Article

Estimation of Land Surface Temperature from Chinese ZY1-02E IRS Data

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Abstract: The role of land surface temperature (LST) is of the utmost importance in multiple academic disciplines, such as climatology, hydrology, ecology, and meteorology. To date, many methods have been proposed to estimate LST from satellite thermal infrared data. The single-channel (SC) algorithm can provide an accurate result in retrieving LST based on prior knowledge of known land surface emissivity (LSE). The SC algorithm is extensively employed for retrieving LST from Landsat series data due to its simplicity and its reliance on just one thermal infrared channel. The Thermal Infrared Sensor (IRS) on the Chinese ZY1-02E satellite is a pivotal instrument employed for gathering thermal infrared (TIR) data of land surfaces. The objective of this research is to evaluate the feasibility of a single-channel approach based on water vapor scaling (WVS) for deriving LST from ZY1-02E IRS data because of its wide spectrum range, i.e., 7–12 µm, which is affected strongly by both atmospheric water vapor and ozone. Three study areas, namely the Baotou, Heihe River Basin, and Yantai Sea sites, were selected as validation sites to evaluate the LST inversion accuracy. This evaluation was also conducted via cross-comparison between the retrieved LST and MODIS LST products. The results revealed that the WVS-based method exhibited an average bias of 0.63 K and an RMSE of 1.62 K compared to the in situ LSTs. The WVS-based method demonstrated reasonable accuracy through cross-validation with the MODIS LST product, with an average bias of 0.77 K and an RMSE of 2.0 K. These findings indicate that the WVS-based method is effective in estimating LST from ZY1-02E IRS data.

Keywords: land surface temperature; WVS; SC algorithm; Chinese ZY1-02E satellite

1. Introduction

Land surface temperature (LST) is a crucial parameter in multiple fields of study, such as in climatology [1–5], ecology [6,7], and surface energy [8–10]. It is widely recognized as a significant Earth surface parameter [11] and is considered one of the ten essential climate variables in the land biosphere, as defined by the Global Climate Observing System [12,13].

Satellite observations offer a precise method for obtaining LST on a global scale due to their large spatial resolution and regular temporal revisiting [11]. In recent decades, various...
algorithms have been developed to retrieve LST from thermal infrared instruments carried on satellites, such as the single-channel (SC) algorithm [14–16], the split-window (SW) algorithm [17,18], multiple angle methods [17,19–21], and the temperature and emissivity separation (TES) algorithm [22–26]. A comprehensive overview of LST retrieval methods can be seen in previous research [11,13]. SW algorithm provides a method to reduce the atmospheric effect utilizing the differential absorption in two adjacent TIR channels [17,27]. The TES algorithm increases the number of equations by constructing the empirical relationship between spectral contrast and minimum emissivity and finally completes the solution of the LST inversion problem [22].

With the exception of single-channel methods, other methods require two or more thermal infrared channels. The single-channel algorithm [28] uses the radiance measured by the satellite sensor in a single channel and conducts atmospheric correction using the atmospheric radiative transfer model. LST is then retrieved from the at-sensor radiance based on the radiative transfer equation and prior knowledge of known land surface emissivity (LSE) [28,29]. Some previous research has proposed several efficient methods to estimate LST from satellite data based on the SC algorithm. Qin et al. [14] used near-surface air temperature and water vapor content instead of atmospheric profiles to estimate the LST from Landsat-5 Thematic Mapper channel 6 data. The single-channel algorithm can provide theoretically accurate LST retrieval if the LSE is known in advance. Jiménez-Muñoz et al. proposed an update and extension of the generalized single-channel algorithm which extended the application of the SC algorithm to the Landsat-4 TM sensor and enhanced the TM plus sensor onboard the Landsat-7. A series of research studies have indicated that the SC algorithm is extensively employed for retrieving LST from Landsat series data due to its simplicity and its reliance on just one thermal infrared channel [30].

The ZY1-02E satellite was successfully launched on 26 December 2021 from the Taiyuan Satellite Launch Centre, China, aboard a Long March-4 carrier rocket. Developed by the Fifth Academy of Aerospace Science and Technology Corporation, the ZY1-02E satellite is classified as a medium-resolution remote-sensing satellite. Its primary purpose is to conduct land resource surveying and monitoring, providing domestic data support for the investigation, monitoring, supervision, and production capacity monitoring of land resources. Additionally, it contributes to disaster reduction, environmental protection, housing and construction, transportation, agriculture, forestry, marine surveying, and mapping industries.

The ZY1-02E satellite carries a payload comprising three instruments—the Visible Near-Infrared Multispectral Camera (VNIC), the Advanced Hyperspectral Imager (AHSI), and the Thermal Infrared Sensor (IRS). The AHSI instrument features 166 bands, offering a resolution of 30 m and a width of 60 km. The VNIC sensors provide panchromatic imagery at 2.5 m resolution and multispectral data with eight bands at 10 m resolution covering a width of over 100 km. The IRS has a single thermal infrared band, providing a spatial resolution of 16 m and covering a width of 60 km.

Unlike the traditional thermal sensor, the ZY1-02E IRS sensor has a wider spectral coverage, i.e., 7–12 µm, which includes a stronger atmospheric water vapor absorption and ozone absorption band. The aim of this study was to evaluate the feasibility of temperature inversion using a single-channel algorithm based on WVS from single-channel ZY1-02E IRS data because of its wide spectrum range affected by both atmospheric water vapor and ozone. This paper is structured as follows: Section 2 introduces the used ZY1-02E IRS and VNIC data, atmospheric profiles, and in situ field measurements. Section 3 shows the WVS-based LST inversion method. Sections 4 and 5 give the results and discussion. Section 6 outlines the conclusions.

2. Study Area and Data
2.1. Study Area

The global LST validation sites were summarized, and it can be found that the validation sites were selected as uniform surfaces, including water, vegetation, sand, agricultural
fields, barren soil, etc., to evaluate the LST products, such as MODIS, SEVERI, VIRRS, ABI, SLSTR, ASTER, VIMS LST products. Among them, SURFRAD (Surface Radiation Budget) Network is currently the most widely used authenticity LST testing site, including grassland, rice, forest land, desert, etc. It can be seen that these verification sites are located in a large area of plains. This article is not aimed at the LST inversion over mountainous areas because the LST validation is very difficult due to the complex mountainous terrain and because the topography changes the surface structure, which leads to changes in the geometric relationship between the ground and the sensor, resulting in changes in the composition of the radiant energy received by the sensor. In addition, the shadow also varies from the sun’s location in mountainous areas. Thus, field campaigns including the commonly used surface types were conducted to validate the accuracy of the algorithms using ZY1-02E IRS data. For validation purposes, three field sites in Figure 1 were chosen: Baotou, Heihe, and the Yantai Sea. The selection of these three sites seen in Table 1 mainly considers regional differences, climate differences, and surface type differences, including desert, bare soil, water body, vegetation, wetland, which can provide a more comprehensive evaluation of temperature inversion.

![Figure 1. The study areas used for validation.](image)

The Baotou site [31,32] is located in Urad Front Banner, in Western Inner Mongolia, with coordinates of approximately 40.85°N latitude and 109.6°E longitude. The Baotou site encompasses two different target categories for validation. The first category consists of a crop target measuring 300 × 600 m, primarily comprising corn, which is ideal for validating LST. The second category comprises a desert target, measuring around 300 × 300 m. Figure 1 shows both the crop target and natural desert target at the Baotou site, with a separation distance of approximately 6 km between them. Water bodies serve as natural targets for thermal infrared calibration and validation due to their high thermal inertia and minimal spatiotemporal temperature variability. Thus, Ulansuhai Lake, located in the Urad Qianqi, was used to obtain the water temperature for validation. Additionally, bare soil and the Kebuqi desert surrounding Ulansuhai Lake were also selected for validation purposes. The Baotou site and Ulansuhai Lake have average ground elevations of 1290 m and 1021 m, respectively.
Table 1. Information of the seven stations selected in the study area for validation.

<table>
<thead>
<tr>
<th>No.</th>
<th>Station</th>
<th>Land Cover</th>
<th>Study Area</th>
<th>Longitude (°)</th>
<th>Latitude (°)</th>
<th>Elevation (m)</th>
<th>LSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ulansuhai</td>
<td>Water body</td>
<td>Baotou</td>
<td>108.7706E</td>
<td>40.8476N</td>
<td>977</td>
<td>0.9869</td>
</tr>
<tr>
<td>2</td>
<td>Bare soil</td>
<td>Bare soil</td>
<td>Baotou</td>
<td>108.8176E</td>
<td>40.7978N</td>
<td>977</td>
<td>0.9257</td>
</tr>
<tr>
<td>3</td>
<td>Kubuqi desert</td>
<td>Desert</td>
<td>Baotou</td>
<td>108.6203E</td>
<td>40.4551N</td>
<td>977</td>
<td>0.8836</td>
</tr>
<tr>
<td>4</td>
<td>Baotou sand</td>
<td>Sand</td>
<td>Baotou</td>
<td>109.6187E</td>
<td>40.8659N</td>
<td>1296</td>
<td>0.9159</td>
</tr>
<tr>
<td>5</td>
<td>Baotou Crop</td>
<td>Vegetation</td>
<td>Baotou</td>
<td>109.5537E</td>
<td>40.8708N</td>
<td>1295</td>
<td>0.9718</td>
</tr>
<tr>
<td>6</td>
<td>Zhangye wetland</td>
<td>Reed wetland</td>
<td>HRB</td>
<td>100.4464E</td>
<td>38.9751N</td>
<td>1460</td>
<td>0.9869</td>
</tr>
<tr>
<td>7</td>
<td>Desert</td>
<td>Reaumuria desert</td>
<td>HRB</td>
<td>100.9872E</td>
<td>42.1135N</td>
<td>1054</td>
<td>0.8836</td>
</tr>
<tr>
<td>8</td>
<td>Yantai Sea</td>
<td>Water body</td>
<td>Yantai</td>
<td>121.4653E</td>
<td>37.5148N</td>
<td>0</td>
<td>0.9869</td>
</tr>
</tbody>
</table>

The Heihe River Basin (HRB) serves as the second site in this study. Situated in the arid region of Northwestern China, it is the second largest endorheic basin in China. The HRB is well suited for investigating land surface processes due to its diverse landscapes [33]. The hydrometeorological observatory consists of over 20 observation stations that cover the main land surfaces in the HRB. These surfaces include alpine meadows, forestlands, croplands, deserts, bare lands, and wetlands. For the purposes of validation, two stations, namely Zhangye wetland and desert, were chosen. These stations are located in the upstream region, midstream region, and downstream region in the HRB, respectively.

The third site, the Yantai Sea, is located in eastern China at a latitude of 37.51°N and a longitude of 121.47°E, which is close to the Yellow Sea and Bohai Sea, with an average elevation of 0 m. The Yantai Sea experiences a warm-temperature monsoonal continental climate, characterized by mild temperatures and abundant precipitation throughout the year. The Yantai Sea was selected as an important validation site.

2.2. ZY1-02E Data

The ZY1-02E satellite captures visible and infrared imagery to measure various parameters of the land, atmosphere, and oceans. As a cutting-edge, operational high-resolution imaging instrument, it belongs to a new generation of remote sensing technology. The ZY1-02E satellite enables the generation of various critical environmental products, such as snow and ice cover, clouds and city monitoring, sea surface temperature and LST, and vegetation and surface albedo. Table 2 provides a comprehensive summary of its detailed spectral characteristics in its 10 spectral bands, which range from 0.45 to 12.0 µm. The data were obtained from both the VNIC and IRS sensors. The VNIC sensor has nine bands with a spatial resolution of 2.5 m (Pan) and 10 m (multispectral) at nadir. Additionally, the IRS sensor includes one thermal infrared band with a 16 m spatial resolution at nadir, specifically designed for LST retrieval. The ZY1-02E VNIC and IRS spectral response functions are shown in Figures 2 and 3.

Figure 3 shows the transmittance of atmospheric water vapor and ozone from 7 µm to 12 µm using MODTRAN (moderate resolution atmospheric transmission) US 1976 Standard atmosphere. The minimum of ozone transmittance ranging from 9 to 10 µm is nearly 0.2. Meanwhile, the IRS channel covers both continuous water vapor absorption and line absorption, especially 8–9 µm. Compared to the traditional Thermal Infrared Sensor used for LST estimation, the ZY1-02E IRS channel is strongly influenced by water vapor and ozone.
Table 2. Spectral characteristics of ZY1-02E VNIC/IRS.

<table>
<thead>
<tr>
<th>Bands</th>
<th>Bands No.</th>
<th>Spectral Range (µm)</th>
<th>Resolution (m)</th>
<th>NEDT/SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIC</td>
<td>Pan</td>
<td>0.45~0.90</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>0.45~0.52</td>
<td>10</td>
<td>≥28 dB@sun altitude angle is 30° and surface reflectance is 0.03</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>0.52~0.59</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>0.63~0.69</td>
<td>10</td>
<td>≥48 dB@sun altitude angle is 70° and surface reflectance is 0.5</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>0.77~0.89</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5</td>
<td>0.40~0.45</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6</td>
<td>0.59~0.625</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7</td>
<td>0.705~0.745</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B8</td>
<td>0.860~1.040</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>IRS</td>
<td>B9</td>
<td>7~12</td>
<td>16</td>
<td>NEAT ≤ 0.1 K@300K</td>
</tr>
</tbody>
</table>

Figure 2. Relative spectral response function (a) ZY1-02E VNIC; (b) ZY1-02E IRS.
Aqua and Terra Earth Observing System satellites is one of the key instruments mainly used in the Moderate Resolution Imaging Spectroradiometer (MODIS) developed by AFRL/VSBT (The Air Force Research Laboratory (AFRL), the United States Air Force, and the United States Army). MODIS provides per-pixel LST (https://modis.gsfc.nasa.gov/data/dataprod/mod11.php, accessed on 7 July 2022 to 29 March 2023) and sea surface temperature (SST, https://oceancolor.gsfc.nasa.gov/cgi/browse.pl?sub=level3&prm=SST, accessed on 7 July 2022 to 29 March 2023) products, covering from 5 min temporal to multi-day averages. In this study, two temperature products (i.e., MOD11_L2 and SST data) were used to validate the accuracy of the WVS-based method. The spatial resolution of both temperature products is 1 km. The MOD11_L2 LST product (https://doi.org/10.5067/MODIS/MOD11_L2.061, accessed on 7 July 2022 to 29 March 2023) was retrieved by using the generalized split-window algorithm [34]. A comparison was performed between the MOD11_L2 LST and ground measurements at several sites: Brookings, Audubon, Canaan Valley, and Black Hills [35]. Results show that the absolute biases and RMSEs between MOD11_L2 LST and ground measurements were less than 0.8 K and 1.7 K, respectively.

2.4. The ASTER Spectral Library

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) spectral library v2.0 [36], developed jointly by the Jet Propulsion Laboratory (JPL), Johns Hopkins University (JHU), and the United States Geological Survey (USGS), comprises a comprehensive collection of data. It encompasses over 2300 spectra covering a broad range of materials, such as vegetation, man-made materials, soil, minerals, rocks, water, ice, and snow. The wavelength range covered is from 0.4 µm to 15.4 µm, with specific wavelengths falling between 3.0 µm and 14.5 µm. From this library, 108 emissivity spectra were selected to represent various surface features, including 70 soil/mineral types, 28 vegetation types, and 10 man-made material types.

2.5. ERA5 Atmospheric Profiles

In order to determine the LST, atmospheric correction is essential. In this study, the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 atmospheric profile dataset (https://cds.climate.copernicus.eu/, accessed on 7 July 2022 to 29 March 2023) was used to obtain the atmospheric parameters by using the radiative transfer code (MODTRAN 5.3) developed by AFRL/VSBT (The Air Force Research Laboratory (AFRL), established on 31 October 1997, is a dedicated scientific research organization of the United States Air Force).
States Air Force) in collaboration with Spectral Sciences, Inc. (Spectral Sciences Incorporated (SSI), established on 1981, is an internationally recognized resource hub for expertise in spectroscopy, remote sensing and imaging, in Burlington, United States). ERA5, the fifth-generation ECMWF reanalysis, offers global climate and weather data spanning the past eight decades. The dataset begins from 1940, replacing the ERA-Interim reanalysis. By leveraging the ERA5 profiles, atmospheric parameters, such as atmospheric transmittance, atmospheric downwelling, and upwelling radiances, are derived.

ERA5 profiles provide geopotential height, temperature, relative humidity information at 37 pressure levels, and total column ozone on a $0.25^\circ \times 0.25^\circ$ grid, with updates every hour in UTC time. ERA5 atmospheric profiles provide the pressure, geopotential height, air temperature, relative humidity, etc., including $0.25^\circ$ of the spatial resolution, 37 pressure levels (1, 2, 3, 5, 7, 10, 20, 30, 50, 70, 100, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 775, 800, 825, 850, 875, 900, 925, 950, 975, and 1000), 48 km height, and 1 h temporal resolution. It is worth noting that, due to the wide spectrum of ZY1-02E covering the ozone absorption band, the total column ozone is also applied in the algorithm process and simulation for WVS coefficients. The ERA5 profiles were used to calculate the atmospheric transmittance and upwelling and downwelling radiances with the aid of MODTRAN 5.3.

2.6. In Situ Data

At the Baotou site, SI-111 thermometers with a spectral range of 8–12 $\mu$m were employed to measure the temperature of various surfaces, including sand, crops, Ulansuhai Lake, bare soil, Kubuqi desert, etc. At the Baotou site, two thermometers were distributed in a sand area, bare soil, Kubuqi desert, and four thermometers were distributed in crop areas to capture the in situ field LSTs, and the temporal sampling interval was 2 s with an altitude of approximately 2.0 m. An additional SI-111 thermometer was used to observe the sky at an angle of 53$^\circ$ relative to the zenith and measure the atmospheric downwelling radiance to correct for the atmospheric effect. For Ulansuhai Lake, a 102 F Fourier transform infrared spectroradiometer (FTIR) with a spectrum ranging from 2 to 16 $\mu$m, a spectral resolution of 4 cm$^{-1}$, and a field of view (FOV) of 4.8$^\circ$ and two thermometers were deployed on a boat to measure the water temperature. At the Heihe River Basin, two SI-111 thermometers were mounted at 6m, facing due south, with the probe facing straight down to measure the LST. Land emissivity measurements were performed using the 102F FTIR.

Two automatic water observation buoys in the Yantai Sea were equipped with an automatic weather station to measure wind speed, wind direction, atmospheric temperature, humidity, pressure, and rainfall. An SI-111 thermometer was used to measure the sea temperature.

The next equation was used to calculate the in situ LSTs from surface-leaving radiance and atmospheric downwelling radiance:

$$T_s = B^{-1} \left( \frac{L - (1 - \varepsilon)L_{atm}}{\varepsilon} \right)$$  (1)

where $T_s$ represents LST, $B$ denotes the Planck function, $L$ is the radiance measured by the SI-111 radiometer, $\varepsilon$ is the channel-effective land surface emissivity (LSE) specifically for the SI-111 thermometer, and $L_{atm}$ is the atmospheric downwelling radiance calculated by the spectral response function of the SI-111 thermometer.

In this study, several natural scenes (refer to Figure 4) were selected to evaluate the accuracy of LST estimated from the ZY1-02E IRS data. Table 3 provides a summary of the main technical characteristics of the thermal instruments. Figure 4 illustrates the primary attributes of the measurement targets.
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**Table 3. Main technical specifications for the thermal instruments.**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spectral Range (µm)</th>
<th>Operating Environment (°C)</th>
<th>Accuracy</th>
<th>Resolution</th>
<th>FOV (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI-111</td>
<td>8–14</td>
<td>−55–80</td>
<td>±0.2 K</td>
<td>0.1 K</td>
<td>44</td>
</tr>
<tr>
<td>KT-15</td>
<td>9.6–11.5</td>
<td>0–55</td>
<td>±0.5 K</td>
<td>0.06 K</td>
<td>2</td>
</tr>
<tr>
<td>102 F</td>
<td>2–16</td>
<td>15–35</td>
<td>1 cm⁻¹</td>
<td>4 cm⁻¹</td>
<td>4.8</td>
</tr>
</tbody>
</table>

**3. Methodology**

### 3.1. WVS-Based LST Method

The theoretical basis of radiative transfer in the TIR spectral region (8–14 m) has been developed [11]. In the case of a cloud-free atmosphere at the local thermodynamic equilibrium, the radiative transfer equation (RTE) can approximately be expressed as:

$$L_\lambda(T) = \tau_\lambda [\epsilon_\lambda B_\lambda(T_s) + (1 - \epsilon_\lambda)L_{\text{atm,}\lambda} \downarrow] + L_{\text{atm,}\lambda} \uparrow$$

where $T$ is the at-sensor brightness temperature (BT) and $L_\lambda(T)$ is the at-sensor radiance at wavelength $\lambda$. $\tau_\lambda$ is the atmospheric transmittance at wavelength $\lambda$. $\epsilon_\lambda$ is the land surface emissivity. $B_\lambda(T_s)$ is the Planck function of the wavelength $\lambda$. $T_s$ is the LST. $L_{\text{atm,}\lambda} \downarrow$ is the atmospheric upwelling radiance, and $L_{\text{atm,}\lambda} \uparrow$ is the downwelling radiance. Obviously, the atmospheric parameters were estimated by using a radiative transfer code, such as MODTRAN, with atmospheric profiles and elevation data. Thus, the LST based on the RTE method is derived from the at-sensor radiance.

As is well known, the existing single-channel method for LST retrieval, the reanalysis of atmospheric profile datasets, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP), is generally preferred to correct the atmospheric effect [37,38]. However, the reanaly-
sis of atmospheric profile data has a certain uncertainty, which may influence the accuracy of atmospheric transmittance and atmospheric upward/downward radiance, and then, the retrieval accuracy of LST will be affected. The WVS-based method proposed by Tonooka [39,40] is based on the standard atmospheric correction algorithm for ASTER/TIR. A significant enhancement of this method involves determining a water vapor scaling factor $\gamma$, which serves to mitigate the errors resulting from multiple sources. These errors include not only a bias error in the water vapor profile but also random errors in the water vapor profile, errors in the air temperature profile, and elevation errors since all of these errors contribute to the bias error in the water vapor profile. Once an appropriate $\gamma$ is determined, the improved atmospheric parameters are calculated as:

$$
\tau(\theta, \gamma) = \tau(\theta, \gamma_1) \left(\frac{\gamma_1^\beta - \gamma_2^\beta}{\gamma_1^\beta - \gamma_2^\beta}\right) \cdot \tau(\theta, \gamma_2) \left(\frac{\gamma_2^\beta - \gamma_2^\beta}{\gamma_2^\beta - \gamma_2^\beta}\right)
$$  \hspace{1cm} (3)

$$
L_{\text{atm, } \lambda_\uparrow}(\theta, \gamma) = L_{\text{atm, } \lambda_\uparrow}(\theta, \gamma_1) \cdot \frac{1 - \tau(\theta, \gamma)}{1 - \tau(\theta, \gamma_1)}
$$  \hspace{1cm} (4)

$$
L_{\text{atm, } \lambda_\downarrow}(\gamma) = a + bL_{\text{atm, } \lambda_\uparrow}(0, \gamma) + cL_{\text{atm, } \lambda_\uparrow}(0, \gamma)^2
$$  \hspace{1cm} (5)

$$
\gamma = \frac{U'}{U} = \frac{\omega'(z)}{\omega(z)}
$$  \hspace{1cm} (6)

where $\gamma$ is the water vapor scaling factor. $U$ and $U'$ are the total water vapor content of atmospheric parameters for water vapor profiles P and P', respectively, where P' is a water vapor profile scaled from a water vapor profile P by a factor of $\gamma$. $\omega(z)$ and $\omega(z)'$ are water vapor amounts at an arbitrary height z. $\gamma_1$ and $\gamma_2$ are different appropriate values (e.g., $\gamma_1 = 1$ and $\gamma_2 = 0.7$ in this paper).

$$
\gamma = \left(\ln \left(\frac{\tau(\gamma_2)^\gamma - \tau(\gamma_0)^\gamma}{\tau(\gamma_1)^\gamma - \tau(\gamma_0)^\gamma} \cdot \left(\frac{B(T_\text{atm}) - L_{\text{atm, } \lambda_\uparrow}(\gamma_1)}{B(T_\text{sensor}) - L_{\text{atm, } \lambda_\uparrow}(\gamma_1)}\right)\right) \right)^{1/\beta}
$$  \hspace{1cm} (7)

where $B(T_\text{atm})$ is at-surface radiance, i.e., $B(T_\text{atm}) = eB(T_\text{s}) + (1 - e) L$. From Figure 3, it can be found that the IRS has been influenced by atmospheric water vapor and ozone. Therefore, in this study, the WVS coefficients were simulated by using the global atmospheric profile library, i.e., the Thermodynamic Initial Guess Retrieval (TIGR) database [30], including the band model parameter $\beta$ and regression coefficients $a$, $b$, and $c$ of atmospheric downward radiation. The TIGR atmospheric profile database contains 2311 representative atmospheric situations. Each profile records the atmospheric pressure, temperature, humidity, and ozone content. The atmospheric transmittance with different water vapor scaling factors $\gamma$ (0.7, 0.9, and 1.0, respectively) was obtained using MODTRAN 5.3 with the band model parameter, and the $\beta$ parameters were obtained using least square regressions. $\beta$ is equal to 1.4072 calculated from a large amount of simulation data. The coefficients $a$, $b$, and $c$ can be obtained from the simulated atmospheric downwelling and upwelling data, and their values are $-0.3630, 2.2013$, and $-0.1080$, respectively. Obviously, the calculation of atmospheric parameters takes into account the influence of water vapor and ozone, which provides more accurate atmospheric data for LST inversion.

### 3.2. Land Surface Emissivity Inversion

The estimation of land surface emissivity (LSE) relies on the fraction vegetation coverage method (FVC), which integrates two constant emissivity values representing the bare ground and full vegetation conditions of each pixel. The real-time emissivity is then adjusted according to the FVC. The classification of land surfaces into distinct types necessitates the adoption of varied processing approaches owing to their diverse thermal emission characteristics. The inland water and full vegetation emissivities are directly converted from the mean value determined according to the ASTER spectral library dataset, and
the bare soil emissivity is calculated based on the relationship between emissivity and the reflectance of the red band (Tang et al., 2015 [41]), i.e., \( \varepsilon = a + b \cdot \rho_{\text{red}} \), where \( a \) and \( b \) are the channel-dependent regression coefficients and \( \rho_{\text{red}} \) is the reflectance of the red band. For mixed pixels, the emissivity can be expressed as a linear relationship between the bare soil and vegetation fraction [42]:

\[
\varepsilon = \varepsilon_v f_v + \varepsilon_s (1 - f_v) + d \varepsilon
\]

where \( \varepsilon_v \) and \( \varepsilon_s \) are the emissivities of the vegetation and bare soil, respectively, and \( f_v \) is the fractional vegetation coverage (FVC) [43]:

\[
f_v = \frac{\text{NDVI} - \text{NDVI}_{\text{min}}}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}}
\]

where normalized difference vegetation index (NDVI) is acquired from the target pixel and \( \text{NDVI}_{\text{max}} \) and \( \text{NDVI}_{\text{min}} \) are calculated from the full vegetation and bare soil pixels in the whole image.

\[
d \varepsilon = 4(1 - \varepsilon_s) \varepsilon_v F f_v (1 - f_v)^2
\]

where \( F \) is the shape factor depending on the vegetation structure information in which \( F \) is set up to be 0.55 [44].

In total, the emissivity can be written as Equation (11), where pixels with NDVI values below 0 are considered as water bodies \( (\varepsilon = \varepsilon_{\text{water}}) \). The pixels with NDVI values below 0.2 are considered bare soil. NDVI values above 0.5 represent full vegetation pixels. Therefore, the pixels with NDVI values ranging from 0.2 to 0.5 are considered as a mixture of soil and vegetation [41,45].

\[
\varepsilon = \begin{cases} 
\varepsilon_{\text{water}}, & \text{NDVI} < 0 \\
\varepsilon = a + b \cdot \rho_{\text{red}}, & 0 \leq \text{NDVI} < 0.2 \\
\varepsilon_v f_v + \varepsilon_s (1 - f_v) + d \varepsilon, & 0.2 \leq \text{NDVI} \leq 0.5 \\
\varepsilon_v, & \text{NDVI} > 0.5
\end{cases}
\]

where \( \varepsilon_{\text{water}} \) is the emissivity of water, \( \varepsilon_s \) is the emissivity of soil, and \( \varepsilon_v \) is the emissivity of vegetation. \( \rho_{\text{red}} \) is the land surface reflectance of the red band.

3.3. Atmospheric Parameter Inversion

To obtain the atmospheric parameters for each pixel of ZY1-02E IRS images, the interpolation of atmospheric profiles in time and space must be performed, specifically temporal linear interpolation of the atmospheric parameters in terms of the time of the ERA5 profiles (https://cds.climate.copernicus.eu/#!/home, accessed on 7 July 2022 to 29 March 2023) and the ZY1-02E acquisition time and spatial interpolation of the atmospheric parameters in terms of geographic latitudes and longitudes of the closest four grid points. In addition, there is a certain uncertainty in the reanalysis of atmospheric profile data, and the water vapor scaling factor \( \gamma \) should be calculated with simulation data using the WVS-based LST method. Then, the modified atmospheric parameters can be obtained.

3.4. WVS-Based LST Retrieval

DN values in ZY1-02E IRS band data should be converted to top-of-the-atmosphere (TOA) radiance using the calibration coefficients provided in the metadata file.

\[
L = a \cdot \text{DN} + b
\]

where \( L \) is TOA radiance, \( \text{DN} \) is a digital number of IRS data, and \( a \) and \( b \) are calibration coefficients.

In addition, the TOA radiance should be converted to TOA brightness temperature (BT). Considering the wide spectral range (7–12 \( \mu \text{m} \)) of ZY1-02E IRS, the look-up table
(LUT) between radiance and temperature of ZY1-02E should be set up from 200 K to 400 K with a step of 0.1 K.

The LST retrieval process is depicted in Figure 5 as the following steps:

1. Land surface emissivity retrieval. Firstly, land surface reflectance is retrieved from the ZY1-02E VNIC data using the ERA 5 atmospheric profile from MODTRAN. Then, the NDVI and FVC can be obtained from land surface reflectance data. Subsequently, the land surface emissivity is accurately retrieved based on FVC and NDVI.

2. TOA brightness temperature retrieval: The DN values received by the ZY1-02E IRS data are converted into radiance data with the calibration parameters. Subsequently, the TOA radiance is converted into TOA BT using the look-up table between radiance and brightness temperature.

3. Adjusted atmospheric parameters: The atmospheric parameters in the ERA5 spatial scale can be calculated using ERA5 profile data from MODTRAN. Then, the atmospheric parameters in the ZY1-02E spatial scale can be estimated using temporal and spatial interpolation. Finally, the WVS method is used to adjust the ZY1-02E atmospheric parameters.

4. Based on the adjusted atmospheric parameters and LSE data, the ZY1-02E LST can be inversed using the thermal radiative transfer Equation (2).

Figure 5. Flow chart of LST retrieval from ZY1-02E IRS data.

4. Results
4.1. LST Results

Figure 6 shows the false color band composition (Band 7, 4, 3 | red, green, blue) from ZY1-02E VNIC images for the Heihe River Basin and Baotou, encompassing surfaces characterized by vegetation, rock, soil, and urban areas. Table 4 presents the number of images used for the validation of sites in each study area.
Figure 6. False color images of sites. (a) Ulansuhai Lake on 13 July 2022; (b) Baotou site on 10 July 2022; (c) Yantai Sea on 7 September 2022; (d) HRB site on 22 November 2022.

Table 4. The number of images used for validation of sites in each study area.

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Site</th>
<th>Number of Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baotou</td>
<td>Ulansuhai</td>
<td>3</td>
</tr>
<tr>
<td>Baotou</td>
<td>Bare soil</td>
<td>3</td>
</tr>
<tr>
<td>Baotou</td>
<td>Kubuqi desert</td>
<td>3</td>
</tr>
<tr>
<td>Baotou</td>
<td>Baotou sand</td>
<td>2</td>
</tr>
<tr>
<td>Baotou</td>
<td>Baotou Crop</td>
<td>3</td>
</tr>
<tr>
<td>HRB</td>
<td>Zhangye wetland</td>
<td>4</td>
</tr>
<tr>
<td>HRB</td>
<td>Desert</td>
<td>3</td>
</tr>
<tr>
<td>Yantai</td>
<td>Yantai Sea</td>
<td>5</td>
</tr>
</tbody>
</table>

The LST was estimated from ZY1-02E IRS data using a WVS-based method. Based on the FVC and NDVI calculated using land surface reflectance and the emissivity for the Ulansuhai, Kubuqi desert, Baotou desert, Zhangye wetland, desert, and Yantai Sea sites were estimated. Emissivity measurements for bare soil were obtained on different days due to variations in local FVC and NDVI.

Some of the inversed LST images of three study areas derived from ZY1-02E IRS data are presented in Figure 7. We selected four specific days of ZY1-02E IRS images that cover the Baotou site, HRB, and Yantai Sea. The average UTC time of the ZY1-02E overpass at the Baotou site, HRB, and Yantai Sea is 03:50, 04:20, and 03:00, respectively. Figure 7 demonstrates that the temperature of Ulansuhai Lake during local noon is typically lower than other landscapes while bare soil and sand exhibit higher temperatures. The reflectance of water bodies exceeds that of other land cover types.
4.2. Validation

Two validation methods were selected, i.e., based on in situ data and based on cross-validation with the MODIS LST product, and employed to evaluate the LST inversion accuracy. A total of 25 scenes of ZY1-02E satellite images have been used for statistical analysis, covering the period from July 2022 to March 2023. The number of sampled points from the Baotou site, HRB, and Yantai Sea are 14, 6, and 5, respectively. In addition, cross-validation with MODIS LST products has also been conducted for further analysis.

4.2.1. Validation Based on In Situ Data

The LST derived from the WVS-based method was evaluated using comparisons with the ground measurements (GMs) LST obtained from the Baotou, HRB, and Yantai Sea sites. The ZY-1F satellite images, including those from July, September, October, November 2022 and February and March 2023, have some images for validation. The in situ averaged LST before and after 10 min against the ZY1-02E overpass time was selected as the validation data and compared with the inversed LST from these sites. During the validation of the LST retrieval, we employed the average LST value of $3 \times 3$ pixels surrounding the target site in the ZY1-02E IRS images. Figure 7 shows scatterplots depicting the inversed LST versus the in situ LST at the eight sites. The results in Figure 8a reveal that the average bias and root mean square error (RMSE) between the WVS-based method and in situ LSTs are 0.63 K and 1.62 K, respectively. This shows a high agreement between the WVS method and field measurement data. Additionally, the results in Figure 7b indicate that the LST inversion in the water body, desert, sand, reed wetland, and vegetation exhibits the closest proximity to the measured temperature data, with an average LST bias of 0.24, $-0.17$, $-0.7$, 0.27, and 0.27 K, respectively. Comparatively, the average LST bias for the bare soil is 1.7 K. And the RMSEs of these six land surface types (water body, bare soil, desert, sand, reed wetland, and vegetation) are 1.39 K, 1.77 K, 0.53 K, 0.99 K, 0.42 K, and 0.42 K, respectively.

![Figure 7. The retrieved LST images of Ulansuhai Lake (a), Baotou site (b), Yantai Sea (c), and HRB (d) from ZY1-02E IRS data based on WVS method.](image-url)
4.2.2. Cross-Validation Compared to MODIS LST and SST Products

As is well known, the MODIS LST product offers high accuracy, making the MODIS Terra daily LST product (MOD11_L2) with a spatial resolution of 1 km suitable for cross-validation. According to satellite overpass time, the time differences between the MOD11_L2 and ZY1-02E data range from 0 to 50 min for study areas A and B. To minimize the error caused by the difference due to overpass time, a temporal correction method was considered to correct the MODIS temperature product using the measured surface temperatures over the two satellites’ overpass times, i.e., \( LST = a \times \text{time} + b \). The coefficients \( a \) and \( b \) can be calculated using field measurement data. This is because the surface temperature shows a certain change rule over a short period of time. The ground measurement temperature data were plotted as a function of viewing time in Figure 9, and then, the time-corrected MODIS LST values were obtained with a linear function expression.

The results in Figure 10a indicate that the average bias and RMSE between the inversed LSTs from the WVS-based method and the MODIS LST/SST product are 0.77 K and 2.0 K, respectively. Figure 10b reveals that the LST biases between the WVS-based method and

---

**Figure 8.** (a) Scatterplots of the inversed LST using WVS-based method versus the in situ LST at six land surface types (water body, bare soil, desert, sand, reed wetland, and vegetation). (b) LST bias between WVS-based method and ground measurements. Different colors represent different surface types.

**Figure 9.** (a) LST change in desert site on 22 October 2022. (b) LST change in Kubuqi desert site on 7 July 2022.
the MODIS LST product are consistent across five land surface types (water body, bare soil, desert, sand, and reed wetland), with average biases of 0.88 K, 1.5 K, −0.73 K, 1.3 K, and 3.9 K, respectively. And the RMSEs are 1.75 K, 1.51 K, 0.71 K, 1.86 K, and 4.05 K, respectively.

![Figure 10](image-url)

**Figure 10.** (a) Scatterplots of the inversed Ts (LST) versus the MODIS LST product at five land surface types (water body, bare soil, desert, sand, and reed wetland). (b) LST bias between WVS-based method and MOD11_L2.

The data collection period for the ZY1-02E IRS scenes spanned from July 2022 to March 2023. For evaluating the accuracy of LST retrieval from ZY1-02E IRS data, Figure 11 presents the results that the absolute errors (AEs) between the WVS-based method and ground measurement range from 0.1 K to 3.5 K, with an average AE of 1.31 K. Moreover, the average absolute error between the WVS-based method and MODIS LST&SST product is 1.82 K.

![Figure 11](image-url)

**Figure 11.** Evaluating accuracy of LST retrieval using WVS-based method. The boxplots are centered on the errors of retrieved LST using WVS-based method and other retrieval LST methods.

To validate the reliability of the WVS-based LST method, we conducted calculations using the variance of the LST values for the target sites and their surrounding eight pixels in the retrieved LST images, with a spatial resolution of 48 m for the variance statistics. The results in Figure 10 demonstrate that the average variance of LST at the target site was 0.134 K, indicating a minimal deviation in the retrieved LST for the target stations. These findings affirm that the proposed method can accurately retrieve LST from single-channel TIR data.

5. Discussion

In this study, the single-channel algorithm based on a water vapor scaling (WVS) method proposed by Tonooka [39] to correct the error caused by uncertain atmospheric profile data was used to estimate LST from ZY1-02E thermal infrared data. The ZY1-02E
IRS data is more affected by the atmosphere due to its wide channel compared to Landsat 8, 9, and ASTER. Therefore, the LST retrieval method based on WVS considers the effects of the strong absorption of water vapor (7–8.2 µm) and ozone (~9.6 µm) during the model construction process.

In terms of validation based on in situ data, the WVS-based method exhibits poorer performance on bare soil and Zhangye wetland sites, as illustrated in Figure 12. The challenge of accurately defining the emissivity of Zhangye wetland and Baotou bare soil sites results in significant LST deviation, leading to the reduced accuracy of LST inversion for these locations. To quantitatively describe the accuracy of LST inversion, the biases and RMSEs were calculated as the evaluation index [46,47]. The average LST biases between the WVS-based method and in situ LSTs for the Ulansuhai, bare soil, Kubuqi desert, Baotou sand, Zhangye wetland, desert, and Yantai Sea sites are as follows: 1.3 K, 1.4 K, −1.3 K, 1.3 K, 3.9 K, −0.69 K, and 0.65 K, respectively. Therefore, the WVS-based method demonstrates higher accuracy for uniform land cover, such as water bodies and deserts. The results show the effectiveness of LST inversed from ZY1-02E IRS data using the WVS-based method. Although the spatial resolution of Landsat 9’s Thermal Infrared Sensor 2 (TIRS-2) (Landsat 9 is the ninth satellite in the U.S. Landsat program, which carries a NASA-built thermal infrared sensor 2) and ECOTRESS LST product are higher compared to the MODIS LST product, by 100 m and 70 m, respectively, the transit dates for either Landsat or ECOTRESS are different with ZY1-02E. Cross-validation based on MODIS LST and SST products was performed. To ensure comprehensive coverage of the corresponding areas in the MODIS LST product, we analyzed the average LST value and LST variance per site in ZY1-02E IRS images using the area-weighted pixel aggregation algorithm [48]. The method used to correct the temporal difference between ZY1-02E and MODIS has been introduced in Section 4.2.2. Figure 12 illustrates that the average LST biases between the WVS-based method and MODIS are lower in Baotou sites compared to HRB sites and Yantai Sea. The vegetation area of the Baotou Crop site is less than the MODIS single pixel size of 1 × 1 km, so the retrieval LST of the Baotou Crop was not considered in the comparison with the MODIS LST product. The dissimilarity in spatial resolution accounts for another possible reason since the ZY1-02E has a resolution of 16m, while the MODIS temperature product has a resolution of 1KM. This discrepancy can result in inaccuracies when observing bare soil, mainly due to scaling effects within the area-averaged FOV [49].

The results of average LST bias between the WVS-based method and the MODIS product for each study site indicate that the homogeneity of land cover types plays a critical role in LST retrieval across various spatial scales. This is evidence that the lower LST biases can be found in water bodies, deserts, and vegetated areas compared to other mixed surface features.

Figure 12. The LST bias retrieved by WVS-based method and MODIS in all study areas.
This study employed two validation methods to assess the accuracy of retrieved LSTs. The results demonstrate a close approximation between the WVS-based method and the in situ LST, exhibiting an average bias of 0.63 K and RMSE of 1.62 K. However, this study’s focus was limited to six types of landscapes across three study areas. Future research should explore a wider range of landscape types to comprehensively assess the applicability of the WVS-based method. Additional and more data samples should also be collected for specific stations in future research.

6. Conclusions

In this study, a water vapor scaling (WVS-based) method was used to estimate the LST from ZY1-02E IRS data and evaluate its feasibility. The ERA5 atmospheric profile dataset and the radiative transfer code were used to correct atmospheric effects. A water vapor scaling factor was used to reduce the errors in atmospheric correction caused by various atmospheric factors. Additionally, the LSE was estimated based on NDVI and FVC data. We obtained ZY1-02E data for three study areas from July 2022 to March 2023. To ensure the accuracy and reliability of the data, we conducted a series of validation and screening procedures and ultimately determined the samples for comparison. We compared the LST retrieval from ZY1-02E IRS data with the in situ LST and MOD11_L2 products.

The estimated LST was validated by collecting in situ LST data from three study areas. For study area A (Baotou site), the WVS-based method showed an absolute bias of approximately 0.2 to 3.3 K compared to the in situ LST, with the RMSEs ranging from 0.42 to 2.3 K. In study area B (Heihe River Basin), the LST biases ranged from 0.1 to 2.9 K, with the RMSEs between 0.5 and 2.4 K. In study area C (Yantai Sea), the SST biases ranged from 0.1 to 1.6 K, with an RMSE of ~0.8 K. In addition, according to each surface type, the statistical analysis shows that LST inversion in the water body, bare soil, desert, sand, reed wetland, and vegetation exhibit the closest proximity to the measured temperature data, with an average LST bias and RMSE of 0.24 K and 1.39 K, 1.7 K and 1.77 K, −0.17 K and 0.53 K, −0.7 K and 0.99 K, 0.27 K and 0.42 K, and 0.27 K and 0.42 K, respectively. These results show that the WVS-based method can accurately retrieve LST from single-channel thermal infrared data, though there is a wide spectrum range, i.e., 7–12 µm, affected strongly by both atmospheric water vapor and ozone. However, further validation work is necessary to evaluate the method’s performance across different land cover types and geographical locations.

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