Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: an application over complex terrain in Austria

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Abstract

Using daily observations of temperature, precipitation, radiation, and humidity from 24 stations spanning a large elevation gradient in Austria, we tested several previously defined algorithms for estimating daily radiation and humidity. The estimation algorithms were first tested independently, and then combined, resulting in a combined algorithm for estimating both radiation and humidity that relies only on temperature and precipitation inputs. Mean absolute errors (MAE) for joint radiation and humidity estimates were 2.52 MJ m$^{-2}$ per day and 85.6 Pa, respectively, close to values reported for the algorithm development studies. Biases were low: $+0.02$ MJ m$^{-2}$ per day and $+28.2$ Pa for radiation and humidity, respectively. Initial results showed biases in estimated radiation related to horizon obstruction and snowpack. We amended the original algorithm, successfully eliminating these effects. Annual prediction MAE was weakly correlated with elevation, and annual bias was not correlated with elevation. Analysis of seasonal patterns in error-elevation relationships showed several periods with significant trends. Radiation MAE was slightly higher in mid-summer for higher elevations, and radiation biases were in general closer to zero throughout the spring and summer at higher elevations. Humidity estimates showed an increased MAE and positive bias at higher elevations in winter. We concluded that the effect of different temperature lapse rates for daily maximum and minimum temperature on the relationship between diurnal temperature range and atmospheric transmittance does not seriously impair predictions over steep elevation gradients in complex terrain. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Solar radiation; Humidity; Temperature; Lapse rate; Snowcover; Biometeorology

1. Introduction

Radiation and humidity are essential environmental driving variables for many land surface processes, but systematic measurements of these variables over large areas are scarce compared to measurements of temperature and precipitation (Running et al., 1987; Scheifinger and Kromp-Kolb, 2000). Computer simulation of terrestrial ecosystem processes over large regions depends on accurate estimates of radiation and humidity, as well as temperature and precipitation (VEMAP Members, 1995). Given observations of daily maximum and minimum temperature ($T_{\text{max}}$ and $T_{\text{min}}$) and daily total precipitation, previous
studies have shown that accurate daily total radiation estimates can be obtained by using additional observations of daily humidity (Thornton and Running, 1999, hereafter TR), and that accurate humidity estimates can be obtained by using additional observations of daily radiation (Kimball et al., 1997). For greatest utility, estimates of radiation and humidity must be made simultaneously, and must rely only on temperature and precipitation observations. TR suggested a linked radiation-humidity estimation algorithm but did not show it in operation. Our objective here was to develop such a linked algorithm and test it against a new set of radiation and humidity observations from an area outside the original calibration region.

We used data from a network of meteorological observation sites in Austria spanning a large elevation gradient (153–3105 m). We chose this network in part because TR suggested two possible problems with the radiation algorithm that could be addressed by a network of observations in complex terrain. First, it appeared that stations in snowy climates had an underprediction bias related to the presence and possibly the amount of snow on the ground. Multiple reflections between a snowpack and the atmosphere are known to influence incident shortwave radiation (Sellers, 1992), and observations of snowpack across the Austrian network permitted a more detailed analysis of this effect. Second, the use of the TR algorithm in complex terrain might introduce biases related to differential elevation gradients in maximum and minimum temperature. Since the TR algorithm is sensitive to the diurnal temperature range ($\Delta T = T_{\text{max}} - T_{\text{min}}$), and since the elevation lapse rates for $T_{\text{max}}$ and $T_{\text{min}}$ are usually different, it is not clear that a single set of parameters for the algorithm will be adequate for radiation estimates over steep elevation gradients. Observations of temperature, precipitation, radiation, and humidity from the Austrian network cover a large elevation gradient with a relatively high station density, providing a unique opportunity to explore these questions.

Earlier implementations of the radiation algorithm recognized the importance of obstructed horizons on estimated radiation (Running et al., 1987; Glassy and Running, 1994). This effect was not considered in the TR analysis, since the observations were mostly from flat terrain, but we considered it here. Finally, we assessed two approaches to the estimation of humidity, and demonstrated the influence of joint humidity-radiation prediction on estimation errors when only temperature and precipitation observations are available.

In summary, our main objectives were to evaluate the TR radiation algorithm with an independent dataset, extend the algorithm if necessary, incorporate a joint estimation of humidity, and assess possible components of error for the Austrian climate conditions.

2. Data

We obtained, from 24 Austrian weather stations, daily surface weather records consisting of observations of daily maximum and minimum near-surface air temperature, daily total precipitation, daily total global shortwave radiation, and near-surface air temperature and relative humidity at 07.00 h. We calculated water vapor pressure at 07.00 h from the temperature and relative humidity data (Abbott and Tabony, 1985). We assumed that the diurnal changes in water vapor pressure are small, and so used a single value of vapor pressure (VP, Pa) for each day.

From the period of record at each station, we extracted the longest period having complete temperature, precipitation, and humidity data. Precipitation recorded as ‘trace’ was replaced with 0.0 cm. Some stations had missing radiation observations within the retained period of record. Station locations, climatological data, retained periods of record, and numbers of missing radiation observations are listed in Table 1.

3. Methods

3.1. Initial radiation estimates

Using observed temperature, precipitation, and humidity, we made initial radiation estimates following exactly the algorithm described in TR. For reference, the primary expressions for prediction of daily total global radiation on a horizontal surface ($R_{\text{gh}}, \text{MJ m}^{-2} \text{per day}$) are reproduced here:

$$R_{\text{gh}} = R_{\text{pot}} \times T_{\text{f,max}} \times T_{\text{f,max}}$$
Table 1
Site locations and climatological summaries*

<table>
<thead>
<tr>
<th>Station name</th>
<th>Elev (m)</th>
<th>Lon</th>
<th>Lat</th>
<th>Prcp (cm)</th>
<th>$T_{avg}$ (°C)</th>
<th>$\Delta T$ (°C)</th>
<th>VP (Pa)</th>
<th>Stad (MJ)</th>
<th>Years</th>
<th>Missing days</th>
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<td>351.7</td>
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</tbody>
</table>

*Elevation, longitude and latitude (Lon and Lat, decimal degrees), annual total precipitation (Prnp), average near-surface air temperature ($T_{avg}$), average near-surface diurnal temperature range ($\Delta T$), average vapor pressure (VP), average daily total incident short-wave radiation (Stad), years of record used in this study (years), number of days with missing radiation data during this period (missing days).

\[
T_{t,max} = \left[ \frac{\sum_{s=ss}^{ss} R_{pot,s} \times \tau_{0,nadir,dry} (P_z/P_0)m_0}{\sum_{s=ss}^{ss} R_{pot,s}} \right] 
+ (\alpha \times VP)
\]

\[
T_{t,max} = 1.0 - 0.9 \exp(-B \times \Delta T^C)
\]

\[
B = b_0 + b_1 \exp(-b_2 \times \Delta T)
\]

where $R_{pot}$ is the daily total top-of-the-atmosphere radiation on a horizontal surface (MJ m\(^{-2}\) per day), $T_{t,max}$ the maximum (cloud-free) daily total transmittance at a location with a given elevation and near-surface water-vapor pressure on a given yearday, $T_{t,max}$ the proportion of $T_{t,max}$ realized on a given day (cloud correction), $R_{pot,s}$ the instantaneous potential horizontal radiation at solar time $t$, sr and ss are times of sunrise and sunset, $\tau_{0,nadir,dry}$ the instantaneous transmittance at sea level, at nadir, for a dry atmosphere (unitless), $P_z$ and $P_0$ are the surface air pressures at elevation $z$ and at sea level, $m_0$ the optical air mass at solar zenith angle $\theta$, $\alpha$ (Pa\(^{-1}\)) a parameter describing the effect of VP on $T_{t,max}$, $B$ and $C$ are parameters describing the effect of diurnal temperature range ($T_{max} - T_{min} = \Delta T$) on daily total transmittance, $\Delta T$ a 30-day moving average of $\Delta T$, and $b_0$, $b_1$, and $b_2$ are empirical parameters controlling the shape of the relationship between $\Delta T$ and $B$.

We used standard methods to estimate $R_{pot}$, ss, sr, $P_z$, $P_0$, and $m_0$ (Thornton and Running, 1999). The remaining parameters are set empirically, and their values as determined by TR are given in Table 2. We compared the mean absolute error (MAE) and bias obtained over the Austrian network using these default parameters with the MAE and bias reported by TR for predictions at 40 stations in the US (see Appendix A for formal definitions of MAE and bias).
Table 2
Radiation algorithm parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TR value</th>
<th>New value</th>
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</thead>
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<td>τ0, nadir, dry</td>
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<td>0.87</td>
</tr>
<tr>
<td>α</td>
<td>−6.1e−5</td>
<td>−6.1e−5</td>
</tr>
<tr>
<td>b0</td>
<td>0.031 (0.005)</td>
<td>0.013 (0.005)</td>
</tr>
<tr>
<td>b1</td>
<td>0.201 (0.030)</td>
<td>0.200 (0.025)</td>
</tr>
<tr>
<td>b2</td>
<td>0.185 (0.030)</td>
<td>0.190 (0.030)</td>
</tr>
<tr>
<td>C</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

a Values from the original algorithm description (TR), and new parameters optimized for the Austrian data. Standard errors in parentheses for parameters estimated by regression. See text for parameter descriptions. Parameters are dimensionless, except α which has units Pa⁻¹.

b Parameter with new value significantly different from TR value (P < 0.05).

3.2. Horizon angles

We know from firsthand knowledge of the sites in the Austrian network that radiation observations at many stations are influenced by obstructed horizons, so that direct radiation is blocked during part of the time when the solar elevation angle is greater than zero. This effect was not included in the algorithm from TR, since most of the stations for that study are in flat terrain, and so the radiation estimates from the TR algorithm are likely to have a positive bias. We did not have available the detailed descriptions of site geometry required to make accurate calculations of the horizon angles as a function of solar azimuth. We did have hourly data for a number of years from each station which showed the fraction of each hour with direct radiation. From this data we selected at each station a subset of days distributed across the seasonal cycle with the longest recorded period of direct radiation. This algorithm includes a separation of the incident radiation between direct and diffuse components, with no direct component when the solar elevation angle is smaller than the horizon angle, and the diffuse component scaled to take account of the sky fraction obscured by the average horizon (Appendix B). All parameters were maintained as in TR. We calculated MAE and bias for comparison with results without horizon angle correction.

3.3. Snowpack

The presence of snowpack increases incident shortwave radiation through multiple reflections between the high-albedo snow-covered surface and the atmosphere, effectively increasing the diffuse component of global radiation (Meek, 1997; Ellis and Leathers, 1999). We expected this effect to be important for many of the Austrian stations, so we examined the bias in radiation predictions as a function of site snowpack in hopes of identifying a consistent pattern in the biases which could be easily corrected. We had snowpack observations for multiple years at only three sites (Obertauern, Feuerkogel, and Schmittenhoehe), but we were able to use a very simple temperature-based snowmelt model (after Running and Coughlan, 1988), calibrated at these three sites, to estimate snowpack at all sites. The simple snow model operates on a daily time step, accumulating snow for precipitation events on days with \((T_{\text{max}} + T_{\text{min}})/2.0 < 0.0^\circ C\), and melting snow at a calibrated rate \((r, \text{cm}^2\text{C}^{-1} \text{per day})\) when \(T_{\text{min}}\) is above a calibrated threshold \((T_{\text{crit}}, \text{C})\). We chose this very simple formulation for the snowpack model in order to maintain independence from the radiation and humidity data, two variables that are usually included in more sophisticated snowpack models.

Using the radiation estimated with horizon angle correction, we compared the average bias for all days with snowpack to the average bias for all days without snowpack to assess the likelihood that snowpack has a significant effect on radiation estimation bias. We suspected that the influence of snow should increase
### Table 3
Radiation estimation results

<table>
<thead>
<tr>
<th>Station name</th>
<th>( H (^\circ) )</th>
<th>fds</th>
<th>( T_b^a )</th>
<th>TR+hc(^e) MAE</th>
<th>Bias</th>
<th>TR+hc+sc(^d) MAE</th>
<th>Bias</th>
<th>New+hc+sc(^e) MAE</th>
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\(^{a}\) First two columns show the estimated horizon angle (\( H \)) and the fraction of days with snow cover (fds).

\(^{b}\) Preliminary radiation estimates (TR) without horizon or snow corrections.

\(^{c}\) Original algorithm parameters, with horizon correction (TR+hc).

\(^{d}\) Original algorithm parameters, with horizon and snow corrections (TR+hc+sc).

\(^{e}\) New \( b_0 \), with horizon and snow corrections (new+hc+sc). Units for all MAE and bias results are MJ m\(^{-2}\) per day.

With increasing snowpack, at least for low snowpack amounts, due to increasing regional fractional snowcover (Sellers, 1992). To test this we grouped the days with snowpack in specified ranges (bins) from all stations together, calculated the mean bias for each bin, and examined the relationship for significant trends.

#### 3.4. Parameterization of radiation algorithm

TR suggested that the parameters used to estimate \( T_{1, \text{max}} \) should not vary greatly with climate or latitude, since the derivation of these relationships is largely mechanistic. On the other hand, the parameters used to estimate \( T_{f, \text{max}} \) were shown to have significant climatic variation, and the single set of default parameters from TR is likely to produce biased results for some climates. In particular, TR identified a gradient between stations with summer-maximum and winter-maximum precipitation that has a strong influence on the best-fit parameters for Eq. (2). We expected that some modification of the default parameters from TR would produce lower bias and smaller MAE for predictions in the Austrian climate.

After implementing corrections for horizon angle and snowpack, we used the same methods described in TR to estimate the optimal values for the Austrian stations as a group for all parameters listed in Table 2. After determining which new parameters were significantly different from the defaults, we estimated...
radiation again with the new parameters and calculated MAE and bias for comparison.

3.5. Humidity estimates

We tested two approaches for estimating humidity (vapor pressure), one simple and the other more complex. The simple method is based on the assumption that the nighttime minimum temperature approximately equals the dewpoint temperature. Assuming that dewpoint temperature is constant through the day, then $T_{\text{min}} = T_{\text{dew}}$ can be used to estimate the daily average water vapor pressure (Running et al., 1987; Hungerford et al., 1989). The more complex method is that presented by Kimball et al. (1997), which was designed to correct biases in the $T_{\text{dew}} = T_{\text{min}}$ approach for arid climates. The simple approach relies only on observations of $T_{\text{min}}$, while the complex approach requires annual precipitation and daily radiation as additional inputs. For preliminary tests we used the observed $R_{\text{gh}}$ to estimate VP with the complex method, recognizing that for the complex humidity approach an iterative solution would be required to perform joint estimates of radiation and humidity, since they depend on each other. We calculated MAE and bias in humidity predictions from these two methods and compared them to determine which was the most appropriate for the Austrian climate.

3.6. Joint radiation-humidity estimates

Following an assessment of the most appropriate humidity prediction algorithm, we performed a joint prediction of radiation and humidity using only the temperature and precipitation observations as input. The procedure for estimating radiation and humidity jointly is simpler when the simple humidity method is used than when the arid correction method is used. For the arid correction method, humidity predictions depend on radiation (to estimate PET), and radiation estimates depend on humidity (to correct $T_{\text{f max}}$ for water vapor effects), so an iterative solution is required. The simple humidity method, on the other hand, depends only on $T_{\text{min}}$ so the joint estimation is straightforward: first estimate $T_{\text{dew}}$ from $T_{\text{min}}$, convert $T_{\text{dew}}$ to VP, then estimate $R_{\text{gh}}$ using VP. We calculated MAE and bias to assess the loss in predictive ability when both radiation and humidity observations are unavailable.

3.7. Application in complex terrain

Methods for estimating daily radiation and humidity are especially useful in regions of complex terrain where instrument installation and maintenance is difficult. The radiation and humidity estimation algorithms considered here were developed using mostly stations from flat terrain. The Austrian database provided an opportunity to test for trends in prediction bias when these methods were applied over steep elevation gradients in complex terrain.

The environmental temperature lapse rate (decrease in near-surface air temperature with increase in elevation) is usually greater for $T_{\text{max}}$ than for $T_{\text{min}}$, resulting in smaller values of $\Delta T$ at higher elevations (Thornton et al., 1997). The combined influence of persistently lower $\Delta T$ in Eqs. (1) and (2) is on average to reduce $T_{\text{f max}}$, reducing $R_{\text{gh}}$ for a given $R_{\text{pot}}$ and $T_{\text{f max}}$. This tendency to predict lower $T_{\text{f max}}$ with increasing elevation will be offset by increases in $T_{\text{f max}}$ due to lower vapor pressure and optical air mass at higher elevations.

The relationship between lapse rates for $T_{\text{max}}$ and $T_{\text{min}}$ varies seasonally, and so it is also important to test for differences in elevation-error trends over time. To do this we first calculated a time series of MAE and bias for one seasonal cycle at each station, averaging results from multiple years in the retained period of record. We then estimated the elevation trend in MAE and bias for data from a moving window of yeardays to assess both the overall elevation trends and the seasonal patterns in these trends.

4. Results

4.1. Initial radiation estimates

MAE and bias from radiation estimates using the algorithm exactly as given in TR are listed for each station in Table 3. Average MAE and bias over all stations, weighted by the number of observations per station, were 2.85 and $+1.22 \text{ MJ m}^{-2}$ per day, respectively. For comparison, average MAE and bias from the 40 US stations in TR were 2.39 and $+0.51$, respectively.
respectively. A recent study by Lexer (1997) of seasonal patterns of transmissivity in Austria produced a model of radiation for this region with MAE of 3.2 MJ m\(^{-2}\) per day.

4.2. Horizon angles

The positive bias in preliminary radiation estimates was due in part to having ignored the influence of obstructed horizons. The average horizon obstruction calculated for the 24 Austrian stations was 6.3°, ranging from 0.0 to 20.6° (Table 3). As a check on our methods for estimating horizon angle, we obtained measurements for the time the sun was above the local horizon at a station which was predicted to have a large average horizon angle (Rauris). The estimated seasonal cycle of daylength using the hourly direct radiation data (available for all stations) compared well with the independent measurements at this station (Fig. 1). The estimated daylength is sometimes longer and sometimes shorter than observed, with the errors distributed symmetrically around the solstices, which is the expected case if the horizons are not smooth.

MAE and bias from predictions of \(R_{gh}\) including the influence of horizon angle were 2.73 and +0.79 MJ m\(^{-2}\) per day, respectively, or a 4% reduction in MAE and a 35% reduction in bias from the preliminary predictions (Table 3). We performed a multiple linear regression of estimation bias by station against both estimated horizon angle and fraction of days with snow. We found that the influence of horizon angle on bias was significant and with the expected sign before horizon corrections were applied, and insignificant after correction (Table 4, algorithms TR and TR+hc, respectively).

4.3. Snowpack

Fitting parameters of our simple snow model to the data from three stations gave values of \(-6.0°C\) and 0.042 cm °C\(^{-1}\) per day for the threshold temperature \(T_{crit}\) and the temperature-driven snowmelt rate \(r\), respectively. MAE and bias for snowpack predictions using this model were 3.91 and 0.06 cm, respectively, based on days with either observed or predicted snowpack. The average observed snowpack for days with snow from these three stations was 8.5 cm, with standard deviation of 5.8 cm and peak seasonal snowpack between 20 and 35 cm.

A significant effect on annual bias related to snow cover remained after correcting for the influence of horizon angle (Table 4, algorithm TR+hc). Separating data from all stations into two groups by the presence of snow (as estimated by our simple model), we found that days without snow cover had a positive radiation estimation bias (+1.30 MJ m\(^{-2}\) per day) while days

Fig. 1. Predicted vs. observed daylength for the Rauris station. Upper solid line shows daylength for a flat horizon; (●) observed daylength for sun above true horizon; (○) estimated daylength from sunshine hours data.
Table 4
Multiple regression results for radiation estimation bias versus estimated horizon angle and fraction of days with snow cover
\[ \text{bias} = a + b_1(H) + b_2(fdS) \]a

<table>
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<th>(b_1)</th>
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<th>(P)</th>
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<tr>
<td>TR+hc+sc</td>
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<td>&lt;0.01</td>
<td>-0.03 (0.02)</td>
<td>0.16</td>
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<td>New+hc+sc</td>
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<td>0.39</td>
<td>-0.03 (0.02)</td>
<td>0.16</td>
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</table>

\[ a \text{ Standard errors for each parameter in parentheses.} \]
\[ b \text{ Algorithm identifiers as in Table 3.} \]

With snow cover had a negative bias (\(-1.20 \, \text{MJ} \, \text{m}^{-2} \, \text{per day}\)), with a significant difference between means \((P < 0.001)\). Grouping snow days from all stations together in bins by snow water equivalent (SWE), we found a strong relationship between snow amount and radiation prediction bias (Fig. 2). The shape of this relationship agreed with the expectation of increased observed \(R_{gh}\) due to multiple reflections when there is any snow cover, and an increasingly strong effect as SWE increases, due to higher regional fractional snow cover. There was an abrupt negative shift in prediction bias between the no-snow bin and the first snow bin (average SWE=0.33 cm), suggesting that the presence of snow, regardless of amount, had an important effect. The effect increased linearly up to SWE of 10 cm.

Results were less certain for higher SWE. Only six stations contributed to the highest two SWE bins, and much of the data in the highest SWE bin was from the Sonnblick station, on an active glacier. Our simple snow model predicted average annual increments of about 60 cm SWE at Sonnblick over the nine years of record included in this study, the net result of 45 cm accumulation for January–March, 30 cm melt for April–September, and 45 cm accumulation for October–December (no other stations were predicted to have annual increments of SWE). We assigned SWE

![Fig. 2. Radiation estimation bias vs. snow water equivalent (SWE). Points are from SWE estimated by the simple snow model, binned for all station-days. Special bin for days with no snowpack, (O) n=45572. Regression based on bins from days with snowpack; (●) total n for these seven bins=111515, n by bin in order of increasing SWE=2824, 1680, 833, 789, 721, 1092, 3576).](image)
of 37.5 cm on all days at Sonnblick for the purpose of deriving a correction factor for the snow effect.

There was a significant positive bias for the no-snow days (Fig. 2), which is most likely related to the use of the TR default parameters. It is clear from Fig. 2 that there is a significant difference in the estimation bias between no-snow days and the lowest bin of snow days, indicating that the presence of any snow has an important impact on the radiation environment. The bias still evident for the no-snow days is assumed to be contributed by other factors that are addressed in the reparameterization exercise described later. Based on the regression shown in Fig. 2 for the snow days, and accounting for the offset of this reference bias, we added the following correction factor to \( R_{gh} \) on each day with predicted snow cover:

\[
sc = 1.32 + 0.096(SWE)
\]

where \( sc \) is the additive correction (MJ m\(^{-2}\) per day) and SWE is limited to a maximum of 30 cm, the average value for the highest bin in Fig. 2. After applying this correction, the MAE and bias for estimated radiation were 2.71 and +1.27 MJ m\(^{-2}\) per day, respectively, or a 1% reduction in MAE, but a 61% increase in bias from the case with only horizon corrections applied (see Section 5).

Multiple regression results (Table 4, algorithm TR\(hc+sc\)) indicated that we had successfully eliminated the influence of both horizon angle and snow cover on the estimation bias. The significant intercept showed that a component of bias remained that was not related to either of these factors.

4.4. Parameterization of radiation algorithm

We suspected that this remaining bias was mostly due to the use of the default parameterization of the basic equations from TR. TR suggested that the seasonality of precipitation and the seasonality of the diurnal temperature range (\( \Delta T \)) affect the optimal parameterization of Eq. (2). The Austrian stations showed a spatially consistent pattern of summer-maximum precipitation and summer-maximum \( \Delta T \) (Fig. 3). TR noted a gradient in optimal parameters for Eq. (2) between stations having summer-maximum precipitation with winter-maximum \( \Delta T \) (Florida), and stations having winter-maximum precipitation with summer-maximum \( \Delta T \) (western Oregon). The climate for the Austrian stations is orthogonal to this gradient, making prediction of the likely parameterization bias difficult.

We applied exactly the same automated cross-validation optimization procedures described in TR for parameterization of the \( T_{t, \max} \) and \( B \) and \( C \) components of the radiation algorithm, with the new horizon and snow corrections in place. We found that the best-fit parameters for \( \tau_{0, \text{nadir, dry}}, \alpha, b_1, b_2, \) and \( C \) were not significantly different for the set of Austrian stations than for the original set of stations in the US (\( P < 0.05 \)). We found that the best-fit parameter for \( b_0 \) was 0.013, significantly lower than the best-fit value of 0.031 found for the pooled US data (Table 2). After changing the \( b_0 \) parameter to 0.013 and using both horizon and snow corrections, MAE and bias for radiation predictions were 2.52 and +0.02 MJ m\(^{-2}\) per day.
respectively; a 7% reduction in MAE from the case with only horizon and snow corrections, and an almost complete elimination of the annual estimation bias.

We examined the seasonal patterns of radiation estimation MAE and bias before and after changing $b_0$ (Fig. 4). Reparameterization greatly reduced the magnitude of the bias and eliminated a broad peak in MAE and bias that extended from April to July. The resulting seasonal pattern was very similar to that found for the pooled US data, with low bias in the winter, a peak of positive bias in the spring, and a peak of negative bias in the mid-summer. Although there was a mid-summer peak in MAE when expressed in absolute units, MAE expressed as a percentage of $R_{gh}$ was highest in the winter (Fig. 4A, dashed line), as was also found for the pooled US data.

4.5. Humidity predictions

Results from the two humidity algorithms showed that humidity prediction errors were slightly lower with the simple approach (MAE and bias of 85.6 and $+28.2$ Pa, respectively) than with the arid correction approach (MAE and bias of 95.9 and $-13.5$ Pa, respectively). Examination of seasonal trends in biases from the two approaches showed that the arid correction method produced strongly seasonal biases, with consistent underestimates of humidity in the spring and early summer, while there was no obvious seasonal pattern of bias from the simple method (Fig. 5). Referring to the tabulated errors for individual US stations presented in Kimball et al. (1997), we observed that the arid correction method was an improvement over the simple method for stations with a ratio of annual total potential evapotranspiration (PET) to annual total precipitation $>2.5$, and that the arid correction almost always resulted in a slightly worse prediction than the simple method for stations with smaller values of this ratio. All of the Austrian stations had values of this ratio $<1.0$; hence we used the simple humidity algorithm for subsequent analysis.
4.6. Joint radiation-humidity predictions

Since humidity estimates do not depend on radiation, joint estimation errors for humidity were unchanged from those already reported. The joint estimation errors for radiation increased, due to errors in estimated humidity used to estimate $T_{\text{t, max}}$. We found that this additional source of error was very small: MAE and bias for radiation estimates from joint prediction of humidity and radiation were 2.54 and $+0.03 \, \text{MJ m}^{-2} \, \text{per day}$, respectively, or $<1\%$ increase in radiation MAE due to error in humidity estimates.

Fig. 6 shows the correlation between station-average estimation errors for radiation and humidity. Results for MAE are shown in Fig. 6A, where the significant positive slope indicates that higher absolute errors for radiation are correlated with higher absolute errors for humidity. Two high-elevation stations, Feuerkogel and Schmittenhoehe, have large errors for both radiation and humidity and are responsible for the strong statistical significance of the relationship. The station-average biases for radiation and humidity are not significantly correlated (Fig. 6B). This suggests that the correlation in MAE is not due to an interaction effect between radiation and humidity predictions, since the expected pattern for an interaction effect would be a positive bias in humidity corresponding to a negative bias in radiation, through the influence of humidity on $T_{\text{t, max}}$.

4.7. Trends with elevation

Environmental lapse rates for $T_{\text{max}}$ and $T_{\text{min}}$ showed a pattern very similar to that found for a collection of stations in the northwestern US by Thornton et al. (1997). $T_{\text{min}}$ lapse rates were closer to zero than were $T_{\text{max}}$ lapse rates in all seasons. Both $T_{\text{min}}$ and $T_{\text{max}}$ lapse rates had a seasonal pattern of low values (closer to zero) in the winter and higher values in the summer (Fig. 7A). The difference between the $T_{\text{max}}$ and $T_{\text{min}}$
lapse rates is also the lapse rate for $\Delta T$ (Fig. 7B), which was near zero in mid-winter and increased to a broad peak around 2.5°C/km through the summer.

There was a significant increase in the MAE of estimated annual radiation for stations at higher elevation. This trend was due in part to higher radiation loads at the higher stations, as evidenced by a decrease in significance when MAE was expressed as a percentage of the observations (Fig. 8A and B). There was no significant elevational trend in annual bias (Fig. 8C and D).

There was a consistent increase in radiation MAE with elevation over the entire year (Fig. 9A), but this trend was mostly due to higher radiation loads at higher elevations (Fig. 9B). There were significant trends in bias with elevation through much of the seasonal cycle (Fig. 9C). These trends were strongest during the period March–September, when there was a general tendency for smaller biases at higher elevations, and weakest in the winter months, when there was a tendency for larger biases at higher elevations (Fig. 9C). Seasonal patterns in bias were very similar when calculated on a percent basis (results not shown).

Trends with elevation in annual MAE and bias for estimation of vapor pressure were not significant ($P>0.05$), but there was some evidence that both MAE and bias were higher for stations above 1000 m than below (Fig. 10). Average bias for stations below 1000 m was very close to zero, while above 1000 m bias averaged about +75 Pa. Seasonal cycle analysis showed that these weak annual trends were the result of significant positive trends in both MAE and bias with elevation during the winter (Fig. 11).

5. Discussion

We conclude that the TR algorithm, with simple modification for horizon angle and snow cover effects, can produce radiation estimates with reasonable precision and accuracy over strong elevation gradients. The fact that a significant recalibration of one model para-
Fig. 8. Elevation trends in radiation estimation annual error statistics. Regression lines shown with $P$-value for slope coefficient. (A) and (C) annual MAE and bias, respectively, in absolute units; (B) and (D) annual MAE and bias, respectively, as a percentage of annual averaged observed $R_{gh}$.

Parameter ($b_0$) was required to minimize estimation bias is cause for concern, since this recalibration would not be feasible for most practical applications of the algorithm due to lack of radiation observations. It is possible that the inclusion of horizon and snow effects in the parameterization for the US data would have resulted in a value for $b_0$ closer to that found here. It seems likely, however, that there is some climatic control on the optimal values for this parameter, and a truly general algorithm would need to address this problem. TR and now this study provide some guidance, suggesting that the seasonality of precipitation and $\Delta T$ are useful discriminants. Testing this hypothesis would require radiation observations from a wider range of climates than is present in either the US study or the current study. Inclusion of stations from the wet and dry tropics would be especially important.

Another concern for practical applications is the estimation of horizon angles in complex terrain when daylength data, such as were used here are not available. Methods are already well-developed that use digital terrain maps to estimate horizon angles (Dozier and Frew, 1981; Proy et al., 1989), and these methods could be easily adapted to provide an average horizon angle. A more serious concern is that our use of horizon angle in estimating direct versus diffuse radiation (Appendix B) used only an empirical treatment of the effects of radiation reflected from adjacent terrain. This component varies strongly with changing snow cover on adjacent slopes and with the distance to obstructing terrain (Proy et al., 1989). An explicit accounting of these effects is computationally expensive and probably not feasible for large gridded applications as in Thornton et al. (1997).
Fig. 9. Seasonal pattern of elevation trends in radiation estimation error statistics. Based on regression intercepts and slopes, as described in Fig. 7, but regressing MAE and bias against elevation. For all panels: the full seasonal cycle of regression intercepts is shown (●), corresponding to the zero-elevation errors, while only 5-day periods with significant regression slopes of error against elevation (P<0.05) are shown as the regression-estimated errors at an elevation of 1000m (∗). (A) MAE in absolute units; (B) MAE as a percentage of observed $R_{gh}$; (C) bias in absolute units; dashed line shows zero bias.

We used a very simple snow model here as a first-order test for identifying and eliminating potential radiation biases, and this approach appeared successful. The snow model suffers from too little training data, and many mechanistic improvements are possible. The installation of global radiation sensors currently underway at many of the SNOTEL stations in the high country of the western US (Bob Hammer, personal communication) should provide an excellent opportunity to further test and develop this component of the radiation estimation algorithm.

Our observation that the arid-correction humidity algorithm introduces seasonal bias for humid stations suggests that in applications over regions with both arid and humid climates it would be necessary to switch between the simple and more complex algorithms. The possible discontinuity generated at this transition remains to be explored. In the current study the joint radiation-humidity estimation algorithm avoids the need for iteration by using the $T_{dew}=T_{min}$ approach, but an iterative algorithm would still be required for arid conditions, and the effects of this
Fig. 10. Elevation trends in vapor pressure estimation annual error statistics. Regression lines shown with $P$-value for slope coefficient. (A) Annual MAE; (B) annual bias; dashed line shows zero bias.

Fig. 11. Seasonal pattern of elevation trends in vapor pressure estimation error statistics. Interpretation of symbols as in Fig. 9, (A) MAE; (B) bias.
iteration on radiation and humidity predictions have yet to be identified. Results here suggest that the effects on radiation estimates will be small. Significant overprediction of vapor pressure at higher elevations in the winter (Fig. 11B) suggests that the aridity correction might be appropriate in these cold, low vapor pressure environments.

It appears that the seasonal patterns in $T_{\text{max}}$ and $T_{\text{min}}$ lapse rates did not have much effect on radiation predictions over the elevation gradient. We can conclude that the scatter (MAE) in radiation estimates increases with elevation, especially in the summer, and that not all of this increase is the result of higher radiation loads at higher elevation (Fig. 9B). This reduced accuracy could be due to the unaccounted effects of adjacent terrain, varying snowcover conditions, or by the influence of upper air conditions on diurnal temperature variations. We are encouraged to find that the seasonal pattern of low elevation bias is very similar to that found for the US study, and that the bias is generally reduced at higher elevations (Fig. 9C).

The consistency of the seasonal bias pattern between the Austrian and US studies suggests that the basic algorithm introduces some systematic bias, producing overestimates in the spring and underestimates in the late summer and early fall. One possible explanation is that seasonal trends in temperature overlaid on the radiation-driven changes in diurnal temperature range lead to increased $\Delta T$ in the spring when temperatures are rising and decreased $\Delta T$ in the late summer and fall as temperatures drop. These biases in $\Delta T$ would be expected if $T_{\text{min}}$ were usually recorded at the same time of day. This argument suggests that the sort of 2-day averaging of $T_{\text{min}}$ suggested by Bristow and Campbell (1984) could help reduce the bias, but we found for both the US and Austrian data that this approach increased MAE without changing the seasonal bias pattern.

In conclusion, we found that the incorporation of horizon and snowpack controls in the TR model resulted in good radiation estimates, and that minimization of radiation MAE required changing only one of the six original model parameters ($b_0$). Joint estimates of radiation and humidity had very little effect on radiation estimation error. There are several parts of the seasonal cycle that showed small elevation trends in error for radiation and humidity. For application to regional terrestrial ecosystem process modeling, it is important to understand how these errors affect predictions of fundamental processes, such as net primary production. Preliminary results from another study suggest that the errors and biases illustrated in Fig. 9 have a relatively small effect on predictions of net primary production in complex terrain (M.A., unpublished data).

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Appendix A. Definition of MAE and bias

For the case of a set $X_o$ of daily observations of variable $X$ and a corresponding set $X_p$ of daily model predictions, where $\{1, 2, \ldots, n\}$ is the set of observation days, the mean absolute error (MAE) and bias are defined as:

\[
\text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |X_p(i) - X_o(i)|
\]

\[
\text{bias} = \frac{1}{n} \sum_{i=1}^{n} (X_p(i) - X_o(i))
\]

Appendix B. Estimation of direct and diffuse radiation

We first estimate the fraction of the sky hemisphere that is not obstructed by the average horizon. Since
we assume that $H$ (horizon obstruction angle) is equal at all azimuths, the open-sky fraction is defined as a spherical cap centered at nadir. The fraction of the total hemisphere area within the spherical cap ($S_h$) is:

$$S_h = 1.0 - \sin(H)$$  \hspace{1cm} (B.1)

Having already estimated the daily total transmittance ($T_T = T_{\max} \times T_{\max}$), we estimate the fraction of daily total radiation that arrives at the surface as diffuse ($p_{\text{dif}}$), using the relationship with daily total transmittance shown in Jones (Jones, 1992, Fig. 2.8, p. 25) and Gates (Gates, 1980, Fig. 6.14, p. 122) (based on measurements for a flat horizon):

$$p_{\text{dif}} = -1.25T_t + 1.25,$$  \hspace{1cm} with $p_{\text{dif}}$ constrained to $\times$ the range 0.0 to 1.0.  \hspace{1cm} (B.2)

Calculations of potential (horizontal top-of-the-atmosphere) radiation are made for the direct radiation estimate ($R_{\text{pot,dir}}$) and for the diffuse radiation estimate ($R_{\text{pot, dif}}$). Horizon obstruction geometry is used to estimate $R_{\text{pot,dir}}$. Flat horizon geometry is used to estimate $R_{\text{pot, dif}}$, since diffuse radiation is being received when the sun is above a flat horizon but still below the local terrain horizon. Although we do consider the influence of sub-daily variation in optical air mass when estimating $T_t$, we ignore the diurnal variation of $p_{\text{dif}}$ due to the influence of optical air mass on instantaneous transmittance in estimating the contributions of direct and diffuse radiation. We also make the simplifying assumption that the diffuse component is distributed evenly over the sky hemisphere at any given time. We include a simple correction for the non-zero albedo of the visible terrain elements, assuming that they have a constant albedo (a) of 0.6. Final estimates for direct ($R_{\text{dir}}$) and diffuse ($R_{\text{dif}}$) components are:

$$R_{\text{dir}} = R_{\text{pot, dir}} \times T_t (1 - p_{\text{dif}})$$  \hspace{1cm} (B.3)

$$R_{\text{dif}} = R_{\text{pot, dif}} \times T_t \times p_{\text{dif}} (S_h + a(1.0 - S_h))$$  \hspace{1cm} (B.4)

and total global horizontal radiation ($R_{gh}$) is given as $R_{\text{dir}} + R_{\text{dif}}$.

References


