Geofísica Internacional (2001), Vol. 40, Num. 3, pp. 207-218

Satellite measurements of solar radiation in the Yaqui Valley, northern Mexico

Jaime Garatuza-Payán[1], W. James Shuttleworth[2] and Rachel T. Pinker[3]
[1]*Instituto Tecnológico de Sonora, Cd. Obregón, Son., México*
[2]*Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ*
[3]*Department of Meteorology, University of Maryland, College Park, MD*

Received: September 29, 2000; accepted: June 15, 2001.

RESUMEN

Se realizaron estimaciones cada media hora de radiación solar a partir de datos de satélite para el Valle del Yaqui en Sonora, México, para el período de noviembre de 1998 a marzo de 1999. Las estimaciones se hicieron en una malla de 50 km usando el algoritmo de "Global Energy and Water-Cycle Experiment Surface Radiation Budget (GEWEX/SRB)" aplicado con datos de GOES-East y, en una malla de 4 km, usando una versión de alta resolución del mismo algoritmo con datos de GOES-West. Los resultados se compararon con mediciones de terreno en dos sitios. En promedio, usando la actual calibración de los radiómetros de los satélites, los valores derivados de GOES-East son 18% mayores que los medidos en terreno, mientras que los de GOES-West son 9% menores. Asumiendo que estas diferencias sistemáticas reflejan la pobre calibración de los sensores en los satélites, las estimaciones fueron recalibradas por separado para ajustarse a los datos de campo. Después de la recalibración, existen aún diferencias entre las estimaciones y las observaciones porque el satélite da una estimación instantánea promedio de un área, mientras que la observación de campo representa una medición puntual promedio para un cierto intervalo de tiempo. Estas discrepancias se reducen cuando se comparan valores promedios diarios. El error entre el satélite y las mediciones es menor para la estimación de alta resolución, y existe mejoría en el detalle espacial con los datos de alta resolución, haciéndolos preferibles en aplicaciones hidrológicas. Investigaciones anteriores han demostrado la capacidad para estimar evaporación potencial a partir de radiación solar diaria usando una versión de la ecuación de Makkink calibrada localmente y los factores de cultivo relevantes han sido derivados para trigo y algodón. Finalmente, se demuestra la aplicación de las estimaciones de radiación solar de alta resolución para derivar estimaciones diarias de evapotranspiración en campos de trigo y algodón.

PALABRAS CLAVE: Radiación solar, percepción remota, GOES, Makkink, evaporación.

ABSTRACT

Half-hourly estimates of solar radiation were obtained from satellite data for the Yaqui Valley in Sonora, Mexico for the period November 1998 to March 1999. Estimates were made on a 50 km grid using the Global Energy and Water-Cycle Experiment Surface Radiation Budget (GEWEX/SRB) algorithm applied with GOES-East data and, on a 4 km grid, using a high-resolution development of the GEWEX/SRB algorithm with GOES-West data. The resulting values were compared with field measurements made at two field sites. On average, using the presently specified calibration of the radiometers on the two satellites, the values derived from GOES-East data are 18% greater than field measurements, while those from GOES-West are 9% lower. If these systematic differences reflect the current poor calibration of the satellite sensors, the estimates obtained from each satellite may be corrected to agree with the surface data. After re-calibration, significant random differences between the hourly satellite estimates and surface observations remain because the satellite provides an instantaneous area-average estimate, while the field observation is a time-average single-point measurement. These discrepancies are reduced when daily-average values of solar radiation are compared. The error between the satellite and ground measurements is lower for the high-resolution estimates than it is for the low-resolution estimates, and there is an enhancement of spatial detail with the high-resolution data, making the latter preferable for hydrological applications. Previous research demonstrated the capacity for estimating potential evaporation in the area from daily-average solar radiation using a locally calibrated version of the Makkink equation. Locally relevant crop factors also have been derived for wheat and cotton.

KEYWORDS: Solar radiation, remote sensing, GOES, Makkink equation, evaporation.

1. INTRODUCTION

The Yaqui Valley irrigation project in Sonora, Mexico is located in a semi-arid region of northern Mexico where water is a critical resource for economical development. Crop evaporation estimates for the Obregon region can provide an important source of information for the more efficient use of water. This paper demonstrates the potential use of satellite data for rapid routine estimation of water use in the Yaqui Valley.

Previous attempts to apply satellite data in agricultural practice were plagued by difficulties in information transfer, but this situation has changed dramatically in recent years. The timely retrieval of near real-time satellite data and of supporting information for agricultural applications is now feasible via the Internet. Along with satellite-based data services and telecommunications the Internet may also aid in disseminating evaporation estimates to end users.

The Timely Satellite Data for Agricultural Management project (Diak *et al.*, 1998) used multiple GOES satellite images to estimate regional evaporation for irrigation scheduling. Studies in the Yaqui Valley have shown that geostationary satellite data can be used to estimate solar radiation (Gautier *et al.*, 1980; Pinker and Laszlo, 1992; Stewart *et al.*, 1998). Potential evaporation has been estimated from solar radiation and temperature using a locally calibrated version of the Makkink equation, without the need to include other meteorological variables such as humidity and wind speed (Garatuza *et al.*, 1998). The present work explores the use of half-hourly GOES satellite images to provide daily estimates of crop evaporation in the Yaqui Valley for wheat and cotton fields over one growing season, using the Makkink equation with locally calibrated crop factors.

The Yaqui Valley irrigation project is located on the coastal plain near Ciudad Obregón, 430 km south of the U.S.-Mexico border. The irrigated area is very flat and has an average altitude of about 25 masl. It covers about 40 km by 70 km. Main drainage channels are spaced every 2 km. The average rainfall is 270 mm, 70% from July to September and little rain between March and June. The mean daily temperature ranges from 16°C in January to 30°C in July and August. The irrigation project includes a patchwork of fields between 0.25 and 4 km^2 each depending on the crops. Up to 1/3 of the irrigated area lies fallow at any given time. The main crops are cotton and wheat with some maize and soybeans; they are grown throughout the year.

2. MAKKINK EQUATION

The Penman-Monteith equation (Monteith, 1965) is widely used for describing transpiration from uniform vegetation which completely covers the ground. However, in the case of irrigated agricultural crops, canopy cover is not always complete, and the aerodynamic and stomatal transfer resistances in the Penman-Monteith equation are difficult to measure or estimate.

The common way to estimate the evaporation from irrigated crops is to multiply an estimated reference crop evapotranspiration rate by a crop coefficient (or "crop factor"). Once specified, the crop coefficients for a particular crop are used to calculate the evaporation loss for an estimated reference (or "potential") evaporation rate. The potential rate is calculated from meteorological data (Doorenbos and Pruitt, 1977; Shuttleworth, 1993; Garatuza *et al.*, 1998). Crop evaporation is written as

$$E_c = K_c E_o , \tag{1}$$

where E_c is the actual evapotranspiration rate, E_o is the potential or reference rate, and K_c is the dimensionless crop factor for the particular crop, which depends on its development stage.

E_o can be estimated by several formulae (de Bruin, 1987), some of which are obtained by setting the surface resistance equal to zero and specifying an expression *F(U)* for the aerodynamic resistance in the Penman-Monteith equation:

$$\lambda E_p = \frac{\Delta(R_n - G) + F(U)\left[e_s(T_a) - e\right]}{\Delta + \gamma}, \tag{2}$$

where λ is the latent heat of vaporization of water (J kg^{-1}); E_p is the evaporation (kg m^{-2} s^{-1}); R_n is the net radiation (W m^{-2}); *G* is the soil heat flux (W m^{-2}); *D* is the slope of the saturation vapor pressure curve (kPa K^{-1}); g is the psychrometric constant (kPa K^{-1}); T_a is the air temperature (°K); $e_s(T_a)$ is the saturated vapor pressure at air temperature (kPa); and *e* is the air vapor pressure (kPa). The equation derived by Penman (1948) is still widely used to estimate the potential evaporation, E_o. However, the Penman equation requires measurements or estimates of air temperature and humidity, wind speed, net radiation and (preferably) soil heat flux near the transpiring crop.

Simpler equations to estimate E_o have been used in the Yaqui Valley irrigation project (Garatuza *et al.*, 1998). Evapotranspiration is more strongly dependent on the energy term, $\Delta(R_n - G)$, in Equation (2) than on the aerodynamic term, $F(U)(e_s(T_a)-e)$. If so, Equation (2) may be approximated by Priestley and Taylor, 1972

$$\lambda E_p = \alpha \frac{\Delta(R_n - G)}{\Delta + \gamma} \quad . \tag{3}$$

For well-irrigated vegetation growing in humid climates α is around 1.26. Thus the energy term in Equation (2) is approximately four times larger than the aerodynamic term. However, higher values of α are not uncommon in arid environments (Shuttleworth, 1993).

Net radiation can be expressed as

$$R_n = (1-a)R_s - \varepsilon(\sigma T_s^4 - R_{sky}) \ , \tag{4}$$

where R_s is the downward solar (short-wave) radiation (in W m^{-2}), R_{sky} is the downward (long-wave) atmospheric radiation (in W m^{-2}), and a, e, and T_s are the surface albedo, emissivity, and temperature, respectively. During the daytime the first term in Equation (4) is much larger than the second term. Thus, in general, net radiation is strongly determined by solar radiation. Furthermore, the average soil heat flux over periods of one (or several) days is often negligible, thus suggesting a simplified version of the Penman-Monteith equation, namely Makkink's equation (de Bruin, 1987; Feddes, 1987; Stewart *et al.*, 1995). This equation has proven reliable for estimating ET_p in the Yaqui Valley region (Garatuza *et al.*, 1998), as follows:

$$\lambda E_p = C_M \frac{\Delta}{\Delta + \gamma} R_s, \qquad (5)$$

where R_s is the short-wave radiation (Wm^{-2}) and C_M is a locally relevant empirical calibration constant. The value of C_M has been determined to be approximately 0.65 on a yearly basis in the Yaqui Valley (Moene and Garatuza, 1992; Garatuza *et al.*, 1992).

The term $\Delta/(\Delta + \gamma)$ in Equation (5) accounts for the temperature dependency of the saturation vapor pressure. It changes by just 1-2% for a 1°C change in temperature; hence, climatological values of temperature can be used in the estimated value of E_o.

Testing the Makkink equation requires reliable measurements of crop evaporation. A previous study (Garatuza-Payan *et al.*, 1998) showed that the Makkink equation, when applied with an appropriate crop factor, provides an estimate of crop evaporation that compares favorably with other estimates when calibrated to local conditions and crops in the Yaqui Valley.

3. SATELLITE ESTIMATES OF SOLAR RADIATION

Several methods for solar energy measurement have been developed (e.g., Tarpley, 1979; Gautier *et al.*, 1980; Möser and Raschke, 1983; Raphael and Hay, 1984; Dediu *et al.*, 1987; Pinker and Laszlo, 1992; see Pinker *et al.*, 1995 for a recent review).

In this study, the GEWEX/SRB algorithm (Whitlock *et al.*, 1995) was used to compute the downward solar radiation at the ground from satellite observations. This algorithm is based on a model developed by Pinker and Lazslo (1992). The broadband albedo at the top of the atmosphere—which is routinely observed by GOES satellites—is used to infer atmospheric transmissivity by radiative transfer modeling for a wide range of surface and atmospheric conditions. Once this relationship has been specified the radiative flux at the surface can be determined by deriving the transmittance of the atmosphere from the reflected radiation observed by the satellite. The short-wave radiative fluxes are computed for a plane-parallel, vertically inhomogeneous scattering and absorbing atmosphere in five spectral intervals (0.2-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, and 0.7-4.0 µm), using the δ-Eddington approximation for radiative transfer (Pinker and Ewing, 1985). In each spectral interval, upward and downward fluxes at the top of the atmosphere and at the surface are computed by determining the spectral transmittance from the top-of-atmosphere short-wave reflectance. The latter is estimated from the radiance in the narrow wavelength bands using a transformation between narrow waveband radiance and shortwave reflectance (Zhou *et al.*, 1996). The spectral transmittance-reflectance relationships are stored as a look-up table for discrete values of the solar zenith angle and for different atmospheric water vapor, ozone, aerosol loading and cloud optical thickness.

In context of the GEWEX Continental Scale Project (GCIP), the GEWEX/SRB algorithm is used with data from the GOES-East satellite and appropriate data from the NCEP regional forecasts to provide satellite estimates of surface and top of the atmosphere radiative fluxes. This product is provided within one to two days of real-time at one-hourly intervals on an equal area 0.5° grid mesh for the area 67°-125° West, 25°-50° North. At the end of each month, the data are transferred to a data archive at the University of Maryland. In the present study, data were extracted from this archive for the period November 1998 to March 1999 to provide the 50 km grid mesh, GOES-East satellite based estimates of solar radiation.

A modified version of the GEWEX/SRB algorithm was also used to provide estimates on a 4 km grid mesh using data from the GOES-West satellite that was received at the Instituto Tecnológico de Sonora (ITSON). Implementing the algorithm at high resolution requires preprocessing of the satellite data to identify and define the radiance for clear and cloudy skies. Half-hourly visible GOES images for the area 22.5°-36.0° North and 102.0°-117.5° West (corresponding to 2132 x 1304 pixels at full spatial and radiometric resolution) were collected, preprocessed, and stored. Image preprocessing involves applying a cloud detection algorithm that relies on the fact that, when observed from a geostationary orbit, the clear-sky surface brightness at each location at a given time of day changes only slowly with time. Changes do occur, but these are in response to changes in the geometry of solar illumination and due to slow changes in surface albedo caused by seasonal variation in vegetation and surface conditions. The algorithm assumes that any partial cloud cover in a selected target area increases the variance in the visible and infrared radiance over the area.

A Clear Composite Radiance (CCR) is required as a threshold in the cloud detection algorithm, the CCR being the radiance of an area under clear sky conditions with minimum aerosol and atmospheric contribution to the signal. To compute CCR, the radiance for each individual pixel is first corrected to allow for changes in the Sun-to-Earth distance and solar zenith angle using standard equations and parameters from the Nautical Almanac. The full-resolution (approximately 1 km) pixels are then grouped into 4 km x 4 km "target areas", and the average value, *R*, and standard deviation, *s*, of the corrected radiance are computed for each target area and for each half-hourly image. During preprocessing, fields of CCR are maintained in the visible waveband for every 4 km x 4 km target area and for every daylight half-hour for which the solar zenith angle is less than 75°. These fields are updated very conservatively to minimize the risk of cloud contamination. Corresponding fields of *s*, the standard deviation of radiance in the visible waveband in clear sky conditions, are also stored.

For a specific target area at a given time of day, the CCR and standard deviation fields are updated if there are no clouds in the corresponding target area. To guarantee totally clear conditions, a target is updated only if $R < (R_{clear} + 1.5\, s_{clear})$ and $s < 4\, s_{clear}$, where *R* is the currently measured radiance, R_{clear} is the stored minimum value of radiance, s is the new standard deviation of radiance for the target area, and s_{clear} is the previously stored value of standard deviation. When the observation from a target area meets the above criteria, CCR is updated with a weighted average of the new and the old values, the new value being given a weight, *W*, which is an exponential function of the number of days, N_{days}, since the last update, i. e. W = 0.7 exp(N_{days}/10). This weighting factor was selected by trial and error to minimize the possibility of subpixel cloud cover contributing to the observed radiance of accepted values to give slow brightening of the CCR fields.

The values of R_{clear} and s_{clear} are also used to define the threshold between clear and partly cloudy pixels in the cloud detection algorithm. Each pixel in each target area is classified on the basis of its top of the atmosphere albedo as being clear, partly cloudy, or cloudy. Thus, the observed value of radiance for the pixel is compared against R_{clear}, the clear-sky composite value for the target area in which it falls and, if the observed value is less than $(R_{clear} + 13\, s_{clear})$, the pixel is classified as a clear-sky pixel. If the observed raw data count is greater than 35% of the albedo value for cloudy skies, the pixel is classified as being totally cloud-covered. If the pixel does not fall into either of the clear-sky or totally cloud-covered categories, it is classified as having mixed cloud cover. Pixels defined as having mixed cloud cover are then re-allocated between the clear-sky and totally cloud-covered categories (Garatuza *et al.*, 2001).

To provide validation, the satellite-based estimates of the solar radiation reaching the ground were compared with surface observations in the irrigation region. Solar radiation was measured throughout the study period with Eppley pyranometers at two sites, Site 910 (27.37°N, 109.92°W) and Site 1517 (27.20°N, 110.18°W), located 35 km apart.

4. CROP EVAPORATION ESTIMATES

The daily estimates of downward solar radiation derived from satellite data for each target area were used in the Makkink equation to yield daily estimates of potential evaporation. These estimates were then combined with locally calibrated crop factors derived in previous studies (Garatuza *et al.*, 1998) to provide estimates of the actual daily evaporation for individual areas of crop in the Obregon irrigation scheme:

$$E_{crop,total} = K_c C_M \frac{\Delta}{\Delta+\gamma}\left(\frac{R_{s,total}}{\lambda}\right), \qquad (7)$$

where $R_{s,total}$ is the daily total solar radiation estimated from satellite data in J/day, $E_{crop,total}$ is the estimated crop evaporation mm/day, C_M = 0.65 for the Yaqui Valley (Garatuza *et al.*, 1992), and K_c is the appropriate crop factor for the specific crop and day in the crop growth cycle.

Garatuza *et al.* (1998) provided functions for determining the crop factor in the Makkink equation for the Yaqui Valley and for crops that have continuous cover, such as wheat, or for row crops, such as cotton. These are based on the widely used form for crop factors which describes the function in three linear sections:

$$K_c = a_1 + \left(\frac{a_{i+1}-a_i}{d_{1+1}-d_i}\right)(d-d_i)\ , \qquad (8)$$

where *d* is the number of days after emergence, a_i are the four limits on the three linear sections, and d_i are the days on which transitions are made between linear sections. Garatuza *et al.* (1998) found that for continuous-cover crops (e.g., wheat), $K_{cc} = K_c$. However, for row crops (e.g., cotton), where $(d_{irr} + l_{irr}) > d > d_{irr}$,

$K_{row} = a_2$ if $a_2 >= 1$
$K_{row} = 1$ if $a_2 < 1$

and, when $d > (d_{irr} + l_{irr})$,

$$K_{row} = K_c+(1- K_c)(\exp(-(d-(d_{irr}+l_{irr}))/t_c))^2\ ,$$

where d_{irr} is the day the last irrigation started, l_{irr} is the number of days over which irrigation was last applied, and t_c is the time constant (in days) for the decay of the influence of irrigation on row crops. The values a_i, d_i, and t_c suggested by Garatuza *et al.* (1998) for the wheat and cotton crops in the Yaqui Valley area are given in Table 1.

Table 1

Values of the parameters a_i and d_i which specify the crop factors for wheat and cotton crops when the Makkink equation is used to calculate potential evaporation in the Yaqui Valley irrigation scheme (from Garatuza *et al.*, 1998)

Parameter	Yaqui Valley Wheat Crop	Yaqui Valley Cotton Crop
a_1	0.34	0.15
a_2	1.28	1.26
a_3	1.28	1.26
a_4	0.08	0.92
d_1	14	34
d_2	38	103
d_3	107	133
d_4	128	150
t_c	(not relevant)	20

5. RESULTS AND DISCUSSION

(a) Solar Radiation Estimates

Low-resolution estimates of solar radiation from the GEWEX/SRB algorithm for GOES-East and GOES-West were compared with surface observations with the two Eppley pyranometers. In the case of GOES-East, comparison was with the value for the 50 km x 50 km grid square within which each field site was located. In the case of GOES-West, the high-resolution estimate was compared with the average value for the nine 4 km x 4 km grid squares closest to each field site.

The calibration of the radiometers on GOES-East and GOES-West is uncertain. Table 2 gives the monthly average solar radiation as estimated by the two satellite systems using current satellite calibrations. In both cases, there are systematic discrepancies. When the values are averaged over the whole period for which data are available, the estimates derived from GOES-East satellite are 18% higher than field measurements, while those from GOES-West are 9% lower than field measurements.

Table 2

Average solar radiation over each month from November 1998 to March 1999 and the whole study period observed at two sites, Sites 910 and 1517, in the Yaqui Valley irrigation scheme compared with equivalent estimates made from data from the GOES-West and GOES-East satellites

	Site 910			Site 1517		
	Ground	GOES-West	GOES-East	Ground	GOES-West	GOES-East
November	429	397	524	417	405	530
December	375	312	498	366	312	495
February	467	427	557	483	414	545
March	596	564	668	607	552	664
Total Period	466	426	562	468	421	559

The two satellite estimates were adjusted by -18% and +9%, respectively, to provide time-average agreement with surface observations. Figure 1 shows a comparison between the re-calibrated hourly averages and daily averages from GOES-East versus observed solar radiation at the two surface sites. Figure 2 shows a similar comparison for estimates from GOES-West. Days with less than six hours of data from the pyranometers (or satellite) were omitted, which left 84 days for Site 910 and 78 days for Site 1517.

Table 3 shows the root-mean-square error (RMSE) in Wm^{-2} and as a percentage of the mean hourly and daily averages of solar radiation. The percentage RMSE for daily average estimates of solar radiation from GOES-West are in the range of 7 to 14% (30 to 55 Wm^{-2}) in agreement with results by other authors (Raphael and Hay, 1984; Stewart *et al.*, 1999). Few authors have reported hourly estimates of discrepancies relative to ground data. Dedieu *et al.* (1987) reported an RMSE of 20% for a study in France, while Stewart *et al.* (1999) obtained an RMSE of 20.2% in the Yaqui Valley using a different radiation model. These compare with the equivalent values found during the present study that lie in the range of 9 to 14% (47-96 Wm^{-2}). As might be expected, the daily average RSME is significantly lower than the hourly average RSME, as the satellite provides an instantaneous area-average estimate while the field observation is a time-average single-point measurement.

The satellite estimates show better agreement with ground data during the less cloudy months of November and

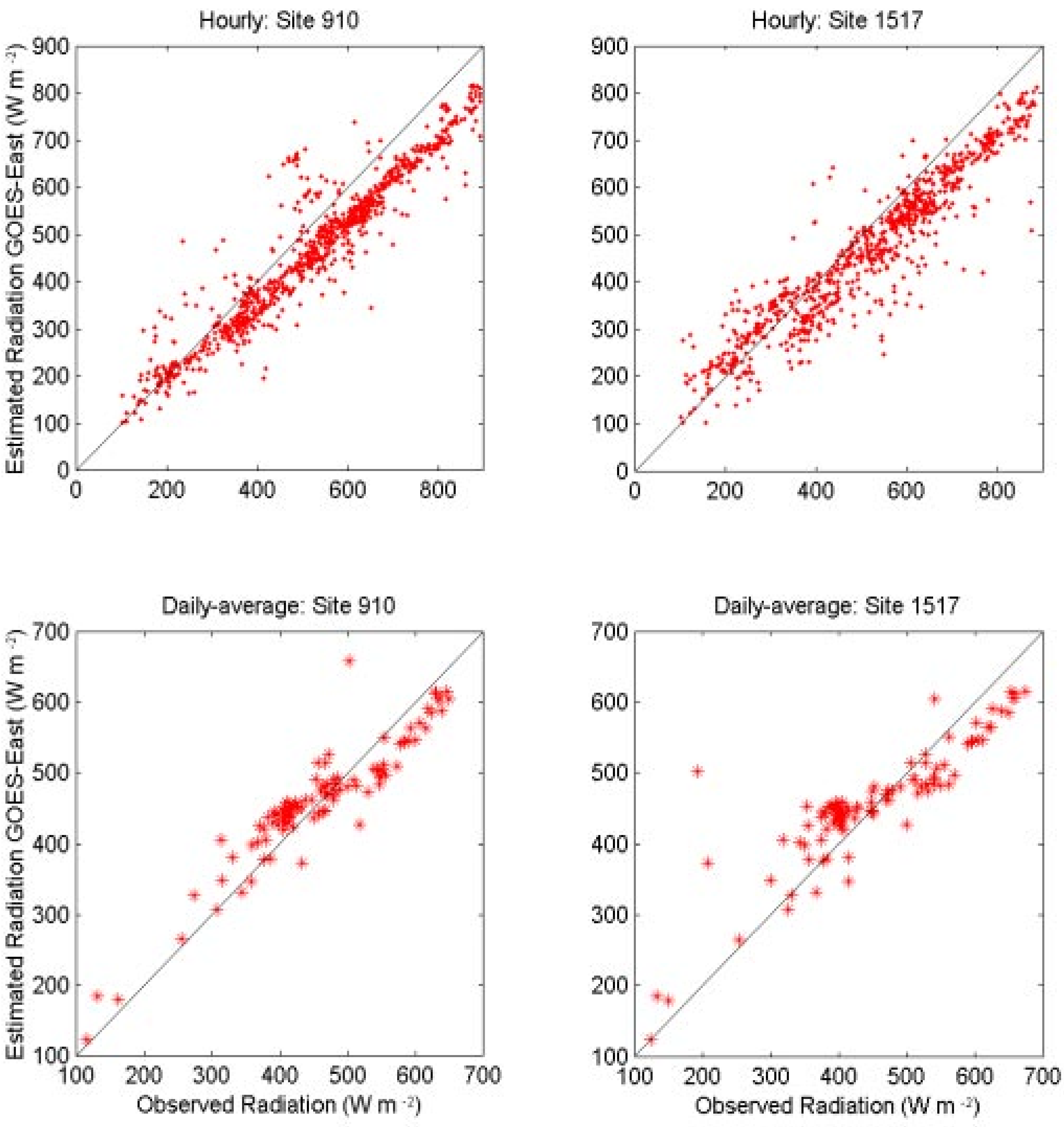

Fig. 1. Comparison between ground-based measurements of solar radiation at two sites (Site 910 and Site 1517) in the Yaqui Valley irrigation scheme and the equivalent solar radiation derived at a 50 km grid resolution from GOES-East data.

March than during more cloudy months (December and February). This result is consistent with previous studies (Raphael and Hay, 1984, Gautier *et al.*, 1980; Stewart *et al.*, 1999). If cloud movement is responsible for these differences, it might be argued that satellite estimates can provide a more reliable measure of the spatial distribution of surface radiation than A local network of ground-based pyranometers. If the differences are due to rapid changes in cloud cover which are poorly sampled by the satellite, more frequent satellite images would reduce the scatter. The discrepancier`may also

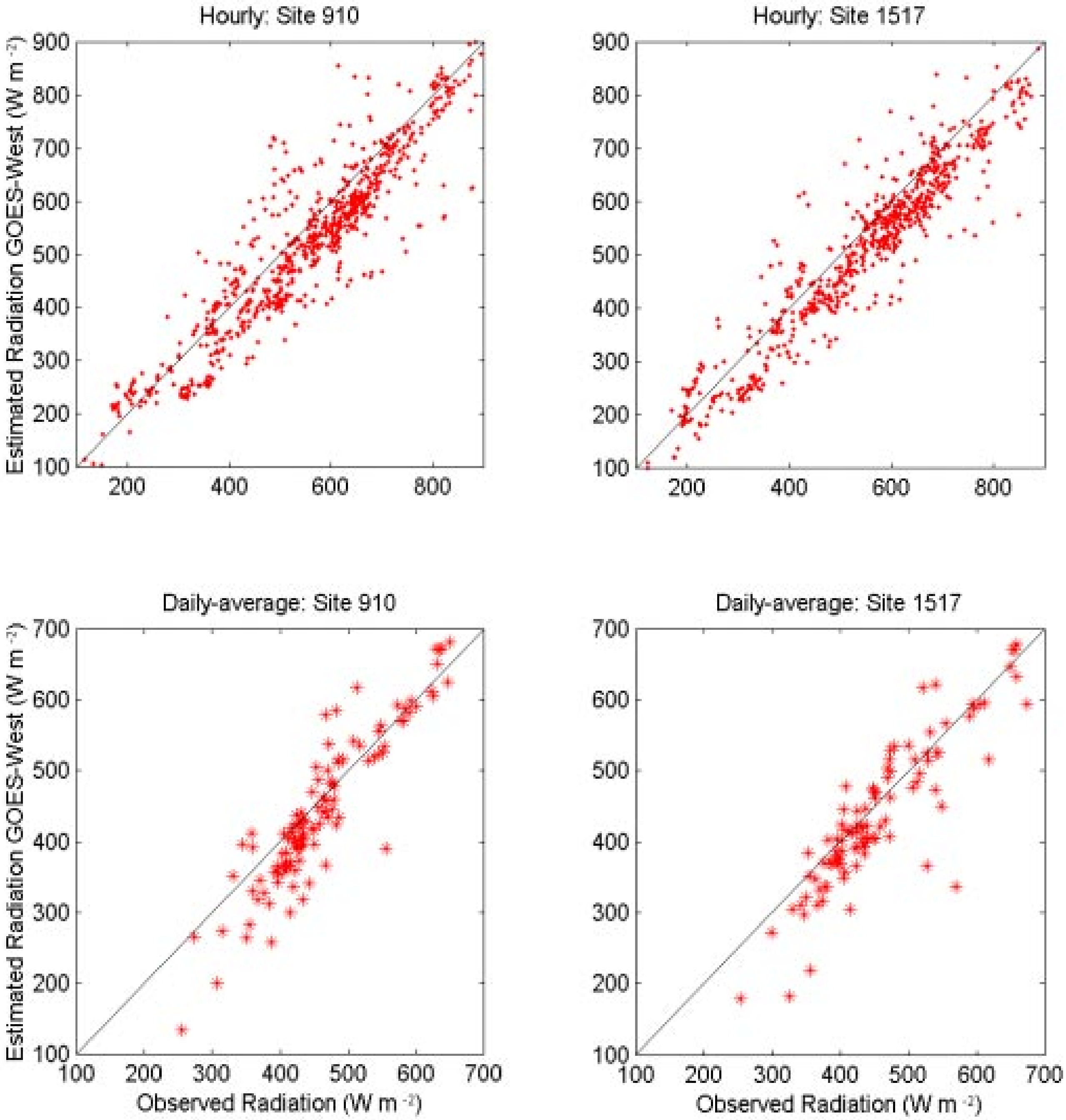

Fig. 2. Comparison between ground-based measurements of solar radiation made at two sites (Site 910 and Site 1517) in the Yaqui Valley irrigation scheme and the equivalent solar radiation derived at a 4 km grid resolution from GOES-West data.

be due in part to changes in atmospheric water and aerosol content. The GOES-NEXT satellite allows capture of four images each hour rather than one image as used in this paper.

The results given in Table 3 and Figure 1 show that high-resolution solar radiation estimates based on GOES-West data show somewhat better agreement with the surface measurements than do lower-resolution estimates based on GOES-East data. Presumably, use of a larger grid brings out the effect of the land cover and of changes in the concentration

Table 3

Root mean squared errors in W m^{-2} and as percentages of the average flux (in brackets) between hourly-average and daily-average estimates based on GOES-East and GOES-West data relative to ground-based observations at Sites 910 and 1517

	Site 910				**Site 1517**			
	GOES-West		**GOES-East**		**GOES-West**		**GOES-East**	
	Hourly	**Daily**	**Hourly**	**Daily**	**Hourly**	**Daily**	**Hourly**	**Daily**
November	53.73 (10.35)	42.97 (9.91)	62.24 (12.71)	34.96 (7.78)	46.93 (9.32)	29.93 (7.07)	63.51 (13.17)	46.67 (11.28)
December	66.67 (13.39)	55.36 (14.75)	75.92 (15.79)	41.68 (11.15)	49.03 (10.84)	50.28 (13.75)	71.45 (15.34)	48.96 (13.35)
February	79.69 (13.95)	62.15 (13.48)	91.68 (18.17)	45.95 (9.94)	79.42 (13.4)	63.75 (13.48)	98.48 (18.66)	73.55 (16.17)
March	95.97 (14.23)	53.00 (8.92)	89.57 (14.78)	53.72 (9.11)	77.10 (11.43)	78.08 (12.90)	98.24 (18.54)	54.80 (9.12)
All Months	72.83 (13.22)	50.91 (11.17)	80.52 (15.52)	39.21 (9.61)	65.80 (12.06)	53.59 (11.78)	83.65 (16.27)	55.61 (12.35)

of water vapor and aerosols in the atmosphere. Moreover, low-resolution satellite estimates are arguably less relevant to hydrological (as opposed to meteorological) applications because areas of land relevant in hydrology, such as catchments or irrigation projects are often better sampled by 4 km estimates. Figure 3 illustrates this point by comparing images of the daily averages of solar radiation for both satellites (GOES-East referred as "GCIP" and GOES-West as "GOES") on two days with different cloudiness conditions (February 2 and 14, 1999) and for the region of the Yaqui Valley. The greater specificity in the spatial distribution given by the 4 km grid affords more accurate estimates of evaporation using field scale information on crop cover.

(b) Crop Evaporation Estimates

The goal of the present study was to show how satellite data can be used to estimate the evaporation from the component crops in the Yaqui Valley irrigation scheme. Figure 4 demonstrates that this is indeed feasible. The figure shows the actual evaporation during a growth season for two fields, one centered on 27.37°N, 109.92°W which was planted with wheat on November 16, 1998, and one centered on 27.20°N, 110.18°W which was planted with cotton, on January 1, 1999. The evaporation estimates are derived by multiplying the daily estimates of potential evaporation for each field by the relevant crop factor as specified by Garatuza *et al.* (1998). The estimate of potential evaporation used in these calculations is from the Makkink equation and for the high-resolution (4 km) satellite estimates of solar radiation.

6. CONCLUSIONS

The potential value of using satellite-based estimates of the evaporation from irrigated crops was explored. Two sources of satellite estimates of solar radiation were considered: (a) estimates on a 50 km grid spacing using the GEWEX/SRB algorithm for GOES-East data, and (b) estimates on a 4 km grid spacing using a high-resolution development of the GEWEX/SRB algorithm with GOES-West data. The resulting values were compared with ground observations made at two field sites in the Yaqui Valley irrigation project near Ciudad Obregón for the period November 1998 to March 1999. Comparison between ground observations and satellite estimates suggested that there are significant biases in the calibration of the satellite

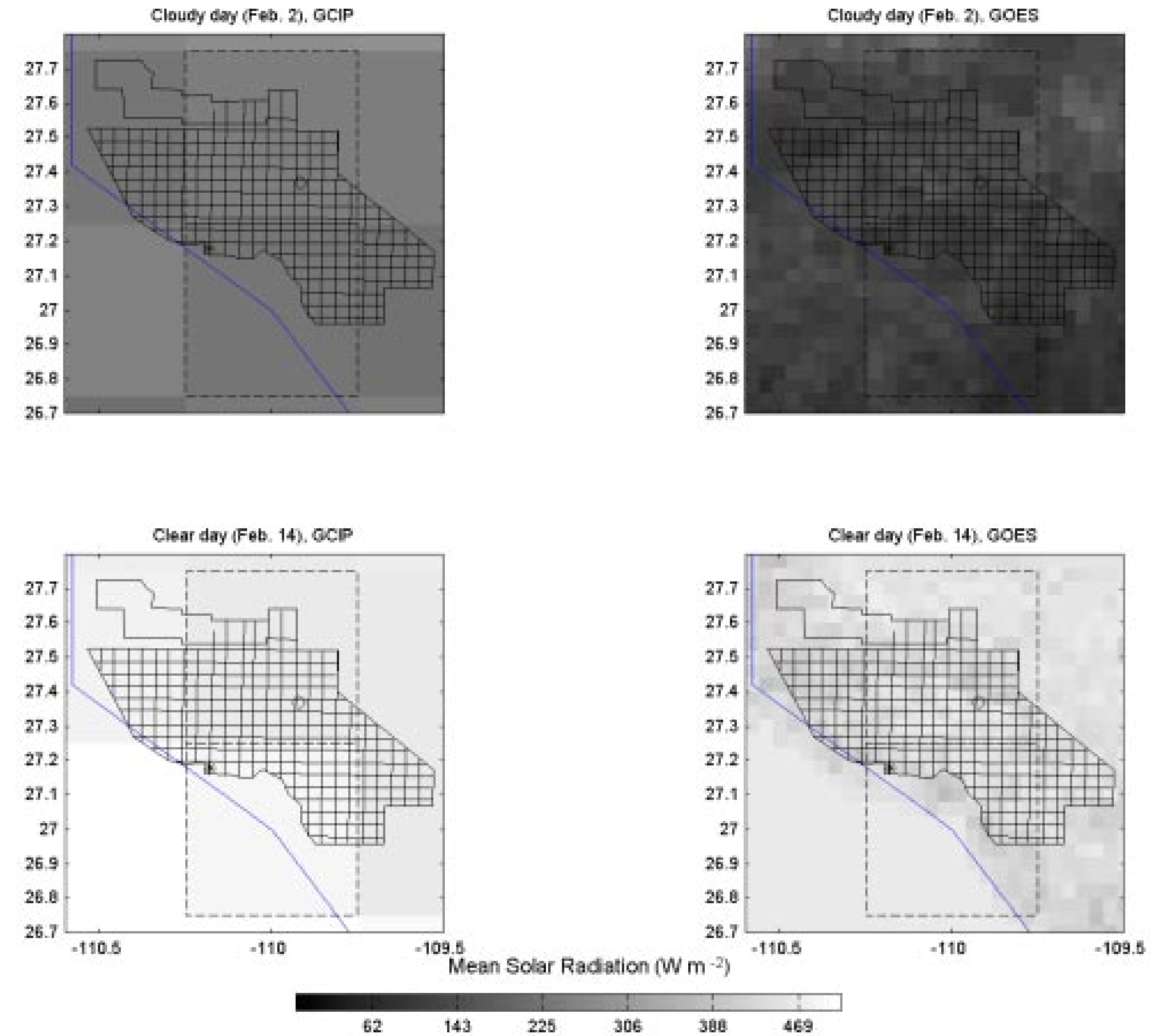

Fig. 3. Spatial distribution of daily incoming solar radiation, over the Yaqui Valley irrigation scheme, for a cloudy and a clear day (February 2 and 14, 1999, respectively), after empirical correction. The boundary and drainage ditches in the Yaqui Valley irrigation scheme and the two 50 km x 50 km grid boxes for which data were available from GOES-EAST (GCIP) are also shown. The location of the two ground-based measurements is shown as a circle for Site 910 and a star for Site 1517.

sensors. The satellite data were recalibrated to give adequate time-average agreement with the field observations.

The re-calibrated satellite estimates show significantly greater scatter as compared to field observations for hourly data than for daily average data. This is consistent with the fact that the satellites provide an instantaneous area-average estimate, while the ground observations are time-average single-point measurements. The scatter in the lower-resolution (50 km) estimates is somewhat greater than for the high-resolution (4 km) estimates.

Use of high-resolution solar radiation estimates to calculate the seasonal evaporation rate for a wheat crop and a cotton crop in the Yaqui Valley was demonstrated. We drew on the results of previous studies for a local version of the Makkink equation (Garatuza *et al.*, 1992) and locally calibrated crop factors (Garatuza *et al.*, 1998) for these two cases.

It appears to be feasible to provide routine estimates of evaporation for common crops in the Yaqui Valley irrigation project from satellite data. A system to provide such estimates

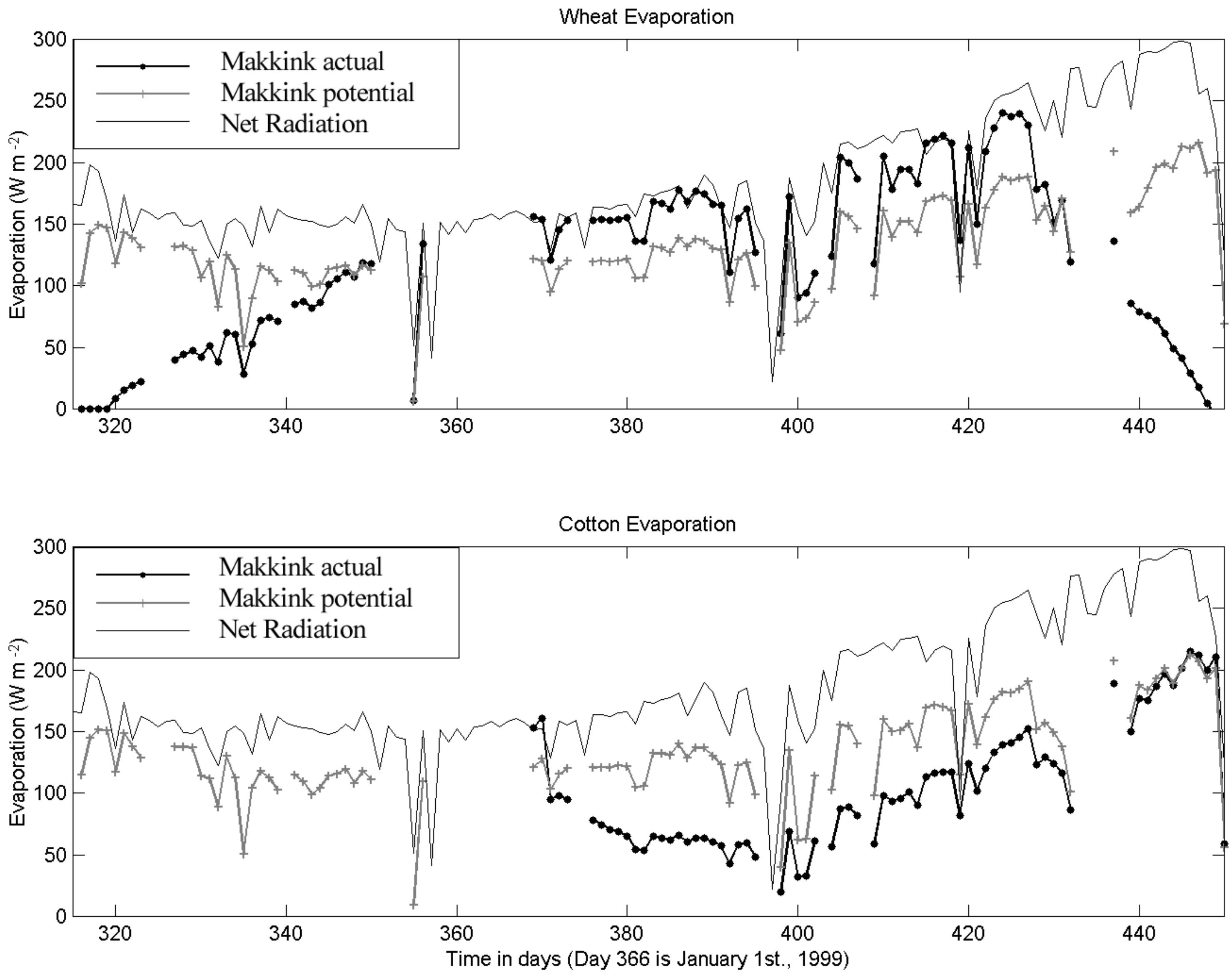

Fig. 4. Actual evaporation estimates calculated for two fields: (a) planted with wheat on November 16, 1998, and (b) planted with cotton on January 1, 1999. The estimates were calculated from Equation (5) using the high-resolution (4 km) daily average estimates of solar radiation from the GOES-West satellite with the appropriate crop factor given by Garatuza *et al.* (1998). The daily average net radiation is also shown.

has now been established, and the Water Users Association of Yaqui Valley is using them to decide which specific fields need irrigation. A Web site is also being created which will provide direct access to evaporation estimates via the Internet.

ACKNOWLEDGEMENTS

Support at the University of Arizona was provided under NASA Grant NAG8-1531. Jaime Garatuza received support from a CONACYT Fellowship. The satellite data from GOES-West were gathered as part of research supported by the European Community (CI1-CT94-0059). The authors wish to acknowledge the editorial assistance of Corrie Thies.

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Jaime Garatuza-Payán[1], W. James Shuttleworth[2], and Rachel T. Pinker[3]

[1]*Instituto Tecnológico de Sonora, Cd. Obregón, Sonora, México, 85000 México*
email: garatuza@yaqui.itson.mx
[2]*Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ*
[3]*Department of Meteorology, University of Maryland, College Park, MD*