Development and validation of algorithms for LST measurement from NOAA-11/AVHRR satellite data

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Abstract. The purpose of this project was to develop the algorithms and characterise measurement errors of land surface temperature (LST). An initial investigation of the accuracy of retrieval of LST has employed synthetic radiances, produced using Lowtran7, for a series of land and atmospheric situations representative of the Australian continental climate. The synthetic data have been modelled to incorporate variation of surfaces emissivity, atmospheric temperature, water vapour profile, and the surface or boundary temperature. The study indicated that the success of the scheme depended on the validity of the modelled radiances, particularly with respect to the formulation of the radiative role of the water vapour constituent of the atmosphere. Whirls, the use of regression in deriving the coefficients for LST equation minimised the bias errors in the radiative transfer calculation that may arise from air mass dependence. However, our algorithms derived using statistical regression and synthetic atmospheres indicated good accuracy for LST measurement with an rms error of order 1°C when validated using data for an instrumented field site.

1. Introduction

Land Surface Temperature (LST) is an important physical parameter used in the description of environmental, meteorological and biological processes. If it can be estimated accurately from satellite data, it is potentially valuable in modelling and predicting studies of small scale through to synoptic scale processes. Because of the of LST variability, both spatially and temporally [7], the access to space-borne observations of LST by NOAA/AVHRR offers considerable advantage to these applications. However, the matter of accurately estimating LST is a more complex problem compared, for example, with sea surface temperature (SST) measurement. Although AVHRR collects radiometric data that are directly related to LST, difficulty arises in accurately determining LST from the radiances. The sources of these difficulties include in-homogeneity of the land surface [3], due to the variability of surface emissivity and topography, and the temperature and moisture structure of the overlying atmosphere.

The use of two adjacent spectral channels in the long wave window region, known as the split window method, has successfully retrieved SST from clear sky satellite radiance measurements. The relative flateness of emissivity for the land surface in the 10 - 12 µm thermal region [16] encourages the use of split window approach to correct upwelling radiances for atmospheric water vapour absorption. In principle, knowledge of the surface emissivity with an appropriate characterisation of atmosphere should permit accurate LST estimation.

This article reports the progress on the work in which radiances have been computed using Lowtran7, for a series of land and atmospheric conditions model, and investigated the accuracy of the retrieved LST. The least squares method was utilised to determine the linear regression coefficients for the split window algorithm. The linear dependence of LST on the brightness temperature difference of the
window channels involves several approximations [10], [2] and [4]. A second order least squares regression scheme was also investigated.

2. Methods

2.1. Radiative Transfer Equation in the Thermal Infrared

For a non-scattering and cloud free atmosphere under local thermodynamic equilibrium, and a land surface considered to be a Lambertian reflector, the radiative transfer equation for the outgoing thermal infrared radiance $I_i$ received by channel $i$ of a satellite’s sensor may be expressed as:

$$I_i(\theta) = \varepsilon_i(\theta)B_i(T_s)\tau_i(\theta) + \int_0^p B_i(T_p)\frac{\partial \tau_i(p)}{\partial p} dp + [1 - \varepsilon_i(\theta)]\tau_i(\theta)L_i$$

(1)

where $\rho_i(\theta) = [1 - \varepsilon_i(\theta)]$ is the hemispherical reflectivity, $\varepsilon_i$ is the surface emissivity, $\theta$ is zenith angle, $L_i$ is the hemispherical down-welling atmospheric radiances at a wavelength $i$, $B_i$ is the Planck function, $T_s$ and $T_p$ are respectively the surface temperature and the atmospheric temperature at pressure level $p$, $\tau_i$ is atmospheric transmittance, and $\frac{\partial \tau}{\partial p}$ is defined as a weighting function.

Equation (1) may be rewritten in the following simplified form:

$$I_i = \tau_i[\varepsilon_i B_i(T_s) + (1 - \varepsilon_i)L_i] + \int_0^p B_i(T_p)\frac{\partial \tau_i(p)}{\partial p} dp.$$

(2)

In order to cast equation (2) into a more appropriate form, we apply the mean value theorem to an atmospheric layer between pressure level $p$ and the top of the atmosphere, yielding:

$$\int_0^p B_i(T_p)\frac{\partial \tau_i(p)}{\partial p} dp = (1 - \tau_i)_B$$

(3)

$\tau_i_B$ is the Planck radiance averaged over the transmission function. Rewriting (2) using (3), we obtain:

$$I_i = \tau_i[\varepsilon_i B_i(T_s) + (1 - \varepsilon_i)L_i] + (1 - \tau_i)_B$$

(4)

where now $\varepsilon_i$ is the band averaged emissivity for channel $i$, $\tau_i$ is the band averaged transmittance for channel $i$, $L_i$ is the down-welling component of the flux of sky radiance, $B_i(T_s)$ is the surface Planck radiation, $T_s$ is the surface temperature and $B_i$ is the radiance emitted by the atmosphere.

2.2. Split Window Method

Based on the regression scheme proposed by [1], which related window radiance measurements at two adjacent wave lengths to SST, [6] used the radiative transfer equation to develop a theoretical justification for that method. The essence of the scheme showed that the radiance attenuation, due to atmospheric absorption, was proportional to the difference of simultaneously measured radiances for two adjacent window channel wavelengths, where each measurement was subjected to a different amount of atmospheric absorption. Accordingly, LST is linearly dependent on the radiances or brightness temperatures measured in the two adjacent thermal infrared channels. This approach is termed as the split window method.

Using equation (4) above, the upwelling radiance at the satellite may be written in terms of the split window channels 4 and 5 of AVHRR:

$$I_4 = \tau_4[\varepsilon_4 B(T_4) + (1 - \varepsilon_4)\tau_4L_4] + (1 - \tau_4)\tau_4B_4,$$

(5)
\[ I_5 = \tau_5 [\varepsilon_5 B(T_5) + (1 - \varepsilon_5) L_5] + (1 - \tau_5) B_i \]  

The Planck radiances are usually evaluated at an equivalent wave number to avoid the need to include the integration over the channel filter function. Solving (5) and (6) for the surface radiance term, by expanding the Planck function to first order about a mean radiance value, would produced;

\[ T_s = \left( 1 + \frac{1}{T_4} \right) T_4 - \frac{\varepsilon}{T_4} \left( 1 + \frac{\varepsilon}{T_5} \right) T_5 + \left( 1 - \frac{\varepsilon}{T_4} \right) L_{sky} \left( \frac{cB}{cT} \right)^{-1} \]  

where:  
\[ \chi = \frac{1 - \tau_4}{\tau_4 - \tau_5} \]  
\[ \Delta \varepsilon = \varepsilon_4 - \varepsilon_5 \]  
\[ T_4 = \text{the brightness temperature of AVHHR channel 4.} \]  
\[ T_5 = \text{the brightness temperature of AVHRR channel 5.} \]  
\[ L_{sky} = \text{the sky radiance, assumed to be the same for both channels.} \]

The last term in equation (7) generally is small because the sky radiance is low (for clear skies with low water vapour, \( L_{sky} \) (11 \( \mu \)m) < 60 mW/(m² str cm⁻¹), and the emissivity is typically high (\( \varepsilon > 0.9 \)).

With the Planck derivative evaluated for 285K, and the highest expected value for the sky radiance, the term will give \( L_{sky} (cB/cT) = 40 \) [8]. Equation (7) above may be simplified further by assuming the spectral emissivity difference \( \Delta \varepsilon \) is very small, yielding:

\[ LST = 40 \left( 1 - \frac{1}{\varepsilon} \right) + \left( 1 + \frac{\varepsilon}{T} \right) T_4 - \left( \frac{\varepsilon}{T} \right) T_5 \]  

which may be simplified to the form:

\[ LST = a + bT_4 + cT_5 \]  

Where \( a, b, \) and \( c \) are appropriate coefficients defined in equation (8).

The outcome of a recent study [2] indicates that a constraint may be applied to the coefficients in equation (5). Specifically, \( b + c = 1 \), may be used without any significant increase of the estimated error, especially for SST determination. Using a similar assumption, equation (9) can be rewritten in the form which expresses the difference between the actual LST and the channel 4 brightness temperature, \( T_4 \):

\[ LST - T_4 = a_o + b_o (T_4 - T_5) \]  

where \( a_o \) and \( b_o \) are the appropriately adjusted coefficients.

If the quantity \( (T_4 - T_5) \) is set equal to \( \Delta T \), then equation (10) might be regarded as the first order term of the more general expansion:

\[ LST - T_4 = a_o + a_1 \Delta T + a_2 \Delta T^2 \]  

where we have retained just the term up to order \( \Delta T^2 \) in the series. The magnitude of the coefficient \( a_2 \) provides an indication of the validity of the approximations made in the linear formulation [8] and [6]. Equations (10) and (11) were used in the synthetic studies.

3. Results

3.1. Regression Equation Coefficients

The approach by [7] developed algorithm coefficients for equation (9) by regressing satellite measured brightness temperatures against surface observations. This approach is different in that the algorithms has been derived using radiometric data synthesised from radiosonde measurements. The success of the
scheme depends on the validity of the modelled radiances, particularly with respect to the formulation of the radiative role of the water vapour constituent of the atmosphere. Using climatological radiosonde data for a number of Australian regions [5], the impact of the region can be examined, and season on the LST regression coefficients. Lowtran7 atmospheric transmittance code has been used to calculate radiances, brightness temperatures and transmittances from which we have retrieved the LST. The synthetic data have been modelled to incorporate variation of surfaces emissivity, atmospheric temperature, water vapour profile, and the surface or boundary temperature. We note that use of regression in deriving the coefficients for equation (10) and (11) minimised the bias errors in the radiative transfer calculation which may arise from air mass dependence.

Based on the LST algorithm of equation (11), linear regression was used to determine the coefficients relating LST to the brightness temperatures of channel 4 and 5 of NOAA/AVHRR. Alice Springs’ climatological radiosonde data for January [5] were used as the input to Lowtran7 with the surface temperature varied over the range ±10 K greater or less than the temperature of the lowest atmospheric layer (27.8 °C or 300.95 K), and a surface emissivity set to 0.96. Thus, 21 synthetic profiles have been generated for Alice Springs’ (23.817 °S, 133.833 °E) data with land surface temperature varied from 290.95 K to 310.95 K in 1 K increment. Lowtran7 was used to compute the radiances from which we calculated the brightness temperatures for spectral intervals and filter band-pass functions corresponding to channels 4 and 5 of NOAA-11/AVHRR. The coefficients in equation (10) and (11) were derived by regressing these brightness temperatures against the surface temperatures included in the 21 synthetic input data sets. Our synthetic study yielded an LST algorithm to first order given by,

\[ LST - T_4 = 2.0687 + 2.8093(T_4 - T_5) \]  \tag{12}

and, to second order,

\[ LST - T_4 = 2.1489 + 2.5961(T_4 - T_5) + 0.1099(T_4 - T_5)^2 \]  \tag{13}

where \( T_4 \) and \( T_5 \) are the brightness temperatures, now in °C for channel 4 and 5 respectively. Note, that in equation (13) the second order term has the potential to be significant for moist atmospheres where \( T_4 \) and \( T_5 \) may differ significantly. Following the addition of Gaussian noise to the synthetic brightness temperatures, we simulated the impact of AVHRR radiometer instrument noise of 0.12 K of standard deviation typical for this sensor on the stability of the coefficients in the above algorithms. For this purpose, we computed the regression coefficients with 30 different sets of Gaussian distribution random noise. The mean values of the individual coefficient from the 30 sets were derived together with their uncertainty. We obtained respectively the LST regression relations for first and second order as follows,

\[ LST - T_4 = (1.9745 \pm 0.0297) + (2.7608 \pm 0.0322)(T_4 - T_5) \]  \tag{14}

\[ LST - T_4 = (2.1031 \pm 0.0527) + (2.5539 \pm 0.0468)(T_4 - T_5) + (0.0564 \pm 0.0302)(T_4 - T_5)^2 \]  \tag{15}

3.2. Expected Algorithm Performance

The synthetic study performed using Alice Springs’ (January) climatological data indicated the LST algorithms (equations 12 and 14) could provide accurate estimates of LST. We note that the use of regression in deriving coefficients for equation (10) and (11) minimised the bias errors in the radiative transfer calculation, which might arise from air mass dependence. However, this analysis identified that the second order relationships (equations 13 and 15) provided a slightly reduced rms errors when compared to the performance of the first order schemes (equation 12 and 14). Using the brightness temperatures for channels 4 and 5 for the Alice Springs’ data set, the performance, without additive Gaussian noise, gave an rms error of 0.15 °C, for both the first and second order regression schemes. Whereas, an rms error of about 0.55 °C was determined for the first and second order formulations using the additive Gaussian noise of 0.12 K standard deviation. This study recommends the application of these algorithms for estimating LST yield, to an accuracy of about 1°C, providing that land surface’s physical properties are well characterised.
The expected performance figures quoted earlier, were based on how the algorithm estimated LST compared to the LST input to the radiative transfer calculation, with the latter using climatological data. We now describe the performance using NOAA/AVHRR radiances and in-situ LST measurements. We validated the LST retrieval by applying the algorithms (equations 12 -15) to field data measurement at the Walpeup Field Site (35°11'58" S, 142°03'51" E) located in a wheat growing area in NW Victoria (Australia). The site has been instrumented by CSIRO Division Atmospheric Research with an array of temperature sensors installed over an area roughly 1.1 km by 1.2 km. It is a large uniform field of red sandy soil typical of the inland parts of semi-arid Australia. The field was initially bare, then sown to wheat, then barley and finally left fallow, over a period of 2 years. Measurements used in this study were developed during the whole of the last two years [9]. In-situ measurements were sampled at intervals of 1 minute then subsequently uplinked to NOAA satellites data using the ARGOS telemetry system. A detailed description of the site could be found [7].

An analysis of in-situ measurement (50 measurements) that are coincident in time with the satellite's measurements, yield overall LSTs of about 1 °C accuracy. The analysis also indicates high correlation between satellite and in-situ measurements with a correlation coefficient r² of about 0.99. The algorithm of equation (12) gave an rms error of 1.00 °C with bias of -0.16. Further, rms errors of 0.98 °C with bias of -0.28 were achieved using the algorithm described by equation (13). Figure 1 and 2 shows the correlation of LSTs’ in situ and satellite measurements, for the first (equations 12) and second (equation 13) order regression, respectively [15].

The algorithms of equations (14) and (15) yielded rms errors of 0.98 °C with a bias of -0.03, and 0.95 °C with the bias of -0.11 respectively. Figures 3 and 4 [15] present the correlation of LSTs for in-situ and satellite measurements, for both the first (equations 14) and second (equation 15) order regression schemes using data which included Gaussian noise synthetized sensor, respectively.

![Figure 1](image1.png)  
Figure 1. The correlation of LSTs’ in situ and satellite measurements for the first equation (equation 12).

![Figure 2](image2.png)  
Figure 2. The correlation of LSTs’ in situ and satellite measurements for the second equation (equation 13).

![Figure 3](image3.png)  
Figure 3. The correlation of LSTs for in-situ and satellite measurement applying the first equation (equation 14).

![Figure 4](image4.png)  
Figure 4. The correlation of LSTs for in-situ and satellite measurements applying the second equation (equation 15).
4. Conclusions

The estimation of LST to acceptable accuracy was very dependent on correctly characterising the atmosphere. The analysis indicated that using brightness temperature of the thermal channels of AVHRR/NOAA, algorithms may be used to determine LST to an accuracy of order 1°C with a correlation coefficient of about 0.99. The second order regression scheme indicated a possibility for improving LST measurement accuracy. An analysis of in-situ measurement (50 measurements) data from Victoria field station of the CSIRO Division of Atmospheric Research that coincident in time with the satellite's measurements, yield an overall LSTs of about 1°C accuracy.

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