Land surface temperature retrieval from MODIS and VIRR data in northwest China

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Abstract. By using the Gulang Heterogeneous Underlying Surface Layer Experiment (GHUSLE) data, the accuracy of land surface temperature (LST) in Northwest China retrieved by the Moderate-Resolution Imaging Spectroradiometer (MODIS) and Visible and InfraRed Radiometer (VIRR) data is verified. Furthermore, a new LST algorithm for heterogeneous underlying surface is developed and the LST retrieved by the two remote sensing data using three algorithms are compared with the observed data. Results suggest that the new algorithm is the best one in the case of heterogeneous underlying surface. Kerr algorithm accuracy is not satisfying and Becker algorithm is ranked just ahead Kerr algorithm. Especially, the differences in retrieval accuracy among them are more obvious when using the VIRR data. Compared with the observed LST, the root mean square errors of the LST retrieved by MODIS and VIRR data are the least when using the new algorithm, the specific values are 2.55 K and 3.78 K, respectively. The LST retrieved by MODIS data are closer to observed values and higher than its counterpart retrieved by VIRR data. When the new LST retrieval algorithm used, the LST retrieved by MODIS and VIRR data are the closest.

1. Introduction

The LST is a major factor for energy and substance exchange between the land and atmosphere, an important index for the measurement of global temperature changing and a key determinant for regional and global land surface process[1-4]. Surface temperature retrieval began from the middle of the last century. It’s becoming more temptations to exploit satellites’ thermal infrared data for retrieving land surface temperature as sea surface temperature retrieval accuracy exceeded 1.0 K[5].

Based on the NOAA/AVHRR channels 4(10.3–11.3µm) and 5(11.5–12.5µm), Spilt-window algorithms can be expressed as: $T_s = T_4 + A(T_4 - T_5) + B$. The coefficient A and B vary with different spilt-window algorithms due to various conditions of land surface and atmosphere[6]. It was the first time that the split-window algorithms of retrieving sea surface temperature introduced into retrieving land surface temperature by Price[7] in 1984. A LST retrieval algorithm was given under the approximate blackbody surface condition. Then various split-window algorithms had been developed which considered the influence of vapour, vegetation and channel emissivity[8-9]. Most of these...
algorithms were aimed at the thermal infrared channels of NOAA/AVHRR. Along with the successful launch of all kinds of satellites, the split-window algorithms applicable for corresponding satellite sensors are different. Therefore many kinds of modified split-window algorithms have been presented \cite{10-11}. With the increasing number of thermal infrared channels as well as the evolvement of multi-channel algorithm and multi-angle algorithm\cite{12}, the retrieval accuracy was improved to 1.0 K. However, owing to the complexity and the immaturity of algorithms, the multi-channel algorithm and multi-angle algorithm have not been widely used. The split-window algorithm is still widely applied and the most mature surface temperature retrieval algorithm whose accuracy stays within 3.0 K.

Using the TEERA/MODIS and FY-3A/VIRR data of MODIS and VIRR, different surface temperature retrieval algorithms are involved in estimating LST in northwest China. By comparing with the GHUSLE observed data, we are able to analyze the similarities and differences of the remote sensing data, to discover a more suitable retrieval algorithm for research area and to provide important reference for defining the parameters of heterogeneous underlying.

2. Field experiment and data using

2.1 Field experiment introduction
The Gulang experiment area is set up in Haizi village, Gulang county, Wuwei in Gansu province, generally called Gulang Heterogeneous Underlying Surface Layer Experiment (GHUSLE). The experiment area is a typical arid and semi-arid region where an oasis which width is not more than 10.0 km is included in the desert. The area is the junction of Gansu and Inner Mongolia, lies to the southern margin of the fourth biggest desert—(Tengger Desert) of China, as it is shown in figure 1. Three meteorological observation sites(named as west desert site(W), cropland site(M) and east desert site(E)) and four encrypted sites(named as the first east site(E1), the second east site(E2), the third east site(E3) and the first west site(W1),) are set up for GHUSLE experiment in the profiles of desert-oasis-desert. The oasis is the emphasis of experiment where a 32m observation tower was set up. The experiment contains three parts: basic observation, intensive observation and parallel instrumental contrast observation. The land surface temperature is computed from upward thermal radiance applying Planck’s law in the experiment area, and the surface emissivity can be referred from literature\cite{13}.

![Figure 1. The location of experimental area](image)

2.2. Satellites data selection
The remote sensing data are downloaded from NOAA MODIS official website and NMC(National Satellite Meteorological Center of China). Considering the weather condition, we choose satellite data in fine days in this paper. The specific time labels of MODIS data are 11:55 on May 29 , 12:15 on June 10, 12:05 on June 12, 11:55 on June 14, 11:40 on June 16, 12:25 on June 17, 12:00 on June 21, 11:45 on June 23, 12:10 on July 5, 2010. These are first level geographical calibration products of MODIS which are named MOD021KM and MOD03 data. The specific time labels of VIRR data are
11:35 on May 29, 11:40 on June 3, 11:20 on June 4, 11:00 on June 15, 11:40 on June 16, 12:10 on June 12, 12:15 on June 17, 12:20 on June 22, 12:05 on June 23, 2010. These are VIRR first level geographical calibration products data. The satellite data of all sites are retrieved by nearest interpolation method, and the time zone used in this paper is Beijing time.

3. Research methods

3.1. Channel emissivity

Using the visible bands and near infrared data of NOAA/AVHRR, an empirical method for calculating the channel emissivity $\varepsilon$ was given by Sobrino[14], of which the emissivity of different surface was provided by Salisbury. Considering the channel emissivity varies with different soil types, bare soil emissivity was calculated by means of visible channel reflectivity. The emissivities of satellite thermal infrared channels can be calculated as follow:

\begin{align}
\text{When } 0.2 \leq \text{NDVI} \leq 0, \quad & \varepsilon_{\text{tir}1} = 0.98 + 0.021p_v, \quad \varepsilon_{\text{tir}2} = 0.974 + 0.015p_v \tag{1} \\
\text{When NDVI} < 0.2, \quad & \varepsilon = 0.98 - 0.042r_{\text{vis}}, \quad d\varepsilon = -0.003 - 0.029r_{\text{vis}} \tag{2} \\
\text{When NDVI} > 0.5, \quad & \varepsilon_{\text{tir}1} = \varepsilon_{\text{tir}2} = 0.989 \tag{3}
\end{align}

Where tir1 and tir2 are the thermal infrared channels of satellite. And $p_v$ is the vegetation coverage[15]:

\begin{align}
\text{NDVI}_S &= \frac{(\text{NDVI} - \text{NDVI}_S/\text{NDVI}_V - \text{NDVI}_S)}{2} \tag{4}
\end{align}

Where NDVI$_S$ is the typical NDVI value for bare soil condition, assumed to be 0.2; NDVI$_V$ is the typical NDVI value for complete vegetation cover condition, assumed to be 0.5.

3.2. The local split-window algorithms

(1) Becker’s LST retrieval algorithm

The LST algorithm in concrete form can be expressed as follow[8]:

\begin{align}
T_{s_b} = A_0 + p(T_{\text{tir}1} + T_{\text{tir}2})/2 + m(T_{\text{tir}1} - T_{\text{tir}2})/2 \tag{5}
\end{align}

Where $T_{s_b}$ is the retrieved LST and the unit is K; $A_0$=1.274; P and M are functions of $\varepsilon$.

(2) The Kerr’s LST retrieval algorithm

An empirical LST retrieval algorithm was given by Kerr in 1992 which can be expressed as two independent split-window algorithms[9]:

\begin{align}
T_{s_k} &= p_vT_{\text{veg}} + (1.0 - p_v)T_{\text{soil}} \tag{6a} \\
T_{\text{veg}} &= T_{\text{tir}1} + 2.6(T_{\text{tir}1} - T_{\text{tir}2}) - 2.4 \tag{6b} \\
T_{\text{soil}} &= T_{\text{tir}1} + 2.1(T_{\text{tir}1} - T_{\text{tir}2}) - 3.1 \tag{6c}
\end{align}

Where $T_{\text{veg}}$ and $T_{\text{soil}}$ are LST of bare soil and complete vegetation cover conditions, respectively; $T_{s_k}$ is the LST estimated by Kerr’s LST retrieval algorithm and the unit is K.

(3) The new LST retrieval algorithm

The new LST retrieval algorithm for heterogeneous underlying surface is developed basing on Sobrino’s surface emissivity algorithm. Two independent split-window algorithms under bare soil and complete vegetation cover condition can be given by combining Becker’s algorithm and Kerr’s. To estimate the LST of mixed pixels, the circumstance of two independent split-window algorithms by virtue of vegetation coverage. The specific calculation suggests as follow:

First, when NDVI$>$0.5, $\varepsilon=0.989$, $d\varepsilon=0.0$, take these values into Becker’s LST retrieval algorithm, the split-window algorithm for complete vegetation cover condition can be given as follow:

\begin{align}
T_{b_{\text{veg}}} = A_0 + p_{\text{veg}}(T_{\text{tir}1} + T_{\text{tir}2})/2 + m_{\text{veg}}(T_{\text{tir}1} - T_{\text{tir}2})/2 \tag{7}
\end{align}

Where $p_{\text{veg}}$=1.00319; $m_{\text{veg}}$= 6.34122.
Second, when NDVI<0.2, the split-window algorithm for bare soil condition as follows:

- \[ T_{b\_soil} = A_0 + p_{\_soil}(T_{tir\_1} + T_{tir\_2})/2 + m_{\_soil}(T_{tir\_1} - T_{tir\_2})/2 \] (8)

The \( p_{\_soil} \) and \( m_{\_soil} \) are parameters which can be calculated in the former method using the thermal infrared channels emissivities. The value of \( r_{\_vis} \) can be determined by the average reflectance of all \( r_{\_vis} < 0.2 \) pixels.

Third, when 0.2 \( \leq \) NDVI \( \leq \) 0.5. The split-window algorithm for mixed pixels as follows:

- \[ T_{b\_k} = P_{\_veg}T_{b\_veg} + (1 - P_{\_veg})T_{b\_soil} \] (9)

4. Results

4.1. The verification of retrieving results

Figure 2(a) shows the retrieved LST results of three split-window algorithms using MODIS data in experimental area. RMSE is the root mean square error, ARE is the average relative error, R is correlation coefficient, and N is the total number of samples. The retrieved LST is close to the observed results as correlation coefficients are all above 0.90. Compared with the observed results, the RMSE of Kerr’s LST retrieval algorithm is the maximum by 3.22 K, and correlation coefficient is 0.90. The results of the new LST retrieval algorithm and Becker’s LST retrieval algorithm are approximately the same; both of the RMSE are less than 3.0 K. Specific values are 2.55 K and 2.69 K. Correlation coefficients are 0.92 and 0.91, respectively.

Figure 2(b) shows the retrieved LST results of the three split-window algorithms using the VIRR data in the experimental area. On the whole, the retrieving LST of VIRR is lower than those of MODIS. Compared with the observed values, the RMSE of Kerr’s LST retrieval algorithm is still the maximum, it is 4.83 K, and correlation coefficient is 0.79. The accuracy of the new LST retrieval algorithm is significantly higher than those of Becker’s, the RMSE are 3.78 K and 4.20 K, respectively, and correlation coefficients are 0.83 and 0.82, respectively.

![Figure 2. Comparison of retrieved LST and the observed value](image-url)
4.2. **Comparison the retrieval results of different satellites data**

The NDVI are retrieved by MODIS and VIRR data in GHUSLE experimental area and nearby on June 23, 2010 during intensive observation period is shown in figure 3. The retrieved NDVI results of the two remote sensing data are similar as the regional distribution characteristics are the same.

Using the two remote sensing data, the regional distributions of land surface temperature retrieved by the three split-window algorithms are shown in figure 4. Based on the measured land surface temperature analysis and the retrieved regional distribution of NDVI, it is suggest that bare soil and full vegetation cover condition divided by NDVI is consistent with experimental area. Bare soil in the experimental area is the desert, complete vegetation cover is the oasis. The mixed region is the transitional zone of the oasis and desert. Both of the vegetation index NDVI and LST distribution characteristics of oasis-desert-transition area are similar to the aforementioned observational LST analysis. In oasis area, the NDVI and LST fluctuate less drastically than those in transitional area, NDVI range from 0.5 to 0.7, and LST are between 32°C and 35°C. In desert area, trends of NDVI and LST are similar to that of oasis with minor gradients, NDVI range mainly from 0.1 to 0.2, and most LST are between 47°C and 53°C. In transitional regions of oasis and desert, NDVI and LST change more obviously, NDVI decrease rapidly from 0.5 to 0.2 within a short distance from oasis to desert, and LST increase from 35°C to 47°C.

![Figure 3. Distribution of NDVI in the study area on June 23, 2010](image)

![Figure 4. Distribution of LST in the study area on June 23, 2010](image)
5. Conclusions
Using MODIS and VIRR data, the LST have been estimated in the experimental area during GHUSLE period. Combined with the observed results, the LST deviations of MODIS and VIRR data have been analyzed and the applicability of different split-window algorithms has been verified. Main conclusions are as below:

(1) Compared with the observed data, the result suggests that the new LST retrieval algorithm is the best of three algorithms and Kerr’s algorithm is relatively the worst for LST retrieving on the heterogeneous underlying surface.

(2) Using the regional distribution diagrams of NDVI and LST in the experimental area on June 23, 2010, the boundaries of the oasis, transitional area and the desert can be clearly distinguished. The NDVI shows a decreasing trend while the LST shows an increasing trend in oasis - transitional - desert region. The gradients of NDVI and LST in oasis and desert regions are smaller than that in transitional region.

(3) Compared with the LST retrieved by VIRR data, the LST retrieved by MODIS data are closer to the observed values and higher than VIRR results. The LST retrieved by MODIS are the most closely to those retrieved by VIRR data when using the new algorithm.

Acknowledgments
Thanks for assistance and financial support from the Institute of Arid Meteorology, CAM (the project of KYS2012SS03) on this paper, and thanks for data support from Lanzhou University.

References
[1] Taconet O, Bernard R and Vidal-Madjar D 1986 Evapotranspiration over an agricultural region using a surface flux/temperature model based on NOAA-AVHRR data Journal of Climate Applied Meteorology 25 284–307
[2] Chbouni A, Lo seen D, Njoku E G, Lhmme J P, Monteny B and Kerr Y 1997 Estimation of sensible heat flux over sparsely vegetated surface: relationship between radiative and aerodynamic surface temperature Journal of Hydrology 155–159 555–868
[3] Chehbouni A, Nouvellon Y, Kerr Y H, Moran M S, Watts C, Prevot L, Goodrich D C and Rambal S 2001 Directional effect on radiative surface temperature measurements over a semiarid grassland site. Remote Sensing of Environment 76 360–372
[4] Running S W, Juatiee C O, Salominson V, Hall D, Barker J, Kaufmann Y J, Strahler A H, Huete A R, Wan Z M, Teillet P and Carnegie D 1994 Terrestrial remote sensing science and algorithms planned for EOS/MODIS International Journal of Remote Sensing 15(17) 557–620
[5] Wark D Q, Yamamoto Y and Lienesch J H 1962 Methods of estimating infrared flux and surface temperature from meteorological satellites J Atmos Sci 19 369–384
[6] Yu H and SHI H Q 2002 Progress in split-window algorithm for retrieval land surface temperature Journal of the Meteorological Sciences 22(4) 494–500
[7] Price J C 1984 Land surface temperature measurements from the split window channels of the NOAA7 Advanced Very High Resolution Radiometer Journal of Geophysical Research 89(D5) 231–237
[8] Becker F and Li Z L 1990 Towards a local split-window method over land surfaces Int J Remote Sensing 11(3) 369–393
[9] Kerr Y H, Lagouarde J P and Imbernon J 1992 Accurate land surface temperature retrieval from AVHHR data with use of an improved split window algorithm Remote Sensing of Environment 41 197–209
[10] Qin Z H, Gao M F, Qin X M, Li W J and Xu B 2005 Methodology to retrieval land surface temperature from MODISdata for agriculatural droughtmonitoring in China Journal of Natural Disasters 14(3) 64–71
[11] Wu X, Chen W Y 2005 Land surface temperature estimated by remote sensing data from FY-1D polar meteorological satellite *Journal of Applied Meteorological Science* **16**(1) 45–53

[12] Dash P, Gottsch F M, Olesen F S and Fischer H 2005 Separating surface emissivity and temperature using two-channel spectral indices and emissivity composites and comparison with a vegetation fraction method *Remote Sensing of Environment* **96** 1–17

[13] Xiao R B, Ouyang Z Y, Zheng H, Li W F, Schienke E W and Wang X K 2007 Spatial pattern of impervious surface and their impacts on land surface temperature in Beijing China *Journal of Environmental Sciences* **19** 250–256

[14] Sobrino J A, Raissouni N and Li Z L 2001 A comparative study of land surface emissivity retrieval from NOAA data *Remote Sens Environ* **75** 256–266

[15] Andersen H S 1997 Land surface temperature estimation based on NOAA-AVHRR data during the HAPEX-Sahel experiment *Journal of Hydrology* **189** 788–814