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

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LAND SURFACE TEMPERATURE (LST):

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- 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:

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- 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.

Complete equation (leq)

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

Simplified equation (seq)

$$L_{up} = \epsilon \sigma T_s^4$$

Absence of L_{down} in last decades and ε close to 1

where, L_{up} is the up-welling longwave, L_{down} is the down-welling longwave, σ is the Stephan-Boltzmann constant and ε is the surface emissivity.

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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.

Fig. 1 (a): Airborne radiometers[1]

Plot scale:

- At plot scale both *leq* and *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 (b): EC Tower at Adelaide river[2]

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1) https://phys.org/news/2017-07-seasons-space.html
2)http://www.ozflux.org.au/monitoringsites/adelaideriver/adelaideriver_pictures.html

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:

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- 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

Site Name	Land Cover types
Adelaide River	Savanna dominated by Eucalyptus
Alice Spring	Mulga Canopy
Howard Spring	Woodland Savanna
Litchfield	Tropical Savanna
Sturt Plains	Grassland (Mitchell grass)
Ti Tree East	Grassy mulga woodland & Triodia savanna
Tumbarumba	Wet Sclerophyll forest

Fig. 2: Map showing site locations

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3) http://data.ozflux.org.au/portal/home.jspx

GENERAL APPROACH: STEPS

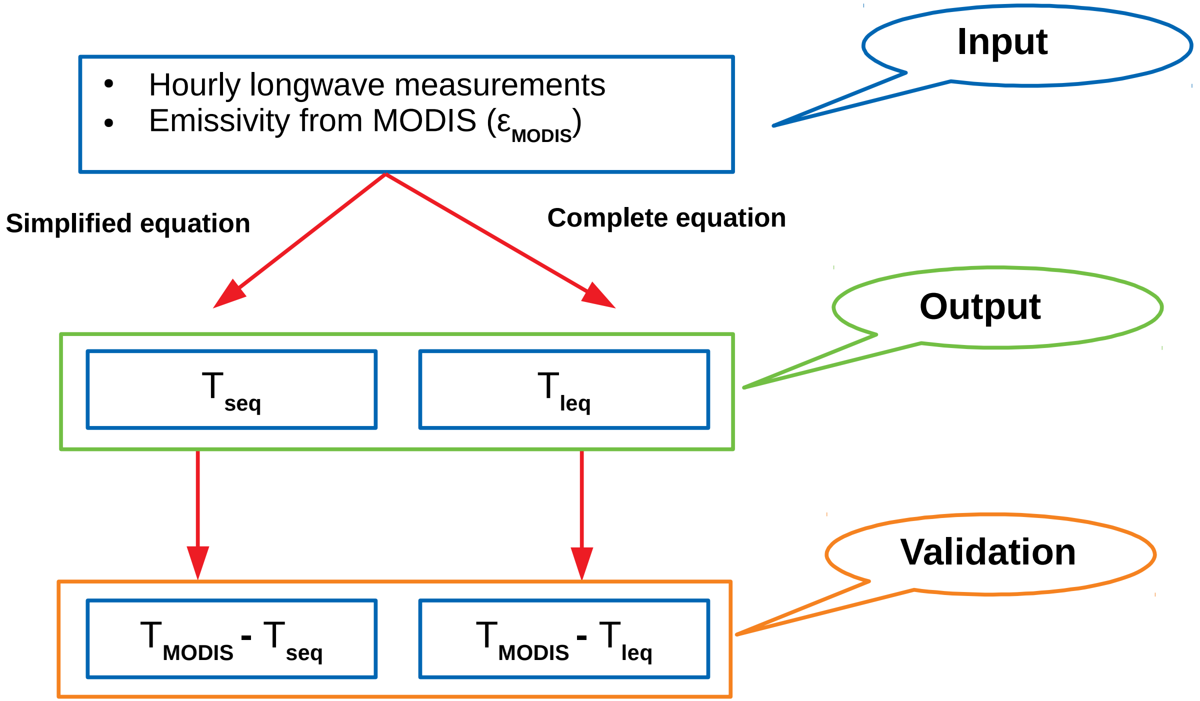

Fig. 3: Schematic showing the common approach followed for LST estimation and validation @ plot scale

ESTIMATED LST: MODIS EMISSIVITY

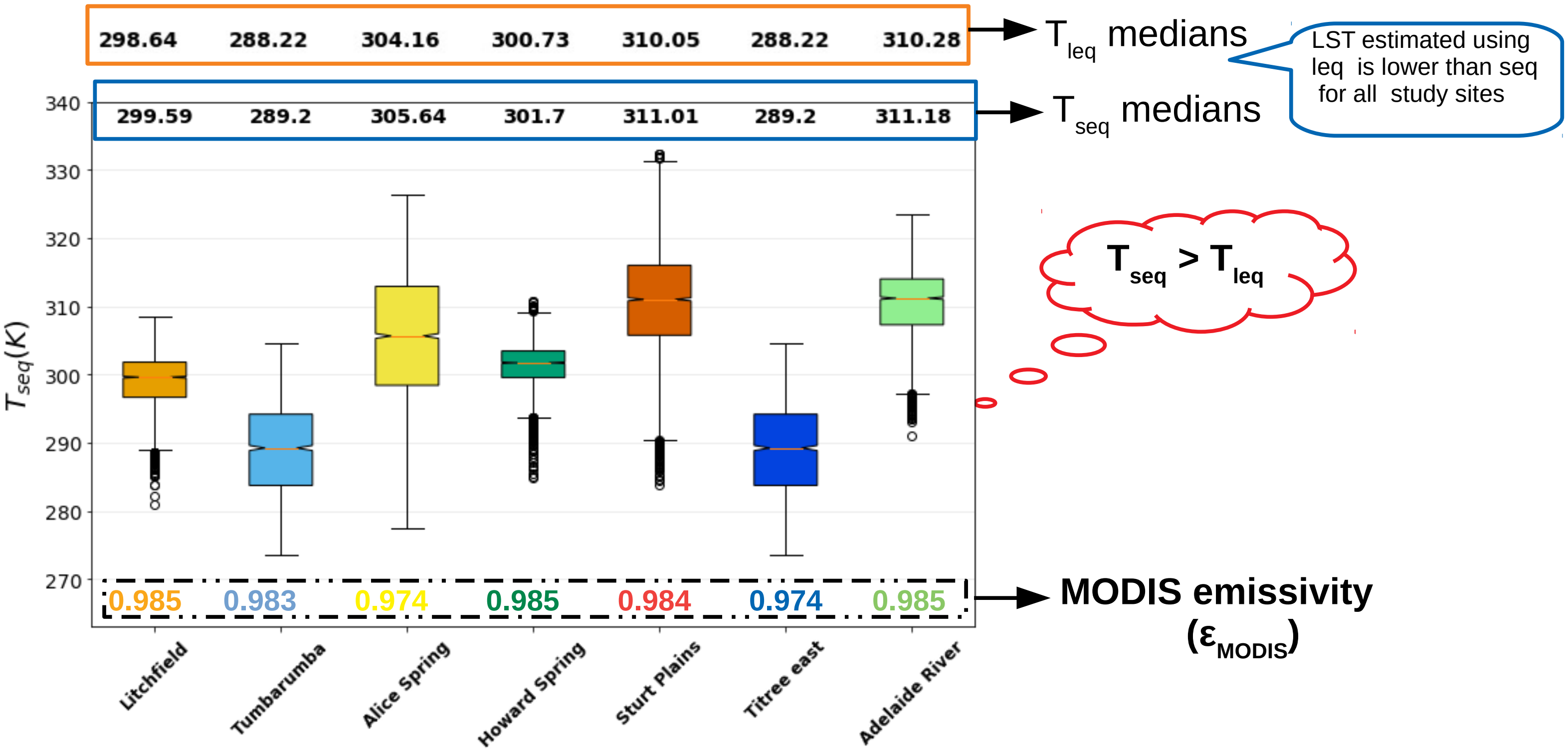

Fig. 4: Box plot showing range of estimated LSTs obtained using site specific MODIS (TERRA) emissivity

COMPARISON: PLOT SCALE & MODIS LST

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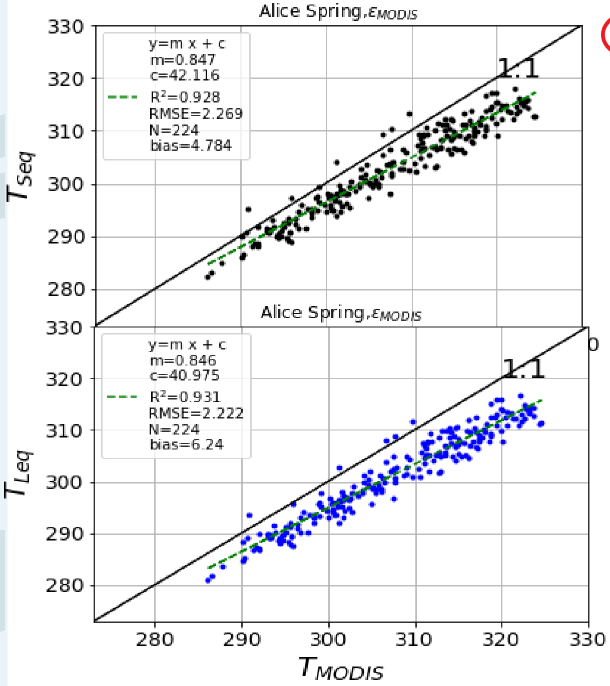

Fig. 5: Plot showing LST bias @ Alice spring at MODIS measurement time

$T_{MODIS} > T_{seq} > T_{leq}$

MODIS emissivity results high bias

Table 2. LST bias & R^2 values @ study sites

Site	seq		leq	
	R^2	Bias	R^2	Bias
Litchfield	0.40	10	0.41	11
Tumbarumba	0.89	0.99	0.89	1.93
Alice Springs	0.93	4.78	0.93	6.24
Howard Springs	0.16	8.99	0.16	9.90
Sturt Plains	0.80	3.67	0.81	4.61
Ti tree East	0.55	6.76	0.57	8.30
Adelaide River	0.19	2.61	0.27	3.47

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LST SENSITIVITY TO EMISSIVITY:

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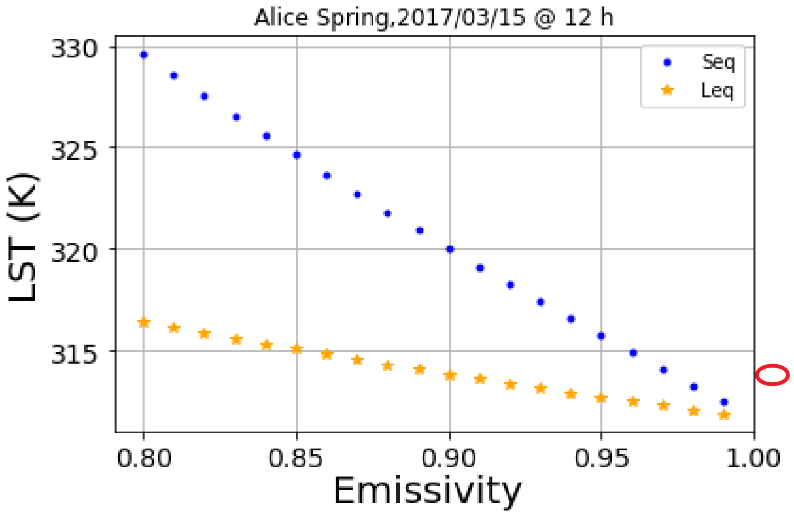
$$T_{leq} = \sqrt[4]{\frac{L_{down}}{\sigma} - \frac{L_{down}}{\epsilon\sigma} + \frac{L_{up}}{\epsilon\sigma}}$$

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



Seq is more sensitive to emissivity

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

OPTIMIZED EMISSIVITY & LST ESTIMATION:

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Step 1: Assume range of ε values (0.99 to 0.4)

Step 2: Calculate LST ($\mathbf{T_s}$) for each value of emissivity

Step 3: Plot sensible heat (H) vs ($\mathbf{T_s}$-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

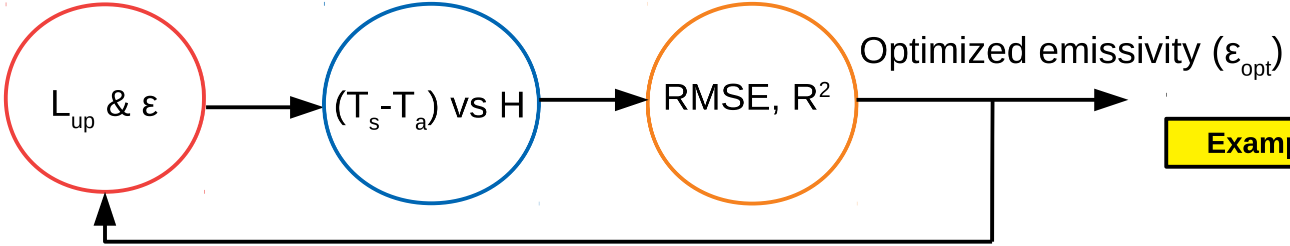
Theory

Sensible heat is driven by surface-air temperature difference

$$H = C \Delta T$$

$$H = 0 \; when \; \Delta T = 0$$

Regression line of H vs ΔT goes through 0 if LST estimates are correct



Example

Fig. 7: Work flow for calculation of optimum emissivity (ε_{opt})

OPTIMIZED EMISSIVITY: SEQ & LEQ

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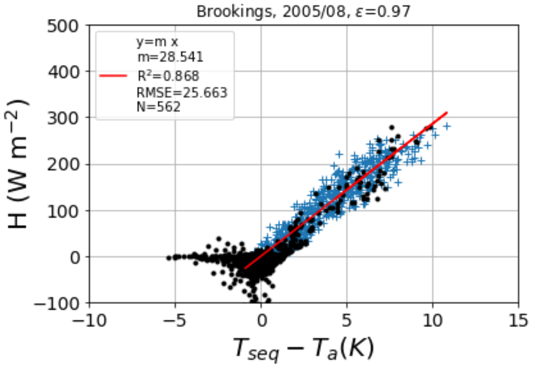
Reproducing Holmes et. al (2009, Fig. 2(a) & 3(c))



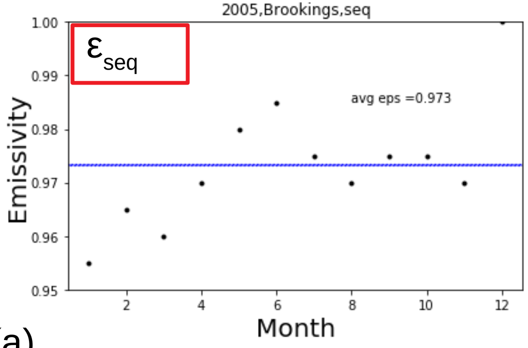
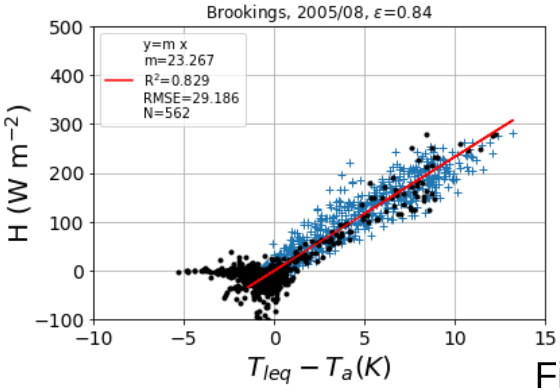


Fig. 8(a)

Using long equation



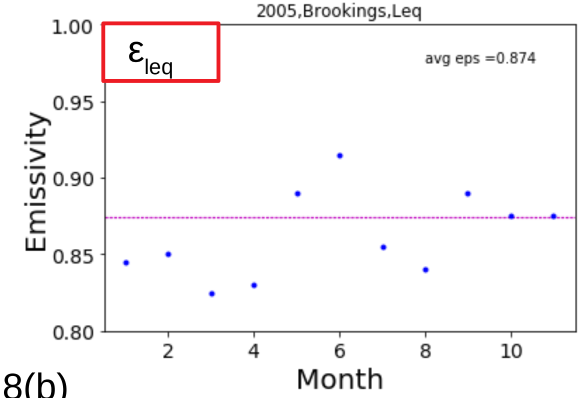


Fig. 8(b)

$\varepsilon_{leq} < \varepsilon_{seq}$

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OPTIMIZED EMISSIVITY: LEQ @ STUDY SITES:

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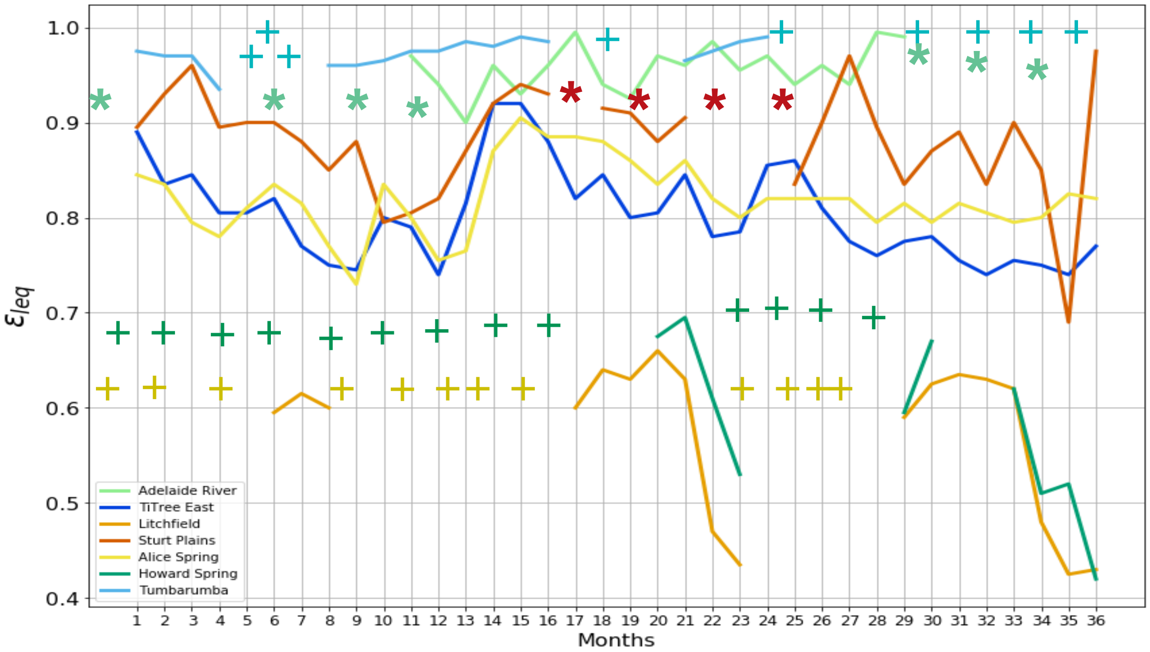

Fig. 9: Optimized emissivity values for three consecutive years at the study sites

ε_{leq} values are much lower than ε_{seq} and ε_{MODIS}

Broken lines due to:
* → Missing data
+ → R^2 (H vs ΔT) < 0.5

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COMPARISON: PLOT SCALE OPTIMIZED LST WITH MODIS LST

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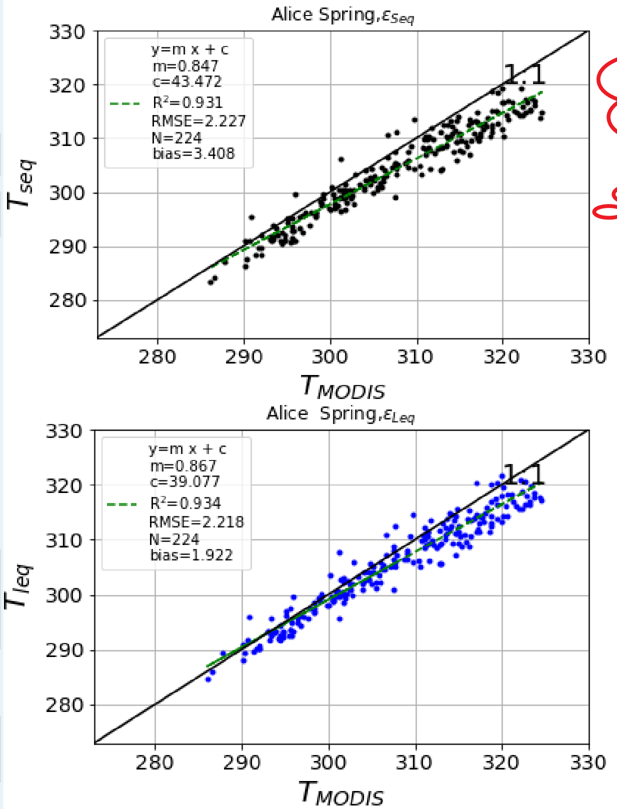

Fig. 9: Plot showing LST bias using ε_{opt} @ Alice spring at MODIS measurement time

LST bias is reduced using optimized emissivity

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

Table 3. LST bias & R^2 values @ study sites using optimized emissivity

Site	Seq		Leq	
	R^2	**Bias**	**R^2**	**Bias**
Litchfield	0.40	4.41	0.41	2.57
Tumbarumba	0.82	2.27	0.84	2.10
Alice Springs	0.93	3.41	0.93	1.92
Howard Springs	0.21	4.78	0.22	2.47
Sturt Plains	0.81	3.00	0.82	1.91
Ti tree East	0.58	5.06	0.52	4.02
Adelaide River	0.61	0.35	0.24	2.93

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CONCLUSIONS:

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- Plot-scale land surface temperature (LST) derived using MODIS emissivity is generally lower than MODIS LST **Results**
- Short equation produces different results to long equation and therefore should not be used **Results**
- Long equation is less sensitive to emissivity, therefore bias cannot easily be "corrected" by small changes in emissivity
  → bigger LST bias compared to MODIS **Results**
  → lower optimized emissivity **Results**
- Reduction in H vs DT bias leads to better match with LST from MODIS **Results**

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Appendix

REFERENCES:

1) Norman, J. M., & Becker, F. (1995). Terminology in thermal infrared remote sensing of natural surfaces. Agricultural and Forest Meteorology, 77(3-4), 153-166.

2) Holmes, T. R. H., De Jeu, R. A. M., Owe, M., & Dolman, A. J. (2009). Land surface temperature from Ka band (37 GHz) passive microwave observations. Journal of Geophysical Research: Atmospheres, 114(D4)

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EXAMPLE ESTIMATION OF EMISSIVITY

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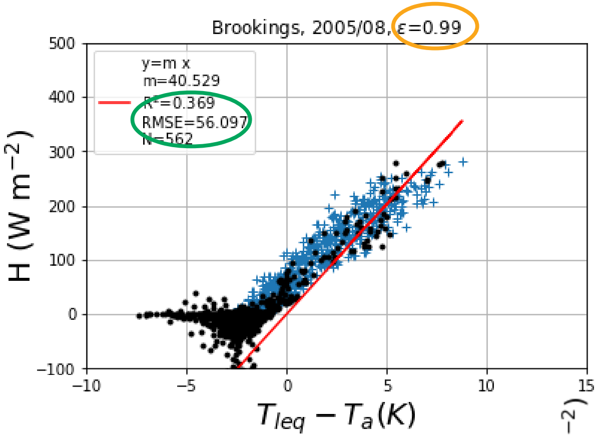
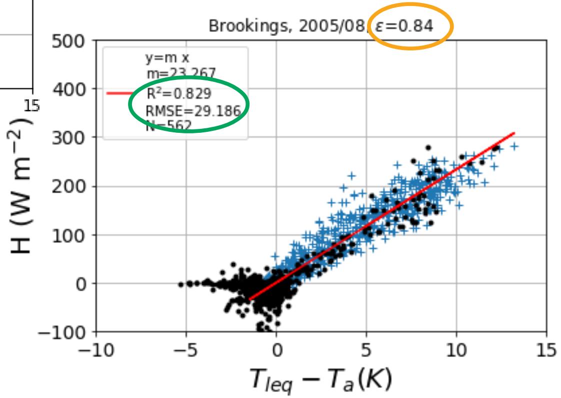


Optimized value of epsilon giving the least RMSE value. (Step 5)

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



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

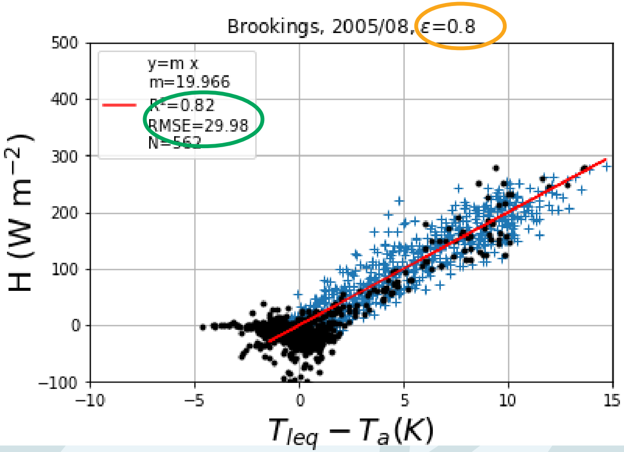


Fig. A: H vs ΔT (**T_{leq}-T_a**) plots illustrating the steps for obtaining optimized emissivity

To method