

Generation of angular-normalized, cloud-filled, 0.01°-downscaled land surface temperature from 2018 to 2023 based on official FY-4A dataset

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Abstract. Land surface temperature (LST) is an essential climate variable in geophysical, ecological, and environmental research. Remote sensing provides a unique observation approach for obtaining large-scale LST products. However, current official LST datasets (such as FY-4A) are limited by the unaddressed thermal radiation directionality effect, and suffer from the spatial discontinuities due to the pervasive presence of clouds. Moreover, the geostationary LST products have relatively coarser resolution than those of polar-orbiting satellites due to trade-off between spatial and temporal resolutions. Based on the official hourly FY-4A LST dataset, this study proposes a novel framework for generating angular-normalized, cloud-filled, and 0.01°-downscaled LST (ANCFDS-LST) product, encompassing directional (T_{dir}), nadir (T_{nadir}), and hemispherical (T_{hemi}) LST layers. First, the angular-normalized T_{nadir} and T_{hemi} were generated using a time-evolving kernel driven model (TEKDM) with the inputs of multi-temporal FY-4A T_{dir} . Subsequently, hypothetical clear-sky LST was predicted using a CatBoost model optimized via Bayesian methods. The cloudy-sky LST values were then derived through a cloud radiation force (CRF) correction. Finally, the 0.05° all-weather T_{dir} , T_{nadir} , and T_{hemi} values were downscaled to 0.01° resolution using an improved hybrid downscaling algorithm (IHDA) combining fusion- and kernel-based methods. Taking the daytime clear-sky near-nadir VNP21A1 LST as reference, the 0.05° T_{dir} before angular-normalization has a root mean squared difference

(RMSD) of 4.53 K and a mean bias difference (MBD) of -1.85 K, whereas the angularly normalized T_{nadir} has a much smaller RMSD of 2.56 K and a better MBD of 0.06 K. For the all-weather T_{hemi} , temperature-based validation over 8 sites in the Heihe River Basin and the Australia shows a root mean squared error (RMSE) and mean bias error (MBE) of 2.48 K and -0.83 K under clear-sky conditions, 3.65 K and -1.43 K under cloudy-sky conditions. After the spatial downscaling, the 0.01° all-weather T_{hemi} with abundant texture details. The generated LST products from 2018 to 2023 over the FY-4A disk exhibit enhanced angular consistency, spatial continuity, and finer resolution, offering valuable support for subsequent LST-related applications. The ANCFDS-LST data is freely available at <https://doi.org/10.11888/RemoteSen.tpd.303249> (last access: 30 January 2026; Na et al., 2026).

45 1 Introduction

Land Surface Temperature (LST) quantifies the thermal properties of the Earth's land surface and serves as a driving force of climate change, radiation budgets, water cycle, and atmospheric processes (Wei et al., 2020, 2021). Compared to polar-orbiting satellite LST products, geostationary LSTs have the advantage of enhanced temporal resolution, which is more suitable to characterize the dynamic variations of land surface thermal conditions (Li et al., 2023c). To ensure both retrieval accuracy and computational efficiency, numerous easy-to-implement methods such as the split-window (SW) and temperature and emissivity separation (TES) methods have been developed for the geostationary satellites over the past decades (Li et al., 2013). These methods have been successfully applied in the generation of official LST products, including the Fengyun-4A (FY-4A) Advanced Geosynchronous Radiation Imager (AGRI) LST product (Dong et al., 2013, 2023a), Geostationary Operational Environmental Satellites R-Series (GOES-R) Advanced Baseline Imager (ABI) LST products (Yu et al., 2009), and the Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) LST product (Freitas et al., 2013; Trigo et al., 2011).

Despite the significant advancement of LST retrieval methods, current geostationary LST products still suffer from three major limitations: 1) Most existing LST retrieval methods assume that surface-emitted radiance is isotropic. However, the complex structure and heterogeneous sub-pixel temperature distribution lead to different LST values when observing a pixel from different directions at the same time, i.e., the thermal radiation directionality (TRD) effect (Cao et al., 2019a). As a result, current LST products are directionally dependent, requiring to be normalized into a reference direction. 2) Because thermal-infrared (TIR) signals cannot penetrate clouds, current LST products exhibit significant spatial discontinuities, with more than half of the land surface often obscured by cloud cover (Stubenrauch et al., 2013). Therefore, generating all-weather (including clear-sky and cloudy-sky conditions) LST has attracted considerable research interest in the TIR remote sensing community (Jia et al., 2024; Wu et al., 2021). 3) A trade-off between spatial and temporal resolution is inherent to LST products. Hourly LST products from geostationary satellites typically have a spatial resolution of 2~5 km. Improving sensor performance is one direct approach, while spatial downscaling methods offer a more practical and efficient alternative for enhancing the texture detail of LST products (Sun et al., 2024; Wu et al., 2021; Zhan et al., 2013).

The influence of TRD effect during summer is as large as 4.0 K in sparsely vegetated areas and 5.1 K in urban regions (Coll et al., 2019; Du et al., 2023, 2025; Zhan et al., 2025). The semi-physical kernel-driven model (KDM) is regarded as the most potential approach to reduce the LST angular dependence and achieve the aim of angular normalization (Cao et al., 2019b, 2021; Michel et al., 2023). It simulates the LST angular distribution through a linear combination of several kernel functions. The primary step is to calibrate the kernel coefficients, which then allows for correcting the directional LST (i.e., T_{dir}) to a nadir LST (i.e., T_{nadir}) or to a hemispherical LST (i.e., T_{hemi}) by integrating over the upper hemisphere. Solving for three or four unknown kernel coefficients typically requires at least three or four simultaneous multi-angle observations which cannot be satisfied by current satellite sensors. To address this problem, previous studies have either omitted one anisotropic kernel (Qin et al., 2023; Teng et al., 2023) or assumed that certain kernel coefficients remain constant over broad spatial or temporal scales (Chang et al., 2025; Ermida et al., 2017, 2018a, b; Vinnikov et al., 2012). Recently, Qin et al. (2025) proposed a time-evolving kernel-driven model (TEKDM) with seven parameters which captures the multi-temporal multi-angle LST patterns within a single day and enables the coefficient calibration in the overlapping region of two geostationary satellites. To broaden the application region of TEKDM, Na et al. (2024b) normalized the LST in the overlapping region of TERRA/AQUA Moderate Resolution Imaging Spectroradiometer (MODIS) and GOES-16 ABI LST products. Results showed the root mean squared error (RMSE) was reduced from 3.29 K to 2.34 K. Although angular normalization methods have been well developed, their large-scale application, validation, and the generation of operational nadir and hemispherical LST products remain unsolved, which has long been a key objective in the thermal infrared (TIR) remote sensing field. Here, the FY-4A AGRI and TERRA/AQUA MODIS official LST products were jointly employed for solving the TEKDM and achieving the angular normalization of FY-4A LST (i.e., producing T_{nadir} and T_{hemi}).

Due to the lack of TIR information of the land surface under cloudy-sky conditions, all-weather LST estimation for geostationary satellites typically relies on various types of auxiliary data and can be categorized into three main approaches: interpolation-based methods, surface energy balance (SEB) based methods, and simulation-based methods. Interpolation-based methods utilize spatially or temporally adjacent information to estimate missing LST values (Hong et al., 2021, 2022; Quan et al., 2018; Wang et al., 2024b). These methods can effectively preserve fine spatial textures, but they are uncertain under extensive cloud cover (Jia et al., 2024). Furthermore, they do not account for the influence of cloud radiation force (CRF). The SEB-based methods are commonly used to calculate the CRF effects in all-weather LST estimation. For example, Jia et al. (2021) proposed an iterative CRF correction method, Liu et al. (2023) solved a quartic equation to perform CRF correction, and Zhang et al. (2024) developed an analytical CRF correction formula. LST values after CRF correction can represent the actual thermal properties of the land surface and are recommended for large-scale applications (Jia et al., 2024; Wu et al., 2021). Simulation-based methods also show excellent potential for estimating all-weather LST, but they suffer from coarse resolution and substantial biases in simulated LST (Ding et al., 2022; Dong et al., 2022). The rapid advancement of machine learning (ML) models offers promising opportunities to improve the all-weather LST estimation. Zhang et al. (2024) proposed a two-step gap-filling algorithm in recent. In the first step, hypothetical LST values are estimated using an

ML model with the input of reanalysis data. Then, an SEB-based CRF correction is applied to generate the all-weather LST. Results showed stable accuracy with the maximum RMSE within 4 K. Physically, the clear-sky LST in SEB calculation should represent an integrated quantity over the upper hemisphere, which cannot be satisfied by current LST products (Jia et al., 2024). Instead, existing gap-filling methods typically rely on clear-sky directional LST (i.e., T_{dir}), thereby accumulating uncertainties associated with the TRD effect. In this study, Zhang's method is employed as the basic gap-filling framework. The angular independent clear-sky nadir and hemispherical LST (i.e., T_{nadir} , T_{hemi}) were introduced to improve the reliability of hypothetical LST and further enhance the accuracy of generated cloudy-sky LST.

Downscaling methods are widely used to produce LST products with high spatial resolution. These methods could be generally classified into three categories: kernel-based approaches (Dong et al., 2020; Zhan et al., 2013; Zhang et al., 2020; Zheng et al., 2024), fusion-based approaches (Tang et al., 2024; Wang et al., 2024b), and hybrid downscaling method combining both kernel and fusion-based approaches (Dong et al., 2023b; Li et al., 2023b; Xia et al., 2019). Kernel-based methods typically establish a relationship between LST and regression kernels such as the normalized vegetation index (NDVI) at a coarse resolution. This relationship is then applied at a finer scale to generate high-resolution LST. These methods have evolved from simple linear regressions using single variables to ML-based regressions incorporating multiple kernels (Agam et al., 2007; Ebrahimi and Azadbakht, 2019; Xu et al., 2024; Zheng et al., 2024). Fusion-based methods aim to estimate fine-scale LST variability using multi-resolution LST data as inputs (Tang et al., 2024; Wang et al., 2024b; Wu et al., 2015). In these approaches, high-resolution LST temporal variation is typically estimated by weighting the coarse-resolution LST temporal variation of neighbouring similar pixels. The estimated temporal variation is then added to the high-resolution LST at the initial time to derive the final LST at the target time. Hybrid downscaling method combining both kernel and fusion-based approaches offers improved accuracy and computational efficiency than single method (Dong et al., 2023b), which was adopted in this study. However, this method requires gap-free, high-resolution LST at the initial time as input, which is difficult to obtain at the full-disk scale due to widespread presence of clouds over large areas. The annual temperature cycle (ATC) model has the potential to provide the necessary gap-free high-resolution LST texture information (Quan et al., 2018; Zhan et al., 2016) and thereby ensure the generation of 0.01° LST at the full-disk scale. Therefore, ATC-derived texture information was incorporated to extend and refine the hybrid downscaling method over a broader spatial extent.

It should be noted that this study does not aim to introduce incremental improvements to individual components, as the angular normalization, cloudy-sky reconstruction, and spatial downscaling modules have been previously developed. Instead, the novelty lies in establishing a unified processing framework that explicitly resolves angular inconsistency and enables their synergistic integration toward a conceptually consistent LST. By doing so, this work moves beyond conventional LST product generation and represents a step toward next-generation LST datasets that simultaneously satisfy the requirements of Global Climate Observing System (GCOS, <https://gcos.wmo.int/site/global-climate-observing-system-gcos/essential-climate-variables/land-surface-temperature>), including ~1 km spatial resolution, sub-daily temporal frequency, and climate-

level consistency. The generation of hourly, angular-normalized, cloud-filled, and 0.01°-downscaled LST (ANCFDS-LST) consists of the following key steps: First, the TEKDM was calibrated using FY-4A and MODIS official LST products to generate daytime nadir and hemispherical LST at a 0.05° resolution. Second, an ML-based model was trained to generate hypothetical clear-sky LST, using angular-normalized LST as labels. Then, the all-weather LST was produced through an analytical CRF correction process. Finally, an improved hybrid downscaling algorithm (IHDA) combining fusion- and kernel-based methods was developed and carried out with the input of ATC-simulated gap-free 0.01° LST for producing the 0.01° all-weather directional, nadir, and hemispherical LST products. The hemispherical LST is validated using 8 sites in the Heihe River Basin and Australia, which measure the hemispherical longwave radiation via in-situ pyrgeometer. The nadir LST is cross-validated using Visible Infrared Imaging Radiometer Suite (VIIRS) near nadir LST. The structure of this study is as follows: Section 2 describes the remote sensing and reanalysis data, cross-validation data and in-situ validation data. Section 3 presents the TEKDM-based angular normalization method, the all-weather LST estimation method, and the IHDA downscaling approach. Section 4 provides the results of the generated LST products. Section 5 gives the discussion and limitation of this study. Section 6 and 7 introduce the data availability and the main conclusions, respectively.

2 Data

2.1 Input remote sensing and reanalysis data

Table 1 lists the information of the required 15 datasets for the three main steps in the generation of ANCFDS-LST (namely, LST angular normalization, all-weather LST estimation, and spatial downscaling). The LST dataset produced in this study spans the period from 2018 to 2023, covering the full operational phase of the FY-4A LST product (note that the official FY-4A LST product has not been generated since March 4, 2024, as it has been superseded by a subsequent operational satellite). First, FY-4A and MODIS directional LSTs (i.e., 2 datasets) were used to generate angular-normalized nadir LST (T_{nadir}) and hemispherical LST (T_{hemi}). Next, 10 remote sensing and reanalysis products were employed to drive the generation of hypothetical clear-sky LST and the application of CRF correction, for estimating all-weather T_{dir} , T_{nadir} , and T_{hemi} at a 0.05° spatial resolution. Finally, these three 0.05° all-weather LST products were downscaled using 0.01° regression kernels obtained from 3 datasets, including MYD11A1, GTOPO30 DEM, and ERA5 Land.

Table 1. The employed remote sensing and reanalysis dataset.

Step	Product	Variable	Resolution	Date range	Usage	Access Link
Step 1: LST angular normalization	1) FY-4A	LST	4 km, hourly	2018 - 2023	LST angular normalization	http://data.nsmc.org.cn
	2) MxD11A1	LST	1 km, daily	2018 - 2023	LST angular normalization	https://lpdaac.usgs.gov/product_search/
Step 2: All-weather LST estimation	3) MCD12Q1	Land cover type (LCT)	500 m, yearly	2018 - 2023	Hypothetical clear-sky LST estimation	https://lpdaac.usgs.gov/product_search/

Step 3: Spatial downscaling	4) Köppen-Geiger maps	Climate type (CT)	1 km	-	Hypothetical clear-sky LST estimation	http://www.gloh2o.org/koppen
	5) GLASS	Fractional vegetation cover (FVC)	0.05°, 8 days	2018 - 2023	Hypothetical clear-sky LST estimation	https://www.glass.hku.hk/download.html
	6) GTOPO30	Digital elevation model (DEM)	1 km	-	Hypothetical clear-sky LST estimation	https://www.usgs.gov/search
	7) ERA5 Land	Air temperature and dew-point temperature	0.1°, hourly	2018 - 2023	Hypothetical clear-sky LST estimation	https://cds.climate.copernicus.eu
	8) MxD11A1	LST	1 km, daily	2018 - 2023	Hypothetical clear-sky LST estimation	https://lpdaac.usgs.gov/product_search/
	9) ERA5	Cloudless and cloudy radiation	0.25°, hourly	2018 - 2023	Hypothetical clear-sky LST estimation; CRF correction	https://cds.climate.copernicus.eu
	10) GLASS	Albedo	0.05°, daily	2018 - 2022	Hypothetical clear-sky LST estimation; CRF correction	https://www.glass.hku.hk/download.html
	11) MCD43C3	Albedo	0.05°, 16 days	2023	Hypothetical clear-sky LST estimation; CRF correction	https://lpdaac.usgs.gov/product_search/
	12) FY-3B MuSyQ	Broad band emissivity (BBE)	1 km, daily	2018 - 2023	Hypothetical clear-sky LST estimation; CRF correction	-
	13) MYD11A1	LST	1 km, daily	2018 - 2023	Simulating LST at reference time to be fused	https://lpdaac.usgs.gov/product_search/
Step 3: Spatial downscaling	14) GTOPO30	DEM	1 km	-	Regression kernel	https://www.usgs.gov/search
	15) ERA5 Land	Air temperature	0.1°, hourly	2018 - 2023	Regression kernel	https://cds.climate.copernicus.eu

160 For the first step (i.e., LST angular normalization), the FY-4A directional LST (LST_{FY}) and MODIS LST (LST_{MxD}) products (i.e., dataset 1-2 in Table. 1) were jointly utilized to calibrate the TEKDM model. Based on the calibrated model, clear-sky T_{nadir} and T_{hemi} were derived using the corresponding kernels and kernel coefficients. The official FY-4A LST is retrieved using a SW algorithm, with land surface emissivity (LSE) estimated via NDVI-based threshold method (Dong et al., 2013, 2023a). The MODIS MxD11A1 LST was retrieved using a generalized split-window (GSW) algorithm, incorporating land-

165 cover-based LSE as input (Wan and Dozier, 1996). Both FY-4A and MODIS LST products were resampled to the same spatial resolution (i.e., 0.05°) using plain average before the joint estimation. The pixels with the view zenith angle (VZA) greater than 70° were masked (Freitas et al., 2013). To reduce systematic discrepancies between these two datasets, the 0.05° FY-4A LST was linearly adjusted to match the 0.05° MODIS MxD11A1 LST using a linear transformation (i.e., $LST_{MxD} = a$

170 $\times LST_{FY} + b$). The parameters a and b were determined based on nighttime matchups under the condition of $VZA < 50^\circ$, VZA difference $< 5^\circ$, and LST difference < 5 K, referenced to Ermida et al. (2017, 2018a). A total of 132,972,698 matchup pairs were collected from 2018/1/1 to 2023/12/31 in the disk of FY-4A, resulting in a slope of $a = 1.0240$ and an intercept of $b = -5.7378$.

The second step (i.e., all-weather LST estimation) includes the estimation of hypothetical clear-sky LST and the CRF correction. In the hypothetical clear-sky LST estimation, the dataset 3-7 in Table 1 (including the MCD12Q1 IGBP land cover type (LCT) product (dataset 3), the Köppen-Geiger climate type (CT) product (dataset 4), the Global Land Surface Satellite (GLASS) fractional vegetation cover (FVC) product (dataset 5), the GTOPO30 DEM data (dataset 6), the ERA5-Land 2-m air temperature (T_{2m}), and dew-point temperature (D_{2m}) data (dataset 7)) were employed to depict surface property (Wei et al., 2019). Moreover, the dataset 8-12 in Table 1 were further used to calculate three additional variables to depict surface thermal conditions (including the ATC-simulated LST , the surface incoming radiation (R_{in}), and hypothetical clear-sky skin temperature ($T_{ERA5-skin}$)).

The ATC model has three parameters as shown in Eq. 1, which was calibrated with the input of MxD11A1 LST product (dataset 8). In total, four ATC models were obtained since TERRA and AQUA MODIS sensors provide observations during both day and night. A 3×3 spatial median filter was applied to fill invalid ATC parameters caused by persistent cloud coverage. Then, the LST values simulated using the calibrated ATC model are used in the estimation of hypothetical clear-sky LST . These ATC-simulated LST s are denoted as $T_{ATC,d1}$, $T_{ATC,d2}$, $T_{ATC,n1}$, and $T_{ATC,n2}$, where subscript “ d ” and “ n ” refer to daytime and nighttime data, respectively, and “1” and “2” indicate TERRA and AQUA platforms.

$$T_{ATC}(DOY) = MAST + YAST \times \cos \left[\frac{2\pi}{365} (DOY - dx) \right] \quad (1)$$

where $T_{ATC}(DOY)$ is the ATC-simulated LST as a function of day-of-year (DOY). $MAST$ is the annual mean surface temperature, $YAST$ is the yearly temperature amplitude, and dx is the phase shift. The QC band was filtered to ensure high-quality inputs for the ATC model calibration.

The R_{in} is the sum of absorbed shortwave and longwave radiation as calculated in Eq. 2, with the input of surface downward shortwave radiation ($SDSR_{clr}$), land surface albedo ($Albedo$), surface downward longwave radiation ($SDLR_{clr}$) and broad band emissivity (BBE, ε_{bb}). Both $SDSR_{clr}$ and $SDLR_{clr}$ under hypothetical clear-sky condition are extracted from ERA5 products (dataset 9). The $Albedo$ is from the GLASS product from 2018 to 2022 (dataset 10) and supplemented by MCD43C3 for 2023 (dataset 11). A Harmonic ANalysis of Time Series (HANTS) method was employed to smooth and fill the gaps in MCD43C3 product in this study (Zhou et al., 2023, 2022). The BBE is generated from Multi-source data SYnergized Quantitative (MuSyQ) remote sensing system (dataset 12) (Li et al., 2019). The datasets 9-12 were resampled to 0.05° resolution to match the LST_{FY} .

$$R_{in} = (1 - Albedo) \cdot SDSR_{clr} + \varepsilon_{bb} \cdot SDLR_{clr} \quad (2)$$

Based on the Stefan–Boltzmann's law, the ERA5 hypothetical clear-sky surface thermal radiation (e.g., surface downward longwave radiation ($SDLR_{clr}$) and surface net thermal radiation STR_{clr}) could be used to calculate the hypothetical clear-sky skin temperature ($T_{ERA5-skin}$) in the scale of 0.25° to depict temporal dynamics of LST. It was then physically downscaled to 0.05° resolution using DEM data, assuming a temperature lapse rate (K) of 6.5 K/km (Minder et al., 2010). Therefore, the $T_{ERA5-skin}$ was calculated by the following equation:

$$T_{ERA5-skin} = \sqrt[4]{\frac{SDLR_{clr} - STR_{clr} - (1 - \varepsilon_{bb})SDLR_{clr}}{\varepsilon_{bb}\sigma_s}} + K \cdot (DEM_i - DEM_m) \quad (3)$$

where σ_s is Stefan–Boltzmann's constant 5.67×10^{-8} . The DEM_i and DEM_m refer to the elevation of the 0.05° pixel and the mean elevation of the corresponding 0.25° pixel, respectively.

After generating the hypothetical clear-sky LST, a CRF correction is required to convert it into cloudy-sky LST. This correction is physically based on the surface energy balance differences between clear-sky and cloudy conditions. Specifically, cloud-free and cloudy SDSR from ERA5 reanalysis data (dataset 9), together with albedo data (dataset 10-11), are used to describe the shortwave radiation budget. For the longwave radiation budget, ERA5 cloud-free and cloudy-sky SDLR data (dataset 9), BBE data (dataset 12), the hypothetical clear-sky LST and cloudy-sky LST are required. Then, the only unknown cloudy-sky LST (expressed by the sum of hypothetical clear-sky LST and CRF correction value) can be retrieved by solving the SEB equation. More details will be given in section 3.2.

In the third step (i.e., spatial downscaling), a new algorithm combining existing fusion and kernel-based methods was proposed to downscale LST to the target time, consisting of two main processes. First, a 0.05° gap-free high-resolution LST at the initial time is required. In this study, $T_{ATC,d2}$ simulated by the ATC model (dataset 13) is resampled as the initial LST. Second, the 0.05° LST difference between the initial and target time is predicted using an ML method. The input features include $T_{ATC,d2}$; AQUA MODIS ATC parameters for both day ($MAST_{d2}$, $YAST_{d2}$, and dx_{d2}) and night ($MAST_{n2}$, $YAST_{n2}$, and dx_{n2}), derived from dataset 13; DEM data (dataset 14); and ERA5-Land T_{2m} (dataset 15). Aimed to apply this spatial downscaling model at the 0.01° scale, the T_{2m} data were further downscaled to 0.01° resolution using high-resolution DEM and the temperature lapse rate (K) of 6.5 K/km. Finally, the gap-free high-resolution LST at the target time is obtained by adding the estimated 0.01° LST difference to $0.01^\circ T_{ATC,d2}$.

2.2 Cross-validation dataset for T_{nadir}

For cross-validation of the generated T_{nadir} , the VIIRS VNP21A1 LST data (https://lpdaac.usgs.gov/product_search/) in 2020 was adopted as reference. The VIIRS onboarded Suomi National Polar-orbiting Partnership (S-NPP) provides clear-sky TIR observations at the local time of 1:30 p.m. The VNP21 LST was retrieved using a TES algorithm taking observations from

M14 – M16 bands as input. Recent temperature-based (T-based) evaluation showed its RMSE is 1.79 K during nighttime and 2.79 K during the day (Na et al., 2024a). Here, the VNP21 LST values with the VZA < 5° were employed for cross-evaluation of T_{nadir} as done by Wei et al. (2025). The resulting near-nadir VNP21 LST was first resampled to a spatial resolution of 0.05°, and then bias-corrected to FY-4A LST using nighttime matchups (consistent with the bias correction applied between MODIS and FY-4A LST products). The normalized hourly FY-4A T_{nadir} product was temporally interpolated to match the exact overpass time of S-NPP VIIRS sensor. Finally, the root mean square difference (RMSD), mean bias difference (MBD), and coefficient of determination (R^2) were used as three evaluation indicators. The extracted VNP21 LST results in four typical days are shown in Fig. 1. Only several narrow strips were extracted due to the limitation of VIIRS field-of-view (VZA < 5°). VNP21 LST shows significant seasonal variation. It is relatively lower in 2020/3/1 and 2020/12/1 than that in 2020/6/1 and 2020/9/1 in the northern hemisphere and the situation is reversed in the southern hemisphere.

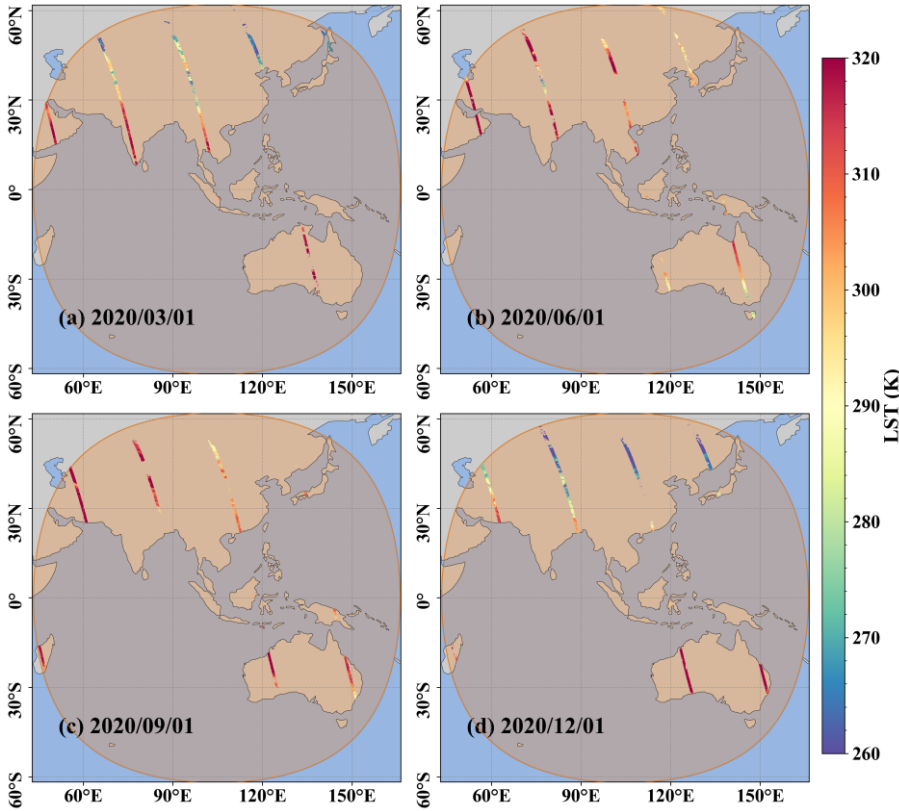


Figure 1: Spatial distribution of the extracted VNP21 LST strips in four typical days (a) 2020/3/1, (b) 2020/6/1, (c) 2020/9/1, (d) 2020/12/1. The FY-4A observed area is marked in orange region.

2.3 In-situ validation dataset for T_{hemi}

T-based evaluation (i.e., directly comparing satellite-derived LST with in-situ LST) is the most widely used validation method and should be conducted whenever possible (Guillevic et al., 2018; Li et al., 2014, 2023a; Na et al., 2024a). The in-situ pyrgeometer measures both upward and downward hemispherical longwave radiation, which can be converted into hemispherical LST to perform the T-based validation for the normalized T_{hemi} products. As shown in Fig. 2, 5 sites from the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) experiment within the Heihe River Basin (HRB) and 3 sites from the Terrestrial Ecosystem Research Network (TERN) OzFlux network in 2020 were selected, which had been used in LST evaluation studies (Beringer et al., 2016; Che et al., 2019; Li et al., 2025, 2020). More detailed information on the spatial representativeness of the in-situ sites is provided in Subsection 5.3.

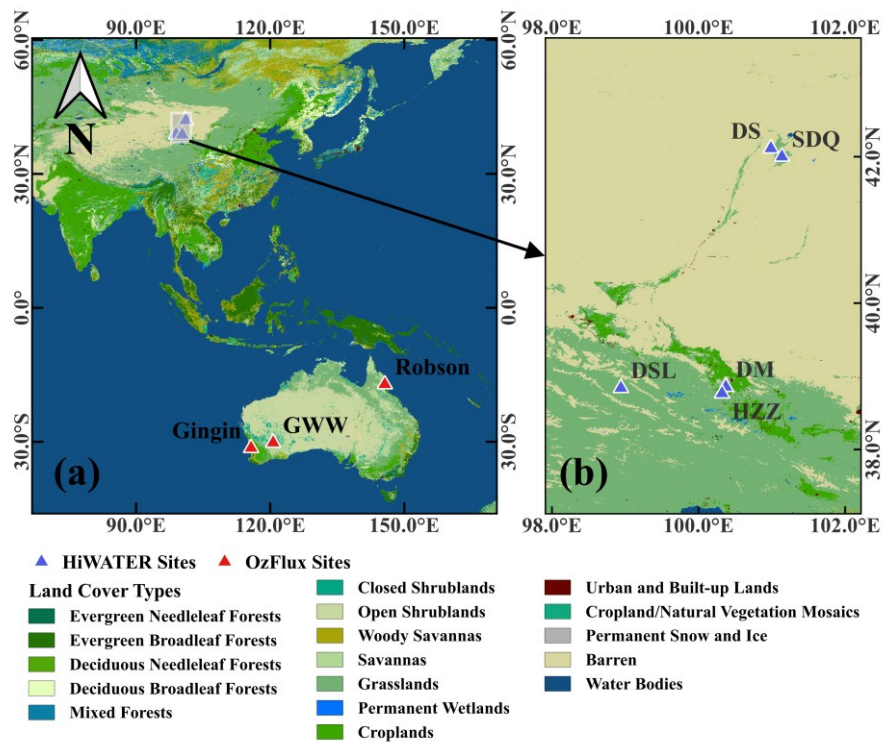


Figure 2: Spatial distribution of selected in-situ sites.

Table 2. Information of the in-situ sites

Network	Site name	Longitude (° E)	Latitude (° N)	Elevation (m)	Temporal resolution (minute)	Land cover type
HiWATER	DM	100.37	38.86	1560	10	CRO
	DSL	98.94	38.84	3787	10	GRA

	DS	100.99	42.11	927	10	BSV
	HZZ	100.32	38.77	1732	10	GRA
	SDQ	101.14	42.00	935	10	GRA
	Gingin	115.71	-31.38	99	30	SAV
OzFlux	GWW	120.65	-30.19	505	30	SAV
	Robson	145.63	-17.12	667	30	EBF

As listed in Table 2, five land cover types are represented across the 8 validation sites: 1 cropland (CRO) site, 3 grassland (GRA) sites, 1 barren/sparse vegetation (BSV) site, 2 savanna (SAV) sites, and 1 evergreen broadleaf forest (EBF) site. The temporal resolution of the in-situ observations varies by network: 10 minutes for the HiWATER sites, and 30 minutes for the OzFlux sites. Linear interpolation was applied to align in-situ measurements with the exact satellite observation time. The in-situ LST (T_{insitu}) is calculated using the Stefan–Boltzmann's law, as shown in Eq. 4:

$$T_{insitu} = \sqrt[4]{\frac{SULR_{insitu} - (1 - \varepsilon_{bb}) SDLR_{insitu}}{\varepsilon_{bb} \sigma_s}} \quad (4)$$

where $SULR_{insitu}$ and $SDLR_{insitu}$ are the surface upward and downward longwave radiation measured by the in-situ pyrgeometer, respectively. ε_{bb} is the broadband emissivity derived from the FY-3B MuSyQ product. Outliers were identified and removed using the “ 3σ -Hampel identifier” method for each site (Davies and Gather, 1993; Pearson, 2002). The RMSE, mean bias error (MBE), and R^2 were used as evaluation metrics to validate the LST products.

3 Method

The generation of 0.01° ANCFDS-LST involves three main steps: 1) angular normalization of daytime LST; 2) generation of 0.05° all-weather LST using clear-sky LST as training labels; 3) downscaling of all-weather LST to 0.01° resolution using an IHDA method. The overall flowchart is shown in Fig. 3. First, 0.05° clear-sky FY-4A and resampled MxD11A1 directional LST products were matched and bias corrected for solving the unknown parameters of TEKDM using auxiliary information of viewing geometry and local time. For the generation of T_{nadir} and T_{hemi} from FY-4A T_{dir} , the KDM coefficients were temporally aggregated over a 17-day window to ensure a complete spatial coverage of the FY-4A disk. Second, clear-sky T_{dir} , T_{nadir} , and T_{hemi} during the day, as well as nighttime FY-4A LST (where $T_{dir} = T_{nadir} = T_{hemi}$ due to the negligible angular effect at night) were used as training labels to predict the hypothetical clear-sky LST under cloudy conditions. A Bayesian optimization-based categorical boosting (CatBoost) model was trained using auxiliary input variables described in Subsection 2.1. The training samples were spatially determined using a widely used conditioned Latin hypercube sampling (cLHS) approach. The predicted hypothetical clear-sky LST requires a CRF correction using the cloudless and cloudy radiation budget variables, ultimately yielding the cloudy-sky T_{dir} , T_{nadir} , and T_{hemi} . In the third step, the 0.05° all-weather LST was downscaled to 0.01° resolution using a proposed IHDA method. This approach downscales the LST difference

(Δ LST) between the 0.05° all-weather LST and the $0.05^\circ T_{ATC,d2}$ at the reference time (i.e., 13:30) using another CatBoost model. After predicting three Δ LSTs at 0.01° resolution and applying a residual redistribution procedure, the final
280 downscaled $0.01^\circ \Delta$ LSTs was obtained. The final 0.01° all-weather T_{dir} , T_{nadir} , and T_{hemi} were derived by summing their own
downscaled $0.01^\circ \Delta$ LST with the corresponding 0.01° ATC-simulated LST.

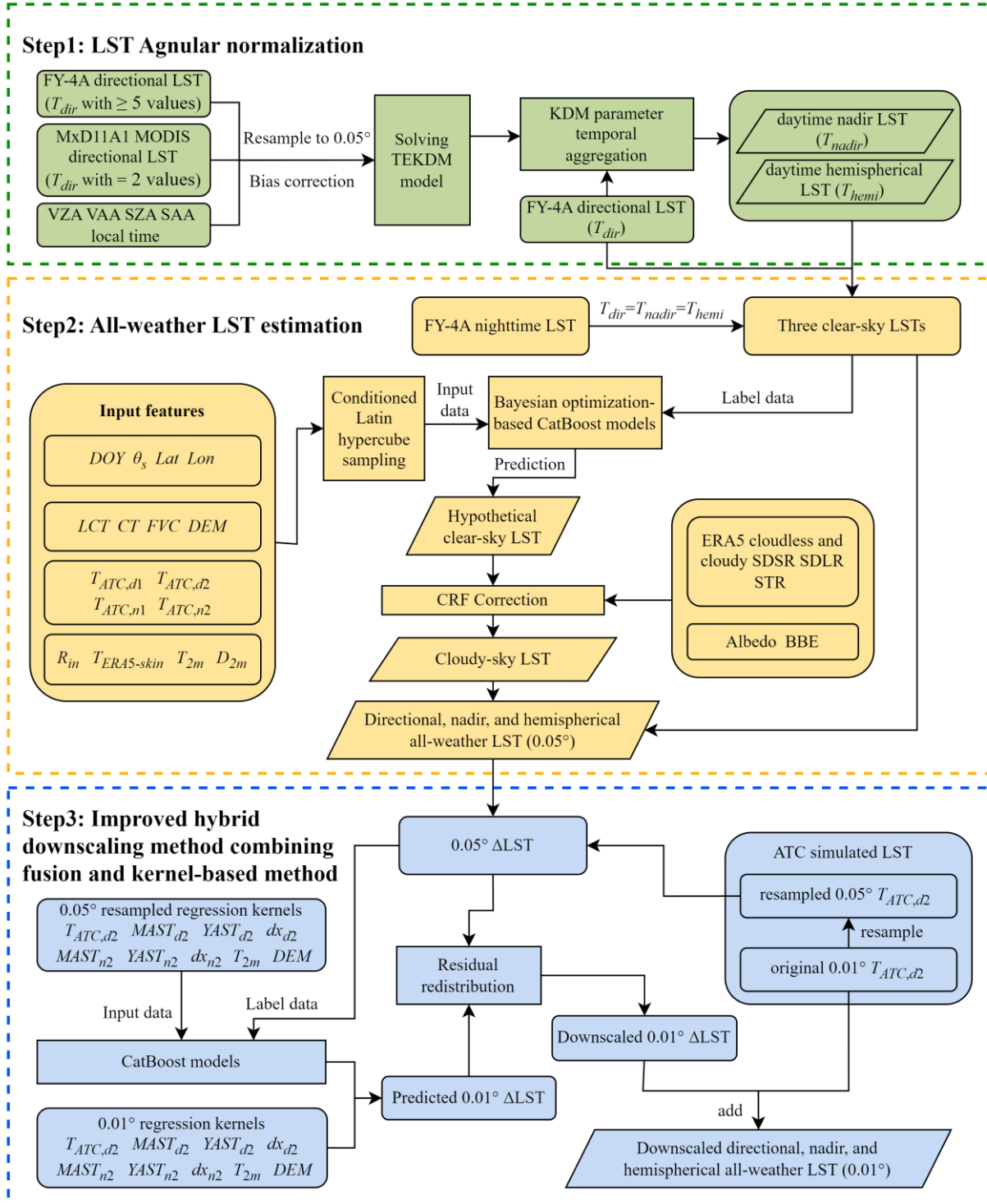


Figure 3: The overall workflow in this study.

3.1 Angular normalization of clear-sky LST

285 The FY-4A LST disk has different viewing geometries for each pixel, and these values need to be normalized to a reference direction before subsequent applications. The KDM offers a solution by simulating the LST angular distribution through a linear combination of several kernel functions. However, traditional KDM typically requires three or four simultaneous clear-sky LST observations to calibrate the unknown kernel coefficients, which cannot be satisfied by FY-4A satellite. To enhance its applicability, Qin et al. (2023, 2025) proposed a time-evolving KDM (TEKDM) by coupling a diurnal temperature cycle (DTC) model (i.e., depicting LST temporal variation) and a KDM model (i.e., depicting LST angular variation) as shown in Eq. 5. Based on this TEKDM model, Na et al. (2024b) further estimated daytime nadir LST using GOES-16 and MODIS LST products, and obtained a significantly improved accuracy.

$$T_{dir}(t, \theta_s, \theta_v, \Delta\varphi) = f_{iso}(t) \times \left[1 + \alpha \cdot K_{GapFraction}(\theta_v) + \beta \cdot \cos \theta_s \cdot K_{Hotspot}(\theta_s, \theta_v, \Delta\varphi, W) \right] \quad (5)$$

where $T_{dir}(t, \theta_s, \theta_v, \Delta\varphi)$ represents the directional LST observed at the local time of t , with the solar zenith angle (SZA) of θ_s , the VZA of θ_v , and the relative azimuth angle (RAA) of $\Delta\varphi$. The term $f_{iso}(t)$ is the isotropic kernel coefficient. The coefficients α and β are unknowns corresponding to the gap fraction kernel ($K_{GapFraction}$) and hotspot kernel ($K_{Hotspot}$), respectively. W is another unknown parameter related to the hotspot width. The temporal dynamics of isotropic kernel coefficient (i.e., $f_{iso}(t)$) during daytime can be effectively modeled using a DTC model as given in Eq. 6:

$$f_{iso}(t) = T_0 + T_a \times \cos \left[\frac{\pi}{\omega} \cdot (t - t_m) \right] \quad (6)$$

300 where T_0 is the temperature at sunrise, T_a represents the amplitude of daily LST variation, ω is the length of the daytime period, t_m is the local time when the LST reaches its maximum. The nighttime LST was not processed here, as the angular effect is generally negligible during nighttime. In this study, the LSF kernel and the Chen kernel were selected to represent $K_{GapFraction}$ and $K_{Hotspot}$ respectively, as shown in Eq. 7-9.

$$K_{GapFraction}(\theta_v) = K_{LSF}(\theta_v) = \frac{1 + 2 \cos \theta_v}{\sqrt{0.96 + 1.92 \cos \theta_v}} - \frac{1}{4} \cdot \frac{\cos \theta_v}{1 + 2 \cos \theta_v} + 0.15 \cdot \left(1 - e^{\frac{-0.75}{\cos \theta_v}} \right) - 1.0304 \quad (7)$$

$$305 \quad K_{Hotspot}(\theta_s, \theta_v, \Delta\varphi, W) = K_{Chen}(\theta_s, \theta_v, \Delta\varphi, W) = e^{\frac{-\xi}{\pi \cdot W}} \quad (8)$$

$$\xi = \arccos(\cos \theta_v \cdot \cos \theta_s + \sin \theta_v \cdot \sin \theta_s \cdot \cos \Delta\varphi) \quad (9)$$

where ξ is the angular distance between the viewing direction and the solar direction. The TEKDM involves seven unknown parameters to be calibrated: T_0 , T_a , ω , t_m , α , β , and W , therefore, at least seven clear-sky daytime observations are required as inputs. To enhance the angular information content of the input data, two daytime clear-sky MODIS observations (i.e.,

310 TERRA and AQUA) were utilized. Then, the TEKDM can be solved for the condition with ≥ 5 clear-sky FY-4A observations. A “trust-region-reflective” algorithm was employed for the non-linear optimization of Eq. 5, with initial values and parameter boundaries set according to Qin et al. (2025). Then, a 17-day moving average (i.e., covering 8 days before and after the target day) was applied to the parameters of α , β , and W for each pixel for two purposes: filling gaps in pixels with fewer than seven observations, and reducing the impact of outliers in the estimated TEKDM parameters. As shown in Eq. 10, 315 the LST at any direction (i.e., the $T_{dir}(t, \theta_s, \theta_v, \Delta\varphi)$) can be simulated with the inputs of FY-4A direction LST (i.e., $T_{dir}(t, \theta_s, \theta_v^{FY}, \Delta\varphi^{FY})$ and averaged α , β , and W parameters.

$$\frac{T_{dir}(t, \theta_s, \theta_v, \Delta\varphi)}{T_{dir}(t, \theta_s, \theta_v^{FY}, \Delta\varphi^{FY})} = \frac{1 + \alpha \cdot K_{LSF}(\theta_v) + \beta \cdot \cos \theta_s \cdot K_{Chen}(\theta_s, \theta_v, \Delta\varphi, W)}{1 + \alpha \cdot K_{LSF}(\theta_v^{FY}) + \beta \cdot \cos \theta_s^{FY} \cdot K_{Chen}(\theta_s, \theta_v^{FY}, \Delta\varphi^{FY}, W)} \quad (10)$$

Specifically, the nadir LST can be derived when setting $\theta_v = 0^\circ$ as shown in Eq. 11:

$$T_{nadir}(t, \theta_s, 0^\circ, \Delta\varphi) = T_{dir}(t, \theta_s, \theta_v^{FY}, \Delta\varphi^{FY}) \cdot \frac{1 + \alpha \cdot K_{LSF}(0^\circ) + \beta \cdot \cos \theta_s \cdot K_{Chen}(\theta_s, 0^\circ, \Delta\varphi, W)}{1 + \alpha \cdot K_{LSF}(\theta_v^{FY}) + \beta \cdot \cos \theta_s^{FY} \cdot K_{Chen}(\theta_s, \theta_v^{FY}, \Delta\varphi^{FY}, W)} \quad (11)$$

320 Correspondingly, the normalized hemispherical LST (T_{hemi}) could be calculated through the integration as shown in Eq. 12.

$$T_{hemi}(t, \theta_s) = \left(\frac{1}{\pi} \cdot \int_0^{2\pi} \int_0^{\pi/2} T_{dir}^4(t, \theta_s, \theta_v, \Delta\varphi) \cdot \cos \theta_v \cdot \sin \theta_v d\theta_v d\varphi_v \right)^{\frac{1}{4}} \\ = \frac{T_{dir}(t, \theta_s, \theta_v^{FY}, \Delta\varphi^{FY}) \cdot \left(\int_0^{2\pi} \int_0^{\pi/2} (1 + \alpha \cdot K_{LSF}(\theta_v) + \beta \cdot \cos \theta_s \cdot K_{Chen}(\theta_s, \theta_v, \Delta\varphi, W))^4 \cdot \cos \theta_v \cdot \sin \theta_v d\theta_v d\varphi_v \right)^{\frac{1}{4}}}{\pi \cdot (1 + \alpha \cdot K_{LSF}(\theta_v^{FY}) + \beta \cdot \cos \theta_s^{FY} \cdot K_{Chen}(\theta_s, \theta_v^{FY}, \Delta\varphi^{FY}, W))} \quad (12)$$

To accelerate the computation of T_{hemi} , the integral in the numerator of Eq. 12 was approximated using a third-order polynomial fit based on the input variables of α , β , W , θ_s and K_{Chen} at nadir. More details about the integration procedure are provided in Appendix A. As shown in Fig. A1, this polynomial approximation substantially reduces computational cost 325 while introducing an uncertainty of less than 0.1 K.

3.2 All-weather LST estimation method

The all-weather LST estimation method consists of two main sub-steps. First, a hypothetical clear-sky LST was predicted using a Bayesian optimization-based CatBoost model. Second, the CRF correction was applied to estimate the cloudy-sky LST, ultimately producing cloud-filled 0.05° all-weather directional, nadir, and hemispherical LST.

330 ML-based LST reconstruction methods have been widely used because it could accurately simulate the non-linear correlation between the hypothetical clear-sky LST and vegetative, meteorological, and topographical parameters (Li et al.,

2024a; Ma et al., 2024a; Zhang et al., 2024). The CatBoost is a recently developed model based on the traditional gradient-boosting decision tree (GBDT) framework with several enhancements: 1) Ordered target statistics, which encode categorical features without target leakage by using permutation-based strategies; 2) Ordered boosting, which minimizes gradient bias by employing permutation-driven training to reduce overfitting; 3) Oblivious trees, which apply the same splitting criterion across all nodes at each level, thereby improving speed and regularization (Prokhorenkova et al., 2018). These improvements enhance the model’s robustness and efficiency, especially when handling large-scale datasets containing categorical variables, and have proven effective in LST reconstruction studies (Dai et al., 2025). Here, the CatBoost model was used to capture the complex non-linear relationship (i.e., f_{clr}) between hypothetical clear-sky LST and auxiliary parameters, as represented in Eq. 13.

$$T_{clr} = f_{clr} \left(DOY, \theta_s, Lat, Lon, LCT, CT, FVC, DEM, T_{ATC,d1}, T_{ATC,d2}, T_{ATC,n1}, T_{ATC,n2}, R_{in}, T_{ERA5-skin}, T_{2m}, D_{2m} \right) \quad (13)$$

where the input features include the geolocation and temporal parameters, such as the DOY , θ_s , latitude (Lat), longitude (Lon). The other parameters in Eq. 13 have been introduced in Table 1. It should be noted that the reanalysis variables are introduced to abundant the spatial texture that was not captured by satellite sensors, rather than to replace satellite information. The primary observational constraint remains the official FY-4A LST products. The clear-sky LST values remain unchanged, and also act as the training labels for cloud-sky LST estimation.

The target labels consisted of daytime T_{dir} , T_{nadir} , and T_{hemi} , along with nighttime FY-4A LST from 2018/1/1 to 2023/12/31. A total of six ML models were trained on a year-by-year basis, rather than using a single model across multiple years. Each model is applied exclusively to data from its corresponding year, without temporal extrapolation to other periods. Considering the large volume of label data, a two-step approach was employed to determine the number and geolocation of sample points as introduced in Appendix B. As shown in Fig. B1, 37,000 locations distributed over the FY-4A disk were selected for each year. Then, the clear-sky LST and corresponding input features were extracted to train the CatBoost model in Eq. 13. To better align with the 0.25° spatial resolution of ERA5, a FY-4A pixel was strictly considered as clear-sky only when all surrounding pixels within a 5×5 neighbourhood were under clear-sky conditions. Six CatBoost models were trained for each year from 2018 to 2023. The average number of extracted samples per year was 138,817,085, which were randomly divided into training, testing, and Bayesian optimization sets in a ratio of 6:3:1. The Bayesian optimization method adjusted the CatBoost hyperparameters by reconstructing the posterior distribution of the cost function, defined as the average fitting RMSE from two-fold cross-validation. After the ML training, the CatBoost model can predict the hypothetical clear-sky T_{dir} , T_{nadir} , and T_{hemi} under cloudy-sky conditions, which requires CRF correction.

The core of the CRF correction lies in establishing the relationship between net radiation changes and CRF-induced LST changes, based on the surface radiation budget equation. The CRF-corrected LST is equal to the sum of hypothetical clear-sky LST with CRF-induced LST variation (i.e., ΔT_{CRF}). Considering that our aim is not to fully resolve the SEB equation, a

simplified analytical correction equation (Eq. 14) proposed by Zhang et al. (2024) was adopted for the CRF correction of T_{hemi} .

365

$$\gamma \cdot \Delta T_{CRF} = \Delta R_{in} - \varepsilon_{bb} \sigma_s \left[\left(T_{clr}^{hemi} + \Delta T_{CRF} \right)^4 - \left(T_{clr}^{hemi} \right)^4 \right] \quad (14)$$

where ΔT_{CRF} is the correction value for hemispherical LST; γ is an energy transfer parameter, which could be estimated by Eq. 15. A temporal median filter with a 17-day window and a spatial median filter with a 3×3 window were applied to replace outlier values in the calculation of γ . ΔR_{in} is the change in surface incoming radiation induced by the CRF effect, which could be estimated by Eq. 16; T_{clr}^{hemi} is predicted hypothetical clear-sky hemispherical LST using Eq. 13.

370

$$\gamma = \frac{\left[R_{in}(t_n) - R_{in}(t_{sr}) \right] - \varepsilon_{bb} \sigma_s \left[T_{clr}^{hemi}(t_n)^4 - T_{clr}^{hemi}(t_{sr})^4 \right]}{T_{clr}^{hemi}(t_n) - T_{clr}^{hemi}(t_{sr})} \quad (15)$$

$$\Delta R_{in} = (1 - Albedo) \cdot (SDSR_{clr} - SDR_{cld}) + \varepsilon_{bb} \cdot (SDLR_{clr} - SDLR_{cld}) \quad (16)$$

375

where R_{in} is the clear-sky surface incoming radiation calculated by Eq. 2. t_n and t_{sr} denote the noon time and sunrise time. The subscripts “clr” or “cld” indicate that the parameter is under hypothetical clear-sky or actual cloudy-sky conditions. After the determination of γ and ΔR_{in} , the only unknown parameter ΔT_{CRF} in Eq. 14 can be estimated. Here, it was analytically solved through neglecting its quartic and cubic terms (see Eq. 17).

$$6\varepsilon_{bb}\sigma_s \left(T_{clr}^{hemi} \right)^2 \Delta T_{CRF}^2 + \left(\gamma + 4\varepsilon_{bb}\sigma_s \left(T_{clr}^{hemi} \right)^3 \right) \Delta T_{CRF} - \Delta R_{in} = 0 \quad (17)$$

380

After the pixel-by-pixel estimation of ΔT_{CRF} , the mean (μ_{CRF}) and standard deviation (σ_{CRF}) of ΔT_{CRF} could be calculated for each image. To reduce the impact of extreme values, the maximum and minimum limits of ΔT_{CRF} were set to $\mu_{CRF} \pm 3\sigma_{CRF}$. In the end, the cloudy-sky T_{dir} , T_{nadir} , and T_{hemi} are obtained by summing CatBoost-estimated hypothetical clear-sky LST (i.e., using Eq. 13) and ΔT_{CRF} (i.e., using Eq. 17).

3.3 IHDA combining fusion- and kernel-based methods

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To meet the 1-km spatial resolution and 1-hour temporal resolution requirement of GCOS, downscaling methods have garnered more and more attention for enhancing the spatial textures of low-resolution LST products (e.g., FY-4A LST). Fusion-based downscaling approaches typically require high-resolution LST data as input, whereas kernel-based methods require LST-related auxiliary data (i.e., regression kernels). Combining fusion-based and kernel-based downscaling methods could achieve higher accuracy than using either method alone (Li et al., 2023b; Xia et al., 2019). Dong et al. (2023b) recently proposed a simple and effective downscaling (SED) method that utilizes clear-sky, high-resolution Landsat 8 LST at an initial time to downscale low-resolution MODIS data at a target time. However, this requirement is difficult to be satisfied

over the full-disk region due to the frequent presence of clouds. To address this limitation, an IHDA method is proposed leveraging the ATC-fitted spatiotemporal trend surface of LST (Liang et al., 2025). First, the ATC model is adopted to estimate gap-free LST at the initial time of 13:30 ($T_{ATC,d2}$) using Eq. 1 with the driven data of MYD11A1 LST products. Although ATC model may introduce additional uncertainty, recent studies have shown that incorporating meteorological data can further reduce the modeling residuals (Liu et al., 2019; Yang et al., 2024). Here, a CatBoost model is employed to establish the non-linear relationship (i.e., $f_{downscale}$) between the resampled 0.05° regression kernels and the 0.05° LST bias (i.e., $\Delta LST_{0.05} = T_{0.05} - T_{ATC,d2}$, where $T_{0.05}$ is the 0.05° all-weather LST at the target time to be downscaled) as shown in Eq. 18.

$$\Delta LST_{0.05} = f_{downscale} \left(T_{ATC,d2}, MAST_{d2}, YAST_{d2}, dx_{d2}, MAST_{n2}, YAST_{n2}, dx_{n2}, T_{2m}, DEM \right) \quad (18)$$

The ATC parameters of daytime (13:30) and nighttime (01:30) MODIS LST were included as regression kernels to characterize surface thermal properties. Additionally, ERA5-Land air temperature (i.e., T_{2m}) was incorporated to capture cloud information, whereas the DEM was introduced to represent the topographic information. For model training, two typical days (i.e., the mid-month of January in winter and July in summer) were initially used to tune the hyperparameters of the CatBoost model using a Bayesian optimization approach. Then, the $f_{downscale}$ was established individually for each image, covering 157,680 images in total (i.e., 6 years $\times$ 365 days $\times$ 24 hours $\times$ 3 types of LST). For each image, 70% of the samples were used to train the CatBoost model, while the remaining 30% were reserved for testing. The 0.01° LST difference ($\Delta LST_{0.01}^{pred}$) was then predicted using the trained CatBoost model with 0.01° regression kernels as input:

$$\Delta LST_{0.01}^{pred} = f_{downscale} \left(T_{ATC,d2}^{0.01}, MAST_{d2}^{0.01}, YAST_{d2}^{0.01}, dx_{d2}^{0.01}, MAST_{n2}^{0.01}, YAST_{n2}^{0.01}, dx_{n2}^{0.01}, T_{2m}^{0.01}, DEM^{0.01} \right) \quad (19)$$

where the “0.01” means the input features are in 0.01° resolution. Finally, a residual redistribution process was applied to produce the final $\Delta LST_{0.01}$ as shown in Eq. 20.

$$\Delta LST_{0.01} = \Delta LST_{0.01}^{pred} + \left(\Delta LST_{0.05} - \Delta LST_{0.05}^{pred} \right)_{0.01} \quad (20)$$

where $\Delta LST_{0.05}$ represents the difference between the 0.05° all-weather LST and the ATC-simulated LST. $\Delta LST_{0.05}^{pred}$ means the 0.05° LST difference obtained by aggregating the predicted $\Delta LST_{0.01}^{pred}$. The second term on the right-hand side of Eq. 20 is the CatBoost modeling residual to be redistributed. A 3×3 median filter was applied to reduce the impact of extreme outliers in the residuals. The notation $(\cdot)_{0.01}$ indicates the process that the 0.05° residual (i.e., $\Delta LST_{0.05} - \Delta LST_{0.05}^{pred}$) was resampled to 0.01° using the widely used bilinear interpolation. Finally, the downscaled 0.01° all-weather directional, nadir, and hemispherical LST ($T_{0.01}$) could be calculated by summing the 0.01° ATC simulated LST at initial time ($T_{ATC,d2}(0.01^\circ)$) and the Eq. 20 estimated $\Delta LST_{0.01}$ as below.

$$T_{0.01} = T_{ATC,d2}(0.01^\circ) + \Delta LST_{0.01} \quad (21)$$

4 Results

4.1 Results of angular normalization

Fig. 4 shows the spatial distributions of FY-4A directional LST (T_{dir}), FY-4A VZA, normalized nadir LST (T_{nadir}), the LST difference between T_{nadir} and T_{dir} , hemispherical LST (T_{hemi}), and the difference between T_{hemi} and T_{dir} on 2020/6/24 at the UTC time of 3:00 (i.e., the Beijing time of 11:00). As shown in Fig. 4c, T_{nadir} is 1.5 K larger than T_{dir} on average. It closely resembles T_{dir} (with a small value of $T_{nadir}-T_{dir}$) when the VZA is within 40° , and becomes significantly higher than T_{dir} as VZA increases, with a correction value of $T_{nadir}-T_{dir}$ exceeding 5 K near the edge of the FY-4A disk as shown in Fig. 4d.

When the VZA is small, the observation angle of FY-4A is close to the nadir direction, resulting in a small correction value from T_{dir} to T_{nadir} . However, more cool vegetated elements were viewed at large VZA (i.e., the well-known gap fraction effect), which resulted in a much lower T_{dir} compared to T_{nadir} and further led to a larger angular correction value. For hemispherical LST, the T_{hemi} (Fig. 4e) is only 0.2 K higher than T_{dir} on average. It is approximately 2 K lower than T_{dir} (Fig. 4a) in Australia, while is very close to T_{dir} in the northern China. At the edge of the FY-4A disk, T_{hemi} is around 3 K higher than T_{dir} (where the VZA exceeds 60° , see Fig. 4b, 4f). This spatial pattern can be partially explained by the value of the hemispherical equivalent angle (i.e., the VZA at which $T_{dir} = T_{hemi}$), which has been reported to range from 44° to 53° in relevant studies (Hu et al., 2023; Zhang et al., 2025). When the VZA is smaller than 44° , T_{dir} tends to be higher than T_{hemi} due to more hotter soil component was viewed. Conversely, for the large VZAs over 53° (e.g., at the edge of FY-4A disk), T_{dir} becomes lower than T_{hemi} as more cooler vegetation component was viewed.

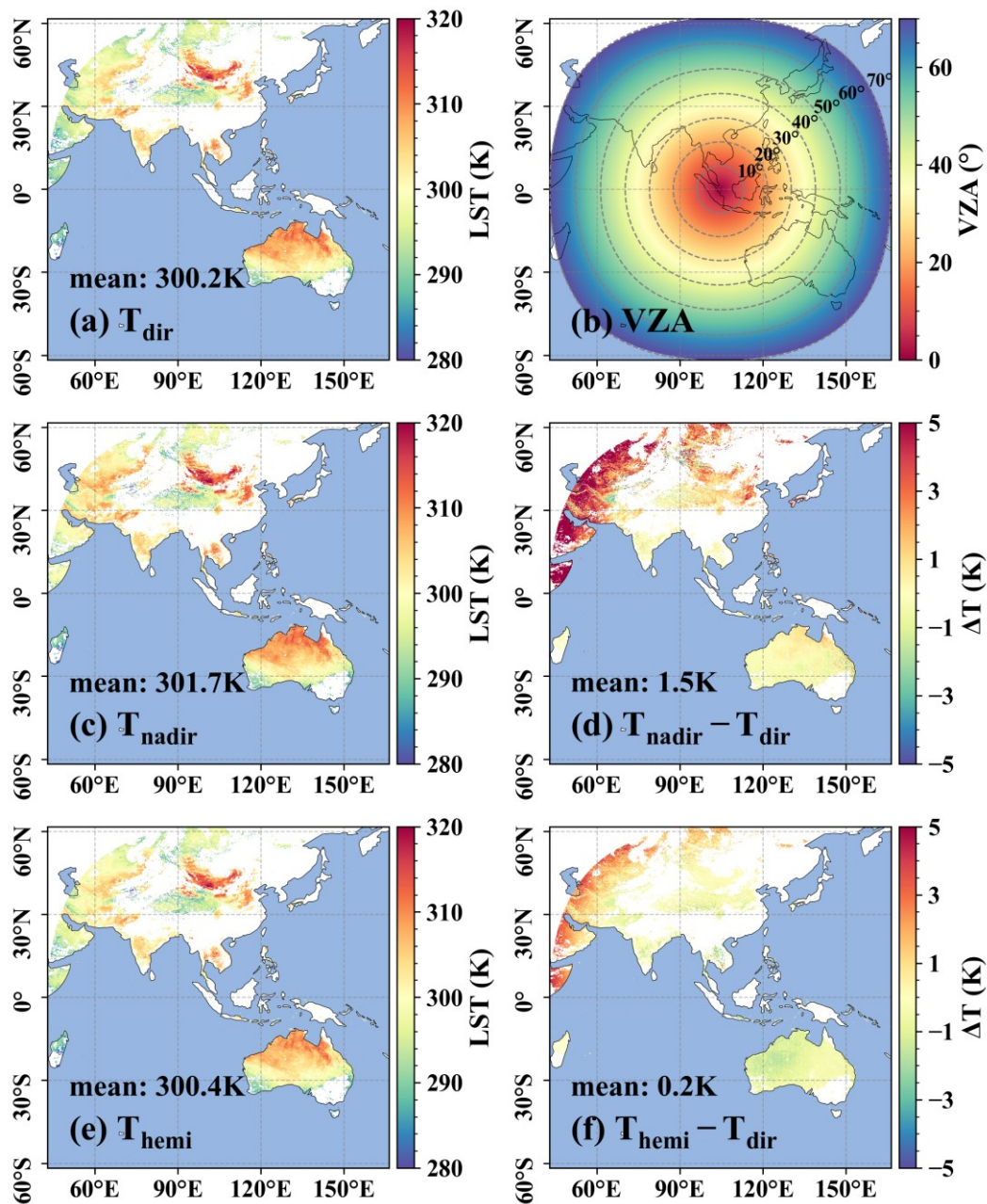


Figure 4: The spatial distribution of (a) directional LST, (b) VZA, (c) nadir LST, (d) LST difference between nadir and directional LST, (e) hemispherical LST, and (f) LST difference between hemispherical and directional LST on 2020/6/24 at the UTC time of 3:00.

There will be significant inconsistencies in directional LST between FY-4A and MODIS due to the TRD effect. Fig. 5a quantifies this discrepancy by presenting the RMSD between FY-4A and MOD11A1 directional LST. After correcting both two LSTs to nadir values, the corresponding RMSD is shown in Fig. 5b. The average RMSD across the full FY-4A disk

decreases from 3.26 K to 2.12 K, representing a reduction of 1.14 K (35.0%). The extremely high values near the western edge of the disk are substantially reduced after correction. However, relatively high values over the western Qinghai–Tibetan Plateau persist, which may be partly attributed to the limitation of the employed LSF-Chen model, as it is derived under the assumption of flat terrain. Overall, the TEKDM demonstrates strong performance in reducing angular inconsistencies between LST products as expected.

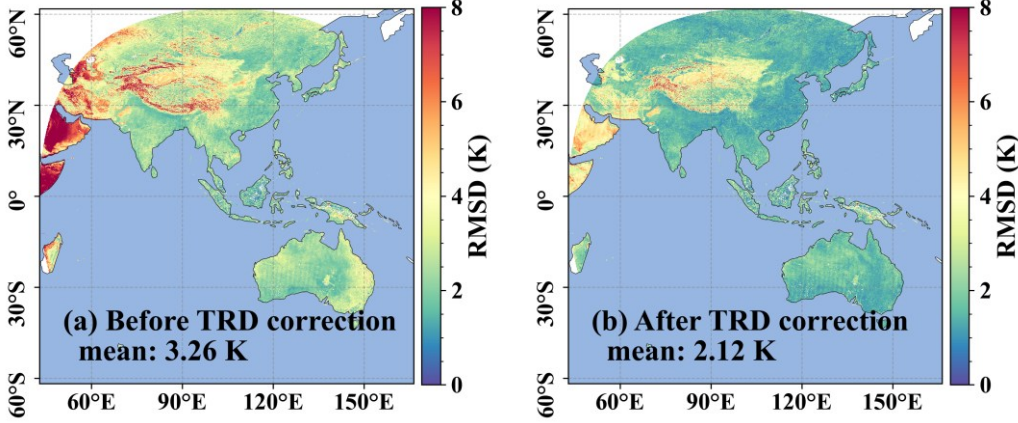
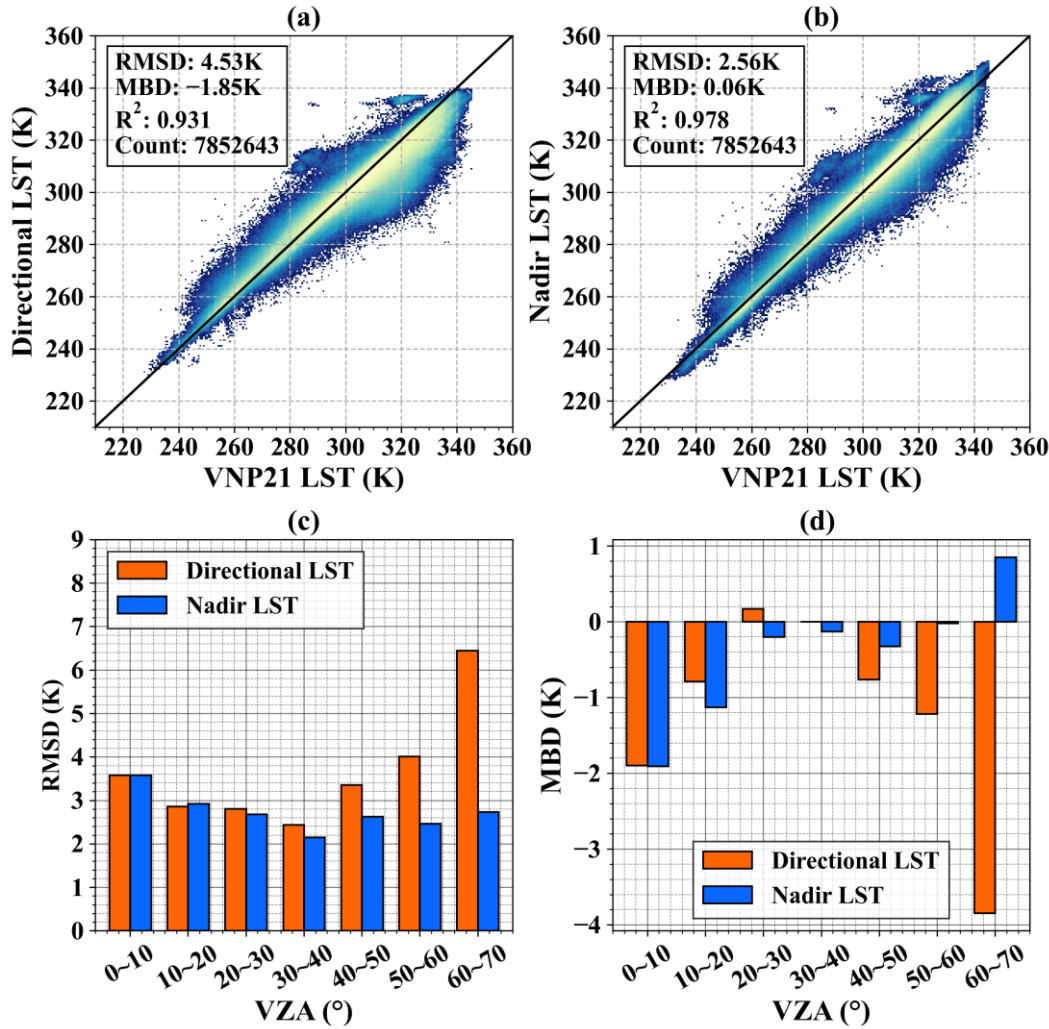


Figure 5: Spatial distribution of RMSD between FY-4A and MODIS (a) before and (b) after TRD correction.

The cross-validation between FY-4A T_{dir} , T_{nadir} , and the VNP21A1 near-nadir LST (i.e., the $VZA < 5^\circ$) in 2020 is shown in Fig. 6. The root mean squared difference (RMSD) and mean bias difference (MBD) are 4.53 K and -1.85 K for T_{dir} as shown in Fig. 6a. After angular normalization, the RMSD and MBD for T_{nadir} is 2.56 K and 0.06 K as shown in Fig. 6b, with a 1.97 K (i.e., 43.5%) reduction in RMSD and almost unbiased for MBD. Fig. 6c shows the RMSD values of T_{dir} and T_{nadir} across different VZA intervals with a step of 10° . The RMSD difference between them remains within 0.2 K when VZA is less than 40° . However, when VZA exceeds 40° , the RMSD for T_{dir} increases substantially (from 3.4 K to 6.5 K), while the RMSD for normalized T_{nadir} remains lower than 3.0 K for large VZA. The higher RMSD of T_{dir} at large VZA can be partially attributed to its significant underestimation as shown in Fig. 6d. The MBD of T_{dir} exceeds -3.8 K when the VZA is between 60° and 70° , whereas it is 0.9 K for the normalized T_{nadir} . The gap fraction effect could explain this angular dependence of MBD, i.e., a larger VZA leads to a smaller T_{dir} compared with nadir LST.



460 **Figure 6: The cross-validation of (a) directional and (b) nadir LST against VNP21 near-nadir LST at 0.05° resolution. The angular variation of (c) RMSD and (d) MBD for directional and nadir LST at 0.05° resolution.**

The evaluation of 0.05° FY-4A T_{dir} and T_{hemi} during daytime over 8 stations is shown in Fig. 7a-b. Results show that the RMSE decreased from 2.22 K to 2.00 K, with an improvement of 0.22 K. The MBE was reduced from 0.19 K to -0.54 K. For the temperatures between 280 K to 300 K with most densely distribution, the scatter points become closer to the 1:1 line after the angular normalization. Fig. 7c-d shows the RMSE and MBE of FY-4A T_{dir} and T_{hemi} at different local times. T_{dir} exhibits a pronounced overestimation with higher RMSE in the morning, and an underestimation with smaller RMSE in the afternoon. After the angular normalization, the T_{hemi} shows significantly improved performance in the morning, with an RMSE reduced by approximately 0.4-0.8 K (Fig. 7c). As shown in Fig. 7d, the MBEs of T_{hemi} is much smaller than those of T_{dir} in the morning, with a maximum reduction of 1.7 K at 11:00.

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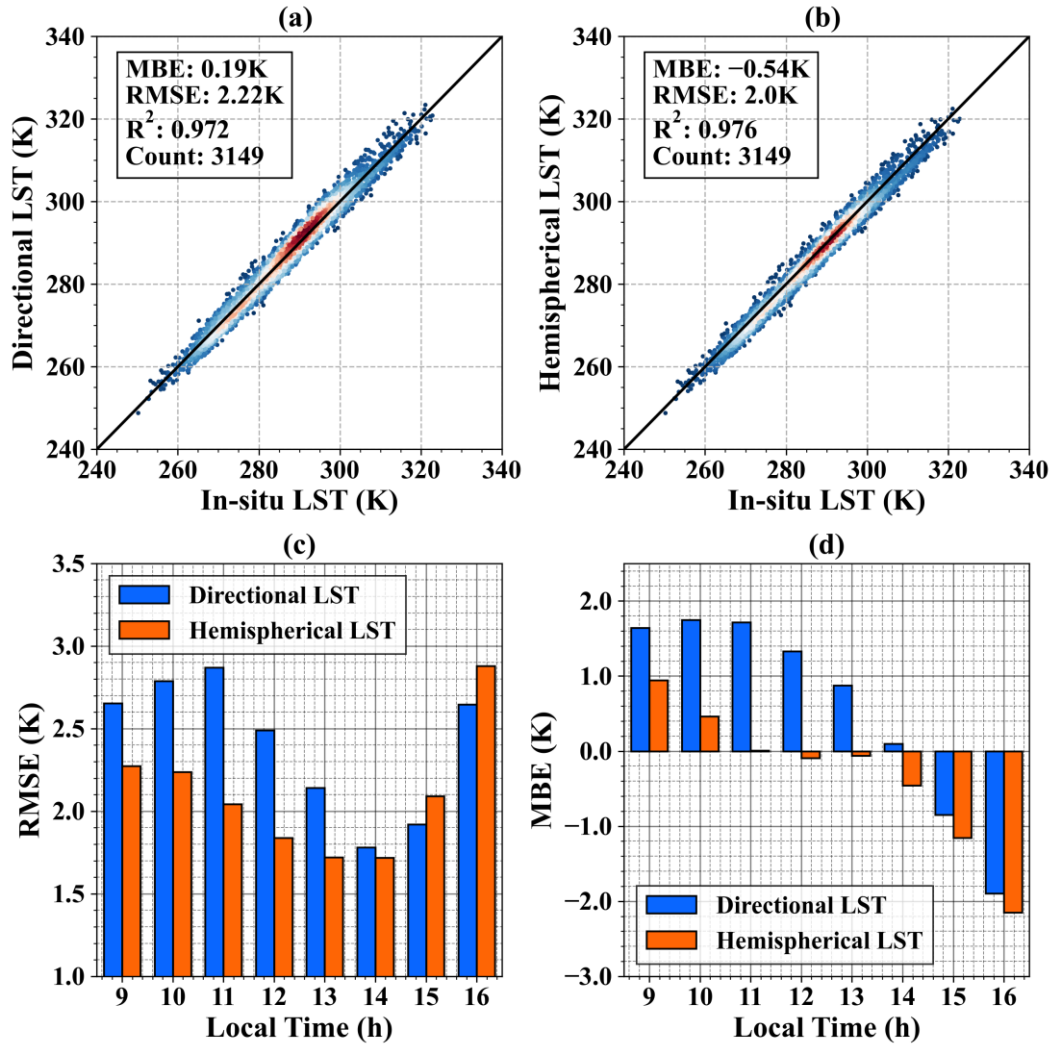


Figure 7: The accuracy of FY-4A (a) directional LST, (b) hemispherical LST, and the temporal variation of (c) RMSE and (d) MBE for directional and hemispherical LST.

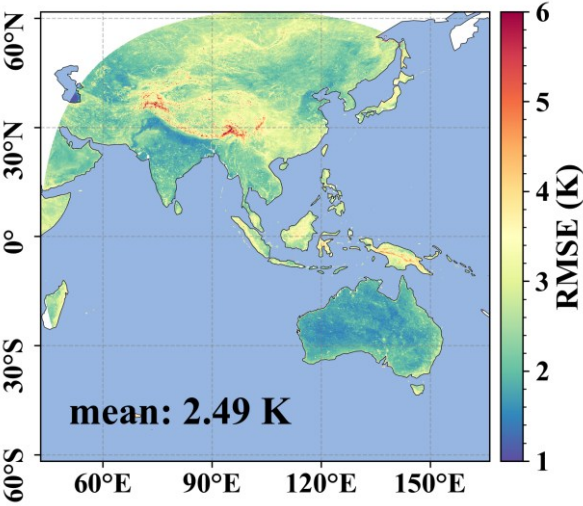
4.2 Results of all-weather LST estimation

The prediction accuracy of f_{clr} in reconstructing hypothetical clear-sky T_{dir} , T_{nadir} , and T_{hemi} over the test set from 2018 to 2023 is summarized in Table 3. The average annual sample size is 41,312,444. The RMSE ranges from 2.22 K to 2.46 K for T_{dir} , from 2.28 K to 2.52 K for T_{nadir} , and from 2.23 K to 2.46 K for T_{hemi} . RMSE values remain relatively stable from 2018 to 2021, followed by an increase of approximately 0.2 K in 2022 – 2023. On average, the RMSE for T_{dir} is 0.06 K lower than that for T_{nadir} , and is the same as that for T_{hemi} , indicating comparable fitting performance across different CatBoost models. The MBE is zero for all models, indicating that no significant systematic bias was introduced in the predicted hypothetical clear-sky LST.

Table 3. The prediction accuracy for reconstructing hypothetical clear-sky directional, nadir, and hemispherical LST

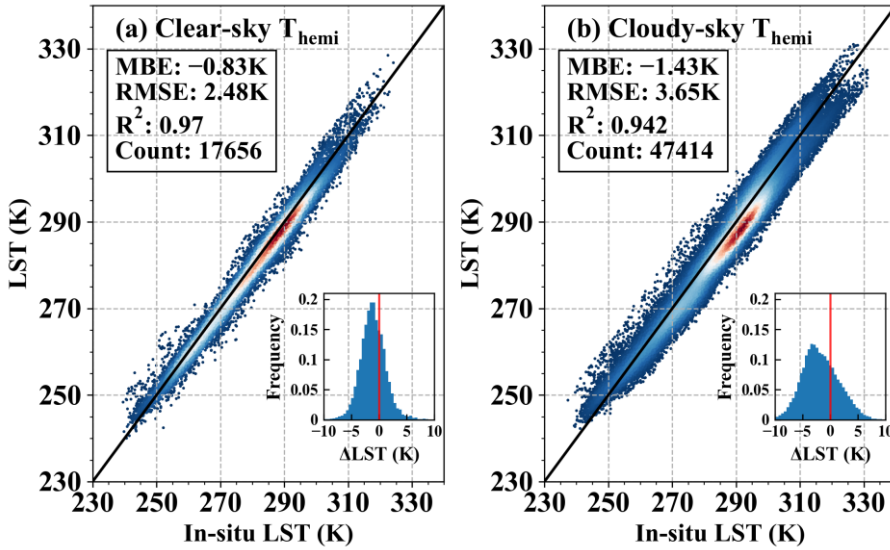
Year	RMSE (K)			MBE (K)			Counts
	T_{dir}	T_{nadir}	T_{hemi}	T_{dir}	T_{nadir}	T_{hemi}	
2018	2.22	2.28	2.23	0.00	0.00	0.00	40,534,869
2019	2.25	2.30	2.25	0.00	0.00	0.00	43,285,823
2020	2.27	2.34	2.28	0.00	0.00	0.00	41,883,982
2021	2.26	2.32	2.26	0.00	0.00	0.00	39,331,441
2022	2.46	2.52	2.46	0.00	0.00	0.00	41,833,769
2023	2.44	2.50	2.44	0.00	0.00	0.00	41,004,779
mean	2.32	2.38	2.32	0.00	0.00	0.00	41,312,444

485 Spatial heterogeneity in LST can lead to variations in model performance. The pixel-level RMSE of the CatBoost model for 2020 was evaluated by comparing the CatBoost-predicted hypothetical nadir LST with the FY-4A nadir LST. The nadir configuration is well suited for quantifying the performance of ML model, as it minimizes systematic uncertainties associated with angular effects. As shown in Fig. 8, the mean RMSE of the cloud-filling results is 2.49 K. Higher uncertainties are observed over regions such as the Qinghai–Tibet Plateau and the Indonesian Peninsula, which can likely be attributed to persistent cloud cover. In such regions, the reduced availability of clear-sky observations limits the training samples, leading to increased uncertainty in the machine learning models.



490 **Figure 8: Pixel-level prediction RMSE of the CatBoost model in 2020.**

The estimated 0.05° all-weather T_{hemi} results were further evaluated by the in-situ hemispherical LSTs from 8 in-situ stations (Fig. 9). The samples are divided into clear-sky (Fig. 9a) and cloudy-sky (Fig. 9b) conditions. The “ 3σ -Hampel identifier” method was applied to minimize the influence of outliers at each site. Both daytime and nighttime T_{hemi} values were considered here. Under clear-sky conditions, $0.05^\circ T_{hemi}$ shows an RMSE of 2.48 K and an MBE of -0.83 K. The distribution of residuals ($\Delta LST = T_{hemi} - T_{insitu}$) approximately follows a normal distribution. Under cloudy-sky conditions, T_{hemi} shows a higher RMSE of 3.65 K and a more significant negative MBE of -1.43 K. It is challenging to maintain the same level of accuracy under cloudy-sky conditions, as uncertainties in both the CatBoost-predicted hypothetical LST and the estimated ΔT_{CRF} are introduced.



500 **Figure 9: The accuracy of all-weather hemispherical LST under (a) clear-sky and (b) cloudy-sky condition.**

Fig. 10a-b show the temporal consistency of FY-4A official LST, T_{hemi} , and in-situ LST at the DM and SDQ sites throughout 2020 at 04:00 and 16:00 UTC (i.e., 12:00 and 00:00 Beijing time). Overall, the all-weather T_{hemi} aligns well with the in-situ LST. At the DM site during daytime (Fig. 10a), the clear-sky RMSE (MBE) of FY-4A official LST is 3.20 K (2.43 K), whereas the corresponding values for T_{hemi} are 2.15 K (0.46 K), indicating that the systematic overestimation is significantly mitigated after angular normalization. Similarly, at the SDQ site during daytime (Fig. 10b), the clear-sky RMSE (MBE) decreases from 4.77 K (4.02 K) for the FY-4A official LST to 3.60 K (2.55 K) for T_{hemi} . During nighttime, the clear-sky T_{hemi} is the same as FY-4A official LST, showing lower RMSE than in daytime. The RMSE (MBE) values are 2.38 K (-0.94 K) at the DM site and 2.2 K (-0.17 K) at the SDQ site. Under cloud-sky conditions, the RMSE (MBE) values are 3.54 K (-0.53 K) at the DM site and 4.09 K (1.97 K) at the SDQ site during daytime, and 4.58 K (-3.77 K) at the DM site and 3.46 K (-1.36 K)

510 at the SDQ site during nighttime. In summary, the all-weather LST could effectively capture the annual temperature cycle characteristics.

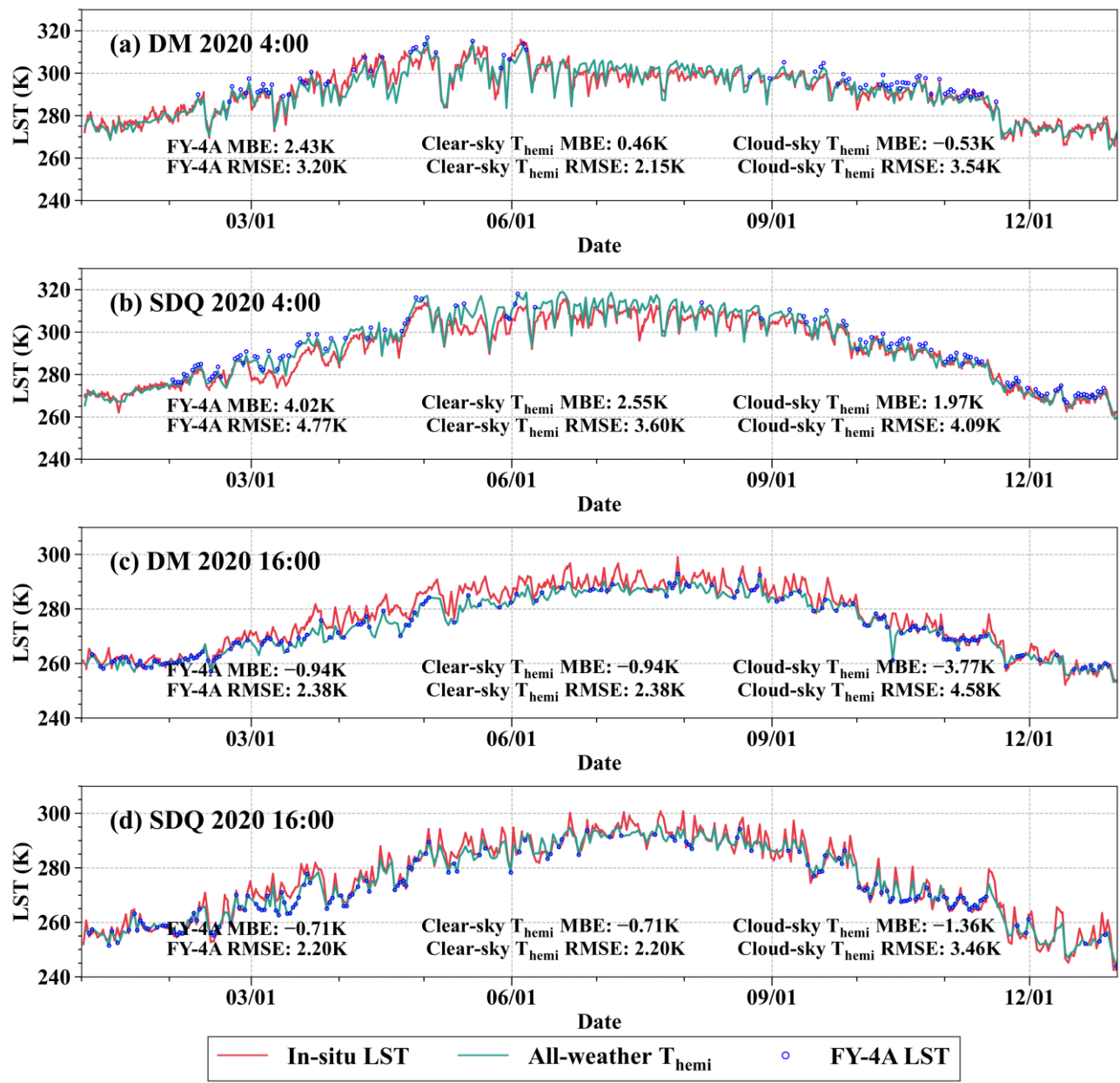


Figure 10: The temporal variation trend of in-situ LST, T_{hemi} , and FY-4A official LST in 2020 for (a) DM site at the UTC time of 4:00, (b) SDQ site at the UTC time of 4:00, (c) DM site at the UTC time of 16:00, (d) SDQ site at the UTC time of 16:00. Note that the clear-sky T_{hemi} is the same as FY-4A LST during nighttime because the TRD effect is ignored at night.

4.3 Results of spatial downscaling

In the spatial resolution downscaling process, the CatBoost model was used to establish the relationship between regression kernels and the LST difference (e.g., the satellite LST minus ATC-simulated LST) at 0.05° resolution. The prediction accuracy of each month over the test set from 2018/1/1 to 2023/12/31 for daytime and nighttime conditions is shown in Fig. 11. The nighttime RMSE ranges from 1.8 K to 2.4 K, which is consistently lower than the daytime RMSE (2.6 K – 3.1 K). This discrepancy can be partially attributed to the fact that daytime LST tends to be more heterogeneous than nighttime LST, leading to greater modeling errors during the day. The daytime RMSE increases from January to May and then decreases. In contrast, the nighttime RMSE decreases from January to July and then rises. The RMSE difference among directional, nadir, and hemispherical LST is within 0.2 K. Overall, the results demonstrate the reliable capability of the CatBoost model in the spatial resolution downscaling.

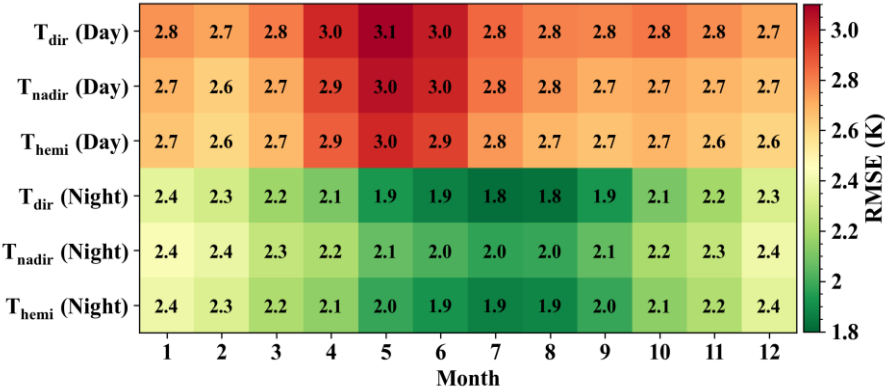


Figure 11: The prediction RMSE over test set for directional, nadir, and hemispherical LST during both day and night for each month.

The spatial distribution of prediction accuracy for the machine learning model during the downscaling process is presented in Fig. 12, where the RMSE is calculated between the CatBoost-estimated LST and the input all-weather nadir LST. The overall RMSE is 2.28 K, with higher values predominantly observed in mountainous regions, likely due to enhanced surface heterogeneity and elevation-induced variability. It should be noted that clear-sky pixels remain unchanged in the all-weather LST product; therefore, the ANCFDS-LST for these pixels is affected only by uncertainties introduced during the downscaling step. In contrast, for cloud-contaminated pixels, the final LST incorporates uncertainties arising from both the cloud-filling and downscaling processes.

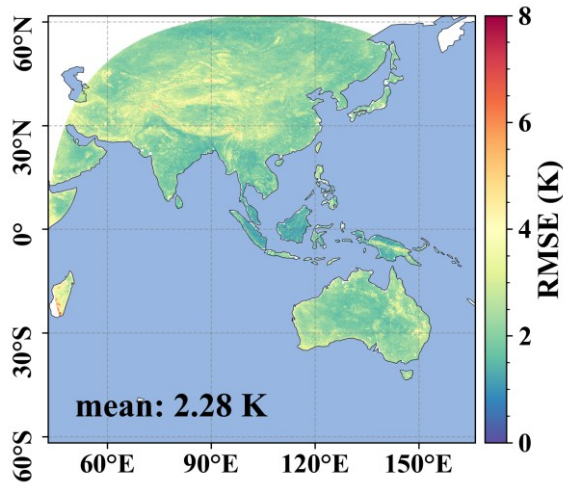


Figure 12: Spatial distribution of prediction RMSE for nadir LST over the test set in 2020.

Downscaled LST is expected to exhibit enhanced spatial texture, which is quantitatively evaluated in this study. The local variance ratio (LVR) and the structural similarity index (SSIM) were employed as metrics to compare the spatial textures of bilinearly interpolated LST (derived from 0.05° all-weather LST) and the downscaled 0.01° nadir LST. The reference texture was reconstructed using the ATC model, as interpolation-based ATC approaches have been shown to better preserve spatial texture characteristics (Jia et al., 2024). Texture similarity improves as LVR and SSIM approach 1. As shown in Fig. 13, the median LVR increases from 0.41 to 0.97, while the median SSIM improves from 0.91 to 0.94. These quantitative results demonstrate that the downscaled LST provides a substantially improved representation of spatial texture.

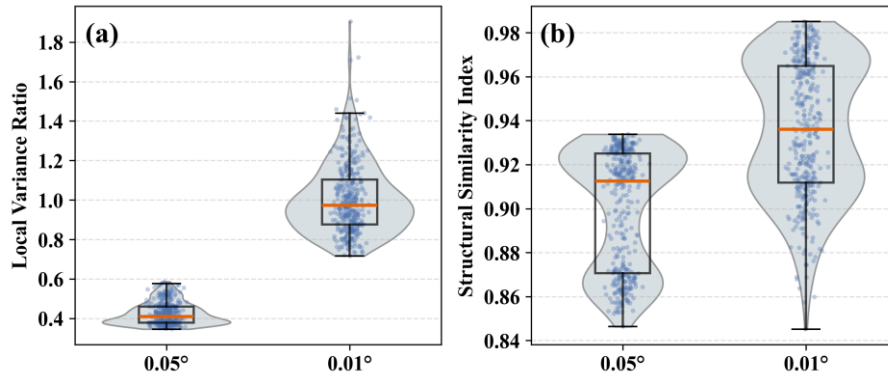


Figure 13: (a) Local variance ratio and (b) structural similarity index between bilinearly interpolated LST and the downscaled 0.01° nadir LST, with ATC-simulated LST used as the reference.

The spatial distributions of all-weather T_{nadir} and T_{hemi} at 0.05° and 0.01° resolutions on 2020/6/24 at 04:00 UTC (12:00 Beijing time) are presented in Fig. 14. Two representative regions are highlighted for detailed comparison: the western Tibetan Plateau (red rectangles in Fig. 14a–d) and the Greater Khingan Mountains (blue rectangles in Fig. 14a–d). As shown

in Fig. 14a–d, the large-scale spatial patterns of LST are well preserved after downscaling, with both T_{nadir} and T_{hemi} exhibiting clear latitudinal and elevational gradients (i.e., lower temperatures are consistently observed in high-latitude and high-altitude regions). The T_{hemi} integrates directional LST values over all viewing angles and thus generally showing smoother spatial variability than T_{nadir} . At finer scales (Fig. 14e–l), the downscaled results (0.01°) reveal substantially enhanced spatial details compared to the coarse-resolution counterparts. In particular, complex terrain features become more distinguishable, such as ridge–valley structures over the Tibetan Plateau and the heterogeneous forest–grassland patterns in the Greater Khingan Mountains. The contrast between sunlit and shaded slopes, as well as between higher and lower elevations, is more pronounced in the downscaled LST fields. These improvements in spatial texture and terrain-related variability demonstrate the effectiveness of the IHDA downscaling method in capturing fine-scale thermal heterogeneity.

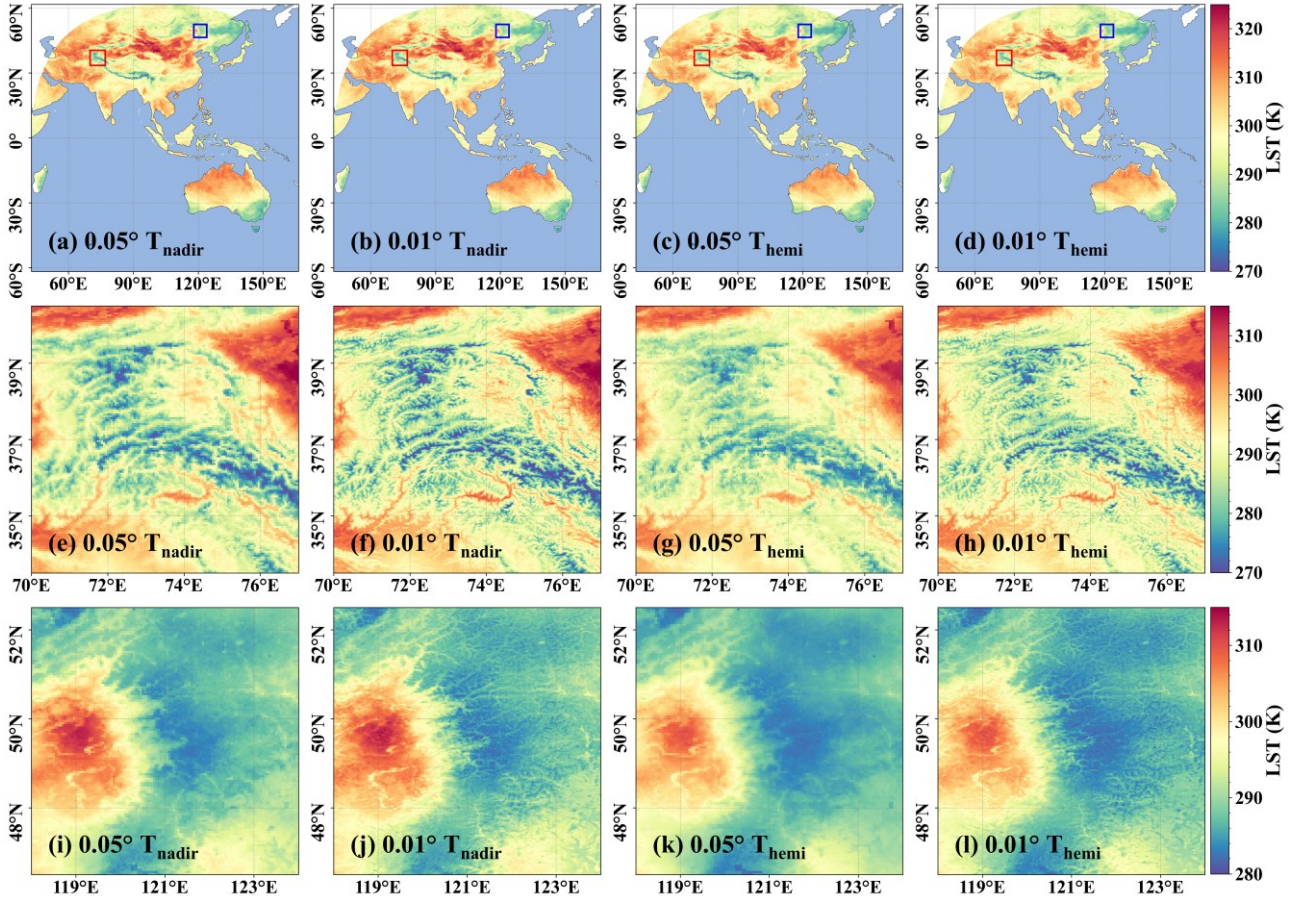


Figure 14: Spatial distributions of nadir LST at 0.05° (first column) and 0.01° (second column), and hemispherical LST at 0.05° (third column) and 0.01° (fourth column) at the UTC time of 4:00 on 2020/6/24. The first row shows LST over the FY-4A full disk, the second row over the western Qinghai–Tibetan Plateau, and the third row over the Greater Khingan Mountains.

5 Discussion

565 5.1 The temporal aggregation method for KDM parameters

In this study, a temporal aggregation method spanning 8 days before and after the target day (a total of 17 days) was employed to aggregate the KDM parameters (i.e., α , β , and W). It not only filtered out extreme values in the TEKDM results but also filled the gaps for pixels where TEKDM could not be solved. The 17-day compositing method was comprehensively compared with three other aggregation approaches: 1) 9-day composition: averaging values from four days before and after the target day (a total of 9 days). 2) Monthly composition (i.e., ~30 days in total): calculating the monthly average of KDM parameters, assuming they remain constant throughout each month. 3) Yearly composition (i.e., ~365 days in total): calculating the yearly average of KDM parameters, assuming they remain constant throughout the whole year. After calibrating the KDM parameters using each approach, FY-4A directional LST could be normalized to T_{nadir} . Then, the T_{nadir} result of 2020 were cross-validated using VNP21A1 near-nadir LST (i.e., $VZA < 5^\circ$) as did in Fig 6.

575 Fig. 15a-e shows the cross-validation result between the T_{dir}/T_{nadir} and VNP21A1 near-nadir LST, whereas Fig. 15f shows the fraction of valid pixels (i.e., the ratio of pixels with valid KDM parameters to the total number of land surface pixels) of above temporal aggregation methods. The RMSD (MBD) of the FY-4A official LST is 4.53 K (-1.85 K), while the RMSD (MBD) for the four compositing methods ranges from 2.53 K to 2.66 K (-0.12 K to 0.07 K). The RMSD in ascending order is monthly method < 17-day method < 9-day method < yearly method. In terms of valid pixel fractions, the order is the 9-day method (89.3%) < 17-day method (93.6%) < monthly method (95.9%) < yearly method (99.5%). The significant lower fractions for the 9-day and 17-day methods in 2020/8 (Fig. 15f) are due to the absence of MYD11A1 LST products between 2020/8/16 and 2020/8/31 (induced by a Formatter-Multiplexer Unit/Solid State Recorder (FMU/SSR) error, more details can be found at <https://atmosphere-imager.gsfc.nasa.gov/issues/11b#Issue01>). The yearly method was not adopted since it has the largest RMSD, whereas the 9-day method was not used since it has the lowest valid pixel fraction. The 17-day and monthly methods could achieve comparable and acceptable accuracy. The 17-day method was ultimately selected referenced to the parameter aggregation method in optical domain (Liu et al., 2013).

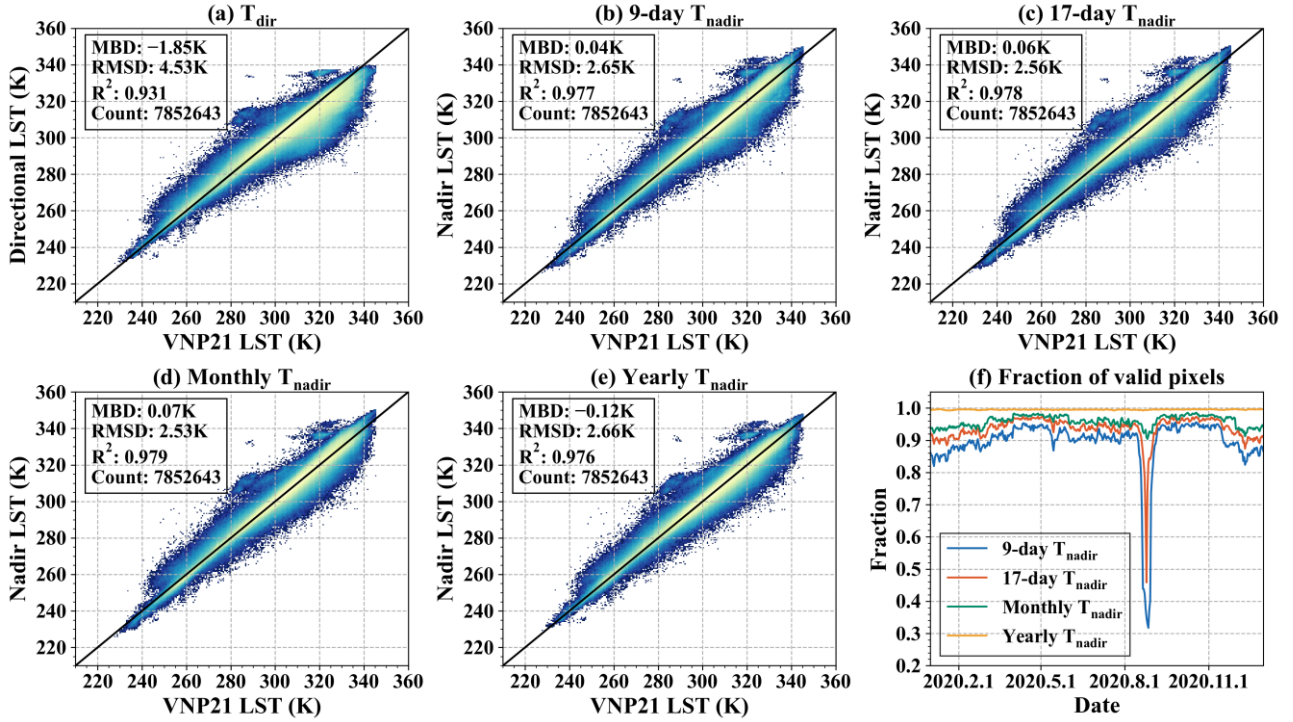
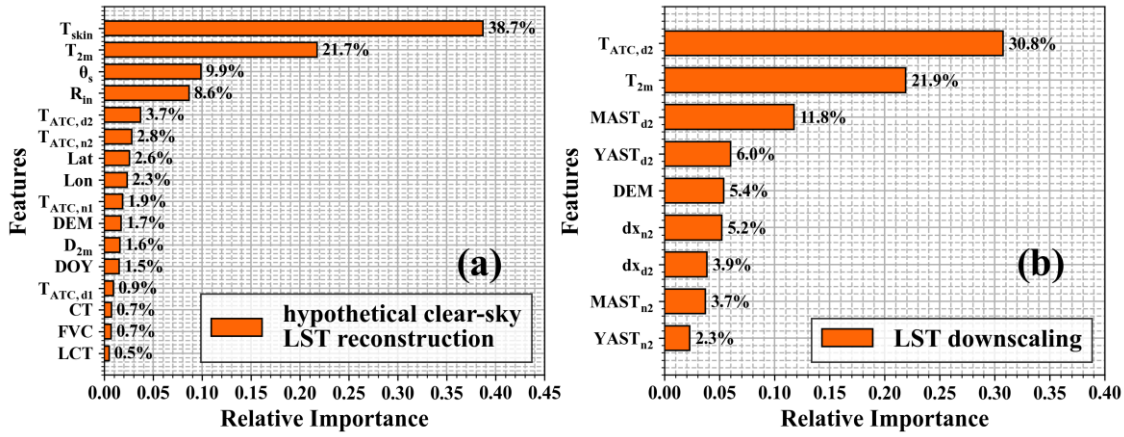


Figure 15: The cross-validation results of (a) FY-4A directional LST, (b) T_{nadir} generated using 9-day composition method, (c) using 17-day composition method, (d) using monthly composition method, (e) using yearly composition method. (f) The fraction of valid pixels for different composition methods.

5.2 Feature Importance for CatBoost models in hypothetical clear-sky LST estimation and LST downscaling

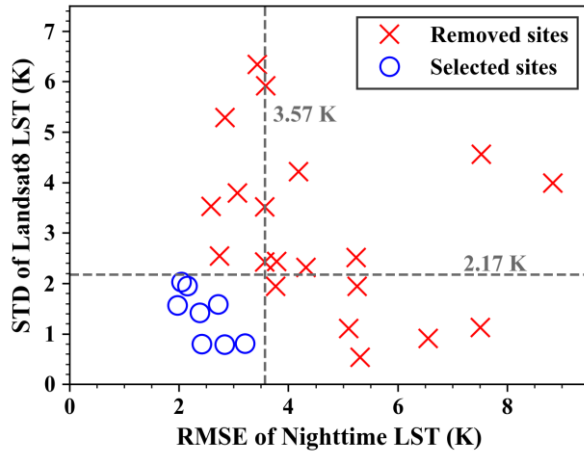
The relative feature importance of CatBoost model was determined based on each feature's contribution to the reduction of the loss function. We employed the logarithmic value of $(1 + \text{score}_{\text{norm}})$ to quantify the importance of each model (where $\text{score}_{\text{norm}}$ is the max-min normalized feature scores). The average relative feature importance across all CatBoost models is shown in Fig. 16. In the estimation of hypothetical clear-sky LST (Fig. 16a), $T_{ERA5-skin}$ exhibited the highest importance. The T_{2m} and R_{in} were also identified as influential predictors, aligning with the findings of Zhang et al. (2024). The θ_s accounted for a significant 9.9% of the importance, reflecting the strong influence of solar radiation on LST. Most other features had relatively low importance (below 5%), and ATC_{d1} , CT , FVC , and LCT contribute less than 1%. In the LST downscaling task from 0.05° to 0.01° using CatBoost model (Fig. 16b), the ATC-simulated LST at the initial time had the highest importance of 30.8%. The air temperature (T_{2m}) and $MAST_{d2}$ also had high importance exceeding 10%. The $YAST_{d2}$, DEM , and dx_{n2} showed moderate importance between 5% and 10%, while the dx_{d2} , $MAST_{n2}$, and $YAST_{n2}$ contributed less than 5%. Eliminating those features with low importance has the potential to enhance computational efficiency and reduce dependency on related auxiliary datasets, which should be carefully assessed in future studies.



605 **Figure 16: The relative importance for the CatBoost model when (a) estimating the hypothetical clear-sky LST using Eq. 13, and (b) downscaling the 0.05° LST difference using Eq. 18.**

5.3 The spatial representativeness of in-situ sites

T_{nadir} was evaluated against near-nadir LST from VNP21A1, whereas the 0.05° T_{hemi} product was validated using in-situ measurements. The T-based validation of T_{hemi} requires that in-situ sites exhibit high spatial representativeness. To this end, the spatial heterogeneity of 11 HiWATER sites, 11 OzFlux sites, and 6 sites over the Tibetan Plateau in 2020 was assessed (Beringer et al., 2016; Che et al., 2019; Ma et al., 2024b). Following Zhang et al. (2024), two metrics were adopted: (1) the median standard deviation (STD) of Landsat 8 LST within a 0.05° window, and (2) the RMSE between nighttime FY-4A LST and in situ LST. Sites that deviated from the median values of these two indicators were excluded, as illustrated in Fig. 17 (a). Ultimately, 8 sites were retained, all satisfying the criteria of nighttime RMSE < 3.57 K and STD < 2.17 K.



615 **Figure 17: The spatial representativeness evaluation of the employed in situ sites.**

5.4 The inter-comparison with other all-weather LST products

The inter-comparison between the generated all-weather T_{hemi} product and four existing all-weather LST products against the in-situ LST measurements in the year 2020 is shown in Fig. 18. Although the absolute accuracy is influenced by the spatial representativeness of in-situ sites as analyzed in section 5.3, the relative accuracy of different LST products is comparable. Two of the employed datasets are reanalysis products: ERA5-Land LST at 0.1° resolution and China Land Surface Data Assimilation System (CLDAS) LST at 0.0625° resolution. Additionally, two remote sensing products were included: a global all-weather 0.05° LST dataset generated by Jia et al. (2023), and a regional 0.02° LST product for East Asia region developed by Dong et al. (2022). Jia's method first estimates hypothetical clear-sky LST using a Kalman filter with ERA5, Himawari-8 and MODIS LSTs as inputs. An iterative CRF correction is then applied to produce the cloudy-sky LST. Dong's approach first retrieves clear-sky LST from Himawari-8 using a TES algorithm, and then estimates cloudy-sky LST using a multiresolution Kalman filter based on CLDAS LST. For consistency, all four products were resampled to 0.05° resolution to match the 0.05° T_{hemi} for inter-comparison, and only HiWATER sites were used due to the limited spatial extent of CLDAS LST. Under clear-sky conditions (Fig. 18a), ERA5 and CLDAS show similar accuracy with RMSE values of 4.2 K – 4.5 K during the day and 4.2 K at night. Our T_{hemi} product has superior accuracy with RMSE values of 2.3 K during both day and night. Dong's LST is similar to T_{hemi} , and Jia's LST have RMSE values between the reanalysis products and the T_{hemi} . Under cloudy-sky conditions (Fig. 18b), ERA5 LST has the lowest accuracy with an RMSE of 5.2 K during the day and an RMSE of 4.1 K at night. CLDAS LST has RMSEs of 5.1 K during daytime and 4.0 K at night, which performs worse than remote sensing-based LST. The RMSE of T_{hemi} is similar to Jia's LST, but lower than Dong's LST. The overall performance of our T_{hemi} product during both clear-sky and cloudy-sky conditions highlights its good potential in the subsequent applications.

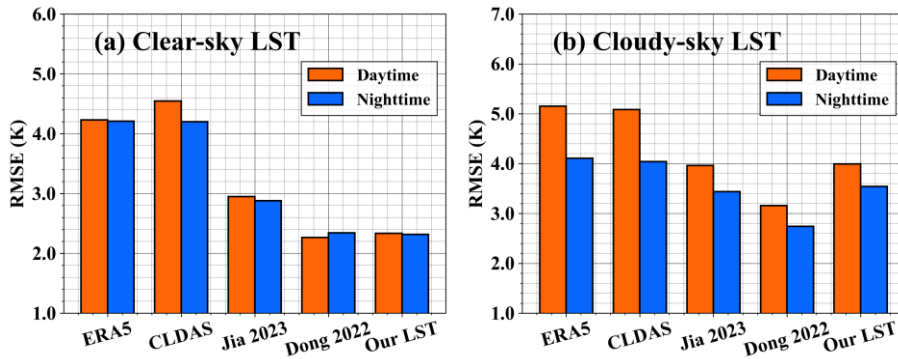


Figure 18: The RMSE comparison of five products during the day and night under (a) clear-sky condition and (b) cloudy-sky condition.

5.5 Limitations and future work

The evaluation results of the generated ANCFDS-LST demonstrate its high accuracy and detailed texture. Several limitations remain to be addressed in future work:

- 1) The TEKDM used in this study is developed for vegetated canopies, which is dominated by the gap fraction and hot spot effects. However, the applicability of this model over other land covers, such as bare soil, snow, and urban areas requires further exploration and validation (Du et al., 2023, 2024; Wang et al., 2024a; Xiong et al., 2024). Moreover, the reliability of TEKDM in complex terrain also demands in-depth studies (Zhan et al., 2025).
- 2) The nighttime TRD effect was neglected in this study, as LST is generally more homogeneous within a pixel and angular effects are typically weak under nighttime conditions (Na et al., 2024a). However, TRD effect may persist in geostationary observations shortly after sunset (Jiang et al., 2022). Modeling daytime and nighttime TRD effects separately is a promising approach for improving nighttime angular normalization; however, this strategy has not yet been implemented in the current TEKDM framework. Therefore, the development of an advanced TEKDM that explicitly accounts for nighttime TRD effects warrants further investigation in future studies.
- 3) Thermal infrared directional anisotropy is primarily governed by surface thermal heterogeneity and canopy structure, both of which are strongly driven by solar illumination and the resulting temperature gradients between soil and vegetation components. Under cloudy conditions, direct solar radiation is reduced, while diffuse radiation and atmospheric longwave emission increase, which tends to weaken the magnitude of TIR directional anisotropy. However, the weakened TRD effect is strongly influenced by cloud optical properties, cloud duration, and atmospheric humidity, making it difficult to model using physical approaches. Future studies are encouraged to incorporate multi-angle observations under cloudy-sky conditions to better characterize TRD effects under cloud cover (Jia et al., 2024).
- 4) In this study, a sinusoidal ATC model was employed to provide auxiliary thermal texture information. However, this approach may introduce uncertainties in tropical regions, where LST typically exhibits bimodal seasonal cycles with two annual peaks. Previous studies have attempted to address this limitation by incorporating dual-sinusoidal functions (Xing et al., 2020). In future work, the adoption of more accurate and universally applicable ATC models would be beneficial for improving the robustness of cloudy-sky LST estimation and downscaling.
- 5) This study extensively employs machine learning methods driven by reanalysis products. Although the primary observational constraints are derived from remote sensing products, uncertainties in the inputs may still propagate through the cloudy-sky LST estimation and downscaling processes. In future studies, developing robust error quantification techniques would aid in tracing how uncertainties in input parameters influence the final 0.01° all-weather LST, thereby further refining the ANCFDS-LST product (Li et al., 2024b).
- 6) The T-based validation in this study is based on 8 in-situ sites from HiWATER and OzFlux networks, which inevitably introduces uncertainty due to their limited representativeness across land cover types. Future studies could incorporate radiance-based (R-based) validation to mitigate this issue, offering a valuable complement to T-based validation (Li et al., 2021).

6 Data availability

675 The hourly, 0.01° , all-weather T_{dir} , T_{nadir} , and T_{hemi} product (ANCFDS-LST) from 2018 to 2023 is freely available at <https://doi.org/10.11888/RemoteSen.tpd.303249> (last access: 30 January 2026; Na et al., 2026). Data are stored in GeoTIFF format with three sequential bands (T_{dir} , T_{nadir} , and T_{hemi} respectively), and the units of each file is kelvin. A scale factor of 0.1 and offset of 0 have been applied for value encoding.

7 Conclusion

680 In this study, the angular-normalized, cloud-filled, and 0.01° -downscaled LST was generated from 2018 to 2023 on the basis of the official FY-4A LST dataset. Firstly, a TEKDM-based angular normalization method was used to generate nadir and hemispherical LST products. Secondly, an all-weather LST estimation approach was adopted to produce 0.05° cloud-filled directional, nadir, and hemispherical LST. Finally, an IHDA method was employed to enhance the spatial resolution of the LST products from 0.05° to 0.01° . The main conclusions are summarized as follows:

- 685 1) The TEKDM model significantly normalized the angular dependence of daytime clear-sky T_{dir} . Taking the near-nadir VNP21A1 LST as reference, the RMSD (MBD) decreased from 4.53 K (-1.85 K) of the T_{dir} to 2.56 K (0.06 K) of normalized $0.05^\circ T_{nadir}$. Taking the in-situ hemispherical LSTs in the Heihe River Basin and the Tibetan Plateau as reference, the RMSE decreased from 2.22 K of the T_{dir} to 2.00 K of the normalized $0.05^\circ T_{hemi}$.
- 690 2) For the all-weather $0.05^\circ T_{hemi}$, the T-based validation shows an RMSE of 2.48 K under clear-sky conditions and 3.65 K under cloudy-sky conditions. The generated all-weather T_{hemi} generates comparable accuracy with the existing four all-weather LST products (i.e., ERA5, CLDAS, Jia2023 and Dong2022). After downscaling, the 0.01° all-weather LST successfully recovered fine spatial details.

Despite the generated directional, nadir, and hemispherical LST products have high accuracy and rich spatial texture, their spatial coverage is currently limited to the FY-4A disk. Further work is needed to expand this methodology for producing
695 global-scale LST products, e.g., gathering Himawari, GOES and MSG satellite datasets. In addition, the T-based validation was performed over limited in-situ sites in this study, and a more comprehensive approach such as R-based validation is still lacking. Future research should focus on performing robust validation over more land covers and also over complex terrains.

Appendix A

Accurate numerical integration for deriving T_{hemi} is computationally expensive. To improve efficiency, a polynomial fitting
700 approach was adopted to approximate the exact integration. As shown in the numerator of Eq. 12, the integration involved in estimating T_{hemi} depends only on α , β , W , and SZA. Accordingly, a look-up table was constructed by traversing α from -0.35 to 0.35 with a step of 0.01 , β from 0 to 0.05 with a step of 0.001 , W from 0.05 to 0.5 with a step of 0.01 , and SZA from 0° to 90° with a step of 1° . In total, 1,479,880 integration values were obtained using accurate but computationally intensive

numerical integration. Subsequently, a third-order polynomial was fitted, taking α , β , W , SZA, and K_{Chen} value at nadir as
705 inputs, and the corresponding integration value as the output. Eq. A1 shows the integration target for fitting, while Eq. A2
shows the final computation of T_{hemi} .

$$\Phi(\alpha, \beta, W, \theta_s) = \frac{1}{\pi} \cdot \left(\int_0^{2\pi} \int_0^{\pi/2} \left(1 + \alpha \cdot K_{LSF}(\theta_v) + \beta \cdot \cos \theta_s \cdot K_{Chen}(\theta_s, \theta_v, \Delta\phi, W) \right)^4 \cdot \cos \theta_v \cdot \sin \theta_v d\theta_v d\phi_v \right)^{\frac{1}{4}} \quad (A1)$$

$$T_{hemi} = f_{iso} \cdot \Phi(\alpha, \beta, W, \theta_s) \quad (A2)$$

where Φ is the integration value to be estimated. The fitting performance is shown in Fig. A1(a), where nearly all data points
710 closely follow the 1:1 line, yielding an RMSE of 0.000158. Fig. A1(b) shows how errors from polynomial fitting propagate
into the final hemispherical LST. Specifically, the isotropic kernel coefficient (f_{iso}) was set to 300 K, and 10,000 sample of α ,
 β , W , and SZA were randomly generated. The T_{hemi} estimated using the polynomial approximation was then evaluated
against the reference T_{hemi} derived from accurate numerical integration. The results indicate strong consistency between the
two estimates, with an RMSE within 0.1 K, which is substantially smaller than the uncertainty associated with TRD
715 correction.

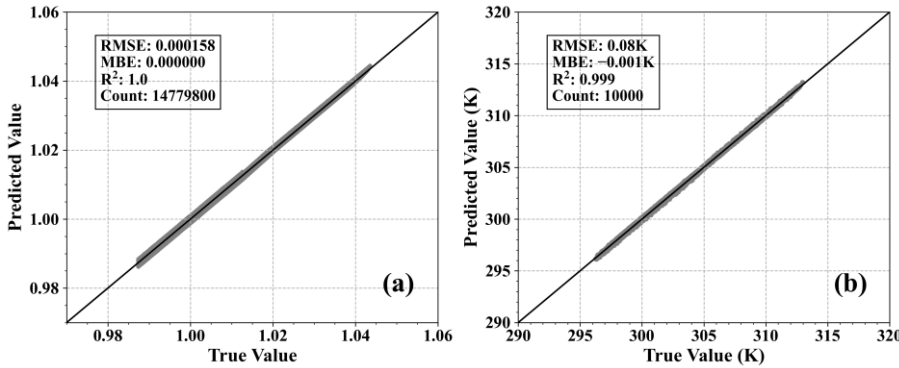


Figure A1: Performance of the polynomial fitting for (a) Φ and (b) T_{hemi} .

Appendix B

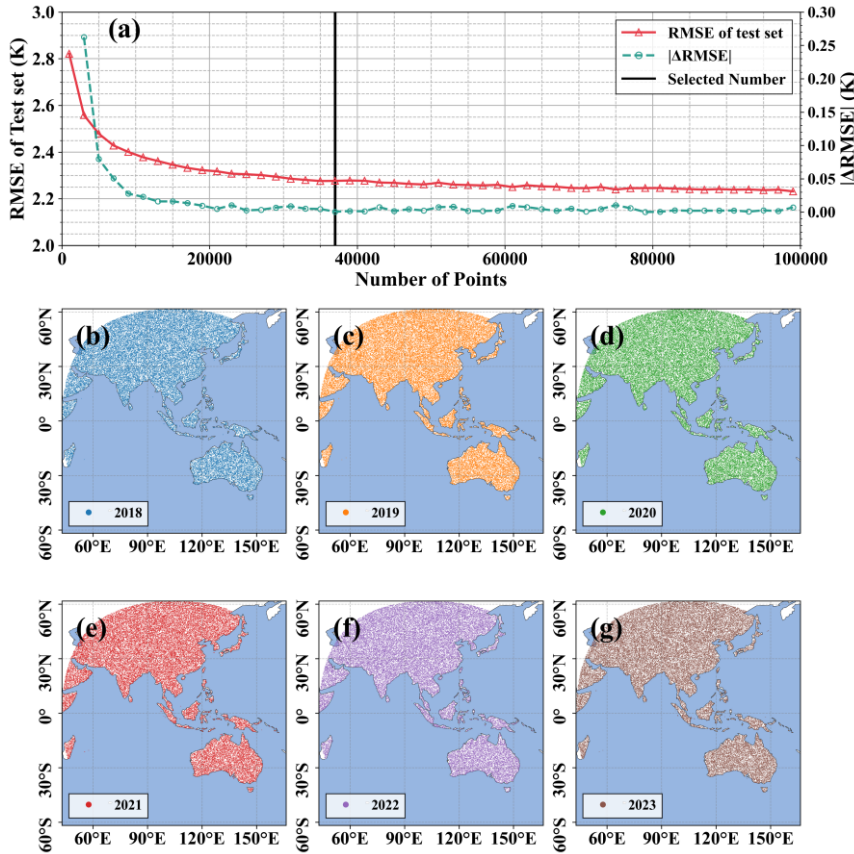
The sampling of label data is essential in the estimation of hypothetical clear-sky LST since the large volume of clear-sky
720 LST observations. In this study, a representative sub-dataset was determined through a two-step sampling approach:

Step 1) Determining the number of samples by evaluating the CatBoost model's performance in fitting the annual maximum
LST (i.e., $T_{max} = MAST + YAST$). Due to its highest level of heterogeneity, T_{max} is the most challenging variable for CatBoost
to fit. Here, a CatBoost model was trained with the inputs of following features: Lat , Lon , LCT , CT , FVC , DEM , and the
annual mean values of R_{in} , T_{2m} , and D_{2m} , as shown in Eq. B1.

$$T_{max} = f_{CatBoost}(Lat, Lon, LCT, CT, FVC, DEM, R_{in}, T_{2m}, D_{2m}) \quad (B1)$$

Firstly, 10% of the samples (974,403 samples) were used to tune the hyperparameters of the CatBoost model using a Bayesian optimization method. Another 30% of the samples (2,923,400 samples) were allocated as the test set. The training set includes a total of 5,847,441 samples (i.e., 60% of the samples). Aimed to determine the optimal sample size, directly transverse all the possible sample sizes over training set is impractical. In this study, the number of training samples was gradually increased from 2,000 to 100,000 with an increment of 2,000. As shown in Fig. B1(a), the optimal sample size (i.e., 37,000) was determined based on the point at which the RMSE variation (i.e., $|\Delta RMSE|$) remained less than 0.001 K.

Step 2) determining the exact geolocations of 37,000 points for each year (i.e., 6 years from 2018 to 2023). Here, a conditioned Latin hypercube sampling (cLHS) method was employed, which first divides the features into equal partitions according to their values and then randomly selects sample points from each partition. It has been demonstrated to be both efficient and reliable for large datasets (Minasny and McBratney, 2006; Yang et al., 2020). The input features for this step are identical to those in Eq. B1. The final spatial distribution of 37,000 selected points per year is shown in Fig. B1b-g, indicating a uniform distribution across the FY-4A disk without significant clustering.



740 **Figure B1: The selection of optimal sample number (a) and the geolocation of 37,000 sample points in (b) 2018, (c) 2019, (d) 2020, (e) 2021, (f) 2022, (g) 2023.**

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