Comparison of the performance of net radiation calculation models

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25 **Abstract**

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

47
48 Suggested keywords: Net radiation, net long wave radiation, albedo, modelling.

49

50 **1. Introduction**

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

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

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

65

$$66 \quad R_n = S_i - S_o + L_i - L_o = (1 - \alpha)S_i - L_n \quad (1)$$

67

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

71 The radiation components are strongly influenced by the presence, type and diurnal distribution of
72 clouds (Duffie and Beckman, 2006). Clouds at high elevations such as cirrus are normally colder

73 and more transparent compared to clouds at medium to low elevations (Monteith and Unsworth,
 74 1990). While S_i received at the Earth's surface is strongly affected by cloud cover and cloud type
 75 due to differences in cloud transparency and geometry, L_i radiation shows less dependence on
 76 clouds (Arking, 1991). Water vapour, aerosols, carbon dioxide and trace gases throughout the
 77 atmosphere emit long wave radiation and more than half of the L_i received at the ground surface is
 78 emitted within the lowest 100 m of the atmosphere (Monteith and Unsworth, 1990; Arking, 1991;
 79 Duffie and Beckman, 2006). Arking (1991) showed that for latitudes less than 65° a relative increase
 80 in cirrus cloud and medium/low cloud amount increases and decreases, respectively net radiation
 81 below the clouds.

82 Detailed information about cloud height, type and distribution is usually not recorded at standard
 83 weather stations. For practical applications, models based on available meteorological information
 84 measured at screen height have been developed (Duffie and Beckman, 2006). Simple linear and
 85 multiple linear regression models have commonly been used to estimate R_n from S_i and other
 86 meteorological parameters (Fritschen, 1967; Aslyng, 1974; Kaminsky and Dubayah, 1997; Irmak et
 87 al., 2003). However, the empirically determined regression coefficients are usually only valid over a
 88 limited spatial scale which restricts their usability on larger scales or at other locations (Fritschen,
 89 1967; Alados et al., 2003; Nandigiri and Kovoov, 2005).

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

97

$$98 \quad \alpha_d = A_d + B_d \theta_m + C_d \exp\left(\frac{-\theta_m}{D_d}\right) \quad (2)$$

99

100 where α_d is average daily albedo, θ_m is the sun angle ($^\circ$) above the horizon at solar noon and
 101 calibration coefficients are $A_d = 0.108$, $B_d = 0.000939$, $C_d = 0.257$ and $D_d = 57.3$. The calibration
 102 coefficients in Eq. 2 were derived for sun angles $\geq 10^\circ$ and a ratio of S_i to extraterrestrial radiation
 103 $S_a \geq 0.375$. For $S_i/S_a < 0.375$, Dong et al. (1992) suggested an albedo value of 0.26.

104 Since it is difficult to obtain reliable long wave radiation measurements (Alados et al., 2003), L_n in
 105 Eq. 1 can be computed based on other meteorological variables such as S_i , water vapour pressure
 106 (e_a) and air temperature (T_a) (Jensen et al., 1990). A widely used method to estimate L_n over short
 107 grass for daily timesteps (Wright and Jensen, 1972; Jensen et al., 1990; FAO, 1990; Allen et al.,
 108 1998; ASCE-EWRI, 2005) is

109

$$110 \quad L_n = \sigma \left[\frac{T_{\max,K}^4 + T_{\min,K}^4}{2} \right] \left(a_l + b_l \sqrt{e_a} \right) \left(a_c \frac{S_i}{S_{io}} + b_c \right) \quad (3)$$

111

112 where σ is Stefan-Boltzmann constant ($4.903 \cdot 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ d}^{-1}$); $T_{\max,K}$ and $T_{\min,K}$ are daily
 113 maximum and minimum air temperature (K) at screen height (normally 2 m), respectively; S_{io} is
 114 clear-sky radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$); a_l , b_l , a_c , b_c are calibration coefficients (dimensionless). Allen
 115 (1996) and ASCE-EWRI (2005) outlined methods to estimate theoretical S_{io} curves.

116 The model in Eq. 3 follows Stefan-Boltzmann relationships for calculating L_o emitted from the
 117 ground and vegetation, and L_i emitted from the atmosphere and clouds. Clear-sky net emittance
 118 based on screen level e_a is calculated using the relationship developed by Brunt (1932). The

119 radiation emitted by clouds is calculated using an empirical relationship based on the ratio between
 120 S_i and S_{io} suggested by Wright and Jensen (1972). The general calibration coefficients used in the
 121 net emittance and cloudiness functions of Eq 3 are subject to local calibration when measurements
 122 of incoming and outgoing long wave radiation are available (FAO, 1990; Jensen et al., 1990; Allen
 123 et al., 1998).

124 In many practical applications the available meteorological input is often limited (Allen et al.,
 125 2007), incomplete or of poor quality (Jensen et. al., 1990; ASCE-EWRI, 2005). In such cases R_n has
 126 to be estimated based on minimum meteorological input. Hence, a new model to calculate L_n based
 127 on only S_i is suggested

$$129 \quad L_n = \left(c_c \frac{S_i}{S_{io}} \right) \quad (4)$$

130
 131 where c_c is a calibration coefficient. Eq 4 is an abbreviated form of Eq. 3 with b_c set to zero, and the
 132 Stefan-Boltzmann constant, air temperature, the Brunt function for net emittance and the a_c in the
 133 cloudiness function are merged into a single calibration coefficient, c_c
 134 Another simple method for calculating L_n was suggested by Slob (unpublished, c.f. De Bruin and
 135 Stricker (2000)).

$$137 \quad L_n = \left(c_s \frac{S_i}{S_a} \right) \quad (5)$$

138
 139 where c_s is a calibration coefficient and S_a is extraterrestrial radiation. The model in Eq. 5 is
 140 intended for use on a daily or n-day basis (De Bruin and Stricker, 2000).

141 The R_n estimation model in Eq. 3 was developed using data from an arid climate regime (Wright
142 and Jensen, 1972). Tests of the model have generally shown better agreement with measured values
143 than other R_n estimation models (FAO, 1990; Allen et al., 1998). However analysis by Jensen et al.
144 (1990) and Yin et al. (2008) indicated that Eq. 3 required further testing under other climate
145 regimes. The purpose of this study was to test the performance of Eqs. 3 through 5 as input to Eq. 1
146 to predict R_n on a daily basis in sub-humid high latitude and semi-arid mid-latitude climate regimes.
147 Calculated values of R_n were compared to measured values from four weather stations. Tests were
148 made to determine how 1) model calibration coefficients, 2) α , 3) location, 4) daily versus sub-daily
149 input data, 5) time of year and 6) cloud amount influenced model performance.

150

151 **2. Materials and methods**

152 *2.1 Experimental sites*

153 Meteorological data from four weather stations were used in this study, Table 1. The Taastrup and
154 Foulum sites are located in a sub-humid, high latitude climate regime in Denmark and the Zaragoza
155 and Córdoba sites are located in a semi-arid, mid-latitude climate regime in Spain. The ground at
156 the climate stations was covered by short green grass. The sites have been described by Jensen
157 (1996), Plauborg and Jensen (1998), Faci et al. (1994), Berengena and Gavilán (2005) and
158 Martínez-Cob et al. (2005).

159 The climate patterns at the high latitude sites were described by Kjaersgaard et al. (2007). There
160 were no objects to obstruct the radiation at low sun angles at the Taastrup and Foulum sites and the
161 levelness and clearness of instrument domes was checked daily. All radiometers at the Taastrup and
162 Foulum sites were calibrated annually against a reference pyranometer, which was calibrated
163 regularly at the World Radiation Centre, Davos, Switzerland. Hence, net radiometers were only
164 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 °C. 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.

182

183 *2.2 Methods*

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

188 The datasets from Taastrup and Zaragoza were split in two parts according to day of the month, 1-
 189 15 and 16+. Days 1-15 were used for calibrating the models against the measured R_n values. Days
 190 16+ were used for model testing. The datasets from Foulum and Córdoba were used for testing the
 191 calibration coefficients from Taastrup and Zaragoza, respectively. The performance of Eq. 3 was
 192 also tested using calibration coefficients suggested by Allen et al. (1998).
 193 All meteorological data from days where the ground had snow cover at the Taastrup and Foulum
 194 sites were excluded from the analysis. Brutsaert (1982) listed the albedo of snow is in the 0.35 –
 195 0.90 range. Hence, to filter measurements with ground snow cover, all time steps with an albedo
 196 greater than 0.35 were removed.
 197 Three sets of estimates of α were considered for Eq. 1: 1) a fixed value of 0.23 (Doorenbos and
 198 Pruitt, 1977); 2) a fixed value of 0.25 (Allen et al., 1998); and 3) estimates calculated from Eq. 2.
 199 Measured values of α were available at the high latitude sites. The three estimation sets of albedo
 200 were therefore tested against measured α at these sites. The best albedo values were used to
 201 calculate new calibration coefficients for Eqs. 3 through 5 and for the subsequent tests of the
 202 models.
 203 No measured albedo values were available at the Spanish sites. Hence, calibration coefficients
 204 suggested by Jensen et al. (1990) for semi-arid locations, and from Allen et al. (1998) were used for
 205 Eq. 3. Calibration of model coefficients for Eqs. 4 and 5, and testing of Eqs. 3 through 5 were
 206 conducted using all three α values. This latter approach introduced an additional uncertainty in the
 207 performance of Eqs. 3 through 5, as an incorrect albedo value may or may not enhance bias and
 208 scatter of the models.
 209 Statistical models, based on residual errors (the difference between predicted and observed values)
 210 were used to evaluate model performance, Table 2 (Loague and Green, 1991; Vereecken et al.,
 211 1991; Der and Everitt, 2002). Although the results of the statistical models were used for relative

212 comparison of the net radiation models, no attempts were made to judge what statistical deviation
213 was acceptable.

214

215 **3. Results and discussion**

216 The L_n estimation method in Eq. 3 has been widely used. The method is recommended to estimate
217 R_n when calculating crop water requirements (Allen et al., 1998; ASCE-EWRI, 2005). Irmak et al.
218 (2003) and Temesgen et al. (2005) used the method as the standard or “truth” when developing and
219 testing new R_n estimation methods.

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

224 At the high latitude sites the annual average α values were 0.25 when measurements with snow
225 cover were removed. As shown in Fig. 1, this value was not constant throughout the year, but
226 showed higher albedo values during winter and lower values during summer. Eq. 2 accounted for
227 this annual pattern, although it is clear that these models generally overestimated the albedo.

228 Differences in α value are often less than the uncertainties in the measurements of S_i and R_n . An
229 albedo value of 0.25 was the best yearly average value of the three values considered and
230 accordingly this value was used at the Taastrup and Foulum sites. This albedo value found at the
231 high latitude sites was in agreement with Doorenbos and Pruitt (1977). A more accurate estimation
232 of the albedo may be obtained when using models like that developed by Dong et al. (1992) (Eq. 2).
233 As suggested by Iziomon and Mayer (2002) a term to account for altitude may further improve this
234 model. Dong et al. (1992) fitted the coefficients of Eq. 2 using albedo data collected over well-

235 watered grass at University of California (UC) – Davis. A better fit of Eq. 2 may be obtained if the
 236 coefficients were fitted using multi-location datasets that included data from high-latitude sites.
 237 Martínez-Cob and Tejero-Juste (2004) and Berengena and Gavilán (2005) successfully used albedo
 238 values of 0.23 in evapotranspiration calculations at the Zaragoza and Córdoba sites, respectively.
 239 Improved model performance when using locally calibrated coefficients for Eq. 3 was reported by
 240 Mayer et al. (1999) and Yin et al. (2008). FAO (1990) and Allen et al. (1998) recommended $a_l =$
 241 0.34 and $b_l = 0.14$ for Eq. 3. Kjaersgaard et al. (2007) found a good agreement between observed
 242 and modelled values when using these coefficients for a_l and b_l in a sub-humid climate regime.
 243 Gavilán et al. (2007) similarly used these coefficients in an evapotranspiration study in a
 244 Mediterranean climate regime.
 245 Jensen et al. (1990) tested different values for a_c and b_c and found that coefficient sets of (1.2, -0.2),
 246 (1.1, -0.1) and (1.0, 0.0) gave the best results for arid, semiarid and humid areas, respectively,
 247 which is in good agreement with the coefficients in Table 3. FAO (1990) and Allen et al. (1998)
 248 recommended values of (1.35, -0.35) for a_c and b_c , based on experimental results from UC – Davis.
 249 The mean bias error, MBE, mean absolute error, MAE and root mean square error, RMSE at the
 250 Taastrup and Foulum sites were generally high when using Eq. 3 with the original model
 251 coefficients, Table 4. The overestimation when using the original model coefficients occurred at all
 252 radiation intensities, Fig. 2 at Taastrup. Improvement in the performance of Eq. 3 occurred when
 253 the original model coefficients were replaced with the locally calibrated ones, Fig 3. In Fig. 4 the
 254 predictions of Eq. 3 are regressed against measured R_n values for Taastrup.
 255 Table 5 shows the results of the statistical analysis for the Zaragoza and Córdoba sites. The best
 256 performance of Eq. 3 occurred when using the calibration coefficients suggested by Jensen et al.
 257 (1990) and an albedo value of 0.25. The better performance of Eq. 3 using an α of 0.25 at the mid-
 258 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 $> 10^\circ$ until midnight and cloud cover from the nearest hour to sunrise with a sun angle $> 10^\circ$ 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 $11.66 \text{ MJ m}^{-2} \text{ d}^{-1}$ for c_s in Eq. 5. A value of $9.50 \text{ MJ m}^{-2} \text{ d}^{-1}$ 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.

283 As water vapour is one of the major atmospheric emitters of L_i testing was conducted to determine
 284 whether including a term for air humidity would improve model performance. An analysis using the
 285 Taastrup data set indicated that including air humidity did not improve the performance of Eq. 5.
 286 A source of apparent bias in model predictions is from uncertainties and biases in the measured
 287 meteorological variables. When using the calibration coefficients suggested by FAO (1990) and
 288 Allen et al. (1998) for Eq. 3, the biases were larger than the instrument bias of $0.25 \text{ MJ m}^{-2} \text{ day}^{-1}$
 289 reported by Halldin and Lindroth (1992) for Ersking radiometers. The bias using different α and R_n
 290 model calibration at Córdoba was not beyond the instruments bias for NR Lite radiometers of 0.5
 291 $\text{MJ m}^{-2} \text{ day}^{-1}$ reported by Brotzge and Duchon (2000). Instrument bias may increase further with
 292 insufficient instrument calibration methods and differences in time constant between sensors
 293 (Halldin and Lindroth, 1992; Brotzge and Duchon, 2000; Samani, 2000).
 294 Another source of error is the “averaging” of cloud type and cover reflected in the calibration
 295 coefficients. The relative sensitivity of model performances to cloud cover was analysed by
 296 dividing the Taastrup dataset into three groups using the S_i/S_{io} ratio as indicator for cloud presence.
 297 The cloud cover thresholds of the groups, fraction of total days and Mean Bias Error for Eq. 3 (MJ
 298 $\text{m}^{-2} \text{ d}^{-1}$) were (0.0 – 0.349, 39 %, 0.03), (0.35 – 0.649, 51 %, -0.03) and (0.65 – 1.0, 10 %, 0.46).
 299 Hence, the model performance is consistent for fully or partly cloudy conditions, while the bias
 300 increases during clear-sky or near clear-sky conditions.
 301 The bias and scatter were higher at the high latitude sites than at the mid-latitude sites. The use of
 302 radiometers from different manufacturers may lead to deviating measurements (Brotzge and
 303 Duchon, 2000). Identical instruments were used at the high latitude sites, while the instruments at
 304 the mid-latitude sites were from different manufacturers. This may explain why the statistics
 305 between the Taastrup and Foulum sites resemble each other more closely than the statistics between
 306 the Córdoba and Zaragoza sites. The accuracy of the cloudiness function was generally lower

307 during periods of low sun angles. This lower accuracy could also be caused by factors such as
308 higher reflection of radiation in the domes and thermopiles of the instrument at low sun angles.
309 Also, despite removing periods with snow cover at the high latitude sites, the α was more variable
310 in winter than in the summer, as shown in Fig. 3. Discarding measurements from the winter period
311 should improve model performance. This may be of importance as e.g. evapotranspiration
312 estimations are often of interest only during the growing season. To test the latter reason, the
313 performance of Eqs. 3 through 5 were evaluated for the Taastrup and Zaragoza sites using sub-daily
314 input during the period 15 March to 1 October (the approximate growing season at high latitude
315 sites), Table 6. No improvement in model performance was found for the Zaragoza site. However,
316 the results suggest that improved estimation of albedo at the high latitude sites is needed.

317

318 **5. Conclusions**

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

326 The predictions of three models (Eqs. 3 through 5) to calculate R_n from other meteorological
327 variables were compared to measured R_n values. Eq. 3 required air temperature, solar radiation and
328 air humidity as input, while Eqs. 4 and 5 required only solar radiation as input. Climatic data from
329 two sub-humid, high latitude and two semi-arid, mid-latitude locations were used. The models were
330 tested using model coefficients from the literature and locally calibrated coefficients. Based on

331 measurements, an albedo value of 0.25 was used at the high-latitude sites. A measured albedo was
332 available for the mid-latitude sites. Hence, values and models commonly used in the literature were
333 applied. This approach introduced an additional uncertainty in the performance of the models, as an
334 incorrect albedo value may or may not enhance bias and scatter of the equations. A fixed value of
335 0.25 resulted in the least bias and scatter at the mid-latitude sites. Eq. 3 was very sensitive to
336 calibration of model coefficients. Using coefficients calibrated locally or for specific climate
337 regimes rather than the originally published coefficients greatly improved model performances.
338 Calibration coefficients varied between the high latitude and mid-latitude sites, indicating that they
339 are latitude and climate specific.

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

347

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472 **Figure captions**

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474 Fig. 1. Albedo values calculated from Eq. 2 for Taastrup and Zaragoza, and 10 year average (1995 –
475 2004) values observed at Taastrup.

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477 Fig. 2. Daily net radiation calculated using Eq. 3 using model coefficients suggested by Allen et al.
478 (1998) regressed against observed net radiation at Taastrup during 1995-2004 (day-of-month>15).
479 Also shown is the 1:1 line.

480

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

484

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

488

489 Table 1. Climate station location and instrumentation. Temperature and humidity instruments were
 490 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

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

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

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

498 P_i = value predicted by the model

499 O_i = value observed

500 $\bar{O}$ = mean of observed values

501 n = number of data pairs

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 504
 505 Table 3. Calibration coefficients for Eqs. 3 through 5 obtained either from the literature or locally at
 506 Taastrup or Zaragoza. The coefficients are dimensionless except c_c and c_s which have the units of
 507 $\text{MJ m}^{-2} \text{d}^{-1}$.

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	

508 ¹For semiarid climate regime

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

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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 $4.52 \text{ MJ m}^{-2} \text{ d}^{-1}$) and Foulum ($n = 1843$, observation mean $4.60 \text{ MJ m}^{-2} \text{ d}^{-1}$) sites. Daily input and a fixed albedo value of 0.25 were used.

Equation For L_n	Calibration	Taastrup			Foulum		
		MBE $\text{MJ m}^{-2} \text{ d}^{-1}$	MAE $\text{MJ m}^{-2} \text{ d}^{-1}$	RMSE $\text{MJ m}^{-2} \text{ d}^{-1}$	MBE $\text{MJ m}^{-2} \text{ d}^{-1}$	MAE $\text{MJ m}^{-2} \text{ d}^{-1}$	RMSE $\text{MJ m}^{-2} \text{ d}^{-1}$
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 $7.62 \text{ MJ m}^{-2} \text{ d}^{-1}$) and Córdoba ($n = 365$, observation mean $8.40 \text{ MJ m}^{-2} \text{ d}^{-1}$) sites. Daily input and different albedo values were used.

Equation for L_n	Albedo	Calibration	Zaragoza			Cordoba		
			MBE $\text{MJ m}^{-2} \text{ d}^{-1}$	MAE $\text{MJ m}^{-2} \text{ d}^{-1}$	RMSE $\text{MJ m}^{-2} \text{ d}^{-1}$	MBE $\text{MJ m}^{-2} \text{ d}^{-1}$	MAE $\text{MJ m}^{-2} \text{ d}^{-1}$	RMSE $\text{MJ m}^{-2} \text{ d}^{-1}$
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.

Equation for L_n	Calibration	Taastrup			Foulum		
		MBE $\text{MJ m}^{-2} \text{ d}^{-1}$	MAE $\text{MJ m}^{-2} \text{ d}^{-1}$	RMSE $\text{MJ m}^{-2} \text{ d}^{-1}$	MBE $\text{MJ m}^{-2} \text{ d}^{-1}$	MAE $\text{MJ m}^{-2} \text{ d}^{-1}$	RMSE $\text{MJ m}^{-2} \text{ d}^{-1}$
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

533 Figure 1.

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