Inconsistencies in the estimation of land surface temperature from longwave radiation measurements

Gitanjali Thakur, Stan Schymanski, Kaniska Mallick, Ivonne Trebs, Mauro Suils
Luxembourg Institute of Science and Technology

INTRODUCTION
Background
Research Questions
Study sites

METHODOLOGY
LST: General approach
Optimized: Emissivity, LST

RESULTS
Estimated LST
LSTs bias
Optimized emissivity
Reduced bias

CONCLUSIONS

Supported by the Luxembourg National Research Fund (FNR) ATTRACT programme (WAVE, A16/SR/11254288)
LAND SURFACE TEMPERATURE (LST):

- LST is defined as the ‘ensemble directional radiometric surface temperature’ (Norman and Becker, 1995)

- LST is an important state variable in land atmosphere process.
  - It controls the energy and water exchange between the Earth’s surface and the atmosphere.
  - It is widely used to estimate evapo-transpiration and vegetation water stress through surface energy balance models.
LST ESTIMATION:

- The longwave measured using airborne radiance or tower mounted radiometers such as Eddy co-variance tower, is used with emissivity (known/assumed) to estimate LST ($T_s$).

- The longwave balance and Stephan-Boltzmann law leads to complete equation (leq), which is solved to estimate LST.

$$L_{up} = \epsilon \sigma T_s^4 + (1 - \epsilon) L_{down}$$

Absence of $L_{down}$ in last decades and $\epsilon$ close to 1

where, $L_{up}$ is the up-welling longwave, $L_{down}$ is the down-welling longwave, $\sigma$ is the Stephan-Boltzmann constant and $\epsilon$ is the surface emissivity.
1. Introduction

1.1 Background

1.2 Objective

1.3 Study sites

2. Objective 1

2.1 Results

2.2 Validation

3. Objective 2

3.1 Holmes approach

3.2 Results

3.3 Validation

4. Conclusions

LST ESTIMATION: @ LARGE AND PLOT SCALE

Large scale (remote sensing):

- Radiance measured on daily basis is used to estimate LST, such as MODIS (Moderate Resolution Imaging Spectroradiometer)

- Remotely sensed LST values are widely used at regional and global scale.

Plot scale:

- At plot scale both $\text{leq}$ and $\text{seq}$ are used to estimate LST with measured longwave and known emissivity.

- Mostly simplified equation is used for LST estimation, arguing MODIS emissivity is close to 1.

Fig. 1 (a): Airborne radiometers

Fig. 1 (b): EC Tower at Adelaide river


LST ESTIMATION @ PLOT SCALE:

Research Question 1.
How the use of complete \((leq)\) and simplified \((seq)\) equation interchangeably @ plot scale leads to bias in LST estimation?

Research Question 2.
How can we obtain emissivity @ plot scale for LST estimation?
STUDY SITES:

- Seven sites\(^3\) having good record of Eddy-covariance data, with different land cover types are selected across Australia for the analysis.

### Table 1: Study sites for the analysis

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Land Cover types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adelaide River</td>
<td>Savanna dominated by Eucalyptus</td>
</tr>
<tr>
<td>Alice Spring</td>
<td>Mulga Canopy</td>
</tr>
<tr>
<td>Howard Spring</td>
<td>Woodland Savanna</td>
</tr>
<tr>
<td>Litchfield</td>
<td>Tropical Savanna</td>
</tr>
<tr>
<td>Sturt Plains</td>
<td>Grassland (Mitchell grass)</td>
</tr>
<tr>
<td>Ti Tree East</td>
<td>Grassy mulga woodland &amp; Triodia savanna</td>
</tr>
<tr>
<td>Tumbarumba</td>
<td>Wet Sclerophyll forest</td>
</tr>
</tbody>
</table>

3) http://data.ozflux.org.au/portal/home.jspx
1. Introduction
   1.1 Background
   1.2 Objective
   1.3 Study sites
2. Objective 1
   2.1 Results
   2.2 Validation
3. Objective 2
   3.1 Holmes approach
   3.2 Results
   3.3 Validation
4. Conclusions

Fig. 3: Schematic showing the common approach followed for LST estimation and validation @ plot scale
1. Introduction
1.1 Background
1.2 Objective
1.3 Study sites

2. Objective 1
2.1 Results
2.2 Validation

3. Objective 2
3.1 Holmes approach
3.2 Results
3.3 Validation

4. Conclusions

Fig. 4: Box plot showing range of estimated LSTs obtained using site specific MODIS (TERRA) emissivity

LST estimated using leq is lower than seq for all study sites

MODIS emissivity (\(\epsilon_{\text{MODIS}}\))
1. Introduction
   1.1 Background
   1.2 Objective
   1.3 Study sites
2. Objective 1
   2.1 Results
   2.2 Validation
3. Objective 2
   3.1 Holmes approach
   3.2 Results
   3.3 Validation
4. Conclusions

**COMPARISON: PLOT SCALE & MODIS LST**

**Fig. 5: Plot showing LST bias @ Alice spring at MODIS measurement time**

**Table 2. LST bias & R² values @ study sites**

<table>
<thead>
<tr>
<th>Site</th>
<th>seq</th>
<th>leq</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litchfield</td>
<td>0.40</td>
<td>0.41</td>
</tr>
<tr>
<td>Tumbarumba</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>Alice Springs</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Howard Springs</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Sturt Plains</td>
<td>0.80</td>
<td>0.81</td>
</tr>
<tr>
<td>Ti tree East</td>
<td>0.55</td>
<td>0.57</td>
</tr>
<tr>
<td>Adelaide River</td>
<td>0.19</td>
<td>0.27</td>
</tr>
</tbody>
</table>

MODIS emissivity results high bias
LST SENSITIVITY TO EMISSIVITY:

\[ T_{seq} = 4 \sqrt{ \frac{L_{up}}{\epsilon \sigma} } \]

\[ T_{leq} = 4 \sqrt{ \frac{L_{down}}{\sigma} - \frac{L_{down}}{\epsilon \sigma} + \frac{L_{up}}{\epsilon \sigma} } \]

Fig. 6: Plot showing sensitivity of estimated LST to emissivity range (0.8 to 1) using \textit{seq} and \textit{leq} @ Alice Spring

Seq is more sensitive to emissivity
OPTIMIZED EMISSIVITY & LST ESTIMATION:

**Step 1:** Assume range of $\varepsilon$ values (0.99 to 0.4)

**Step 2:** Calculate LST ($T_s$) for each value of emissivity

**Step 3:** Plot sensible heat ($H$) vs ($T_s - T_a$), fit regression forced through origin and compute $R^2$ and root mean square error (RMSE)

**Step 4:** Calculate RMSE, $R^2$ values for each emissivity.

**Step 5:** If $R^2 > 0.5$, choose emissivity value resulting in lowest RMSE

---

**Theory**

Sensible heat is driven by surface-air temperature difference

$$H = C \Delta T$$

$$H = 0 \text{ when } \Delta T = 0$$

Regression line of $H$ vs $\Delta T$ goes through 0 if LST estimates are correct

---

Fig. 7: Work flow for calculation of optimum emissivity ($\varepsilon_{opt}$)
1. Introduction
   1.1 Background
   1.2 Objective
   1.3 Study sites
2. Objective 1
   2.1 Results
   2.2 Validation
3. Objective 2
   3.1 Holmes approach
   3.2 Results
   3.3 Validation
4. Conclusions

Reproducing Holmes et al. (2009, Fig. 2(a) & 3(c))

Using long equation

$\varepsilon_{\text{seq}}$ < $\varepsilon_{\text{leq}}$
1. Introduction
   1.1 Background
   1.2 Objective
   1.3 Study sites

2. Objective 1
   2.1 Results
   2.2 Validation

3. Objective 2
   3.1 Holmes approach
   3.2 Results
   3.3 Validation

4. Conclusions

Fig. 9: Optimized emissivity values for three consecutive years at the study sites

$\varepsilon_{\text{leq}}$ values are much lower than $\varepsilon_{\text{seq}}$ and $\varepsilon_{\text{MODIS}}$

Broken lines due to:
- $\ast$ → Missing data
- $+$ → $R^2 (H \text{ vs } \Delta T) < 0.5$
1. Introduction
   1.1 Background
   1.2 Objective
   1.3 Study sites
2. Objective 1
   2.1 Results
   2.2 Validation
3. Objective 2
   3.1 Holmes approach
   3.2 Results
   3.3 Validation
4. Conclusions

COMPARISON: PLOT SCALE OPTIMIZED LST WITH MODIS LST

LST bias is reduced using optimized emissivity

(T_{MODIS} - T_{leq}) < (T_{MODIS} - T_{seq})

Table 3. LST bias & R² values @ study sites using optimized emissivity

<table>
<thead>
<tr>
<th>Site</th>
<th>Seq</th>
<th>Leq</th>
<th>R²</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litchfield</td>
<td>0.40</td>
<td>4.41</td>
<td>0.41</td>
<td>2.57</td>
</tr>
<tr>
<td>Tumbarumba</td>
<td>0.82</td>
<td>2.27</td>
<td>0.84</td>
<td>2.10</td>
</tr>
<tr>
<td>Alice Springs</td>
<td>0.93</td>
<td>3.41</td>
<td>0.93</td>
<td>1.92</td>
</tr>
<tr>
<td>Howard Springs</td>
<td>0.21</td>
<td>4.78</td>
<td>0.22</td>
<td>2.47</td>
</tr>
<tr>
<td>Sturt Plains</td>
<td>0.81</td>
<td>3.00</td>
<td>0.82</td>
<td>1.91</td>
</tr>
<tr>
<td>Ti tree East</td>
<td>0.58</td>
<td>5.06</td>
<td>0.52</td>
<td>4.02</td>
</tr>
<tr>
<td>Adelaide River</td>
<td>0.61</td>
<td>0.35</td>
<td>0.24</td>
<td>2.93</td>
</tr>
</tbody>
</table>

Fig. 9: Plot showing LST bias using $\varepsilon_{opt}$ @ Alice spring at MODIS measurement time
CONCLUSIONS:

- Plot-scale land surface temperature (LST) derived using MODIS emissivity is generally lower than MODIS LST.

- Short equation produces different results to long equation and therefore should not be used.

- Long equation is less sensitive to emissivity, therefore bias cannot easily be "corrected" by small changes in emissivity.
  → bigger LST bias compared to MODIS.
  → lower optimized emissivity.

- Reduction in H vs DT bias leads to better match with LST from MODIS.
REFERENCES:


ACKNOWLEDGMENTS:

We would like to thank Dr. Maik Renner for pointing out to Holmes work. We are also grateful to Prof. Thomas Foken, Prof. Jason Beringer, and, Prof Lindsay Hutley for insightful discussions.
EXAMPLE ESTIMATION OF EMISSIVITY

Calculation of $T_s$ using different epsilon values from the range defined. (Step 3)

RMSE values calculated for the corresponding epsilon values. (Step 4)

Optimized value of epsilon giving the least RMSE value. (Step 5)

Fig. A: $H$ vs $\Delta T (T_{\text{eq}}-T_a)$ plots illustrating the steps for obtaining optimized emissivity

To method