Validation of a Simple Steady-State Forecast of Minimum Nocturnal Temperatures

JATIN KALA AND TOM J. LYONS
School of Environmental Science, Murdoch University, Murdoch, Western Australia, Australia

IAN J. FOSTER
Department of Agriculture and Food, Western Australia, Bentley, Western Australia, Australia

UDAYSANKAR S. NAIR
Earth System Science Center, University of Alabama in Huntsville, Huntsville, Alabama

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ABSTRACT

A two-layer steady-state resistance model is compared with routine meteorological data collected from the Western Australian wheat belt during 2000–06. Major difficulties in implementing such a model are the correct parameterization for the incoming longwave radiation and estimation of daily soil moisture, neither of which are routinely measured. These difficulties are addressed by testing parameterizations for incoming longwave radiation calibrated to local conditions and incorporating a soil–water balance model based on routine weather data. The modified model has RMSE and biases ranging from 2.4 to 3.1°C and −0.2 to 0.8°C, respectively, across the wheat belt when comparing all minimum nocturnal temperatures. The model is shown to predict frost events approximately 55% of the time and illustrates that frost damage to foliage may occur when screen temperatures are <2°C.

1. Introduction

Frost events have significant impacts on crop yield and quality within the agricultural region of southwest Western Australia and their accurate and timely prediction is important for management purposes. Of particular interest is the crop or foliage temperature that provides a direct indication of the extent of potential crop damage, rather than a surface or screen temperature that might not necessarily be representative of the temperature within the foliage. Crop temperatures are a function of the transfer of sensible and latent heat within and above the canopy, as well as the ground heat flux, whereas within the agricultural area only screen temperatures are routinely monitored.

Sensible and latent heat fluxes by definition should strictly be defined within a Lagrangian framework and analytical Lagrangian theories have been developed for soil–plant atmosphere models (e.g., Raupach 1987, 1989a,b; Warland and Thurtell 2000). These models, however, remain somewhat complex and difficult for local implementation. On the other hand, numerous soil–plant atmosphere models (e.g., Monteith 1975; Shuttleworth 1976; Shuttleworth and Wallace 1985; Cleugh and Dunin 1995; Zhang et al. 1995) use the simpler K theory to parameterize the sensible and latent heat fluxes via conceptual resistances, rather than turbulent quantities. The resistance approach has been compared against Lagrangian theory for application in soil–plant atmosphere models and it has been argued that there is no major difference between the two (Wilson et al. 2003).

A recent resistance model for frost prediction (Lhomme and Guillon 2004, hereinafter LG04) assumes a steady-state regime at sunset. This removes the computational requirements inherent in non-steady-state numerical and analytical models (e.g., Cellier 1993; Figuerola and Mazzeo 1997) to greatly simplify the overall complexity of the model and provide a potential on-site frost prediction capability. The underlying assumption is that frost occurs mostly on clear and calm nights, during which it can be assumed that atmospheric variables at some reference height above the ground remain constant.
throughout the night. LG04 takes as input standard meteorological data measured at sunset (air temperature and humidity, wind speed, soil surface temperature) as well as a daily soil thermal conductivity and crop parameters such as the leaf area index, fractional cover of vegetation, surface roughness length, and zero displacement height. Using these data, LG04 predicts a minimum nocturnal soil surface temperature and a canopy temperature and has shown reasonable comparisons with observations. Such a model has the potential to extend the current local detection of frost, based on screen temperatures <2°C, to forecast in-crop foliage temperatures.

A major obstacle in the routine implementation of such a model is the difficulty in correctly parameterizing the downwelling longwave radiation. This is a function of the effective atmospheric emissivity, the parameterization of which remains largely empirical. During calm clear nights, the lack of cloud cover results in a deficit of downwelling longwave radiation, which is one of the main mechanisms for nocturnal cooling. Another difficulty is that the model requires a daily estimate of the soil thermal conductivity. The thermal conductivity drives the ground heat flux, which is the countermechanism for heat loss during the night. It is mainly a function of soil type and soil moisture content. While LG04 utilized gravimetric soil moisture content measurements, these are not routinely available throughout the agricultural area of Western Australia.

The aim of this paper is to investigate the routine on-site application of LG04 within the Western Australian wheat belt to provide estimates of frost occurrence and associated foliage temperatures. We first outline the overall energy balance of LG04, followed by parameterizations for the incoming longwave radiation adapted to local conditions and the incorporation of a soil–water balance model to provide daily estimates of soil moisture. Model outputs corrected to screen-level temperatures are compared against an extensive dataset from routine meteorological stations in the Western Australian wheat belt and model limitations are discussed.

2. The model

a. Energy balance

The energy balance model of LG04 is based on the vegetation–atmosphere transfer model of Shuttleworth and Wallace (1985) and Shuttleworth and Gurney (1990). From conservation of energy, the total fluxes of sensible and latent heat are assumed to be the sum of the component fluxes emanating from the soil surface and canopy. The fluxes of sensible and latent heat from the surface are driven by the air resistance between the surface and the canopy; the fluxes from the canopy are driven by the bulk boundary layer resistance of the vegetative elements; and the total fluxes are a function of the aerodynamic resistance between the canopy and a reference height above the ground. This separation allows for the estimation of both a surface and canopy temperature.

Thus, the energy balance is represented as

\[ R_{as} - G = \rho c_p \frac{T_s - T_0}{r_{as}} \]  \hspace{1cm} (1)

\[ R_n - R_{ns} = \rho c_p \frac{T_c - T_0}{r_{ac}}, \]  \hspace{1cm} (2)

where \( R_{ns} \) is the net radiation of the substrate (W m\(^{-2}\)), \( R_n \) is the canopy net radiation (W m\(^{-2}\)), \( G \) is the soil heat flux (W m\(^{-2}\)), \( T_s \) is the soil surface temperature (K), \( T_0 \) is the air temperature (K) at canopy source height \( z_h \) (m), \( T_c \) is the canopy temperature (K), \( r_{as} \) is the aerodynamic resistance (s m\(^{-1}\)) between the soil surface and the canopy source height, \( r_{ac} \) is the bulk boundary layer resistance of the vegetative elements (s m\(^{-1}\)), \( \rho \) is the air density (kg m\(^{-3}\)), and \( c_p \) is the specific heat of air at constant pressure (J kg\(^{-1}\) K\(^{-1}\)).

From conservation of energy, the sum of the component fluxes entering and emanating from the soil and canopy layers accounts for the total heat flux in the air. Hence,

\[ H = H_c + H_s, \]  \hspace{1cm} (3)

that is,

\[ \frac{T_s - T_0}{r_{as}} = T_0 - T_c + \frac{T_0 - T_s}{r_{ac}}, \]  \hspace{1cm} (4)

where \( H \) denotes the sensible heat flux (W m\(^{-2}\)), the subscripts \( s \) and \( c \) refer to the surface and canopy, respectively, \( T_s \) is the air temperature measured at screen height at sunset (K), and \( r_{as} \) is the aerodynamic resistance (s m\(^{-1}\)).

However, when the soil or crop temperatures drop below the dewpoint temperature, the condensation of water vapor generates energy that is accounted for by adding to the right-hand term of Eq. (1) LG04

\[ \lambda E_s = \left( \frac{\rho c_p}{\gamma} \right) \frac{e_s(T_s) - e_0}{r_{as}}, \]  \hspace{1cm} (5)

and to the right-hand term of Eq. (2)

\[ \lambda E_c = \left( \frac{\rho c_p}{\gamma} \right) \frac{e_s(T_c) - e_0}{r_{ac}}. \]  \hspace{1cm} (6)
as well as the conservation equation for water vapor,

\[
\frac{e_a - e_0}{r_{aa}} = \frac{e_0 - e_s(T_s)}{r_{ac}} + \frac{e_0 - e_s(T_s)}{r_{as}},
\]

(7)

where \(\lambda E\) denotes the latent heat flux (W m\(^{-2}\)), the subscripts \(s\) and \(c\) refer to the surface and canopy, respectively, \(e_a\) is the air vapor pressure at screen height at sunset (Pa), \(e_0\) is the air vapor pressure at canopy source height (Pa), \(e_s(T)\) is the saturated vapor pressure at temperature \(T\) (Pa), and \(\gamma\) is the psychrometric constant (Pa K\(^{-1}\)).

When there is no dew deposition, Eqs. (1), (2), and (4) need to be solved for the unknowns \(T_0\), \(T_s\), and \(T_c\), and when dew is deposited, Eqs. (5)–(7) need to be solved for the additional unknown, \(e_0\). This requires that the air and soil resistances and atmospheric radiation components be specified.

The ground heat flux is assumed to be proportional to the temperature difference between the surface and some reference depth, with the constant of proportionality being the soil thermal conductivity per unit depth,

\[ G = h(T_s - T_{sd}), \quad h = k_s/z_{sd}, \]

(8)

where \(T_s\) is the soil surface temperature measured at sunset (K), \(T_{sd}\) is the temperature (K) at the reference depth \(z_{sd}\) (1 m), and \(k_s\) is the soil thermal conductivity (W m\(^{-1}\) K\(^{-1}\)).

Deep soil temperatures are not routinely measured in Western Australia and so \(T_{sd}\) is approximated as the mean air temperature during the previous 24 h (Monteith and Unsworth 1990).

The net radiation above the canopy during the night is defined as

\[ R_n = e_s (R_s - \sigma T_s^4), \]

(9)

where \(R_s\) is the incoming longwave radiation (W m\(^{-2}\)), \(e_s\) is the surface emissivity (0.97), \(\sigma\) is the Stefan–Boltzmann constant (\(5.67 \times 10^{-8}\) W m\(^{-2}\) K\(^{-4}\)), and \(T_s\) is the radiometric surface temperature (K) calculated as

\[ T_s = [f T_a^4 + (1 - f) T_s^4]^{1/4}, \]

(10)

where \(f\) is the fractional area covered with vegetation.

LG04 outlines the linearization of these equations and their solutions, whereas the following sections describe the modifications introduced to enable the routine application of this model to the agricultural region of Western Australia.

b. Incoming longwave radiation

The incoming longwave radiation \(R_a\) is defined as (Brutsaert 1982)

\[ R_a = e_a \sigma T_s^4, \]

(11)

where \(e_a\) is the effective atmospheric emissivity.

Several models have been proposed to parameterize \(e_a\) for clear-sky conditions (Idso and Jackson 1969; Brutsaert 1975; Idso 1981; Swinbank 1963; Prata 1996) and cloudy-sky conditions (Sugita and Brutsaert 1993; Crawford and Duchon 1999). However, all of these formulations involve the use of empirical constants, specific to the biogeographic regions where the data were collected. Recent investigations by Duarte et al. (2006) and Lhomme et al. (2007, hereinafter LH07) provide methodologies to account for local conditions rather than relying on predefined constants. LH07 proposed the following general formula:

\[ e_a = F(s)e_0, \quad F(s) = As + B, \]

(12)

where \(F(s)\) represents a factor that accounts for the modification caused by cloudiness, \(e_0\) is the clear-sky emissivity, \(s\) is the ratio of incoming solar radiation \(S\) to the clear-sky solar irradiance \(R_s\), and the constants \(A\) and \(B\) are statistically determined and meet the condition that \(A + B = 1\). These constants are estimated via the approximation that \(F(s)\) is the ratio of the measured incoming longwave radiation \(R_a\) to the clear-sky equivalent \(R_{a,0}\):

\[ F(s) = \frac{R_a}{R_{a,0}}, \]

(13)

\[ R_{a,0} = e_0 \sigma T_s^4, \]

(14)

and \(e_0\) is defined as

\[ e_0 = c_0 \left( \frac{e_a}{T_s} \right)^{1/7}, \]

(15)

where \(c_0\) has a theoretical value of 1.24 at sea level for a standard atmosphere.

An alternative approach allowing for site-specific calibration under clear-sky conditions by Rizou and Nnadi (2007, hereinafter RN07) outperformed several others (Brutsaert 1975; Satterlund 1979; Idso 1981; Prata 1996). The main distinction between their model and all of the above is the assumption that air temperature \(T_a\) and vapor pressure \(e_v\), although interrelated, can be superpositioned and have an exponential effect on the emissivity, leading to a general equation of the form

\[ e_a = 1 - (C_1 e^{-T_a/C_2} + C_3 e^{-e_v/C_4}), \]

(16)

where \(C_1–C_4\) are site-specific constants to be determined via nonlinear regression analysis.
LH07 and RN07 are validated against observations in section 4 and incorporated within the model in section 5.

c. Soil–water balance model

The soil type within the Western Australian wheat belt is predominantly sandy soil, and the thermal conductivity \( k_t \) can be estimated using standard regression lines between \( k_t \) and soil moisture (\( \theta \)) (Brutsaert 1982):

\[
k_t = \begin{cases} 
25.0\theta + 0.25, & 0.00 < \theta \leq 0.05 \\ 
10.0\theta + 1.00, & 0.05 < \theta \leq 0.10 \\ 
1.20\theta + 1.90, & 0.10 < \theta \leq 0.50 
\end{cases}
\]

While LG04 measured \( \theta \) gravimetrically, such measurements are not routinely available and instead a time series of daily soil moisture has been estimated from standard meteorological data. This model uses a soil–water balance approach based on the Crop Environment Resource Synthesis (CERES) crop model (Ritchie and Otter 1985; Jones and Kiniry 1986) and the “SIMTAG” model (Stapper 1984), which has been validated by Li and Lyons (2002). The model takes as input the daily rainfall, estimated infiltration, evapotranspiration, and runoff to provide a soil moisture for each day of the year. The model ignores the flow of water caused by hydraulic gradients, a reasonable assumption for the Western Australian agricultural region, which is essentially a flat landscape. In regions without irrigation, as is the case here, the surface water balance is simply expressed as

\[
\theta_{0,i} = \theta_{0,i-1} + P - ET - I_e - Q,
\]

where \( \theta_{0,i} \) is the surface soil moisture at time \( i \) and \( \theta_{0,i-1} \) is the soil surface moisture at a time \( i - 1 \), \( P \) is the rainfall, \( ET \) is evapotranspiration, \( I_e \) is infiltration, and \( Q \) is the runoff.

The model is initiated on a dry day or after heavy rains. Rainfall is obtained from routine observations, and runoff is calculated using the U.S. Department of Agriculture (USDA) Soil Conservation Service Curve number technique (USDA Soil Conservation Service 1972). Evapotranspiration is taken as a function of soil evaporation, potential evapotranspiration, and actual transpiration. Soil evaporation is modeled following the two-stage evaporation model of Ritchie (1972), which has been applied to semiarid agricultural regions of Western Australia (Stephens 1995) and has been evaluated against several other models to provide satisfactory results (Yunusa et al. 1994). Potential evapotranspiration is estimated following the modified Priestly–Taylor model (Ritchie and Otter 1985; Jones and Kiniry 1986), which requires as input daily solar radiation and maximum and minimum temperatures, and actual transpiration is adapted from Stapper (1984) with modifications from Li and Lyons (2002) to include a root distribution factor. Drainage or infiltration is estimated based on the assumption that infiltration to lower layers occurs only when the upper layer is saturated beyond its drained upper limit, and upward flow occurs only when the soil surface dries out.

This water balance model provides a daily time series of estimated soil moisture at each meteorological station at selected depths from routine meteorological data (Li and Lyons 2002).

3. Data collection

The topography of the Western Australian wheat belt is gently undulating terrain of low relief. Common soil types are duplex mallee soils, that is, sand overlying clay. There is a range of soils in the wheat belt, but the duplex type (which itself covers several soil types) is common throughout the central, eastern, and southern wheat belt. Farming is based on rain-fed agriculture and thus cultivates winter growing annual species. Wheat is the major crop in the agricultural area and grows during the austral winter–spring, that is, between May and November. Crops are generally less than 1 m high during the growing season, and after harvest stubbles of about 20 cm or bare soil are common.

a. Routine meteorological data

The Western Australian Department of Agriculture and Food operates a large number of automated meteorological stations throughout the agricultural area of Western Australia measuring hourly values. These observations include wind speed, wind direction, and solar radiation recorded at 3 m above ground, and air temperature and relative humidity measured at 1.25 m. Soil temperatures are recorded at 40 mm below ground surface and rainfall is measured with a 200-mm diameter tipping-bucket rain gauge (0.2-mm resolution). All stations are subjected to routine calibration. For this analysis, data for the period 2000–06 were obtained from six representative sites within the Western Australian wheat belt, as shown in Fig. 1.

b. Incoming longwave radiation measurements

During the period from July to December 2006, a Radiation and Energy Balance Systems, Inc. (REBS) Bowen ratio unit was operated at Merredin (31°52’S, 118°17’E; ME in Fig. 1) to provide additional validation for the incoming longwave radiation parameterization. This station uses a standard Bowen ratio approach with air
temperature and relative humidity measured at two heights (1-m separation) as well as observations of net and solar radiation, soil heat flow, soil temperature, barometric pressure, and wind speed and direction every 15 min. In particular, net radiation was measured with a REBS Model Q*-7.1 net radiometer with an accuracy of ±5% of the measured reading when ventilated.

4. Validation of incoming longwave radiation schemes

Since there were no direct observations of cloud, following LH07 and utilizing the Bowen ratio observations, daytime hours with clear-sky conditions were defined when \( R_a < 350 \text{ W m}^{-2}, R_{a,0} > 500 \text{ W m}^{-2} \), and \( s > 0.95 \). Clear-sky solar irradiance \( R_{a,0} \) was estimated from Lyons and Edwards (1982). A value of \( e_0 = 1.35 \) provided the best fit for the regression of \( R_a \) against \( R_{a,0} \). Although this is higher than the sea level theoretical value, stations in the wheat belt are some 300 m above sea level. Following the methodology of Brutsaert (1975, 1982) using representative radiosonde profiles from the closest radiosonde station under approximately clear-sky conditions leads to a value of \( e_0 = 1.29 \pm 0.03 \), comparable to the above result.

Applying LH07 through Eqs. (14), (15), (13), the resulting line of best fit was \( F(s) = -0.13s + 1.17 \), leading to the modified formulation for atmospheric emissivity of

\[
e_a = 1.35(-0.13s + 1.17)\left(\frac{e_a}{T_a}\right)^{1/7}.
\] (19)

The RN07 analysis nonlinear regression led to

\[
e_a = 1 - \left[ -18.7 \exp\left(-\frac{T_a}{52}\right) + 0.33 \exp\left(-\frac{e_a}{15}\right) \right]. \quad (20)
\]

Figure 2 shows results of both formulations [Eqs. (19) and (20)] applied during the day and night with results superimposed, and Table 1 provides the summary statistics. The LH07 model outperforms the RN07 model during the day with a root-mean-square error (RMSE) of 19.3 W m\(^{-2}\) as compared with 23.0 W m\(^{-2}\), and both models have low biases. In this application, RN07 has been applied to all-sky conditions rather than its assumed clear-sky conditions.

Application of the LH07 model during the night requires an estimate of the cloud cover \( s \) [Eq. (13)] from the preceding evening. By trial and error, the mean cloud cover from the period 1500–1700 (local time) resulted in the lowest RMSE of 17.2 W m\(^{-2}\) and negative bias of −3.4 W m\(^{-2}\). The negative bias suggests that the assumption of the nighttime cloud cover being representative of the mean cloud cover during the preceding day.
evening results in an underestimation of the real cloud cover during the night, resulting in a lower effective emissivity and estimated incoming longwave radiation. The RN07 model performs equally well for nighttime conditions with a lower RMSE of 15.4 W m\(^{-2}\) and bias of \(-3.7\) W m\(^{-2}\). With both daytime and nighttime estimates superimposed, both models perform well with low RMSE of 18.0 and 18.7 W m\(^{-2}\) and biases of \(-1.5\) and \(-2.5\) W m\(^{-2}\), respectively.

Nonetheless this highlights an inherent uncertainty in estimated longwave radiation that will limit the ability of any model based on routine meteorological observations to forecast the onset and level of frost where direct measurements of net radiation are not available.

### 5. Model implementation

The historical meteorological record was used to estimate daily soil moisture at Merredin and combined with the observed air temperature, relative humidity, and wind speed at sunset formed the basic input to the model. The seasonal variation of zero-plane displacement height \(d\), roughness length for momentum \(z_{0m}\), and crop parameters such as the leaf area index, fractional vegetation cover, and albedo were taken from the earlier analyses of Huang et al. (1995) (Table 2).

The model estimates minimum foliage temperature \(T_a\), soil surface temperature \(T_s\), and the air temperature at canopy source height (aerodynamic temperature) \(T_0\). As none of these are routinely observed at the meteorological stations within the wheat belt, the model aerodynamic temperature was corrected to screen temperature using standard boundary layer theory. Figures 3a,b, respectively, show the observed versus modeled minimum temperature at screen height utilizing LH07 and RN07. Clearly, the application of both methods results in overprediction with a high RMSE of 4.0°C and 3.4°C and biases of 2.8°C and 1.9°C, respectively. Screen temperatures below 2°C are correctly predicted only 22% of the time with LH07 and 34% with RN07.

Cases of overprediction corresponded to high estimates of the incoming longwave radiation at sunset, which is assumed to stay constant throughout the night (Cellier 1993). The formulations for the atmospheric emissivity [Eqs. (19), (20)] are based on the temperature and vapor pressure measured at the time of observations of the incoming longwave radiation (Table 1). However, when applying the model, we are using the sunset temperature and vapor pressure measurements to predict incoming longwave radiation throughout the night. Although this effectively assumes that the incoming longwave radiation at sunset will apply throughout the night, observed differences on the order of \(-10\) to \(-20\) W m\(^{-2}\) can lead to significant changes in the estimated temperatures by \(1\)°–3°C.

As a means of better representing the effective atmospheric emissivity experienced during the night, the LH07 and RN07 formulations were recalibrated using temperature and vapor pressures measured at sunset (rather than at the time of the observed longwave radiation) and the measured incoming longwave radiation observed during the night corresponding to the period of lowest observed temperature. The new parameterizations are

\[
e_a = 1.35\left(-0.09s + 1.05\right)\left(\frac{e_a}{T_a}\right)^{1/7}
\]

and

\[
e_a = 1 - \left[-2.20 \exp\left(-\frac{T_a}{52}\right) + 0.30 \exp\left(-\frac{e_a}{15}\right)\right].
\]

Application of Eq. (21) results in an effective decrease in forecast longwave radiation of about 20–30 W m\(^{-2}\). Figure 4 illustrates the ratio of atmospheric emissivity estimated by Eq. (22) and Eq. (20) against temperature for a range of vapor pressures corresponding to relative
humidities of 5%–100%. Clearly the greatest impact is through the temperature. Equation (22) decreases the estimated effective atmospheric emissivity by about 8%.

The RMSE and bias between the observed longwave radiation at minimum temperature and that estimated via Eqs. (21) and (22) are 20.9 and 22.4 W m$^{-2}$ and 0.2 and 5.1 W m$^{-2}$, respectively. These are comparable to the errors experienced with the simultaneous measurements of temperature and longwave radiation shown in Table 1. Application of Eqs. (21) and (22) in the model for all nighttime minimum temperatures (Fig. 5) leads to a reduced RMSE of 3.1°C and bias of $-0.2^\circ$ and $+0.1^\circ$, respectively, which are comparable to the errors observed by LG04 (RMSE $\sim3.1^\circ$ and bias $\sim1.0^\circ$) when comparing observed and modeled canopy temperatures. Screen temperatures below 2°C are now correctly predicted 69% and 70% of the time, respectively, comparable to the 62% found by LG04 in comparing measured and modeled foliage temperatures.

An underlying assumption of the model is that of a theoretical equilibrium state in which observations at sunset equate to constant observations at a reference height (300 m) throughout the night. Figure 6 illustrates the difference between the modeled and observed minimum screen temperatures as a function of the change in wind speed between the time of the observed minimum screen temperature and the sunset wind speed. Although there is considerable scatter, when the wind speed at the time of the observed minimum temperature is higher than the sunset wind speed, this increase in wind speed leads to higher observed temperatures than modeled, as would be expected with the enhanced mechanical mixing and/or advection throughout the lower boundary layer. The converse is apparent for decreasing wind speed. This is an inherent weakness of a steady-state model and highlights a limitation of the routine on-site application of such a model.

Figure 7 highlights the relationship between model-predicted screen temperature and modeled foliage temperature. Screen temperatures less than 2°C are consistently related to foliage temperatures below 0°C. This confirms the historical practice of the Western Australia Department of Agriculture and Food, in the absence of detailed foliage temperatures, using screen temperatures below 2°C as an indication of potential frost damage to crops. Thus, in the absence of detailed observations or crop models, regional predictions of screen temperatures below 2°C provide a clear indication of potential frost impact.

The model was applied to the remaining stations in Fig. 1, assuming that the parameterization for the incoming longwave radiation at Merredin is representative across the wheat belt and using the in situ meteorological
measurements to estimate local soil moisture. Comparisons between modeled and observed screen temperature are summarized in Table 3, showing equivalent RMSE and biases to those obtained for Merredin that are compatible with the uncertainty observed by LG04. Thus without detailed observations of incoming longwave radiation, a steady-state model can realistically be expected to predict frost over the agricultural area of Western Australia approximately 55% of the time. Significant improvement could be achieved by having accurate estimates of longwave radiation. However, since longwave radiation is not routinely measured, this is dependent on improved parameterizations for its prediction throughout the night. Nevertheless, such a model still suffers from the steady-state assumption and this limits its broader applicability.

**TABLE 3.** Sample size (*n*), RMSE, and bias for comparisons between the modeled and observed minimum screen temperatures at the stations East Beverly, Jerramungup, Newdegate, Salmon Gums, and Wickepin for the years 2000–06 and the percentage of observations correctly predicted below 2°C.

<table>
<thead>
<tr>
<th>Station</th>
<th><em>n</em> (W m⁻²)</th>
<th></th>
<th>B (W m⁻²)</th>
<th>% &lt; 2°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH07 scheme [Eq. (21)]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ME</td>
<td>1603</td>
<td>3.1</td>
<td>-0.2</td>
<td>69</td>
</tr>
<tr>
<td>EB</td>
<td>1602</td>
<td>2.7</td>
<td>0.8</td>
<td>64</td>
</tr>
<tr>
<td>JE</td>
<td>1486</td>
<td>2.4</td>
<td>0.2</td>
<td>52</td>
</tr>
<tr>
<td>NE</td>
<td>1357</td>
<td>2.7</td>
<td>0.5</td>
<td>61</td>
</tr>
<tr>
<td>SG</td>
<td>1533</td>
<td>3.0</td>
<td>0.1</td>
<td>53</td>
</tr>
<tr>
<td>WI</td>
<td>1607</td>
<td>2.7</td>
<td>0.5</td>
<td>48</td>
</tr>
<tr>
<td>RN07 scheme [Eq. (22)]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ME</td>
<td>1603</td>
<td>3.1</td>
<td>0.1</td>
<td>70</td>
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<tr>
<td>WI</td>
<td>1607</td>
<td>2.8</td>
<td>0.5</td>
<td>50</td>
</tr>
</tbody>
</table>
6. Conclusions

A steady-state model for the prediction of minimum nocturnal temperatures (LG04) was modified with new parameterizations for the incoming longwave radiation (LH07 and RN07) and the incorporation of a soil–water balance model (Li and Lyons 2002). The model was tested against an extensive dataset from the Western Australian wheat belt for the years 2000–06 and has RMSE and biases ranging from 2.4° to 3.1°C and −0.2° to 0.8°C, respectively, when comparing all minimum nocturnal temperatures, and is shown to predict frost approximately 55% of the time.

The LH07 and RN07 methodologies, although adequately validated against observations of longwave radiation (Fig. 2), lead to overprediction of minimum nocturnal temperatures (Fig. 3). This was a direct result of the steady-state assumption that longwave radiation remained constant at its sunset value throughout the night. The recalibration of both schemes using temperatures and vapor pressures at sunset to forecast longwave radiation observed at the time of minimum temperatures led to more accurate estimates of minimum nocturnal temperatures.

Hence, the major deficiencies in the on-site application of the model are an accurate prediction of the incoming longwave radiation during the night and the limitations of the steady-state assumption. Nevertheless, the model illustrates the close relationship between frost events and screen temperatures <2°C, which have historically been used as the first approximation to regional frost formation. Within the limitations of a steady-state model, LG04 has the potential of providing a clear indication of foliage temperatures and a measure of the risk associated with frost.

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REFERENCES


