Comparison of the performance of net radiation calculation models

J.H. Kjaersgaard[a,b*], R.H. Cuenca[b], A. Martínez-Cob[c], P. Gavilán[d], F. Plauborg[e], M. Mollerup[a], S. Hansen[a]

[a] Department of Agricultural Sciences, University of Copenhagen, Højbakkegaard Alle 9, DK-2630 Taastrup, Denmark

[b] Department of Biological and Ecological Engineering, Oregon State University, 116 Gilmore Hall, Corvallis OR 97331, USA

[c] Departamento de Suelo y Agua, Est. Exp. Aula Dei (CSIC), Apartado 202, 50080 Zaragoza, Spain

[d] Instituto de Investigación y Formación Agraria y Pesquera, CIFA Alameda del Obispo, Apartado 3.092, 14080 Córdoba, Spain

[e] Department of Agroecology, University of Aarhus, P.O. Box 50, DK-8830 Tjele, Denmark

*Corresponding author: Jeppe Kjaersgaard, Department of Agricultural Sciences, University of Copenhagen, Højbakkegaard Alle 9, DK-2630 Taastrup, Denmark. jehk@dsr.life.ku.dk, phone +45 3528 3396, fax +45 3528 2175.

Abstract

Daily values of net radiation are used in many applications of crop growth modelling and agricultural water management. Measurements of net radiation are not part of the routine measurement program at many weather stations and are commonly estimated based on other meteorological parameters. Daily values of net radiation were calculated using three net outgoing long wave radiation models and compared to measured values. Four meteorological datasets representing two climate regimes, a sub-humid, high latitude environment and a semi-arid mid-latitude environment, were used to test the models. The long wave radiation models included a physically based model, an empirical model from the literature and a new empirical model. Both empirical models used only solar radiation as required meteorological input. The long wave radiation models were used with model calibration coefficients from the literature and with locally calibrated ones. A measured, average albedo value of 0.25 was used at the high-latitude sites. A fixed albedo value of 0.25 resulted in less bias and scatter at the mid-latitude sites compared to other albedo values. When used with model coefficients calibrated locally or developed for specific climate regimes, the predictions of the physically based model had slightly lower bias and scatter than the empirical models. When used with their original model coefficients, the physically based model had a higher bias than the measurement error of the net radiation instruments used. The performance of the empirical models was nearly identical at all sites. Since the empirical models were easier to use and simpler to calibrate than the physically based models, the results indicate that the empirical models can be used as a good substitute for the physically based ones when available meteorological input data is limited. Model predictions were found to have a higher bias and scatter when using summed calculated hourly time steps compared to using daily input data.

Suggested keywords: Net radiation, net long wave radiation, albedo, modelling.

1. Introduction

Net radiation R_n is the quantity of radiant energy available at a vegetation or ground surface to drive biological and physical processes. Quantification of R_n is required in numerous practical applications in agricultural crop planning and management and at various scales in crop yield modelling studies, plant and nutrient cycling assessments. and agricultural water management. With the advance of models used in real-time irrigation planning and plant biomass estimation, R_n is required at daily timesteps (Hansen et al., 1990; Allen et al., 1998).

Direct measurement of R_n is complicated by net radiometers being delicate instruments that require frequent maintenance and calibration. An additional problem is providing a standard surface for the measurement (Monteith and Unsworth, 1990; Alados et al., 2003). R_n data are therefore not readily available from many weather stations (Dong et al., 1992; Kessler and Jaeger, 1999) or may not be of high quality (ASCE-EWRI, 2005), and calculated values of R_n are commonly used (FAO, 1990; Monteith and Unsworth, 1990; Allen et al., 1998).

Denoting radiation flux directed towards the surface as positive, R_n is the sum of incoming and outgoing shortwave and long wave radiation

$$R_n = S_i - S_o + L_i - L_o = (1-\alpha)S_i - L_n \qquad (1)$$

where S_i is incoming shortwave radiation; S_o is outgoing shortwave radiation; L_i is incoming long wave radiation; L_o is outgoing long wave radiation; α is albedo, i.e. canopy reflection coefficient integrated over all shortwave bands; and L_n is net outgoing long wave radiation.

The radiation components are strongly influenced by the presence, type and diurnal distribution of clouds (Duffie and Beckman, 2006). Clouds at high elevations such as cirrus are normally colder and more transparent compared to clouds at medium to low elevations (Monteith and Unsworth, 1990). While S_i received at the Earth's surface is strongly affected by cloud cover and cloud type due to differences in cloud transparency and geometry, L_i radiation shows less dependence on clouds (Arking, 1991). Water vapour, aerosols, carbon dioxide and trace gases throughout the atmosphere emit long wave radiation and more than half of the L_i received at the ground surface is emitted within the lowest 100 m of the atmosphere (Monteith and Unsworth, 1990; Arking, 1991; Duffie and Beckman, 2006). Arking (1991) showed that for latitudes less the 65° a relative increase in cirrus cloud and medium/low cloud amount increases and decreases, respectively net radiation below the clouds.

Detailed information about cloud height, type and distribution is usually not recorded at standard weather stations. For practical applications, models based on available meteorological information measured at screen height have been developed (Duffie and Beckman, 2006). Simple linear and multiple linear regression models have commonly been used to estimate R_n from S_i and other meteorological parameters (Fritschen, 1967; Aslyng, 1974; Kaminsky and Dubayah, 1997; Irmak et al., 2003). However, the empirically determined regression coefficients are usually only valid over a limited spatial scale which restricts their usability on larger scales or at other locations (Fritschen, 1967; Alados et al., 2003; Nandigiri and Kovoor, 2005).

Other R_n estimation methods solve Eq. 1 by estimating the individual terms separately. Daily values of S_i are readily obtainable from many weather stations (Alados et al., 2003). Albedo values vary for different surfaces, but generally range from 0.20 to 0.25 for shortwave radiation for most green field crops with full vegetation cover when viewed from nadir (Fritschen, 1967; Brutsaert, 1982; Mayer et al., 1999). The albedo varies as a consequence of changing sun angles during the day and over the year. With lower sun angles, the albedo is normally higher (Paltridge and Platt, 1976). USDA-SCS (1993) suggested calculating daily albedo as

$$\alpha_d = A_d + B_d \theta_m + C_d \exp\left(\frac{-\theta_m}{D_d}\right) \qquad (2)$$

where α_d is average daily albedo, θ_m is the sun angle (°) above the horizon at solar noon and calibration coefficients are $A_d = 0.108$, $B_d = 0.000939$, $C_d = 0.257$ and $D_d = 57.3$. The calibration coefficients in Eq. 2 were derived for sun angles ≥ 10° and a ratio of S_i to extraterrestrial radiation $S_a \geq 0.375$. For $S_i/S_a < 0.375$, Dong et al. (1992) suggested an albedo value of 0.26.

Since it is difficult to obtain reliable long wave radiation measurements (Alados et al., 2003), L_n in Eq. 1 can be computed based on other meteorological variables such as S_i, water vapour pressure (e_a) and air temperature (T_a) (Jensen et al., 1990). A widely used method to estimate L_n over short grass for daily timesteps (Wright and Jensen, 1972; Jensen et al., 1990; FAO, 1990; Allen et al., 1998; ASCE-EWRI, 2005) is

$$L_n = \sigma\left[\frac{T_{\max,K}{}^4 + T_{\min,K}{}^4}{2}\right]\left(a_l + b_l\sqrt{e_a}\right)\left(a_c\frac{S_i}{S_{io}} + b_c\right) \qquad (3)$$

where σ is Stefan-Boltzmann constant (4.903 10^{-9} MJ K^{-4} m^{-2} d^{-1}); $T_{max,K}$ and $T_{min,K}$ are daily maximum and minimum air temperature (K) at screen height (normally 2 m), respectively; S_{io} is clear-sky radiation (MJ m^{-2} day^{-1}); a_l, b_l, a_c, b_c are calibration coefficients (dimensionless). Allen (1996) and ASCE-EWRI (2005) outlined methods to estimate theoretical S_{io} curves.

The model in Eq. 3 follows Stefan-Boltzmann relationships for calculating L_o emitted from the ground and vegetation, and L_i emitted from the atmosphere and clouds. Clear-sky net emittance based on screen level e_a is calculated using the relationship developed by Brunt (1932). The radiation emitted by clouds is calculated using an empirical relationship based on the ratio between S_i and S_{io} suggested by Wright and Jensen (1972). The general calibration coefficients used in the net emittance and cloudiness functions of Eq 3 are subject to local calibration when measurements of incoming and outgoing long wave radiation are available (FAO, 1990; Jensen et al., 1990; Allen et al., 1998).

In many practical applications the available meteorological input is often limited (Allen et al., 2007), incomplete or of poor quality (Jensen et. al., 1990; ASCE-EWRI, 2005). In such cases R_n has to be estimated based on minimum meteorological input. Hence, a new model to calculate L_n based on only S_i is suggested

$$L_n = \left(c_c \frac{S_i}{S_{io}} \right) \tag{4}$$

where c_c is a calibration coefficient. Eq 4 is an abbreviated form of Eq. 3 with b_c set to zero, and the Stefan-Boltzmann constant, air temperature, the Brunt function for net emittance and the a_c in the cloudiness function are merged into a single calibration coefficient, c_c

Another simple method for calculating L_n was suggested by Slob (unpublished, c.f. De Bruin and Stricker (2000)).

$$L_n = \left(c_s \frac{S_i}{S_a} \right) \tag{5}$$

where c_s is a calibration coefficient and S_a is extraterrestrial radiation. The model in Eq. 5 is intended for use on a daily or n-day basis (De Bruin and Stricker, 2000).

The R_n estimation model in Eq. 3 was developed using data from an arid climate regime (Wright and Jensen, 1972). Tests of the model have generally shown better agreement with measured values than other R_n estimation models (FAO, 1990; Allen et al., 1998). However analysis by Jensen et al. (1990) and Yin et al. (2008) indicated that Eq. 3 required further testing under other climate regimes. The purpose of this study was to test the performance of Eqs. 3 through 5 as input to Eq. 1 to predict R_n on a daily basis in sub-humid high latitude and semi-arid mid-latitude climate regimes. Calculated values of R_n were compared to measured values from four weather stations. Tests were made to determine how 1) model calibration coefficients, 2) α, 3) location, 4) daily versus sub-daily input data, 5) time of year and 6) cloud amount influenced model performance.

2. Materials and methods

2.1 Experimental sites

Meteorological data from four weather stations were used in this study, Table 1. The Taastrup and Foulum sites are located in a sub-humid, high latitude climate regime in Denmark and the Zaragoza and Córdoba sites are located in a semi-arid, mid-latitude climate regime in Spain. The ground at the climate stations was covered by short green grass. The sites have been described by Jensen (1996), Plauborg and Jensen (1998), Faci et al. (1994), Berengena and Gavilán (2005) and Martínez-Cob et al. (2005).

The climate patterns at the high latitude sites were described by Kjaersgaard et al. (2007). There were no objects to obstruct the radiation at low sun angles at the Taastrup and Foulum sites and the levelness and clearness of instrument domes was checked daily. All radiometers at the Taastrup and Foulum sites were calibrated annually against a reference pyranometer, which was calibrated regularly at the World Radiation Centre, Davos, Switzerland. Hence, net radiometers were only calibrated for shortwave radiation. Discrepancies between the field radiometers and the reference of up to ± 8.0 % were observed occurring after rebuilding instruments after animal attacks. Data from periods with damaged instruments were identified from the station records and discarded.

The climate at the two mid-latitude sites is Mediterranean semi-arid. The Zaragoza site is located in northeast Spain in central Ebro River valley. The mean air temperature is 14.6 °C. Annual precipitation averages 330 mm, of which 60 % falls during spring and autumn (Cuadrat, 1999). The Córdoba site is located in south-central Spain in the Guadalquivir River Valley. Precipitation average 540 mm per year which is recorded during fall, winter and spring. Precipitation is usually absent during summer. The mean annual air temperature is 17.6 ºC. The site has generally low wind speeds and are subject to advective conditions during summer (Berengena and Gavilán, 2005). NR-Lite outputs were previously corrected by a 10% increase (Brotzge and Duchon, 2000), as recommended by the manufacturer.

The quality and integrity of the meteorological data sets were analysed for all four datasets following the procedures outlined by Allen (1996) and ASCE-EWRI (2005). Results from the analysis are shown in Kjaersgaard et al. (2007). All four datasets had gaps in the data sequence e.g. no data was recorded during May and the first week of June 2002 at the Taastrup site due to datalogger failure. No gap filling was performed and time steps with missing data were excluded from the computations.

2.2 Methods

The Taastrup dataset included observations from January 1995 to December 2004 and the Foulum dataset included observations from January 1998 to December 2003. The Zaragoza dataset had observations from August 1999 to May 2002 and the Córdoba dataset included data from mid-December 2003 to mid-December 2004.

The datasets from Taastrup and Zaragoza were split in two parts according to day of the month, 1-15 and 16+. Days 1-15 were used for calibrating the models against the measured R_n values. Days 16+ were used for model testing. The datasets from Foulum and Córdoba were used for testing the calibration coefficients from Taastrup and Zaragoza, respectively. The performance of Eq. 3 was also tested using calibration coefficients suggested by Allen et al. (1998).

All meteorological data from days where the ground had snow cover at the Taastrup and Foulum sites were excluded from the analysis. Brutsaert (1982) listed the albedo of snow is in the 0.35 – 0.90 range. Hence, to filter measurements with ground snow cover, all time steps with an albedo greater than 0.35 were removed.

Three sets of estimates of α were considered for Eq. 1: 1) a fixed value of 0.23 (Doorenbos and Pruitt, 1977); 2) a fixed value of 0.25 (Allen et al., 1998); and 3) estimates calculated from Eq. 2. Measured values of α were available at the high latitude sites. The three estimation sets of albedo were therefore tested against measured α at these sites. The best albedo values were used to calculate new calibration coefficients for Eqs. 3 through 5 and for the subsequent tests of the models.

No measured albedo values were available at the Spanish sites. Hence, calibration coefficients suggested by Jensen et al. (1990) for semi-arid locations, and from Allen et al. (1998) were used for Eq. 3. Calibration of model coefficients for Eqs. 4 and 5, and testing of Eqs. 3 through 5 were conducted using all three α values. This latter approach introduced an additional uncertainty in the performance of Eqs. 3 through 5, as an incorrect albedo value may or may not enhance bias and scatter of the models.

Statistical models, based on residual errors (the difference between predicted and observed values) were used to evaluate model performance, Table 2 (Loague and Green, 1991; Vereecken et al., 1991; Der and Everitt, 2002). Although the results of the statistical models were used for relative comparison of the net radiation models, no attempts were made to judge what statistical deviation was acceptable.

3. Results and discussion

The L_n estimation method in Eq. 3 has been widely used. The method is recommended to estimate R_n when calculating crop water requirements (Allen et al., 1998; ASCE-EWRI, 2005). Irmak et al. (2003) and Temesgen et al. (2005) used the method as the standard or "truth" when developing and testing new R_n estimation methods.

Temesgen et al. (2007) found L_n estimations using Eq. 3 compared poorly to values measured at Davis, California and recommended that the method should be revised. However, photographic documentation provided by Temesgen et al. (2007) indicates an undesirable weather station design including a solar panel placed well within the radiometric footprint for the net radiometer.

At the high latitude sites the annual average α values were 0.25 when measurements with snow cover were removed. As shown in Fig. 1, this value was not constant throughout the year, but showed higher albedo values during winter and lower values during summer. Eq. 2 accounted for this annual pattern, although it is clear that these models generally overestimated the albedo. Differences in α value are often less than the uncertainties in the measurements of S_i and R_n. An albedo value of 0.25 was the best yearly average value of the three values considered and accordingly this value was used at the Taastrup and Foulum sites. This albedo value found at the high latitude sites was in agreement with Doorenbos and Pruitt (1977). A more accurate estimation of the albedo may be obtained when using models like that developed by Dong et al. (1992) (Eq. 2). As suggested by Iziomon and Mayer (2002) a term to account for altitude may further improve this model. Dong et al. (1992) fitted the coefficients of Eq. 2 using albedo data collected over well-watered grass at University of California (UC) – Davis. A better fit of Eq. 2 may be obtained if the coefficients were fitted using multi-location datasets that included data from high-latitude sites. Martínez-Cob and Tejero-Juste (2004) and Berengena and Gavilán (2005) successfully used albedo values of 0.23 in evapotranspiration calculations at the Zaragoza and Córdoba sites, respectively. Improved model performance when using locally calibrated coefficients for Eq. 3 was reported by Mayer et al. (1999) and Yin et al. (2008). FAO (1990) and Allen et al. (1998) recommended a_l = 0.34 and b_l = 0.14 for Eq. 3. Kjaersgaard et al. (2007) found a good agreement between observed and modelled values when using these coefficients for a_l and b_l in a sub-humid climate regime. Gavilán et al. (2007) similarly used these coefficients in an evapotranspiration study in a Mediterranean climate regime.

Jensen et al. (1990) tested different values for a_c and b_c and found that coefficient sets of (1.2, -0.2), (1.1, -0.1) and (1.0, 0.0) gave the best results for arid, semiarid and humid areas, respectively, which is in good agreement with the coefficients in Table 3. FAO (1990) and Allen et al. (1998) recommended values of (1.35, -0.35) for a_c and b_c, based on experimental results from UC – Davis.

The mean bias error, MBE, mean absolute error, MAE and root mean square error, RMSE at the Taastrup and Foulum sites were generally high when using Eq. 3 with the original model coefficients, Table 4. The overestimation when using the original model coefficients occurred at all radiation intensities, Fig. 2 at Taastrup. Improvement in the performance of Eq. 3 occurred when the original model coefficients were replaced with the locally calibrated ones, Fig 3. In Fig. 4 the predictions of Eq. 3 are regressed against measured R_n values for Taastrup.

Table 5 shows the results of the statistical analysis for the Zaragoza and Córdoba sites. The best performance of Eq. 3 occurred when using the calibration coefficients suggested by Jensen et al. (1990) and an albedo value of 0.25. The better performance of Eq. 3 using an α of 0.25 at the mid-latitude sites did not necessarily prove that an albedo of 0.25 or the coefficients suggested by Jensen et al. (1990) were correct. Rather, it showed that this combination yielded the best results of all combinations of α and model calibration coefficients tested.

R_n normally fluctuates substantially during the course of a day. It was tested if calculating hourly R_n estimates summed to daily values would improve the performances of Eqs. 3 through 5. Night time cloud cover was estimated following recommendations of ASCE-EWRI, 2005.

Model predictions were better using daily input compared to sub-daily input. This may be caused by the approach of establishing the night time cloud cover fraction, as more than half the annual sub-daily time step cloud cover functions were based on estimated rather than measured values. Using other methods to estimate the cloud cover function at night time could possibly improve the R_n estimates when sub-daily meteorological inputs are used. Dong et al. (1992) suggested using cloud cover from the nearest hour to sunset with a sun angle > 10° until midnight and cloud cover from the nearest hour to sunrise with a sun angle >10° between midnight and sunrise. Sridhar and Elliot (2002) calculated the ratio by linear interpolation between sunset and sunrise. For operational purposes these approaches are hampered by the additional calculations needed to look ahead within a dataset.

The only difference between Eqs. 4 and 5 was using either S_{io} or S_a to establish the cloud cover function. The performance of Eqs. 4 and 5 were identical at all sites. Hence, going through the additional calculations of establishing S_{io} compared to S_a offered no improvement in model performance. Despite their simplicity the performance of Eqs. 4 and 5 had an accuracy comparable to that of Eq. 3.

For the Hupselse Beek location in the Netherlands, De Bruin and Stricker (2000) applied a value of 11.66 MJ m^{-2} d^{-1} for c_s in Eq. 5. A value of 9.50 MJ m^{-2} d^{-1} has also been used (De Bruin, personal communication). Comparing these coefficients to the coefficients obtained at Taastrup and Zaragoza indicated that this model is sensitive to local calibration.

As water vapour is one of the major atmospheric emittors of L_i testing was conducted to determine whether including a term for air humidity would improve model performance. An analysis using the Taastrup data set indicated that including air humidity did not improve the performance of Eq. 5.

A source of apparent bias in model predictions is from uncertainties and biases in the measured meteorological variables. When using the calibration coefficients suggested by FAO (1990) and Allen et al. (1998) for Eq. 3, the biases were larger than the instrument bias of 0.25 MJ m^{-2} day^{-1} reported by Halldin and Lindroth (1992) for Ersking radiometers. The bias using different α and R_n model calibration at Córdoba was not beyond the instruments bias for NR Lite radiometers of 0.5 MJ m^{-2} day^{-1} reported by Brotzge and Duchon (2000). Instrument bias may increase further with insufficient instrument calibration methods and differences in time constant between sensors (Halldin and Lindroth, 1992; Brotzge and Duchon, 2000; Samani, 2000).

Another source of error is the “averaging” of cloud type and cover reflected in the calibration coefficients. The relative sensitivity of model performances to cloud cover was analysed by dividing the Taastrup dataset into three groups using the S_i/S_{io} ratio as indicator for cloud presence. The cloud cover thresholds of the groups, fraction of total days and Mean Bias Error for Eq. 3 (MJ m^{-2} d^{-1}) were (0.0 – 0.349, 39 %, 0.03), (0.35 – 0.649, 51 %, -0.03) and (0.65 – 1.0, 10 %, 0.46). Hence, the model performance is consistent for fully or partly cloudy conditions, while the bias increases during clear-sky or near clear-sky conditions.

The bias and scatter were higher at the high latitude sites than at the mid-latitude sites. The use of radiometers from different manufacturers may lead to deviating measurements (Brotzge and Duchon, 2000). Identical instruments were used at the high latitude sites, while the instruments at the mid-latitude sites were from different manufacturers. This may explain why the statistics between the Taastrup and Foulum sites resemble each other more closely than the statistics between the Córdoba and Zaragoza sites. The accuracy of the cloudiness function was generally lower during periods of low sun angles. This lower accuracy could also be caused by factors such as higher reflection of radiation in the domes and thermopiles of the instrument at low sun angles. Also, despite removing periods with snow cover at the high latitude sites, the α was more variable in winter than in the summer, as shown in Fig. 3. Discarding measurements from the winter period should improve model performance. This may be of importance as e.g. evapotranspiration estimations are often of interest only during the growing season. To test the latter reason, the performance of Eqs. 3 through 5 were evaluated for the Taastrup and Zaragoza sites using sub-daily input during the period 15 March to 1 October (the approximate growing season at high latitude sites), Table 6. No improvement in model performance was found for the Zaragoza site. However, the results suggest that improved estimation of albedo at the high latitude sites is needed.

5. Conclusions

Daily values of net radiation R_n are a required input in many practical applications of plant growth modelling and in agricultural water management. The shortwave and long wave components of R_n depend strongly on the presence and type of clouds, optical properties of the atmosphere and characteristics of the surface. However, only a few meteorological variables are available from most modern weather stations, and measurements of R_n and descriptions of clouds, atmosphere and ground are not available. It is thus necessary to establish R_n based on other meteorological variables.

The predictions of three models (Eqs. 3 through 5) to calculate R_n from other meteorological variables were compared to measured R_n values. Eq. 3 required air temperature, solar radiation and air humidity as input, while Eqs. 4 and 5 required only solar radiation as input. Climatic data from two sub-humid, high latitude and two semi-arid, mid-latitude locations were used. The models were tested using model coefficients from the literature and locally calibrated coefficients. Based on measurements, an albedo value of 0.25 was used at the high-latitude sites. A measured albedo was available for the mid-latitude sites. Hence, values and models commonly used in the literature were applied. This approach introduced an additional uncertainty in the performance of the models, as an incorrect albedo value may or may not enhance bias and scatter of the equations. A fixed value of 0.25 resulted in the least bias and scatter at the mid-latitude sites. Eq. 3 was very sensitive to calibration of model coefficients. Using coefficients calibrated locally or for specific climate regimes rather than the originally published coefficients greatly improved model performances. Calibration coefficients varied between the high latitude and mid-latitude sites, indicating that they are latitude and climate specific.

The daily input models had better predictions than the sub-daily input models. Establishing an improved method to determine the cloud cover fraction could improve the performance of the models. When used with appropriate coefficients, Eq. 3 had the best predictions though the performance of Eqs. 4 and 5 very closely resembled their performance. Model performance at the high latitude sites was improved when excluding the non-growing season period. It was also found that uncertainties in sensors and the "averaging" of cloud type and amount caused uncertainties in the evaluation of model performance.

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Figure captions

Fig. 1. Albedo values calculated from Eq. 2 for Taastrup and Zaragoza, and 10 year average (1995 – 2004) values observed at Taastrup.

Fig. 2. Daily net radiation calculated using Eq. 3 using model coefficients suggested by Allen et al. (1998) regressed against observed net radiation at Taastrup during 1995-2004 (day-of-month>15). Also shown is the 1:1 line.

Fig. 3. Daily net radiation calculated using Eq. 3 using model coefficients calibrated at Taastrup regressed against observed net radiation at Taastrup during 1995-2004 (day-of-month>15). Also shown is the 1:1 line.

Fig. 4. Daily net radiation calculated using Eq. 4 using model coefficients calibrated at Taastrup regressed against observed net radiation at Taastrup during 1995-2004 (day-of-month>15). Also shown is the 1:1 line.

Table 1. Climate station location and instrumentation. Temperature and humidity instruments were installed in radiation shields.

	Taastrup 55° 39´N, 12° 20´ E	Foulum 56° 29´ N, 9° 34´ E	Zaragoza 41° 43´ N, 0° 49´ W	Córdoba 37° 51´ N, 4° 51´ W
Net radiation	Ersking R_n meter	Ersking R_n meter	REBS Q7	Kipp & Zonen NR-lite
Solar radiation	Kipp & Zonen C11/ Eppley PSP	Kipp & Zonen C11	Kipp & Zonen CM3	Kipp & Zonen CM6
Shortwave outgoing radiation	Kipp & Zonen C5/ Eppley PSP	Kipp & Zonen C5	n/a	n/a
Air temperature	PT100	Vaisala HMP45	Vaisala HMP45	Vaisala HMP45
Dew point temperature	LiCl probe	Vaisala HMP45	Vaisala HMP45	Vaisala HMP45

Instrument manufacturers: Siemen Ersking, Frederikssund, Denmark; Kipp & Zonen, Delft, The Netherlands; Eppley Laboratory, Newport, USA; Vaisala Oy, Vantaa, Finland; Radiation and Energy Balance Systems (REBS), Seattle, USA.

Table 2. Statistical schemes and criteria for evaluation of model performance.

Scheme	Symbol	Calculation formula	Range	Optimum
Mean bias error	MBE	$\frac{1}{n}\sum_{i=1}^{n}\left(P_i - O_i\right)$		0
Mean absolute error	MAE	$\frac{1}{n}\sum_{i=1}^{n}\left(\left\|P_i - O_i\right\|\right)$	≥0	0
Root mean square error	RMSE	$\left(\sum_{i=1}^{n}\frac{\left(P_i - O_i\right)^2}{n}\right)^{0.5}$	≥0	0

P_i = value predicted by the model

O_i = value observed

$\bar{O}$ = mean of observed values

n = number of data pairs

Table 3. Calibration coefficients for Eqs. 3 through 5 obtained either from the literature or locally at Taastrup or Zaragoza. The coefficients are dimensionless except c_c and c_s which have the units of MJ m^{-2} d^{-1}.

Equation	Calibration	Coefficients			
		a_c	b_c	a_l	b_l
3	Allen et al. (1998)	1.35	-0.35	0.34	-0.14
3	Jensen et al. (1990)[1]	1.10	-0.10	0.34	0.34
3	Taastrup	1.00	0.00	0.34	-0.14
		$c_{c0.23}$	$c_{c0.25}$	c_{cEq3}	
4	Taastrup*		6.29		
4	Zaragoza*	5.97	5.56	5.31	
		$c_{s0.23}$	$c_{s0.25}$	c_{sEq3}	
5	Taastrup*		8.38		
5	Zaragoza*	7.90	7.35	7.03	

[1] For semiarid climate regime

*Subscripts for calibration coefficients indicate which albedo value that was used in the calibration.

Table 4. Comparative statistics for three net long-wave radiation estimation models used in combination with Eq. 1 compared to measured net radiation data from the Taastrup (*n* = 1603, observation mean 4.52 MJ m^{-2} d^{-1}) and Foulum (*n* = 1843, observation mean 4.60 MJ m^{-2} d^{-1}) sites. Daily input and a fixed albedo value of 0.25 were used.

		Taastrup			Foulum		
Equation For L_n	Calibration	MBE MJ m^{-2} d^{-1}	MAE MJ m^{-2} d^{-1}	RMSE MJ m^{-2} d^{-1}	MBE MJ m^{-2} d^{-1}	MAE MJ m^{-2} d^{-1}	RMSE MJ m^{-2} d^{-1}
3	Allen et al. (1998)	1.04	1.21	1.47	1.06	1.22	1.46
3	Taastrup	0.04	0.71	0.92	0.03	0.79	1.00
4	Taastrup	-0.01	0.76	0.97	-0.07	0.79	1.00
5	Taastrup	-0.01	0.76	0.97	-0.07	0.79	1.00

Table 5. Comparative statistics for three net long-wave radiation estimation models used in combination with Eq. 1 compared to measured net radiation data from the Zaragoza (*n* = 507, observation mean 7.62 MJ m^{-2} d^{-1}) and Córdoba (*n* = 365, observation mean 8.40 MJ m^{-2} d^{-1}) sites. Daily input and different albedo values were used.

			Zaragoza			Cordoba		
Equation for L_n	Albedo	Calibration	MBE MJ m^{-2} d^{-1}	MAE MJ m^{-2} d^{-1}	RMSE MJ m^{-2} d^{-1}	MBE MJ m^{-2} d^{-1}	MAE MJ m^{-2} d^{-1}	RMSE MJ m^{-2} d^{-1}
3	0.23	Allen et al. (1998)	0.70	0.94	1.16	0.72	0.83	1.09
3	0.25	Allen et al. (1998)	0.38	0.77	0.98	0.38	0.64	0.92
3	Eq. 2	Allen et al. (1998)	-0.20	0.89	1.23	-0.16	0.72	1.06
3	0.23	Jensen et al. (1990)	0.36	0.77	0.98	0.37	0.64	0.80
3	0.25	Jensen et al. (1990)	0.04	0.65	0.84	0.04	0.52	0.69
3	Eq. 2	Jensen et al. (1990)	-0.54	1.02	1.45	-0.51	0.81	1.25
4	0.23	Zaragoza	0.03	0.71	0.88	0.04	0.51	0.68
4	0.25	Zaragoza	0.03	0.69	0.86	0.01	0.52	0.68
4	Eq. 2	Zaragoza	0.03	0.71	0.88	0.04	0.52	0.68
5	0.23	Zaragoza	0.04	0.71	0.88	0.06	0.52	0.68
5	0.25	Zaragoza	0.04	0.70	0.86	0.03	0.52	0.68
5	Eq. 2	Zaragoza	0.04	0.71	0.88	0.06	0.52	0.68

Table 6. Comparative statistics for three net long-wave radiation estimation models used in combination with Eq. 1 compared to measured net radiation data from the Taastrup and Foulum sites. Daily input from 15 March to 1 October and a fixed albedo value of 0.25 were used.

		Taastrup			Foulum		
Equation for L_n	Calibration	MBE MJ m^{-2} d^{-1}	MAE MJ m^{-2} d^{-1}	RMSE MJ m^{-2} d^{-1}	MBE MJ m^{-2} d^{-1}	MAE MJ m^{-2} d^{-1}	RMSE MJ m^{-2} d^{-1}
3	Allen et al. (1998)	0.84	1.02	1.26	0.76	0.93	1.13
3	Taastrup	-0.01	0.72	0.91	0.04	0.76	0.94
4	Taastrup	0.03	0.77	0.97	-0.01	0.79	0.97
5	Taastrup	0.03	0.77	0.97	-0.01	0.79	0.97

Figure 1.

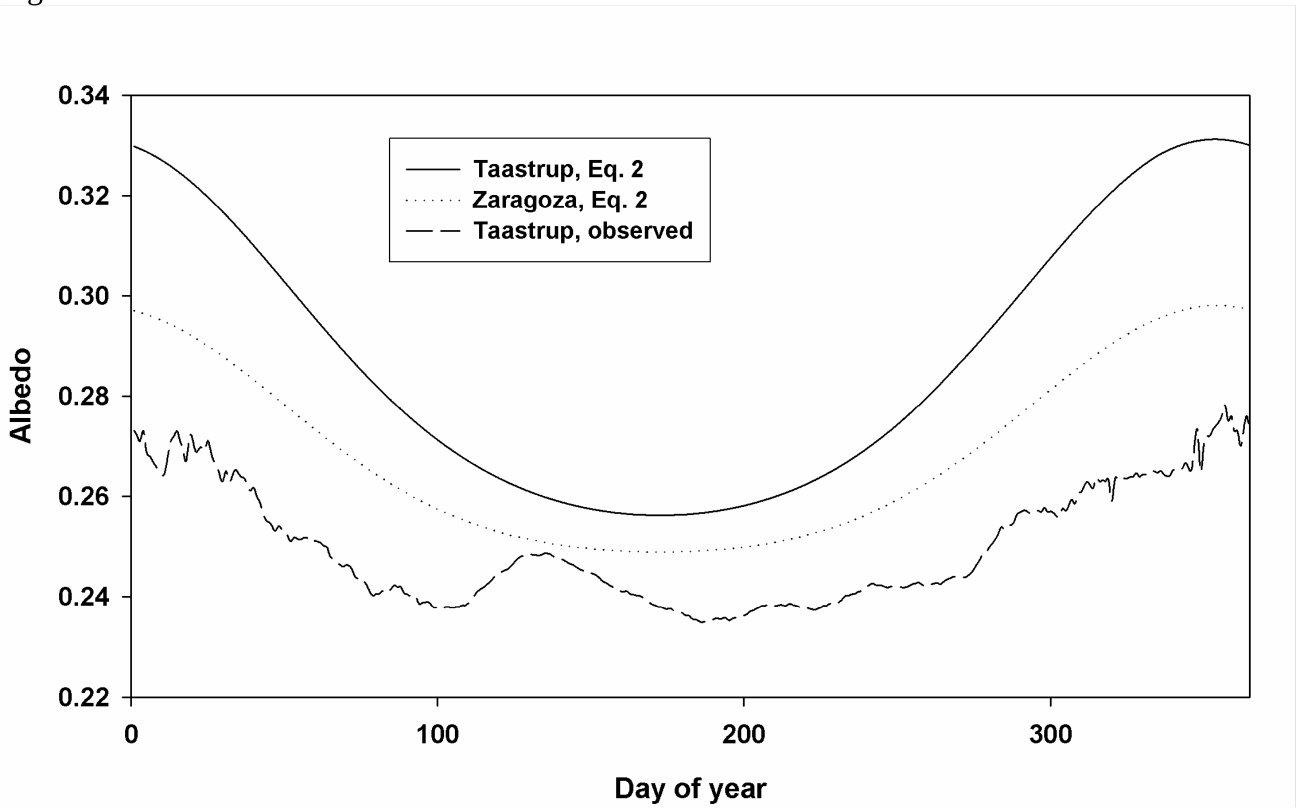

Taastrup, Eq. 2
Zaragoza, Eq. 2
Taastrup, observed
Albedo
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0
100
200
300
Day of year

Figure 2.

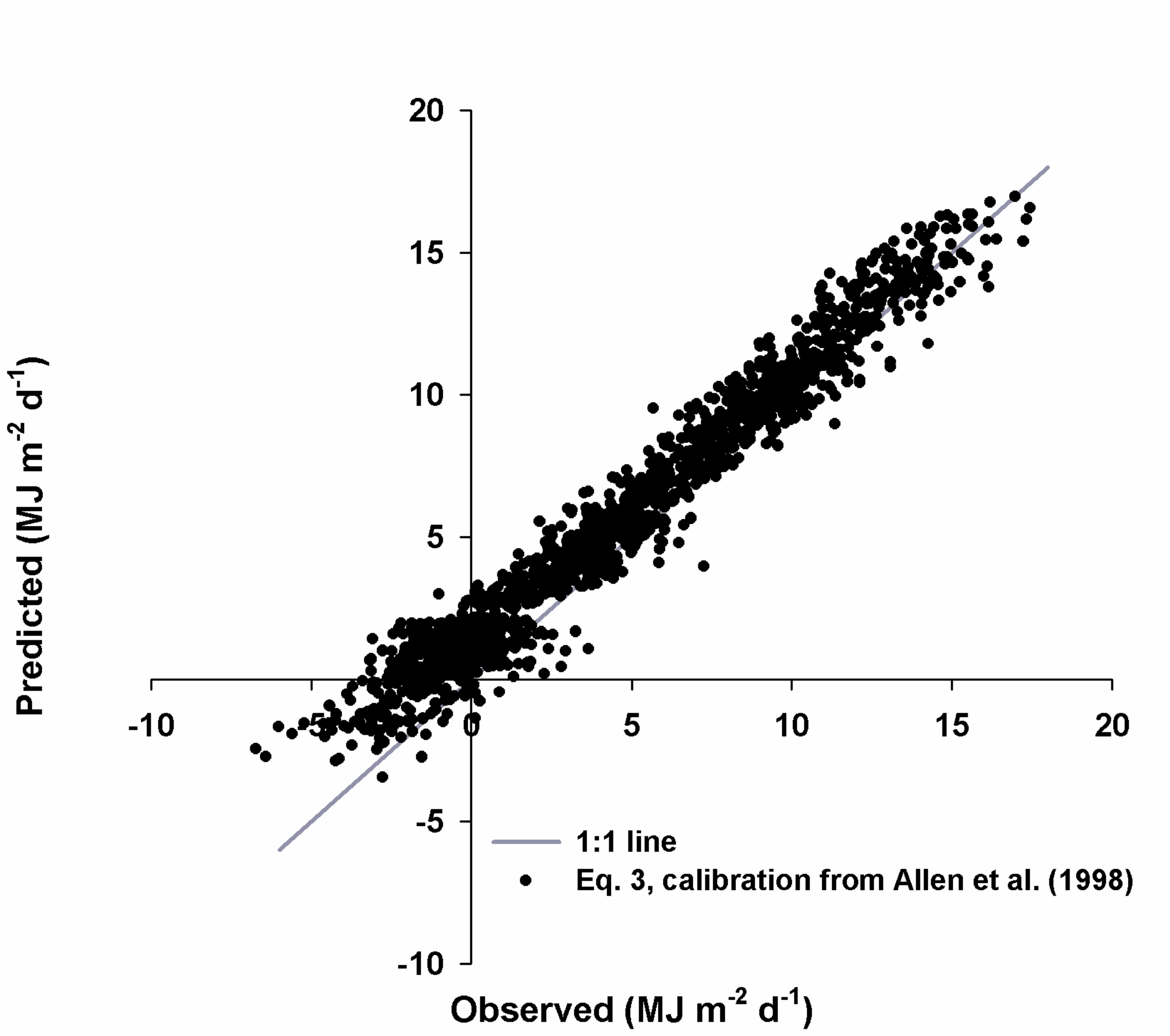
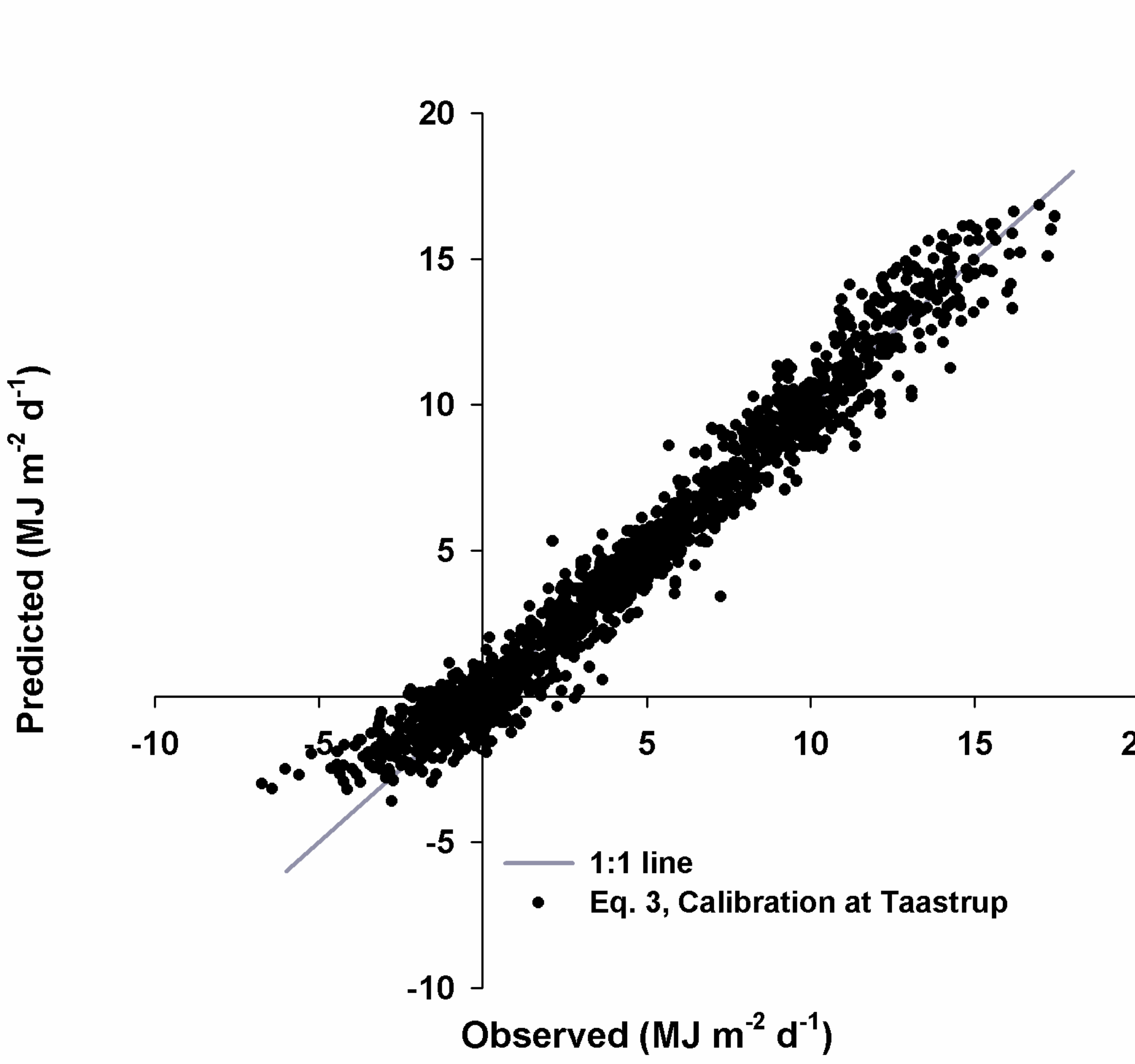

20
15
10
5
-5
-10
-10
-5
0
5
10
15
20
Predicted (MJ m^{-2} d^{-1})
Observed (MJ m^{-2} d^{-1})
1:1 line
● Eq. 3, calibration from Allen et al. (1998)

Figure 3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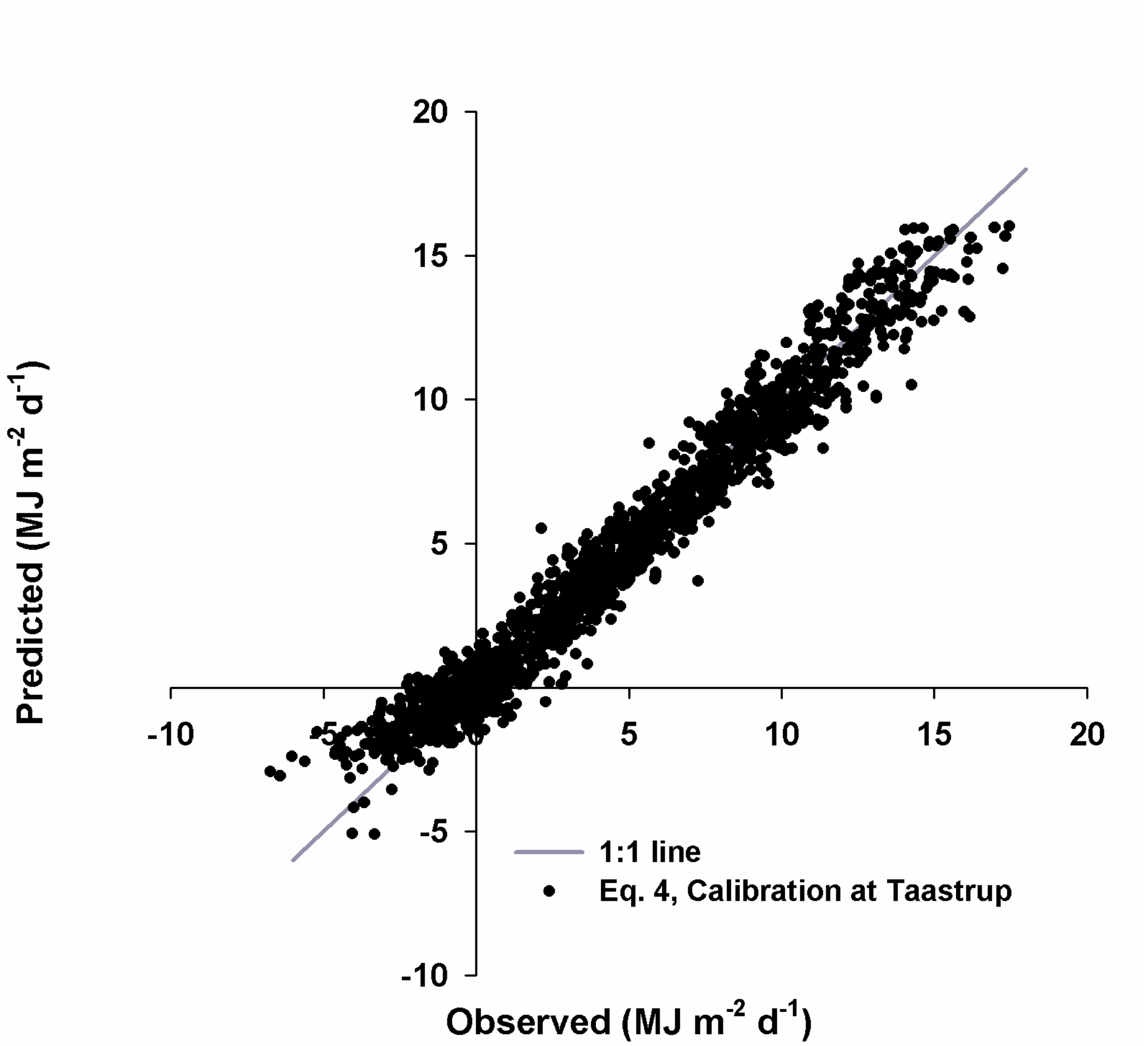
5
10
15
20
Predicted (MJ m^{-2} d^{-1})
Observed (MJ m^{-2} d^{-1})
1:1 line
● Eq. 3, Calibration at Taastrup

Figure 4


20
15
10
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-5
-10
-10
-5
0
5
10
15
20
Predicted (MJ m^{-2} d^{-1})
Observed (MJ m^{-2} d^{-1})
1:1 line
Eq. 4, Calibration at Taastrup