Error Analysis of Multi-source Land Surface Temperature Products Using In-situ Measurements in the Heihe River Basin (Postprint)

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Abstract

Using land surface temperature observations from seven ground-based stations in the Heihe River Basin for the period 2017–2019, we analyzed errors in four land surface temperature products across different temporal scales using statistical metrics of bias (BIAS), root mean square error (RMSE), correlation coefficient (CC), and ratio of standard deviation (RSD). The evaluated products include: the FY-3C VIRR (Visible and Infrared Radiometer) land surface temperature product from the FengYun-3C satellite, the MOD11A1/MOD11C3 land surface temperature product from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite, the ERA5-LAND reanalysis dataset (the fifth-generation land surface reanalysis dataset from the European Centre for Medium-Range Weather Forecasts), and the CLDAS-V2.0 dataset (China Meteorological Administration Land Data Assimilation System Version 2.0). The results demonstrate that: (1) All four products exhibit a spatial distribution pattern of higher temperatures in the south and lower temperatures in the north; however, the FY-3C VIRR and MOD11A1 products display finer spatial details. (2) The FY-3C VIRR daytime land surface temperature product shows relatively low BIAS and RMSE, indicating high accuracy; the MOD11A1 daytime product has the highest CC (ranging between 0.957 and 0.987), but with relatively large errors, and is generally overestimated. (3) The MOD11A1 nighttime land surface temperature product demonstrates superior accuracy compared to the FY-3C VIRR, ERA5-LAND, and CLDAS-V2.0 nighttime products, with the CLDAS-V2.0 nighttime product showing the largest errors. (4) The nighttime land surface temperature products of FY-3C VIRR, MOD11A1, and ERA5-LAND exhibit higher accuracy than their daytime counterparts; conversely, the CLDAS-V2.0 daytime product shows higher accuracy than its nighttime product.

Full Text

Abstract

This study used in-situ land surface temperature observation data from seven stations in the Heihe River Basin (2017–2019) to evaluate four land surface temperature products: Fengyun-3C Visible and Infrared Radiometer (FY-3C VIRR), Terra Moderate Resolution Imaging Spectroradiometer (MOD11A1/MOD11C3), European Centre for Medium-Range Weather Forecasts fifth-generation land surface reanalysis dataset (ERA5-LAND), and China Meteorological Administration Land Data Assimilation System (CLDAS-V2.0). Bias (BIAS), root mean square error (RMSE), correlation coefficient (CC), and ratio of standard deviation (RSD) were employed as statistical metrics for error analysis across different temporal scales. Results indicated: (1) All four products exhibited similar spatial patterns with higher temperatures in the south and lower in the north, though FY-3C VIRR and MOD11A1 showed finer spatial details; (2) FY-3C VIRR daytime product demonstrated relatively low BIAS and RMSE values, indicating higher accuracy, while MOD11A1 daytime product yielded the highest CC values (0.957–0.987) but also larger errors due to overestimation; (3) MOD11A1 nighttime product outperformed FY-3C VIRR, ERA5-LAND, and CLDAS-V2.0 nighttime products; (4) For FY-3C VIRR, MOD11A1, and ERA5-LAND, nighttime accuracy surpassed daytime accuracy, while CLDAS-V2.0 daytime products showed higher accuracy than nighttime counterparts.

Keywords: land surface temperature; FY-3C VIRR; MODIS; ERA5-LAND; CLDAS-V2.0; Heihe River Basin

1.1 Study Area Overview

The Heihe River Basin (97.1°–102.0°E, 37.7°–42.7°N) is located in northern Gansu Province, flowing through Wuwei, Zhangye, and Jiuquan cities, and constitutes an important tributary of the Yellow River (Figure [Figure 1: see original paper]). The Heihe River extends 1250 km, with canyon sections in its upper reaches and valley plains downstream. The basin experiences an arid climate characterized by uneven precipitation distribution and pronounced seasonal temperature variations, with hot, windy summers and cold winters. Primary land cover types include grassland, desert, and farmland.

1.2 Data Sources

1.2.1 FY-3C VIRR

FY-3C is China's second-generation polar-orbiting meteorological satellite designed for all-weather, multi-spectral, and three-dimensional observations of global atmospheric and geophysical elements. The FY-3C VIRR land surface temperature product employs the generalized split-window algorithm proposed by Wan and Dozier, generating datasets with 1 km spatial resolution and

monthly temporal resolution. Daily and monthly products for 2017–2019 were obtained from the Fengyun Satellite Remote Sensing Data Service Platform, reprojected to WGS1984, and cropped to the Heihe River Basin.

1.2.2 MODIS Terra

The Terra Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature product utilizes a physics-based algorithm developed by Wan and Li, retrieving land surface emissivity and temperature from MODIS thermal infrared bands through statistical regression and least squares fitting. MOD11A1 (1 km spatial resolution, daily temporal resolution) and MOD11C3 (5.6 km spatial resolution, monthly temporal resolution) products for 2017–2019 were downloaded from NASA Earthdata, reprojected to WGS1984, and cropped to the study area.

1.2.3 ERA5-LAND

ERA5-LAND is a global land reanalysis dataset developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), providing land surface variables including temperature, humidity, vegetation index, precipitation, and snow depth at 0.1° spatial resolution and hourly temporal resolution from 1981 to present. To match satellite overpass times, data at 10:00 and 22:00 local time for 2017–2019 were downloaded, resampled to 0.0625°, and monthly averages were calculated for the Heihe River Basin.

1.2.4 CLDAS-V2.0

The China Meteorological Administration Land Data Assimilation System (CLDAS-V2.0), developed by the National Meteorological Information Center, covers the Asian region (0°–65°N, 60°–160°E) and provides high-spatiotemporal-resolution fused analysis products at 0.0625° spatial resolution and hourly temporal resolution. The dataset integrates multi-source ground and satellite observations using multi-grid variational assimilation, probability density function matching, and terrain correction techniques. CLDAS-V2.0 land surface temperature analysis products for 2017–2019 were obtained from the National Meteorological Science Data Center, resampled to 0.0625°, and monthly averages were calculated.

1.2.5 Ground Station Data

This study utilized observation data from seven stations in the Heihe River Basin as part of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) for product validation. Station distribution and details are shown in Figure [Figure 1: see original paper] and Table . Observations were collected at 10-minute intervals and averaged to hourly data, including air temperature, humidity, four-component radiation, and surface radiative temperature.

1.3 Methods

1.3.1 Ground Station Data Inversion

Land surface temperature at 10-minute resolution was estimated using four-component radiometer observations. Since satellite overpass times were approximately 10:30 and 22:30 local time, instantaneous temperatures at these times were averaged for validation. The estimation method follows:

$$LST = \left(\frac{F_{up} - (1-\epsilon)F_{down}}{\epsilon\sigma} \right)^{1/4}$$

where F_{up} is upwelling longwave radiation ($\mathrm{W \cdot m^{-2}}$), F_{down} is downwelling longwave radiation ($\mathrm{W \cdot m^{-2}}$), σ is the Stefan-Boltzmann constant (5.67$×10^{-8}$ $\mathrm{W \cdot m^{-2} \cdot K^{-4}}$), and ϵ is broadband emissivity calculated from narrowband emissivity or spectral library data. Radiometer measurement accuracy differed by approximately $±8W \cdot m^{-2}$ between day and night, resulting in land surface temperature uncertainties of $±$0.37 K.

1.3.2 Evaluation Metrics

This study employed four statistical metrics for quantitative accuracy assessment: bias (BIAS), root mean square error (RMSE), correlation coefficient (CC), and ratio of standard deviation (RSD).

2.1 Spatial Distribution Characteristics

Comparison of daytime and nighttime land surface temperature data on May 1, 2017 revealed that all four products showed similar spatial patterns with lower temperatures in southern and higher in northern Heihe River Basin, consistent with actual conditions (Figure [Figure 2: see original paper] and [Figure 3: see original paper]). Due to cloud contamination, both FY-3C VIRR and MOD11A1 exhibited missing data. FY-3C VIRR demonstrated better data completeness than MOD11A1 during daytime, while the opposite occurred at nighttime. ERA5-LAND and CLDAS-V2.0 products had complete coverage. Compared to lower-resolution ERA5-LAND, FY-3C VIRR and MOD11A1 displayed more spatial details and captured local temperature variations. ERA5-LAND and CLDAS-V2.0 daytime products showed overestimation in northern Heihe River Basin, while MOD11A1 showed underestimation in southeastern regions.

2.2 Daily-Scale Evaluation

Using ground station observations, we validated daytime and nighttime land surface temperature products (Table and). To reduce validation uncertainty, data pairs with differences exceeding 5 K were excluded as outliers. FY-3C VIRR daytime product showed excellent agreement with station data, with the lowest

average BIAS (-0.025 K) and RMSE (3.573 K), demonstrating the highest accuracy. MOD11A1 daytime product achieved the highest correlation coefficients (0.957–0.987) but exhibited larger errors, with BIAS of 2.773 K and RMSE of 5.017 K, indicating systematic overestimation. CLDAS-V2.0 daytime product showed relatively high accuracy except at Heihe station. ERA5-LAND daytime product had the smallest BIAS (-0.174 K) but larger RMSE (4.042 K).

At nighttime, all four products showed strong correlations with station data. FY-3C VIRR nighttime product demonstrated the highest accuracy with BIAS of -0.851 K and RMSE of 2.773 K. MOD11A1 nighttime product also showed good performance. CLDAS-V2.0 nighttime product exhibited the largest errors with BIAS of 5.676 K, showing significant overestimation. ERA5-LAND nighttime product had the smallest BIAS (0.502 K) but relatively large RMSE.

2.3 Monthly-Scale Time Series Analysis

To analyze monthly temporal variation characteristics, we plotted time series curves of monthly station observations and four land surface temperature products (Figure [Figure 6: see original paper] and [Figure 7: see original paper]). Due to severe data gaps at Huazhaizi station, its monthly data were excluded from analysis.

At monthly daytime scale, FY-3C VIRR products maintained good consistency with station data, particularly at Dashalong station where overall errors were relatively large. However, ERA5-LAND and CLDAS-V2.0 daytime products showed underestimation, especially at Heihe station. MOD11C3 daytime products exhibited overestimation, particularly at Huazhaizi and Damang stations.

At nighttime monthly scale, FY-3C VIRR products showed good consistency and temporal trends with station data, though MOD11C3 exhibited severe underestimation. CLDAS-V2.0 nighttime products showed overestimation at Sidaogiao station and underestimation during winter at Dashalong station. Overall, all four products captured seasonal variation characteristics of land surface temperature in the Heihe River Basin.

3 Discussion

This study conducted daily and monthly accuracy evaluations of four land surface temperature products using ground station data. Results showed that FY-3C VIRR products exhibited relatively high applicability in the Heihe River Basin across both temporal scales, with daytime accuracy higher than MODIS, ERA5-LAND, and CLDAS-V2.0 daytime products. However, significant errors remained between products and station observations, such as MOD11A1 daytime RMSE of 5.017 K and FY-3C VIRR daytime RMSE of 4.042 K.

These relatively large errors may arise from multiple factors. First, land surface temperature retrieval algorithms and sensors are affected by underlying surface and terrain characteristics. Second, errors in calculating broadband emissivity

during station temperature inversion contribute to uncertainties. For satellite data, the split-window algorithm continues to be optimized, and errors in emissivity estimation increase retrieval uncertainty. Land cover type significantly affects emissivity estimation, and classification-based emissivity values cannot vary with changing surface conditions. For reanalysis data like ERA5-LAND and CLDAS-V2.0, larger errors may relate to temperature-based evaluation methods, spatial thermal homogeneity range, and the fact that reanalysis data involve larger pixel areas more susceptible to surface heterogeneity.

Comparing daytime and nighttime product quality, nighttime accuracy for FY-3C VIRR, MOD11A1, and ERA5-LAND products surpassed daytime accuracy, primarily because: (1) solar radiation directionality creates mixed shadow-sunlit pixels during daytime, while nighttime avoids this issue; (2) reduced human activity at night may decrease retrieval errors; (3) factors like soil moisture, air humidity, wind speed, sensor zenith angle, and instrument calibration all affect retrieval and evaluation accuracy. Validation of these products used only field measurements from Heihe River Basin stations; results may differ at other locations with different atmospheric characteristics and surface conditions. Future evaluations should comprehensively consider these factors to reduce uncertainties.

4 Conclusions

(1) All four land surface temperature products with different spatial resolutions showed similar spatial patterns with higher temperatures in the north and lower in the south. FY-3C VIRR and MOD11A1 products displayed more spatial details than lower-resolution ERA5-LAND and CLDAS-V2.0 products.

(2) For daytime land surface temperature, FY-3C VIRR products showed higher accuracy than other three products; although MOD11A1 products had slightly better correlation, they significantly overestimated temperatures. ERA5-LAND and CLDAS-V2.0 daytime products showed lower accuracy than MOD11A1.

(3) For nighttime land surface temperature, FY-3C VIRR products demonstrated the highest accuracy; MOD11A1/MOD11C3 products showed higher accuracy than ERA5-LAND and CLDAS-V2.0; CLDAS-V2.0 nighttime products exhibited the lowest quality with significant overestimation.

(4) FY-3C VIRR, MOD11A1, and ERA5-LAND nighttime products showed higher accuracy than daytime products, while CLDAS-V2.0 daytime products were more accurate than nighttime products.

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Note: Figure translations are in progress. See original paper for figures.