simply due to the fact Makkink, such as the ET model derived here, considers nonadvective conditions only. Under the conditions observed in Córdoba, however, sensible heat advected from upwind dry terrain is an additional energy source for ET. Then Schmidt's thermodynamic approach, including corrections for entrainment, leads to

$$\lambda ET = \frac{\Delta}{\Delta + \gamma}(Q^* + Q_{adv}) + \beta, \qquad (8)$$

where Q_{adv} is the sensible heat horizontally advected from dry upwind terrain. Besides meteorological variables, this additional energy term will depend on the properties and dimensions of the upwind terrain. The
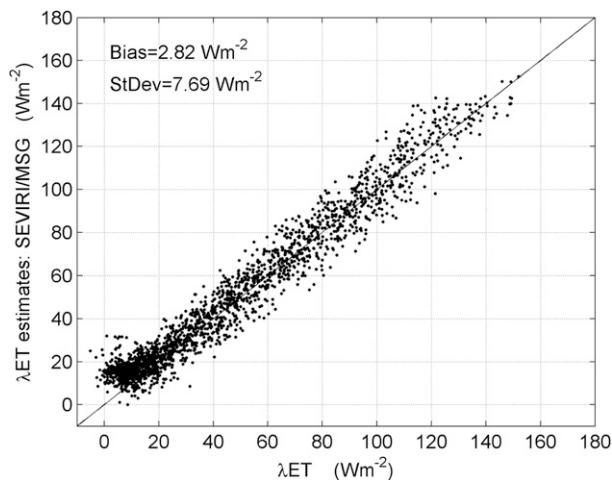
question of how to parameterize in terms of easy-to-measure meteorological quantities is outside the scope of this paper. In irrigation practice, the FAO formula for crop reference evapotranspiration is often applied in semiarid regions using meteorological data gathered over small fields, by which local advection is expected to play a role. Tacitly, it is then assumed that this formula includes effects of Q_{adv} regardless of the properties of adjacent fields.

Our model can be applicable in other areas; for example, in lumped rainfall–runoff models it can be applied to estimate the so-called potential evapotranspiration (see, e.g., Oudin et al. 2005). Furthermore, the approach described here can be applicable in climate change studies such as those carried out by van der Schrier et al. (2006) and Sheffield et al. (2012).

Note that our Eq. (4) in a slightly different form was tested earlier by de Bruin and Holtslag (1997). It has been applied in practical studies on air pollution in which estimates of the evolution of the convective boundary height are needed (van Ulden and Holtslag 1985; Holtslag and van Ulden 1983; Pechinger et al. 1997; Beljaars and Bosveld 1997; de Rooy and Holtslag 1999). Note that Beljaars and Bosveld (1997) found that the Penman–Monteith equation with a fixed surface resistance did not work for Cabauw, that is, they obtained a diurnal variation for the mean surface resistance [as reported by Allen et al. (2006)]. Nowadays, such land parameterization schemes are implemented in weather forecast models (van den Hurk et al. 2000; Ek and Holtslag 2004).

Recently, Kleidon and Renner (2013) and Kleidon et al. (2014) considered the thermodynamic limitations of the hydrological cycle and arrived at a very similar finding to that by Schmidt (1915) and by us.
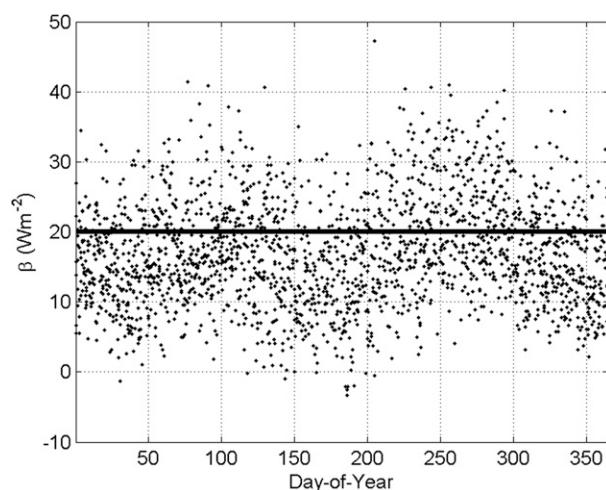
FIG. 7. Measured β as function of day of year.

FIG. 8. Test of the revised Makkink Eq. (7) as proposed by de Bruin (1987). Daily values are for Cabauw during 2007–12.

A by-product of this study is that the SdB parameterization for net radiation over well-watered grass appears to work very well. It has the advantage that it requires global radiation as input only. This confirms the earlier finding by de Bruin (1987), but this was for the same Cabauw site. The question arises whether the constant C_S of $110 \, \mathrm{W \, m^{-2}}$ for SdB is a universal constant. A set of tests taken with measurements from the Haarweg site (near Wageningen, the Netherlands) indicated the same good results, but further tests of SdB are needed. Apparently, net radiation Q_r^* includes empirically both humidity and cloudiness effects on incoming longwave radiation. These features will be discussed in more detail in a separate research note.

We successfully applied the SdB formula using satellite-derived global radiation. Note that Dong et al. (1992) describe satellite-derived net radiation.

It should be stressed that the SdB formula is developed for well-watered grass. De Bruin (1987) showed that "surface dryness" may significantly affect outgoing longwave radiation. See, for instance, de Bruin et al. (2012), who analyzed measured net radiation data gathered in Burkina Faso over bare soil. In the dry season, net radiation is much smaller than that given by SdB or the net radiation estimate given in FAO-56 (Allen et al. 1998).

Another aspect of the present study is that the revised approach for ET estimation yields reasonable results for all seasons. Note that de Bruin and Holtslag (1982) considered the growing season only, when net radiation is relatively high. This is an interesting result, since in wintertime solar radiation is no longer the dominant energy source and actual evapotranspiration can exceed net radiation because of mesoscale advection of sensible heat (Pielke 2013). Further study would still be needed to fully understand the seasonal variability of
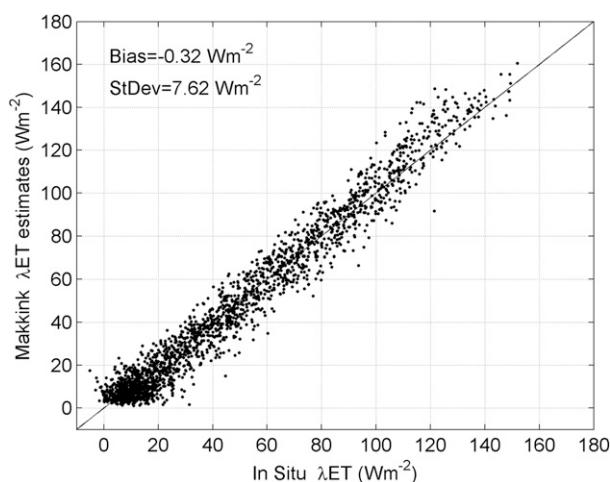
mechanisms involved in ET over nonstressed grass surfaces. In any case, the growing season is most relevant for agriculture, and solar radiation is then the most significant energy source for evapotranspiration.

Finally, the results discussed here reveal that the global radiation MSG products, operationally delivered by the EUMETSAT LSA SAF and by the KNMI SICCS systems, are accurate enough for practical application to estimate our advection-free reference crop in midlatitude climate regions from geostationary satellite imagery.

Despite the fact that installation and maintenance of a ground-based network of standard meteorological (FAO) stations is increasingly expensive and labor intensive, the availability of remote sensing data covering wide areas with high spatial and temporal samplings is increasing. As such, it is shown that actual ET of extensive well-watered grass fields can be reliably estimated from geostationary satellite data, in line with what was proposed in other similar studies such as Choudhury and de Bruin (1995), Bois et al. (2008), Hart et al. (2009), de Bruin et al. (2010, 2012), and Cammalleri and Ciraolo (2013), who explored satellite-derived information for estimation of (crop reference) evapotranspiration.

6. Conclusions

Starting with the 100-yr-old thermodynamic approach by Schmidt (1915) and considering more recent insight into the planetary boundary layer process of entrainment, a simple formula is derived for daily actual evapotranspiration of a well-watered grass field that closely resembles FAO reference grass. In addition, it is found that the empirical SdB formula for daily net radiation of well-watered

grass, as proposed by de Bruin (1987), performs well. Combining these findings yields an approximation of daily actual ET, requiring global radiation and air temperature as input only. This was tested against in situ observations at Cabauw for 2007–12, using (i) in situ measured input and (ii) global radiation obtained from MSG imagery. A fair agreement was found, that is, a bias of $3 \, \mathrm{W \, m^{-2}}$ and an error (standard deviation of estimate minus measured) of $7.6 \, \mathrm{W \, m^{-2}}$. Separately, we tested two algorithms for MSG-derived global radiation, notably, the LSA SAF and SICCS schemes, and found a bias and the standard deviation of this difference of -5.9 and $12.7 \, \mathrm{W \, m^{-2}}$ for LSA SAF and 0.9 and $11.9 \, \mathrm{W \, m^{-2}}$ for SICCS.

It is recalled that our study is confined to cases without local advection. The question of whether or not our new simple approach to estimate actual ET can be applied to determine the FAO reference crop evapotranspiration ET_o could not be answered because of the ambiguity in the definition regarding accounting for local advection effects. If one interprets the definition such that local advection is excluded, our approach can be applied.

If local advection should be included, then the rationale of Schmidt (1915) is still applicable, but then an additional parameterization of the term Q_{adv} in Eq. (8) should be included.

REFERENCES

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith, 1998: Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, 300 pp. [Available online at www.fao.org/docrep/X0490E/X0490E00.htm.]

——, and Coauthors, 2006: A recommendation on standardized surface resistance for hourly calculation of reference ET_o by the FAO56 Penman–Monteith method. *Agric. Water Manage.*, **81**, 1–22, doi:10.1016/j.agwat.2005.03.007.

Beljaars, A. C. M., and F. C. Bosveld, 1997: Cabauw data for the validation of land surface parameterization schemes. *J. Climate*, **10**, 1172–1193, doi:10.1175/1520-0442(1997)010<1172:CDFTVO>2.0.CO;2.

Berengena, J., and P. Gavilán, 2005: Reference evapotranspiration estimation in a highly advective semiarid environment. *J. Irrig. Drain. Eng.*, **131**, 147–163, doi:10.1061/(ASCE)0733-9437(2005)131:2(147).

Bois, B., P. Pieria, C. van Leeuwen, L. Wald, F. Huard, J.-P. Gaudillere, and E. Saur, 2008: Using remotely sensed solar radiation data for reference evapotranspiration estimation at a daily time step. *Agric. For. Meteor.*, **148**, 619–630, doi:10.1016/j.agrformet.2007.11.005.

Cammalleri, C., and G. Ciraolo, 2013: A simple method to directly retrieve reference evapotranspiration from geostationary satellite images. *Int. J. Appl. Earth Obs. Geoinf.*, **21**, 149–158, doi:10.1016/j.jag.2012.08.008.

Carrer, D., S. Lafont, J.-L. Roujean, J.-C. Calvet, C. Meurey, P. Le Moigne, and I. F. Trigo, 2012: Incoming solar and infrared radiation derived from METEOSAT: Impact on the modeled land water and energy budget over France. *J. Hydrometeor.*, **13**, 504–520, doi:10.1175/JHM-D-11-059.1.

CESAR Consortium, 2013: Datasets cesar_surface_meteo_lc1_t10_v10 and cesar_surface_flux_lc1_t10_v10. Subset used 2007–2012, accessed 2013. [Available online at http://www.cesar-database.nl/.]

Choudhury, B. J., and H. A. R. de Bruin, 1995: First order approach for estimation unstressed transpiration from meteorological satellite data. *Adv. Space Res.*, **16**, 167–176, doi:10.1016/0273-1177(95)00398-X.

de Bruin, H. A. R., 1983: A model for the Priestley–Taylor parameter α. *J. Appl. Meteor.*, **22**, 572–578, doi:10.1175/1520-0450(1983)022<0572:AMFTPT>2.0.CO;2.

——, 1987: From Penman to Makkink. *Proceedings and Information: TNO Committee on Hydrological Research No. 39*, J. C. Hooghart, Ed., Netherlands Organization for Applied Scientific Research, 5–30.

——, and A. A. M. Holtslag, 1982: A simple parameterization of the surface fluxes of sensible and latent heat during daytime compared with the Penman–Monteith concept. *J. Appl. Meteor.*, **21**, 1610–1621, doi:10.1175/1520-0450(1982)021<1610:ASPOTS>2.0.CO;2.

——, and J. N. M. Stricker, 2000: Evaporation of grass under non-restricted soil moisture conditions. *Hydrol. Sci. J.*, **45**, 391–406, doi:10.1080/02626660009492337.

——, I. F. Trigo, M. A. Jitan, N. Temesgen Enku, C. van der Tol, and A. S. M. Gieske, 2010: Reference crop evapotranspiration derived from geo-stationary satellite imagery. A case study for the Fogera flood plain, NW-Ethiopia and the Jordan Valley, Jordan. *Hydrol. Earth Syst. Sci.*, **14**, 2219–2228, doi:10.5194/hess-14-2219-2010.

——, ——, P. Galivan, A. Martinez, and M. P. Gonzales, 2012: Reference crop evapotranspiration estimated from geostationary satellite imagery. *IAHS Publ.*, **352**, 111–114.

Deneke, H. M., A. J. Feijt, and R. A. Roebeling, 2008: Estimating surface solar irradiance from METEOSAT SEVIRI-derived cloud properties. *Remote Sens. Environ.*, **112**, 3131–3141, doi:10.1016/j.rse.2008.03.012.

de Rooy, W. C., and A. A. M. Holtslag, 1999: Estimation of surface radiation and energy flux densities from single-level weather. *J. Appl. Meteor.*, **38**, 526–540, doi:10.1175/1520-0450(1999)038<0526:EOSRAE>2.0.CO;2.

Dingman, S. L., 1992: *Physical Hydrology*. Prentice Hall, 575 pp.

Dong, A., S. Grattan, J. Carroll, and C. Prashar, 1992: Estimation of daytime net radiation over well-watered grass. *J. Irrig. Drain. Eng.*, **118**, 466–479, doi:10.1061/(ASCE)0733-9437(1992)118:3(466).

Doorenbos, J., and W. O. Pruitt, 1975: Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24, Food and Agriculture Organization, 179 pp. [Available online at http://www.fao.org/3/a-f2430e.pdf.]

Ek, M. B., and A. A. M. Holtslag, 2004: Influence of soil moisture on boundary layer cloud development. *J. Hydrometeor.*, **5**, 86–99, doi:10.1175/1525-7541(2004)005<0086:IOSMOB>2.0.CO;2.

Geiger, B., C. Meurey, D. Lajas, L. Franchistéguy, D. Carrer, and J.-L. Roujean, 2008: Near real-time provision of downwelling

shortwave radiation estimates derived from satellite observations. *Meteor. Appl.*, **15**, 411–420, doi:10.1002/met.84.

Greuell, W., J. F. Meirink, and P. Wang, 2013: Retrieval and validation of global, direct, and diffuse irradiance derived from SEVIRI satellite observations. *J. Geophys. Res. Atmos.*, **118**, 2340–2361, doi:10.1002/jgrd.50194.

Hart, Q., M. Brugnach, B. Temesgen, C. Rueda, S. Ustin, and K. Frame, 2009: Daily reference evapotranspiration for California using satellite imagery and weather station measurement interpolation. *Civ. Eng. Environ. Syst.*, **26**, 19–33, doi:10.1080/10286600802003500.

Holtslag, A. A. M., and A. P. van Ulden, 1983: A simple scheme for daytime estimates of the surface fluxes from routine weather data. *Climate Appl. Meteor.*, **22**, 517–529, doi:10.1175/1520-0450(1983)022<0517:ASSFDE>2.0.CO;2.

Hu, G., L. Jia, and M. Menenti, 2015: Comparison of MOD16 and LSA-SAF MSG evapotranspiration products over Europe for 2011. *Remote Sens. Environ.*, **156**, 510–526, doi:10.1016/j.rse.2014.10.017.

Ineichen, P., C. Barroso, B. Geiger, R. Hollmann, A. Marsouin, and R. Mueller, 2009: Satellite application facilities irradiance products: Hourly time step comparison and validation over Europe. *Int. J. Remote Sens.*, **30**, 5549–5571, doi:10.1080/01431160802680560.

Jacobs, C. M. J., and H. A. R. de Bruin, 1992: The sensitivity of regional transpiration to land-surface characteristics: Significance of feedback. *J. Climate*, **5**, 683–698, doi:10.1175/1520-0442(1992)005<0683:TSORTT>2.0.CO;2.

Katerji, N., and G. Rana, 2011: Crop reference evapotranspiration: A discussion of the concept, analysis of the process and validation. *Water Resour. Manage.*, **25**, 1581–1600, doi:10.1007/s11269-010-9762-1.

——, and ——, 2014: FAO-56 methodology for determining water requirement of irrigated crops: Critical examination of the concepts, alternative proposals and validation in Mediterranean region. *Theor. Appl. Climatol.*, **116**, 515–536, doi:10.1007/s00704-013-0972-3.

Kleidon, A., and M. Renner, 2013: Thermodynamic limits of hydrologic cycling within the Earth system: Concepts, estimates and implications. *Hydrol. Earth Syst. Sci.*, **17**, 2873–2892, doi:10.5194/hess-17-2873-2013.

——, ——, and P. Porada, 2014: Estimates of the climatological land surface energy and water balance derived from maximum convective power. *Hydrol. Earth Syst. Sci.*, **18**, 2201–2218, doi:10.5194/hess-18-2201-2014.

Kohsiek, W., W. M. L. Meijninger, A. F. Moene, B. G. Heusinkveld, O. K. Hartogensis, W. C. A. M. Hillen, and H. A. R. De Bruin, 2002: An extra large aperture scintillometer for long range applications. *Bound.-Layer Meteor.*, **105**, 119–127, doi:10.1023/A:1019600908144.

McMahon, T. A., M. C. Peel, L. Lowe, R. Srikanthan, and T. R. McVicar, 2013: Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: A pragmatic synthesis. *Hydrol. Earth Syst. Sci.*, **17**, 1331–1363, doi:10.5194/hess-17-1331-2013.

McNaughton, K. G., and T. W. Spriggs, 1986: A mixed-layer model for regional evaporation. *Bound.-Layer Meteor.*, **34**, 243–262, doi:10.1007/BF00122381.

Monna, W., and F. Bosveld, 2013: In higher spheres: 40 years of observations at the Cabauw Site. KNMI-Publication 232,

KNMI, 56 pp. [Available online at http://www.cesar-observatory.nl/publications/reports/knmipub232.pdf.]

Oudin, L., F. Hervieu, C. Michel, C. Perrin, V. Andreassian, F. Anctil, and C. Loumagne, 2005: Which potential evapotranspiration input for a lumped rainfall–runoff model? Part 2—Towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *J. Hydrol.*, **303**, 290–306, doi:10.1016/j.jhydrol.2004.08.026.

Ouwersloot, H. G., and J. Vilà-Guerau de Arellano, 2013: Analytical solution for the convectively-mixed atmospheric boundary layer. *Bound.-Layer Meteor.*, **148**, 557–583, doi:10.1007/s10546-013-9816-z.

Pechinger, U., G. Erbes, P.-E. Johansson, A. Karppinen, L. Musson-Genon, G. Omstedt, and Ph. Tercier, 1997: Surface energy balance. Cost Action 710—Final report: Harmonization of pre-processing of meteorological data for atmospheric dispersion models, European Commission, EUR 18195 EN, 3–94.

Pielke, R. A., Sr., 2013: *Mesoscale Meteorological Modeling.* 3rd ed., Academic Press, 720 pp.

Raupach, M. R., 2001: Combination theory and equilibrium evaporation. *Quart. J. Roy. Meteor. Soc.*, **127**, 1149–1181, doi:10.1002/qj.49712757402.

Schmidt, W., 1915: Strahlung und Verdunstung an freien Wasserflächen; ein Beitrag zum Wärmehaushalt des Weltmeers und zum Wasserhaushalt der Erde (Radiation and evaporation over open water surfaces; a contribution to the heat budget of the world ocean and to the water budget of the earth). *Ann. Hydro. Maritimen Meteor.*, **43**, 111–124, 169–178.

Sheffield, J., E. F. Wood, and M. L. Roderick, 2012: Little change in global drought over the past 60 years. *Nature*, **491**, 435–438, doi:10.1038/nature11575.

Trigo, I. F., and Coauthors, 2011: The satellite application facility on land surface analysis. *Int. J. Remote Sens.*, **32**, 2725–2744, doi:10.1080/01431161003743199.

Valentini, R., 2003: EUROFLUX: An integrated network for studying the long-term responses of biosphere exchanges of carbon, water, and energy of European forests. *Fluxes of Carbon, Water and Energy of European Forests*, R. Valentini, Ed., Ecological Studies, Vol. 163, Springer, 1–8, doi:10.1007/978-3-662-05171-9_1.

van den Hurk, B. J. J. M., P. Viterbo, and A. C. M. Beljaars, and A. K. Betts, 2000: Offline validation of the ERA40 surface scheme. ECMWF Tech Memo. 295, ECMWF, 42 pp. [Available online at http://www.ecmwf.int/sites/default/files/elibrary/2000/12900-offline-validation-era40-surface-scheme.pdf.]

van der Schrier, G., K. R. Briffa, P. D. Jones, and T. J. Osborn, 2006: Summer moisture variability across Europe. *J. Climate*, **19**, 2818–2834, doi:10.1175/JCLI3734.1.

van Heerwaarden, C. C., J. Vilà-Guerau de Arellano, A. Gounou, F. Guichard, and F. Couvreux, 2010: Understanding the daily cycle of evapotranspiration: A method to quantify the influence of forcings and feedbacks. *J. Hydrometeor.*, **11**, 1405–1422, doi:10.1175/2010JHM1272.1.

van Ulden, A. P., and A. A. M. Holtslag, 1985: Estimation of atmospheric boundary layer parameters for diffusion applications. *J. Climate Appl. Meteor.*, **24**, 1196–1207, doi:10.1175/1520-0450(1985)024<1196:EOABLP>2.0.CO;2.