Solar radiation, longwave radiation and emergent wetland evapotranspiration estimates from satellite data in Florida, USA

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Abstract Routine estimates of daily incoming solar radiation from the GOES-8 satellite were compared to locally measured values in Florida. Longwave radiation estimates corrected using GOES-derived cloud amount and cloud top temperature products improved net radiation estimates as compared to a clear sky longwave approach. The Penman-Monteith, Turc, Hargreaves and Makkink models were applied using GOES-derived estimates of solar radiation and net radiation to predict daily evapotranspiration and were compared to evapotranspiration measured with an eddy-correlation system in an emergent wetland experimental site in north-central Florida under unstressed conditions. While the Penman-Monteith model provided the best estimates of evapotranspiration ($R^2 = 0.92$), the empirical Makkink method demonstrated nearly comparable agreement ($R^2 = 0.90$) using only the GOES solar radiation and measured temperature. The results show that it is possible to generate spatially distributed daily potential evapotranspiration estimates using GOES-derived solar radiation and net radiation with limited additional surface measurements.

Key words evapotranspiration; GOES; solar radiation; net radiation; wetlands

INTRODUCTION
Numerous approaches are available to estimate evapotranspiration (ET) over large areas using a combination of remote sensing observations and ancillary surface and
atmospheric data (e.g. Jackson et al., 1977; Seguin et al., 1989; Nemani & Running 1989; Price 1990; Holwill & Stewart, 1992; Bastiaanssen, 2000). Most remote sensing approaches require surface meteorological data, necessitating extrapolation of atmospheric or radiative variables from measurement points to other pixels. For example, the commonly used triangle method uses a combination of remotely sensed vegetation index and surface temperature information to map the ratio of ET to available energy (Moran et al., 1994; Carlson et al., 1995; Gillies et al., 1997; Jiang & Islam, 1999, 2000). This ratio (the evaporative fraction) is then typically combined with ground-based measurements of net radiation to derive actual ET fluxes. Thus, the effectiveness of routine application of remote sensing over large areas to determine spatially distributed ET is dependent on the surface climatological network and is often limited by sparse surface radiation data.

The National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) satellites offer an alternative to surface measurements. The GOES satellites can provide frequent and routine estimates of radiation products that have significantly better spatial resolution than that available from most ground-based pyranometer networks. GOES-based instantaneous solar insolation estimation errors are typically less than 10% (Schmetz, 1989; Pinker et al., 1995; Diak et al., 1996). In addition, recently developed algorithms to estimate longwave radiation from GOES-derived cloud coverage and temperature products (Gu et al., 1999; Diak et al., 2000) may be combined with the solar radiation product to estimate net radiation. A GOES solar radiation product has been used routinely to estimate evapotranspiration from well-watered regions (Diak et al., 1996, 1998). However, relatively few evapotranspiration validation studies have been conducted and these studies have only used various GOES-derived solar radiation products to estimate potential evapotranspiration (PET) (Stewart et al., 1999; Garatuza-Payan et al., 2001; Jacobs et al., 2002b).

The goal of this study is to use GOES shortwave and longwave data to estimate the daily values of solar radiation, net radiation and PET in peninsular Florida. The peninsular region has atmospheric conditions during the growing season that are characterized by active convective systems with extremely dynamic clouds. These conditions represent a significant challenge for remote sensing of radiation. The study site, an emergent wetland experimental site, is characterized by a relatively high water table, moist soil conditions and evapotranspiration at a potential rate. Daily solar and net radiation estimates derived from hourly GOES data are compared to values measured at the wetland experimental site. The derived radiation products are used in the Turc, Hargreaves, Makkink and Penman-Monteith models to predict PET and to compare modelled fluxes with measurements obtained with eddy-correlation instrumentation.

OBSERVATIONS

Surface meteorological observations

This study was conducted for 92 days in May, June and July 2001 (day of year: 121–221) at the Paynes Prairie State Preserve experimental site, a large highland marsh system in north-central Florida, USA (Fig. 1). The study area and instrumentation are
described in detail by Jacobs et al. (2002a). The study was conducted in a wet prairie community located in the Paynes Prairie Preserve (29°34′14″N, 82°16′46″W). The wet prairie is a relatively flat, treeless plain with a moderately dense ground cover: a biome combining characteristics of pasture and marshlands. Emergent herbaceous perennials in this prairie were predominant and dense, and typically 0.4–1.2 m tall. The most common species were *Panicum hemitomon* Schultes (maiden cane), *Polygonum hydropiperoides* Michx. (mild water-pepper), and *Ptilimnium capillaceum* Michx. (mock bishop’s weed). *Eupatorium capillifolium* Lam. (dog fennel) was also prevalent and *Sesbania* sp. was scattered throughout; this vegetation was approximately 1.5 m tall. The experimental period occurred three years into a drought. As a result, the water
table was somewhat low and fluctuated during the experiment from 1.2 m below the surface to slightly above surface level (Jacobs et al., 2002a).

Ground-based measurements acquired at the experiment site included surface meteorological and eddy flux parameters for days 121–201. Net radiation was measured with a Radiation Energy Balance Systems Q7.1 net radiometer. Temperature and relative humidity were measured using a shielded Vaisala model HMP 45C sensor (Campbell Scientific Instruments, Inc. (CSI)). Wind speed and direction were measured with a CS 800-L anemometer (RM Young, Inc.). In addition, near-surface volumetric soil water content was recorded using a CSI 615L water-content reflectometer installed vertically to average over the top 25 cm of soil. Measurements were made every minute and averaged over 30-min intervals.

Actual evapotranspiration was measured directly using the eddy-correlation approach. The sensible and latent heat flux measurements were made using a CSI CSAT3 3-D Sonic Anemometer, which measures the three wind components and the virtual temperature, and a CSI KH20 Krypton hygrometer. Fluctuations in wind speed, virtual air temperature and vapour density were sampled at 8 Hz and 30-min average covariances were aggregated to estimate the daily fluxes.

Satellite data

The satellite data used to estimate solar and net radiation were provided by the GOES-8 system, which served as the active GOES-EAST platform (positioned at 75°W) through the spring of 2003 when it was replaced by GOES-12. The GOES imager and sounder instruments collect one to four observations per hour, from which atmospheric temperature, winds, moisture, skin temperature and cloud cover can be derived. The approach used to estimate insolation from GOES imagery is described in detail by Gautier et al. (1980) with modifications by Diak & Gautier (1983), and is outlined briefly here.

The insolation algorithm employs a simple physical model of radiative transfer. Images are compared against a reference map of surface albedo developed under clear sky conditions. The surface albedo comparison indicates whether a point is clear or cloudy. If the point is clear, a clear model of bulk radiative transfer is used to adjust the insolation for effects of ozone absorption, Rayleigh scattering and water vapour absorption. If the point is cloudy, a cloudy radiation model is applied to determine the cloud albedo, and atmospheric effects are calculated separately above and below the cloud. The GOES satellite solar radiation product $R_{s,\text{GOES}}$ was calibrated using regional ground-based solar radiation measurements.

The insolation data were developed using the methods of Diak et al. (1996). Data collection and processing has been automated using the Man-computer Interactive Data Processing System (McIDAS) at the University of Wisconsin Space Science and Engineering Center (SSEC). For this experiment, the 0.2 degree grid cell (~ 20 km) encompassing the ground site was extracted from maps covering the eastern USA. Up to 12 hourly insolation images were combined to estimate daily radiation values.

The satellite-based estimates of downwelling longwave radiation used in this study were generated with the methods of Diak et al. (2000) and incorporate GOES-derived cloud products obtained through a “CO2-slicing” technique (Menzel et al., 1983; Schreiner et al., 1993). Estimates of effective cloud fraction (the dimensionless
product of areal cloud fraction and cloud emissivity) and cloud-top temperature are used to correct an empirical prediction of clear-sky longwave radiation. This correction procedure is described further in the following section.

THEORIES AND METHODS

Radiation models

Solar radiation may be measured using pyranometers or solarimeters. If a solar radiation measurement is not available, it can be estimated from extraterrestrial radiation, $R_a$. The extraterrestrial radiation, a function of the latitude and day of year, is given as:

$$R_a = \frac{1440}{\pi} G_{sc} d_r \left[ \sin(\omega_s) \sin(\delta) + \cos(\delta) \cos(\omega_s) \right]$$

where $R_a$ is the extraterrestrial (i.e. top-of-the-atmosphere) solar radiation (W m$^{-2}$), $G_{sc}$ is the solar constant (0.949 W m$^{-2}$), $d_r$ is the inverse relative distance of the Earth from the sun, $\omega_s$ is the sunset hour angle (rad), $\phi$ is the latitude (rad), and $\delta$ is the solar declination (rad). The Hargreaves method (Hargreaves et al., 1985) estimates daily incoming solar radiation by combining the clear-sky extraterrestrial radiation and the difference between the daily maximum and minimum air temperature as:

$$R_s = k_{Rs} \sqrt{(T_{\text{max}} - T_{\text{min}})} R_a$$

where $R_s$ is the daily solar radiation (W m$^{-2}$), $k_{Rs}$ is the adjustment coefficient (0.16°C$^{-0.5}$), $T_{\text{max}}$ and $T_{\text{min}}$ are the maximum and minimum daily temperatures (°C), respectively, and $R_a$ is extraterrestrial radiation (W m$^{-2}$) given by equation (1).

The clear-sky downwelling longwave radiation is estimated from Prata (1996) as:

$$R_{ldc} = \varepsilon_a \sigma T_a^4$$

with the clear-air emissivity given by:

$$\varepsilon_a = 1 - \left[ 1 + c_1 \left( \frac{e_a}{T_a} \right) \right] \exp \left[ - \sqrt{c_2 + c_3 \left( \frac{e_a}{T_a} \right)} \right]$$

where $R_{ldc}$ is the clear sky downwelling longwave radiation (W m$^{-2}$), $\varepsilon_a$ is the atmospheric emissivity, $\sigma$ is the Stefan-Boltzmann constant (W m$^{-2}$ K$^{-4}$), $e_a$ is the vapour pressure (mb), $T_a$ is the air temperature (K) and $c_1$, $c_2$, $c_3$ are constant with values of 46.5, 1.20 and 3.0, respectively.

As demonstrated by Diak et al. (2000), the clear-sky downwelling longwave radiation can be adjusted for the contribution from cloud emission by using GOES-derived cloud products (Schreiner et al., 1993):

$$R_{ld} = R_{ldc} + (1 - \varepsilon_a) C \sigma T_c^4$$

In equation (5), $R_{ld}$ is the total downwelling longwave radiation including the contribution from clouds, $1 - \varepsilon_a$ is the effective transmissivity of the atmosphere below the clouds, $C$ is the effective cloud fraction from GOES, and $T_c$ is the cloud temperature.
(K). As noted by Diak et al. (2000), $T_c$ is most correctly defined as the cloud-base temperature, while the GOES satellite only provides information about cloud-top temperature. Diak et al. (2000) estimate that use of proxy cloud-top temperature information in equation (5) results in relatively modest errors in downwelling long-wave flux at the Earth surface.

The net longwave radiation $R_{lc}$ under clear-sky conditions is estimated by combining equation (3) with the upwelling longwave radiation from the surface:

$$R_{lc} = (1 - \varepsilon_s)R_{ldc} - \varepsilon_s\sigma T_s^4$$

(6a)

The GOES net longwave radiation corrected for cloudy sky conditions ($R_l$) is estimated by combining equation (5) with the upwelling longwave radiation from the surface:

$$R_l = (1 - \varepsilon_s)R_{ld} - \varepsilon_s\sigma T_s^4$$

(6b)

In equations (6a) and (6b), $\varepsilon_s$ is the surface emissivity and $T_s$ is the surface temperature (K). For daily estimates of longwave radiation, $T_a$ is often used in equations (6a) and (6b) instead of $T_s$ (Brutsaert, 1982; Diak et al., 2000).

Net radiation at the surface is estimated from the incoming solar radiation, surface parameters, using either the clear-sky net longwave radiation from equation (6a) as:

$$RN_c = R_s(1 - \alpha) + R_{lc}$$

(7a)

or the corrected net longwave radiation from equation (6b) as:

$$RN = R_s(1 - \alpha) + R_l$$

(7b)

where $\alpha$ is the surface albedo. Based on Eagleson’s (1970) value for tall, green vegetated surfaces, the surface albedo for the Paynes Prairie surface was estimated to be 0.15.

Evapotranspiration models

Evapotranspiration models routinely use solar radiation directly or in combination with longwave radiation to provide a measure of the net available radiation. Combination equations, based on the original Penman (1948) combination equation, typically give the best ET estimates for a variety of vegetated surfaces and climates, but their application is suitable only at locations where in situ measurements of temperature, wind, water vapour and sunshine duration or solar radiation are available. For data limited regions, numerous empirical models exist to determine PET. Three methods that apply solar radiation directly, the Hargreaves method, the Turc method and the Makkink method, are considered in this study. In addition to solar radiation, these methods require some measure of mean daily air temperature.

The Hargreaves method (Hargreaves & Samani, 1985) is an empirical approach that can be used to compute daily PET in cases where the availability of weather data is limited. The Hargreaves formula calculates PET from solar radiation and temperature as:

$$LE = 0.01354R_s(T_a + 17.8)$$

(8)

where $LE$ is the mean daily latent heat flux (W m$^{-2}$), $R_s$ is the daily solar radiation (W m$^{-2}$), and $T_a$ is the mean daily air temperature ($^\circ$C).

The Turc radiation method (Turc, 1961), developed in western Europe for regions where the relative humidity is greater than 50%, expresses PET as:
Solar radiation, longwave radiation and emergent wetland evapotranspiration estimates

\[ LE = 0.369 \frac{T_a}{T_a + 15} (2.06R_s + 50) \]  

(9)

where \( LE \) is the mean daily latent heat flux (W m\(^{-2}\)), \( R_s \) is the daily solar radiation (W m\(^{-2}\)), and \( T_a \) is the mean daily air temperature (°C).

The Makkink radiation method (Makkink, 1957) is a simplified version of the Priestley-Taylor equation that assumes that the daily ground heat flux is small and the net radiation is largely a function of the solar radiation (de Bruin, 1987) such that:

\[ LE = C_M \frac{\Delta}{\Delta + \gamma} R_s \]  

(10)

where \( LE \) is the latent heat flux (W m\(^{-2}\)), \( C_M \) is the ratio of net radiation to solar radiation (determined from measured data to be 0.65 for the Paynes Prairie experimental station), \( \Delta \) is the slope of the saturation vapour pressure temperature relationship, \( \gamma \) is the psychrometric constant, and \( R_s \) is the solar radiation (W m\(^{-2}\)).

The Penman-Monteith method is an extension of the Penman equation that calculates ET for a range of vegetated surfaces through the introduction of plant specific resistance factors (Monteith, 1965):

\[ LE = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_d)/r_s}{\Delta + \gamma(1 + r_s/r_a)} \]  

(11)

where \( LE \) is the latent heat flux, \( R_n \) is the net radiation, \( G \) is the ground heat flux, \( \rho_a \) is the mean air density at constant pressure, \( c_p \) is the specific heat of air, \( e_s - e_d \) is the vapour pressure deficit of the air, \( e_s \) is the saturation vapour pressure of the air, \( e_d \) is the actual vapour pressure of the air, \( r_s \) is the bulk surface resistance, and \( r_a \) is the aerodynamic resistance. The aerodynamic resistance was estimated using Monin-Obukhov similarity assuming neutral conditions by:

\[ r_a = \frac{\ln[(z-d)/z_o] \ln[(z-d)/z_{ov}]}{k^2 U} \]  

(12)

where \( z \) is the height at which the wind speed \( U \) was measured, \( d \) is the displacement height estimated to be 0.7\( z_{veg} \) where \( z_{veg} \) is the vegetation height, \( z_o \) is the roughness height approximated as 0.1\( z_{veg} \), \( z_{ov} \) is the roughness height for water vapour approximated as 0.1\( z_o \), and \( k \) is the Von Karman’s constant (0.4). For this wetlands site, under unstressed conditions, the surface resistance was determined to be 50 s m\(^{-1}\) (Jacobs et al., 2002a). In this study, the Penman-Monteith equation is used to predict PET with \( r_s = r_{s,min} \) at a fixed minimum of 50 s m\(^{-1}\).

RESULTS AND DISCUSSION

Analysis of modelled radiation

The solar radiation, longwave radiation and net longwave radiation were estimated using the GOES-based method at the Paynes Prairie. The estimates were examined with respect to both measured values and radiation estimates from temperature-based approaches. The ground-based pyranometer provided measurements of the mean incoming solar radiation each half-hour. These measurements were combined to
provide daily solar insolation values. The GOES imagery provided distributed daily solar insolation maps at approximately a 20-km spatial resolution. The individual pixels corresponding to the location of the ground-based station were extracted to provide daily GOES solar radiation estimates.

Approximately 80 daily solar measurements were compared. Figure 2 shows a comparison between the daily average $R_s$GOES and the observed ground station measurements. The large range of values over the three-month study period reflects the highly variable cloud cover typically observed in summer months in Florida. Overall, the results show comparable values on average and a strong regression relationship with respect to both the correlation coefficient and the slope and intercept (Table 1). The goodness of fit between model and measured data was quantified using the Nash-Sutcliffe efficiency where:

$$\text{Eff} = 1 - \frac{\sum (\text{model} - \text{measured})^2}{\sum (\text{measured} - \text{measured})^2}$$

The Nash-Sutcliffe efficiency results show dramatic improvements due to the inclusion of GOES products. These results are consistent with those from earlier studies (Raphael & Hay, 1984; Stewart et al., 1999; Garatuza-Payan et al., 2001).

Figure 2 shows that the Hargreaves approach provides reasonable estimates for clear-sky conditions. However, the method significantly overestimates solar radiation for days with lower incoming solar radiation. As compared to the $R_s$GOES estimates, the $R_s$Hargreaves estimates have significantly more scatter, lower efficiency and a much higher root mean square error (RMSE) (Table 1). Overall, the results for the Paynes Prairie site strongly support the use of GOES-derived solar radiation and indicate that these values are preferable to the Hargreaves temperature-derived values.

For the peninsular Florida region, strong convective systems resulted in numerous cloudy days during the study period. Gu et al. (1999) found that the GOES retrieval of

![Image](image-url)
Table 1 Comparison of measured and modelled incoming solar radiation and net radiation for the Paynes Prairie experimental site. Solar radiation was modelled using the $R_{s,\text{Hargreaves}}$ and $R_{s,\text{GOES}}$. Net radiation was modelled using only temperature data ($R_{n,\text{Hargreaves}}$ and $R_{n,\text{Hargreaves}}$), combined GOES incoming solar radiation and Prata longwave radiation ($R_{s,\text{GOES}}$ and $R_{l,c}$), and GOES solar and longwave radiation products ($R_{s,\text{GOES}}$ and $R_{l}$).

<table>
<thead>
<tr>
<th>Radiation Method</th>
<th>Mean, measured (W m$^{-2}$)</th>
<th>Mean, estimated (W m$^{-2}$)</th>
<th>Slope Intercept</th>
<th>Coeff. of determination, $R^2$</th>
<th>RMSE (W m$^{-2}$)</th>
<th>Nash-Sutcliffe Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation $R_{s,\text{Hargreaves}}$</td>
<td>241.5</td>
<td>260.5</td>
<td>0.42</td>
<td>160.1</td>
<td>0.40</td>
<td>53.2</td>
</tr>
<tr>
<td>Solar radiation $R_{s,\text{GOES}}$</td>
<td>241.5</td>
<td>238.5</td>
<td>0.94</td>
<td>11.3</td>
<td>0.91</td>
<td>19.4</td>
</tr>
<tr>
<td>Net radiation $R_{s,\text{Hargreaves}}$ and $R_{l,c}$</td>
<td>169.1</td>
<td>174.2</td>
<td>0.48</td>
<td>92.8</td>
<td>0.34</td>
<td>46.0</td>
</tr>
<tr>
<td>Net radiation $R_{s,\text{GOES}}$ and $R_{l,c}$</td>
<td>169.1</td>
<td>151.2</td>
<td>1.20</td>
<td>46.8</td>
<td>0.96</td>
<td>20.7</td>
</tr>
<tr>
<td>Net radiation $R_{s,\text{GOES}}$ and $R_{l}$</td>
<td>169.1</td>
<td>161.0</td>
<td>1.11</td>
<td>20.4</td>
<td>0.95</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Solar radiation degraded with increasing cloud cover such that the coefficients of determination between measured $R_s$ and $R_{s,\text{GOES}}$ were 0.96, 0.77 and 0.59 for clear, partly cloudy and cloudy conditions, respectively. Garatuza-Payan et al. (2001) and Stewart et al. (1999) found that daily RMSE values were higher (14.8 and 13.5%) during cloudy months than during clear months (9.9 and 8.9%) for the Yaqui Valley. Thus, for periods with clearer conditions, it is likely that $R_{s,\text{GOES}}$ estimates would have improved.

Daily net longwave radiation values $R_{l,c}$ and $R_{l}$ were estimated using Prata’s clear sky method (equation (6a)) and Prata’s clear sky method corrected using GOES cloud cover and temperature (equation (6b)), respectively. Figure 3 shows the daily evolution of the net longwave radiation. For most days, differences between the $R_l$ and $R_{l,c}$ are of the order of 10 W m$^{-2}$. The largest differences, up to 30 W m$^{-2}$, occur on highly cloudy days.

![Fig. 3 Daily radiation values, including GOES solar radiation ($R_{s,\text{GOES}}$), clear sky net longwave radiation ($R_{l,c}$) and GOES net longwave radiation corrected for cloud cover and temperature ($R_{l,c}$) at the Paynes Prairie site.](image)
or rainy days. Typically, the differences between the two net longwave radiation estimates are less than 5% of the total solar radiation. However, as cloudy days are also days with reduced incoming solar radiation, the combination of the increased net longwave and the reduced solar radiation results in differences between $R_l$ and $R_{lc}$ that account for approximately 20% of the total solar radiation.

Net radiation was modelled by combining solar and longwave radiation estimates using three approaches: (a) $R_{s,\text{Hargreaves}}$ with $R_{lc}$, (b) $R_{s,\text{GOES}}$ with $R_{lc}$ and (c) $R_{s,\text{GOES}}$ with $R_l$. For the experimental period, the average net radiation is well characterized by all three approaches (Table 1). However, the approaches that use $R_{s,\text{GOES}}$ rather than $R_{s,\text{Hargreaves}}$ significantly improve daily net radiation estimates. When net radiation exceeds 150 W m$^{-2}$, excellent net radiation estimates result when combining $R_{s,\text{GOES}}$ with either $R_{lc}$ or $R_l$ (Fig. 4). For these relatively clear conditions, the GOES cloud cover corrections result in a slight improvement for net radiation estimation. For periods when net radiation is less than 150 W m$^{-2}$, it is underestimated by both approaches. For cloudy days characterized by lower net radiation, the correction for cloud effects on longwave radiation inherent in $R_l$ calculations increased the net available energy and reduced $RMSE$ by 6 W m$^{-2}$. The inclusion of the GOES longwave product with the GOES solar radiation product improves the Nash-Sutcliffe efficiencies for the net radiation models from 0.74 to 0.92, respectively.

Diak et al. (2000) reported a daily $RMSE$ value of 5 W m$^{-2}$ when comparing results obtained with the present $R_l$ algorithm to longwave values measured by pyrgeometers. Thus, the GOES longwave radiation cloud cover corrections represent a small, but non-negligible enhancement to the total available net radiation. In addition, these results represent an improvement over the relationships of Gu et al. (1999) for GOES-based net radiation estimation. Using a different algorithm, they found a coefficient of determination between the measured and the GOES retrieved net radiation of 0.46.

**Modeled latent heat fluxes**

Jacobs et al. (2002a) found that actual evapotranspiration rate was lower than the PET when the volumetric soil moisture content $SWC$ (m$^3$ m$^{-3}$) in the top 25 cm was less than 0.09 m$^3$ m$^{-3}$. As the focus in this study is on modelling PET, the 26 days when the measured $SWC$ fell below this threshold (indicating transpiration rates were likely water-limited) were eliminated from the evapotranspiration analysis. For the remaining days, the latent heat flux values were estimated using the empirical Hargreaves (equation (8)), Turc (equation (9)) and the Makkink (equation (10)) methods, and the physically-based Penman-Monteith method (equation (11)) for both the GOES radiation estimates and the temperature-based estimates. For the three empirical methods, solar radiation was estimated using both the $R_{s,\text{GOES}}$ and the $R_{s,\text{Hargreaves}}$ approaches. For the Penman-Monteith equation, the wind speed, temperature and vapour pressure deficit values were measured at the site and net radiation was determined in three ways: (a) $R_{s,\text{Hargreaves}}$ with $R_{lc}$, (b) $R_{s,\text{GOES}}$ with $R_{lc}$ and (c) $R_{s,\text{GOES}}$ with $R_l$. Daily modelled fluxes were compared to the eddy-correlation data, after accumulating the 30-min measurements to daily values.

The average daily evapotranspiration fluxes measured by the eddy-correlation method were compared to the modelled values using both temperature-based radiation
Fig. 4 Comparison between modelled and measured net radiation at the Paynes Prairie wetland site where net radiation is estimated from (a) equation (7a) with the Hargreaves solar radiation estimates ($R_{s, \text{Hargreaves}}$) and clear-sky net longwave radiation ($R_{lc}$); (b) equation (7a) with the GOES solar radiation estimates ($R_{s, \text{GOES}}$) and clear-sky net longwave radiation ($R_{lc}$); and (c) equation (7b) with the GOES solar radiation estimates ($R_{s, \text{GOES}}$) and GOES net longwave radiation corrected for cloud cover and temperature ($R_l$).
Fig. 5 Comparison of measured and modelled latent heat fluxes for (a) the Penman-Monteith method using estimated net radiation with $R_s,_{\text{Hargreaves}}$ combined with $R_{lc}$, and with $R_s,_{\text{GOES}}$ combined with $R_l$; and for the three empirical PET methods: (b) the Hargreaves method, (c) the Turc method and (d) the Makkink method, using $R_s,_{\text{Hargreaves}}$ and $R_s,_{\text{GOES}}$.

Table 2 shows that $LE$ estimates with GOES radiation products are clearly preferable to the temperature-based approach for all models considered. On average, the temperature-based methods provide reasonable results, but they have considerable errors and poor to moderate efficiencies for daily $LE$ estimates. In particular, these methods overestimate $LE$ on days with low latent heat fluxes. For a given method, the $RMSE$ of $LE$ estimates doubles when radiation is estimated using a temperature-based approach rather than the GOES radiation products.

The GOES radiation products provide reasonable $LE$ results for most of the methods considered. The Penman-Monteith model gives the best estimates when applied using $R_l$. Here, the GOES net radiation data provide excellent daily evaporative flux estimates. The model yields low $RMSE$ errors (10%), a high efficiency and the daily values that closely follow a 1:1 relationship with little variability or bias as...
Table 2 Comparison of daily measured and modelled evapotranspiration for the Penman-Monteith, Hargreaves, Turc and Makkink methods. The linear regression model is $LE_{\text{model}} = A LE_{\text{meas}} + B$.

<table>
<thead>
<tr>
<th>Solar radiation method</th>
<th>Net longwave radiation method</th>
<th>Evapotranspiration method</th>
<th>N</th>
<th>Mean $LE$, predicted (W m$^{-2}$)</th>
<th>Mean $LE$, measured (W m$^{-2}$)</th>
<th>Slope $A$</th>
<th>Intercept $B$ (W m$^{-2}$)</th>
<th>$R^2$</th>
<th>RMSE (W m$^{-2}$)</th>
<th>Nash-Sutcliffe efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_s$,Hargreaves</td>
<td>N/A</td>
<td>Hargreaves</td>
<td>55</td>
<td>131.3</td>
<td>118.8</td>
<td>0.46</td>
<td>94.80</td>
<td>0.56</td>
<td>36.7</td>
<td>-0.46</td>
</tr>
<tr>
<td>$R_s$,Hargreaves</td>
<td>N/A</td>
<td>Turc</td>
<td>55</td>
<td>122.2</td>
<td>118.8</td>
<td>0.36</td>
<td>91.51</td>
<td>0.52</td>
<td>27.1</td>
<td>0.20</td>
</tr>
<tr>
<td>$R_s$,Hargreaves</td>
<td>N/A</td>
<td>Makkink</td>
<td>55</td>
<td>104.7</td>
<td>118.8</td>
<td>0.33</td>
<td>76.23</td>
<td>0.50</td>
<td>22.8</td>
<td>0.44</td>
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<td>$R_s$,Hargreaves $R_{lc}$</td>
<td>Penman-Monteith</td>
<td></td>
<td>55</td>
<td>151.5</td>
<td>118.8</td>
<td>0.63</td>
<td>51.50</td>
<td>0.70</td>
<td>17.9</td>
<td>0.64</td>
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<td>$R_s$,GOES</td>
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<td>Hargreaves</td>
<td>55</td>
<td>140.2</td>
<td>118.8</td>
<td>1.10</td>
<td>9.58</td>
<td>0.91</td>
<td>24.0</td>
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<td>117.1</td>
<td>118.8</td>
<td>0.89</td>
<td>10.50</td>
<td>0.90</td>
<td>9.7</td>
<td>0.90</td>
</tr>
<tr>
<td>$R_s$,GOES $R_{lc}$</td>
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<td></td>
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<td>111.3</td>
<td>118.8</td>
<td>1.13</td>
<td>-22.64</td>
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<tr>
<td>$R_s$,GOES $R_l$</td>
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<td></td>
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<td>118.8</td>
<td>1.06</td>
<td>-9.57</td>
<td>0.92</td>
<td>10.1</td>
<td>0.90</td>
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</table>

compared to the measured data. Only the lowest $LE$ values are slightly underestimated. As the Penman-Monteith model’s canopy parameters were calibrated for the Paynes Prairie site (Jacobs et al., 2002a), the good results observed here reflect the ability of the GOES data to provide reasonable net radiation estimates. In comparison to an earlier study, Jacobs et al. (2002b) found that the Penman-Monteith model provided excellent predictions of daily evapotranspiration when using measured net radiation ($R^2 = 0.98$) for an 18-day period at the Paynes Prairie site. However, predictions using measured solar radiation with estimated longwave radiation did not perform as well ($R^2 = 0.89$) and were comparable to those predictions made using the GOES solar radiation product ($R^2 = 0.89$). For the longer sampling period in this study, $R_l$ provided somewhat improved results ($R^2 = 0.92$).

All metrics in Table 2 improve when the Penman-Monteith model includes GOES-based corrections for thermal cloud emission in the net radiation estimates. Figure 6 shows that, while these corrections have little effect at large $LE$ values, improvement is significant at daily average $LE$ values of the order of 100 W m$^{-2}$ or smaller—days with greater cloud cover. For $LE$ values greater than 100 W m$^{-2}$, modelled values slightly underestimate measured $LE$: 0.3 and 3.6% using $RN$, estimated from the incoming solar radiation, surface parameters, using the clear-sky net longwave radiation, and $RN_c$, estimated from the incoming solar radiation, surface parameters, using the $c$ net longwave radiation corrected for cloud cover, respectively. For $LE$ values less than 100 W m$^{-2}$, these underestimates increase to 7.9 and 19.1% using $RN$ and $RN_c$, respectively.

The three empirical models were applied without a site-specific calibration. Overall, the models do a reasonable job of predicting $LE$ using $R_{s,GOES}$. While the coefficient of determination for all models is nearly identical to the Penman-Monteith model, the Nash-Sutcliffe efficiencies show distinct differences among approaches. The Hargreaves model shows the lowest efficiency due to a consistent bias, overestimating ET measured in this wetland ecosystem by 21 W m$^{-2}$. Both the Makkink and the Turc methods are nearly unbiased with average estimation errors of 2 and 8 W m$^{-2}$, respectively, but the Makkink model is more efficient. The Makkink results are a slight improvement over the GOES-based $LE$ estimates obtained by
Garatuza-Payan et al. (2001) with the Makkink model, which exceeded measured values by 23 and 7 W m\(^{-2}\) for a cotton crop and a wheat crop, respectively. This research supports previous findings that the GOES satellite can provide routine daily solar radiation and net radiation to estimate evapotranspiration accurately under a range of atmospheric conditions. Clearly, the remotely sensed \(LE\) estimates are superior to those estimated using solar and net radiation derived from a temperature-based approach.

**CONCLUSIONS**

GOES-based radiation products were used to characterize available energy in Florida under a range of clear sky and cloudy conditions. The solar radiation estimates performed well in comparison with ground-based pyranometer data. Measurements made at an experimental site in central Florida showed that the net radiation was best characterized when the GOES solar and the GOES longwave radiation products were combined. While net radiation is highly dependent on solar radiation, the importance of longwave radiation increases with increasing cloud cover. The GOES radiation estimates were superior to the temperature-based Hargreaves estimates of solar radiation and clear sky longwave radiation.

Latent heat flux, \(LE\) was estimated using the Penman-Monteith expression (requiring \(RN\)) and three empirical formulas that rely only on solar radiation and temperature. Latent heat flux estimates were much better using the GOES radiation as compared to the Hargreaves temperature-based approach for all models considered. While the Penman-Monteith model gave very good results, the less data-intensive Makkink method gave comparable results when applied using GOES products. The Penman-Monteith model requires both GOES shortwave and longwave radiation products to match the Makkink results using only GOES shortwave radiation. The
ability to characterize longwave radiation using GOES products is most important for cloudy conditions that result in reduced net radiation and LE. Overall, the results strongly support the routine application of GOES radiation products to daily PET estimates and give confidence to the value of the GOES longwave corrections when evapotranspiration methods require solar radiation or net radiation.

Acknowledgements Development of the GOES insolation product was supported by RESAC Grant NAG13-990008. Additional support for this work was provided by the NASA NIP Grant NAG5-10567. The authors thank Brent Whitfield, Andres Lopera, Shannon Mergelsberg and David Myers for their role in collecting the field data set. This work was performed while D. Myers held a Florida Space Grant Consortium Summer Scholarship. Sudheer Reddy Satti is acknowledged for his manuscript review. The authors also thank the Florida Department of Environmental Protection Division of Recreation and Parks for providing access to the field sites with special thanks to J. Weimer for assisting in site selection and ongoing field support. Thanks are also due to two anonymous reviewers for their comments.

REFERENCES


Received 28 February 2003; accepted 11 March 2004