



Article

Estimation of Daily and Instantaneous Near-Surface Air Temperature from MODIS Data Using Machine Learning Methods in the Jingjinji Area of China

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Abstract: Meteorologically observed air temperature (T_a) is limited due to low density and uneven distribution that leads to uncertain accuracy. Therefore, remote sensing data have been widely used to estimate near-surface T_a on various temporal scales due to their spatially continuous characteristics. However, few studies have focused on instantaneous T_a when satellites overpass. This study aims to produce both daily and instantaneous T_a datasets at 1 km resolution for the Jingjinji area, China during 2018–2019, using machine learning methods based on remote sensing data, dense meteorological observation station data, and auxiliary data (such as elevation and normalized difference vegetation index). Newly released Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 surface Downward Shortwave Radiation (DSR) was introduced to improve the accuracy of T_a estimation. Five machine learning algorithms were implemented and compared so that the optimal one could be selected. The random forest (RF) algorithm outperformed the others (such as decision tree, feedforward neural network, generalized linear model) and RF obtained the highest accuracy in model validation with a daily root mean square error (RMSE) of 1.29 °C, mean absolute error (MAE) of 0.94 °C, daytime instantaneous RMSE of 1.88 °C, MAE of 1.35 °C, nighttime instantaneous RMSE of 2.47 °C, and MAE of 1.83 °C. The corresponding R^2 was 0.99 for daily average, 0.98 for daytime instantaneous, and 0.95 for nighttime instantaneous. Analysis showed that land surface temperature (LST) was the most important factor contributing to model accuracy, followed by solar declination and DSR, which implied that DSR should be prioritized when estimating T_a . Particularly, these results outperformed most models presented in previous studies. These findings suggested that RF could be used to estimate daily instantaneous T_a at unprecedented accuracy and temporal scale with proper training and very dense station data. The estimated dataset could be very useful for local climate and ecology studies, as well as for nature resources exploration.

Keywords: near-surface air temperature; land surface temperature; random forest model; Jingjinji area; machine learning; remote sensing



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1. Introduction

Near-surface temperature (T_a) refers to the temperature two meters above the ground, which is an important parameter in many fields such as the studies of the environment [1–3], ecology [4], hydrology [5,6], and meteorology [7–10]. In the context of global warming over the past few decades, accurate estimation of T_a is very important for climate change assessment and global collaborative response and also provides the scientific basis for China's carbon peak and neutrality goals to address climate change. The T_a is usually obtained from

the observations of ground-based weather stations. Although high-resolution and very precise temperature data can be obtained through site observations, obtaining large-scale continuous temperature data through such stations is difficult because these meteorological stations can only provide discrete observational data and the spatial distribution of the stations is not uniform because of variations in geographical conditions [11–13]. Low density with an uneven distribution of ground weather stations may lead to inaccuracies and uncertainties in related studies [14–17].

Before satellite remote sensing technologies were widely used, interpolation was the most common and easy-to-use method for estimating the spatial distribution of T_a , such as Inverse Distance Weighted (IDW), Kriging, Spline method, etc., [18–20]. Some methods such as Kriging and Spline can use secondary variables as auxiliary data for interpolation [21–25]. However, the density and uneven spatial distribution of meteorological stations and variation in terrain greatly affect the accuracy of an interpolation algorithm [26,27].

With the development of remote sensing technology in recent decades, estimating large-scale continuous T_a data through satellite remote sensing data has become an important research direction [28–30]. The surface temperature (LST) obtained by satellite sensors is spatially continuous, has almost global coverage [31], and has strong correlation with T_a [16,32]. The relationship between LST and T_a is also affected by terrain, elevation, vegetation coverage, and other factors. Many different methods have been proposed to increase the accuracy of satellite-based T_a estimating in recent years [18,33,34]. According to the technical principle, these methods can be divided into four groups:

1. Statistical methods such as linear regression models are commonly used to explore the relationship between T_a and other variables [35–39]. Cresswell et al. [40] estimated instantaneous T_a through a multiple regression model; the model used Solar Zenith Angle (SZA) as the only auxiliary variable and achieved an accuracy of mean deviation less than 3 °C for over 70% of the cases. Chen et al. [27] retrieved monthly average temperature (RMSE between 1.29 and 1.45 °C) and eight-day average temperature (RMSE between 0.8 and 1.29 °C) for China in 2010 using a model based on remote sensing data and a geographically weighted regression (GWR) algorithm; the elevation was the only secondary auxiliary variable; the results show that the GWR method performs better than the multiple linear regression method and the regression Kriging method.
2. The temperature–vegetation index (TVX) method is based on the characteristics of plant canopy temperature that is close to the T_a ; this method can be used to calculate the T_a by the relationship between a vegetation index and LST and has also been widely used [31,41,42]. The TVX method was tested in many areas of the world; the resulting RMSE was between 1–3 °C [41–45]. Due to the principle of the method, the TVX method is more suitable for areas with more vegetation coverage. The TVX method shows significant uncertainties while applied to the area with sparse vegetation [43].
3. The energy balance method based on the surface heat flux balance equation, incoming net radiation flux, and anthropogenic heat fluxes equals the sum of outgoing land surface heat flux (sensible and latent heat flux) [46–48]. Zaksek et al. [49] carried out an estimation of T_a in Slovenia and Germany using the energy balance method, having the root mean square deviation (RMSD) of the results at 2 °C. The method can well describe the physical mechanism of the near-surface energy balance process [50]. The main drawback of the method is that many environmental data (usually in hourly intervals) were needed to force the model and not all data were easy to obtain, especially in a large scale [48].
4. Machine learning (ML) methods (such as neural networks, decision trees, support vector machine) are based on nonlinear machine learning algorithms. ML methods greatly improve the computational efficiency and simplify the exploration process of

nonlinear and highly interactive relationships compared with the traditional statistical method, the TVX method, and the energy balance method [51–53].

Numerous studies tested the different ML methods in satellite-based T_a estimating in recent years. Noi et al. [41] compared the accuracy of multiple regression model, decision tree model, and random forest model in estimating near-surface air temperature in the mountainous area of northwest Vietnam from 2009 to 2013. The results showed that the decision tree model and the linear regression model performed better than the random forest model when only LST data were used without auxiliary variables. However, when two easily accessible variables (altitude and Julian day) were introduced into the model as auxiliary variables, the decision tree model and the random forest model performed significantly better than the linear regression model, which indicates that the ML method is more suitable for a multi-auxiliary variable model. Yoo et al. [54] used the random forest model to estimate the daily maximum and minimum temperatures in Los Angeles and Seoul and introduced seven auxiliary variables into the model: elevation, solar radiation, normalized difference vegetation index, latitude, longitude, aspect, and the percentage of impervious area. The simulated R^2 ranged from 0.72–0.85 and RMSE ranged from 1.1–4.7 °C. Zhou et al. [55] proposed a two-stage RF based machine learning hybrid model to estimate intra-daily T_a of Israel during 2004–2016. First, missing LST pixels were estimated and a gap-free LST dataset was obtained, then the RF model was employed to estimate T_a with different auxiliary variables (six auxiliary variables in stage one and seven auxiliary variables in stage two), which reached R^2 0.96, MAE 1.12 °C, and RMSE 1.58 °C. Ruiz-Álvarez et al. [56] compared support vector machines, random forests, multiple linear regression, and Kriging interpolation in estimating the T_a in the DHS region of southeastern Spain and the results showed that RF-based methods are more accurate and their performance improved when spatial components are included. Xu et al. [57] compared the accuracy of ten different machine learning methods in simulating the monthly average T_a of the Qinghai-Tibet Plateau with a 1 km resolution and the result showed that the Cubist model performs better than the other models (RMSE, 1.0 °C; MAE, 0.73 °C). Hrisiko et al. [58] simulated the T_a of urban areas in the United States using a regression neural network based on GEOS-16 satellites with a simulation result RMSE of 2.6 °C. Li et al. [59] simulated the monthly average T_a of China from 2001 to 2015 using the RF model; the simulation results had an MAE between 1.15 and 1.44 °C and an RMSE between 1.57 and 1.99 °C.

The following points can be summarized from previous studies: (1) estimating T_a based on remote sensing data is one of the most feasible methods at present, especially in a large scale, (2) multi-auxiliary variables can greatly improve the T_a estimation accuracy, (3) the machine learning methods with multi-auxiliary variables were suitable for remote sensing based estimation of T_a [52,53,56,57]. Instantaneous T_a is very important for meteorological processes and weather forecasts, such as numerical weather simulation, for its better near-real-time feature [56]; however, this study found that most previous studies focused on the estimation of average T_a over a period of time from daily average T_a to monthly average T_a in a large-scale area, while instantaneous T_a was rarely estimated [53,60,61]. Furthermore, instantaneous T_a is more difficult to estimate due to considerable changes in one day [62,63]. Thus, this study aimed to further improve estimation accuracy by introducing the Downward Shortwave Radiation (DSR) product into the model, by using high dense in-situ observation data as training inputs in a large study area over different land cover types, and finally by estimating 1 km resolution instantaneous T_a while satellites overpassed for the purpose of assessing the ability of machine learning methods.

2. Study Area and Data

2.1. Study Area

Jingjinji area, located in north China between 36°05′N–42°40′N and 113°27′E–119°50′E, covers three administrative regions including Beijing, Tianjin, and Hebei Province, with a total area of about 218,000 km² [64] (Figure 1). By 2019, the permanent population was

about 113.07 million and the GDP was 8.458 trillion yuan, making it the most important economic core area in northern China. Its terrain is complex and the altitudinal gradient is nearly 3000 m from the northwest mountainous area to the southeast plains area. The land use and vegetation cover are diverse, with a high degree of industrial and agricultural development, including farmland, cities and towns, forests and grasslands, and lakes and wetlands. The rapid urbanization in the Jingjinji area will have an impact on urban heat island and other phenomena. Due to its important status as an economic, cultural, and political center, the Jingjinji area is a hot area of climate change and urbanization research, therefore it is necessary to simulate temperature data. This area has two climatic zones. The northwest belongs to the temperate zone continental climate and the southeast belongs to the temperate zone monsoon climate, which means the T_a estimation is very challenging because of the complexity of the geography. Therefore, factors such as topography, vegetation, and climatic types must be taken into account in the T_a estimation.

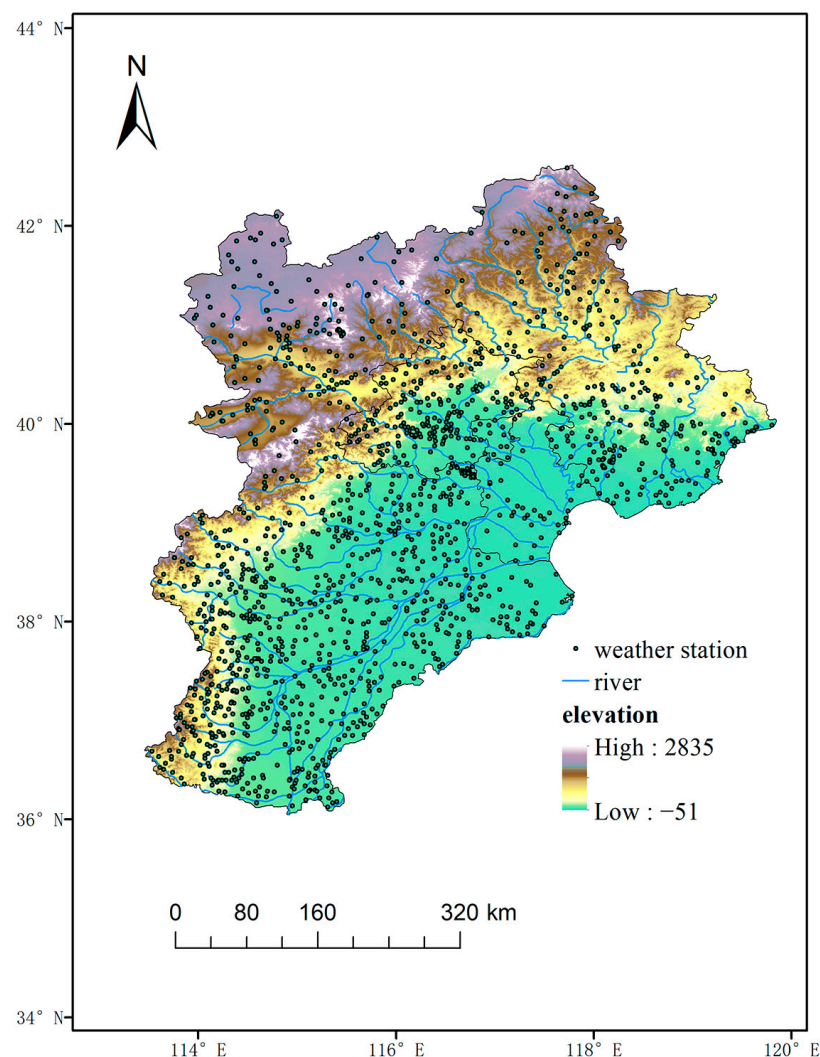


Figure 1. Location of study area and distribution of meteorological stations.

2.2. Ground-Based Weather Data

The T_a observational data were acquired from the hourly observational data of 1527 weather stations in the Jingjinji region from 2018 to 2019. Figure 1 shows the spatial distribution of the stations. The data quality has been preliminarily controlled according to QX/T 458-2018 meteorological observational data interchange specifications.

2.3. Remotely Sensed Data

The remote sensing data used in this paper are shown in Table 1. Digital elevation model (DEM) data with a 1 km resolution were produced after secondary processing of the Shuttle Topography Radar Mission's digital elevation product with a resolution of 90 m. The LST data were derived from MODIS MOD11A1 and MYD11A1 products with a resolution of 1 km released by NASA in 2018–2019. The MODIS remote sensing data come from the infrared radiation sensors carried by Terra and Aqua satellites, which scan the study area twice each day as follows: the transit time of Terra is about 11:00 and 21:00 (Beijing time, also used below), while the transit time of Aqua is about 02:30 and 13:30. Figure 2 show the percentages of available data for each satellite overpass. The mountains in the north and the west have more available data. Data percentage ranged from 50~60%, because high-altitude mountainous areas are less affected by cloud, smog, fog, haze, etc. Overall, the average percentage of valid LST data for the whole study area is about 55%.

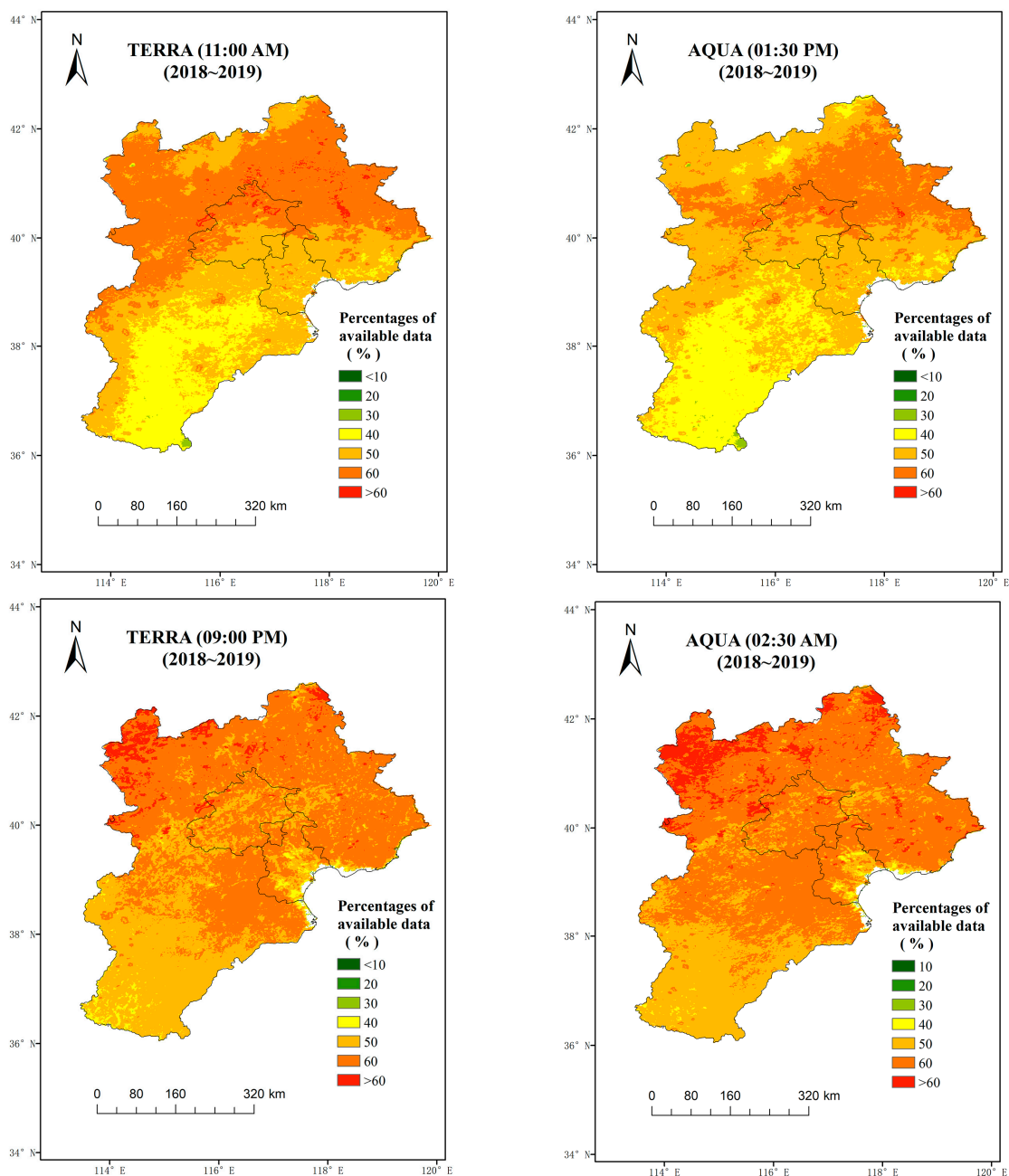


Figure 2. Average percentages of valid LST data for each satellite pass.

Table 1. Remote sensing data used in this study.

Variable	Dataset/MODIS Product Number	Resolution	Data Source
Elevation	STRM	1 km/Unique	www.resdc.cn (accessed on 15 February 2020)
LST	MOD11A1/MYD11A1	1 km/Daily	NASA LP DAAC (accessed on 5 April 2020)
DSR	MCD18A1	5.6 km/Daily	NASA LP DAAC (accessed on 5 April 2020)
NDVI	MOD13A3	1 km/Monthly	NASA LP DAAC (accessed on 5 April 2020)
LC	MCD12Q1	0.5 km/Yearly	NASA LP DAAC (accessed on 5 April 2020)

In this paper, three other types of remote sensing data were used as auxiliary input variables in the model, including Downward Shortwave Radiation (DSR), Normalized Difference Vegetation Index (NDVI), and Land Cover (LC) (Table 1). The DSR data were derived from MODIS daily radiation products, numbered MCD18A1 with a spatial resolution of 5 km, according to NASA's description on its website; the reliability of DSR products has been improved by fixing several errors in the algorithm since 2018. Land Cover data were derived from MODIS annual land cover type data; the product number is MCD12Q1 and has a spatial resolution of 0.5 km. This dataset contains five land cover classification systems. In this paper, the global vegetation classification scheme of the International Geosphere-Biosphere Program was adopted, which divided land cover into 17 types, such as grassland, forest, and water body.

3. Methods

3.1. Variable Selection and Research Framework

Figure 3 presents the framework of model training and validation used in the present study. As shown in the figure, seven variables (latitude, elevation, declination, normalized difference vegetation index, land cover, downward shortwave radiation, land surface temperature) were selected as model inputs in this study. LST, DSR, NDVI, LC, and digital elevation model data were introduced in Section 2.3. In addition, latitude (LAT) and declination of the sun were selected as auxiliary variables. LAT largely determines the climatic and environmental characteristics of an area, while the declination of the sun is closely related to the day length and seasonal changes of a region. These two factors affect the energy balance process near the ground. Solar declination is rarely considered as a variable in the model of previous studies. This paper ranked the importance of each parameter in the model validation stage in order to verify the importance of different parameters. Table 2 shows the input variables for different scenarios. In this paper, two instantaneous T_a estimation models were established, one for day and one for night. In the estimation of daily mean T_a , the daily mean LST was obtained by summing the LST data of four times a day. If data were missing due to cloud cover or other reasons at a certain time, the daily mean LST of this point was considered as missing.

Table 2. Model input variables under different scenarios.

Scenarios	Model Input Variables
Daily average	LAT, ELEVATION, DECLINATION, NDVI, LC, DSR (Daily average), LST (Daily average)
Daytime instantaneous	LAT, ELEVATION, DECLINATION, NDVI, LC, DSR, LST (Daytime instantaneous)
Nighttime instantaneous	LAT, ELEVATION, DECLINATION, NDVI, LC, LST (Nighttime instantaneous)

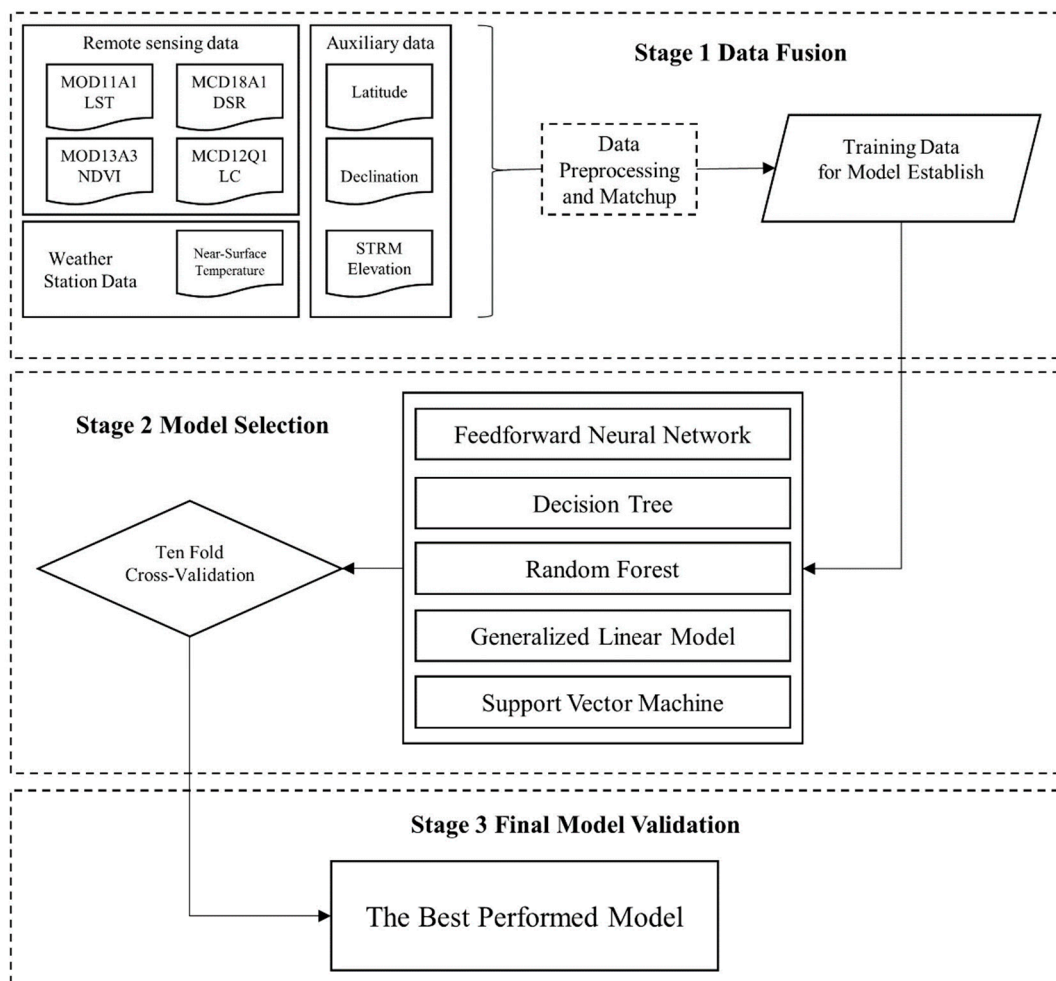


Figure 3. Flowchart of model training and validation of this study.

3.2. Models

As both complicated geographic environment and human factors such as impervious land surfaces have influence, T_a changes dramatically along with time and space. Five typical machine learning models were employed to tackle the spatiotemporal variability and factors with complex effects on the relationship with T_a , including a feedforward neural network (FNN) [65], decision tree (DT) [66], random forest (RF) [67], generalized linear model (GLM) [68], and support vector machine (SVM) [69]. We adjusted these models until the lowest level of error was procured using 10-fold cross-validation to obtain best fitting estimation as these models all have different parameter or algorithm combinations. In addition, the final model used for estimating T_a was selected by comparing the performance of the five models (FNN, DT, RF, GLM, and SVM).

3.2.1. Feedforward Neural Network

Feedforward neural network (FNN) is a kind of artificial neural network that has a simple structure and a wide application. It is a kind of static nonlinear mapping, good at complex nonlinear processing [70]. Most feedforward networks are learning networks and their classification ability and pattern recognition ability are generally stronger than those of feedback networks. FNN adopts a unidirectional multilayer structure; each layer contains several neurons and each neuron can receive the signal of the previous neuron and produce the output to the next layer. The zero layer is called the input layer, the last layer is called the output layer, and the other intermediate layers are called the hidden layers; a hidden layer can be one layer or multiple layers [71].

3.2.2. Decision Tree

Decision tree (DT) is a simple but widely used classifier. In machine learning, DT is a prediction model that represents a mapping relationship between object attributes and object values [72]. A decision tree is a tree structure in which each internal node represents a test on an attribute, each branch represents a test output, and each leaf node represents a category. By training data to build a decision tree, the unknown data can be efficiently classified. The decision tree model is readable, descriptive, helpful for manual analysis, and efficient. The decision tree only needs to be constructed once, used repeatedly, and the maximum calculation times of each prediction does not exceed the depth of the decision tree [73].

3.2.3. Random Forest

Random forest (RF), proposed by Breiman in 2001, is a classifier. RF uses multiple trees to train and predict samples. The output categories of RF are determined by the output mode of individual trees [74,75]. RF runs efficiently on large data bases with high accuracy, which can handle thousands of input variables without variable deletion. RF can estimate which variables are important in classification and generate an internal unbiased estimate of generalization error as forest construction progresses. In addition, RF can also effectively estimate missing data and maintain accuracy when the proportion of missing data is large.

3.2.4. Generalized Linear Model

The generalized linear model is based on a linear model; the relationship between the mathematical expected value of a response variable and the predictive variables of a linear combination is established by means of a joint function [76]. It is characterized by the natural measurement of data without forcing changes and data can have nonlinear and unsteady variance structures. It is a development of a linear model in studying non-normal distribution of response value and simple and direct linear transformation of a nonlinear model [77].

3.3. Variable Importance Analysis

Mean decrease accuracy (IncMSE) [78] was used to calculate the importance of different variables in each model. Each model was recalculated to calculate the mean square error (MSE) increment of the new result after a random increase of $\pm 25\%$ deviation for a certain variable, assuming that other conditions remained unchanged. The average value was obtained after 30 repetitions. If the increase in the MSE value was larger, the importance of the parameter in the model was higher; otherwise, the importance was lower.

3.4. Model Training and Validation

In this study, data fusion correction and spatial matching were carried out based on meteorological and remote sensing data from 2018 to 2019. Ultimately, 166,008 daily sample data points and 992,705 instantaneous sample data points were collected. In this study, the widely used 10-fold cross-validation (10-CV) procedure [79] was selected for model validation, where all data samples were divided into ten subsets randomly; nine of them were used as the training data and the remaining as the testing data, and the holdout method is repeated 10 times. We computed an average accuracy score of all the accuracy scores that were calculated in each 10 iterations. The validation of the model was evaluated by mean absolute error (MAE), root mean square error (RMSE), and the coefficient of determination (R^2). The statistical measures were defined and used as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^n |x_i - y_i| \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2} \quad (2)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (x_i - y_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (3)$$

where n is the sample size, x_i is the simulated value, y_i is the measured value, and \bar{y} is the average value of the measured value.

4. Results

4.1. Comparison of Results of Different Models

We extracted 166,008 samples for the daily model, 456,422 samples for the daytime instantaneous model, and 536,283 samples for the nighttime instantaneous model. Table 3 shows the comparison of simulation results produced by the different models. The results show that the decision tree and RF algorithm performed better than other methods in the model fitting stage; the RMSE of the simulation results of daily mean air temperature, daytime instantaneous T_a , and night instantaneous air temperature ranged from 0.71 °C to 1.42 °C. The RF algorithm is obviously better than other algorithms, while in the model validation stage the RMSEs were 1.29 °C, 1.88 °C, and 2.47 °C, respectively. Therefore, the RF model can be considered as the optimal model in the retrieval of T_a in Jingjinji.

Table 3. Comparison of results of each model.

Scenarios	Model	Model Fitting			Model Validation		
		MAE (°C)	RMSE (°C)	R^2	MAE (°C)	RMSE (°C)	R^2
Daily average	FNN	1.29	1.66	0.98	1.29	1.66	0.98
	DT	0.67	0.88	0.99	1.17	1.66	0.98
	RF	0.48	0.71	0.99	0.94	1.29	0.99
	GLM	1.54	1.97	0.97	1.53	1.97	0.97
	SVM	0.96	1.22	0.99	1.07	1.41	0.98
Daytime instantaneous	FNN	2.02	2.63	0.95	2.02	2.63	0.95
	DT	1.05	1.4	0.99	1.63	2.35	0.96
	RF	0.69	1.04	0.99	1.35	1.88	0.98
	GLM	2.84	3.59	0.91	2.84	3.58	0.91
	SVM	1.79	2.37	0.96	1.84	2.44	0.96
Nighttime instantaneous	FNN	2.21	2.93	0.94	2.21	2.93	0.94
	DT	1.32	1.74	0.98	2.14	2.97	0.94
	RF	0.98	1.42	0.99	1.83	2.47	0.95
	GLM	2.32	3.08	0.93	2.31	3.08	0.93
	SVM	2.06	2.79	0.94	2.08	2.83	0.94

According to the results, RF produced the best simulation results for the daily average temperature in the model validation stage with the RMSE, MAE, and R^2 of 1.29 °C, 0.94 °C, and 0.99, respectively. Meanwhile, the RMSE, MAE, and R^2 of daytime instantaneous T_a simulation were 1.88 °C, 1.35 °C, and 0.98, respectively. The estimation results of instantaneous T_a at night were relatively poor with an RMSE, MAE, and R^2 of 2.47 °C, 1.83 °C, and 0.95, respectively (Table 3).

4.2. Analysis of the Importance of Model Variables

Table 4 shows the IncMSE values and the weight ratios of each parameter in different scenarios. The results show that in the simulation of daily mean T_a , the top four variables of IncMSE were LST, LAT, DECLINATION, and DSR. For daytime instantaneous T_a simulation, the top four variables of IncMSE were LST, DECLINATION, DSR, and LAT. For the simulation of nighttime instantaneous T_a , the top four variables of IncMSE were LST, declination, LAT, and LC. In general, the variable LST was much more important than other variables; IncMSE accounted for about 40–60%, followed by DECLINATION, of which the

proportion of IncMSE was about 12–28%. In the simulation of daytime instantaneous T_a , the importance of the variable DSR was second only to DECLINATION, and the proportion of IncMSE reached 14.93%, while in the simulation of daily average T_a , the proportion of IncMSE was only 6.63%, which is lower than the variable LAT and DECLINATION.

Table 4. Ranking of variable importance.

Variables	Daily Average		Daytime Instantaneous		Nighttime Instantaneous	
	IncMSE (°C)	Weight (%)	IncMSE (°C)	Weight (%)	IncMSE (°C)	Weight (%)
LAT	2.34	12.55	2.09	7.14	3.72	21.10
ELEVATION	0.12	0.67	0.43	1.45	0.27	1.52
LC	0.04	0.23	0.35	1.18	1.42	8.03
DECLINATION	2.23	11.93	5.89	20.07	4.86	27.58
NDVI	0.26	1.40	1.66	5.67	0.49	2.77
DSR	1.24	6.63	4.38	14.93	-	-
LST	12.43	66.60	14.54	49.57	6.88	39.00

4.3. Evaluation of Random Forest Performance

Figure 4 presents the histogram of the distribution validation residuals of daily average T_a , daytime instantaneous T_a , and nighttime instantaneous T_a simulated by the RF model. The figure shows the overall model error has a normal distribution. The error of less than ± 1 °C accounts for 64.95%, 50.74%, and 38.09%, respectively, in the simulation of daily average T_a , instantaneous T_a during the day, and instantaneous T_a at night, while the error of less than ± 2 °C accounts for 89.18%, 77.86%, and 65.54%, respectively, in the simulation of these three types of T_a .

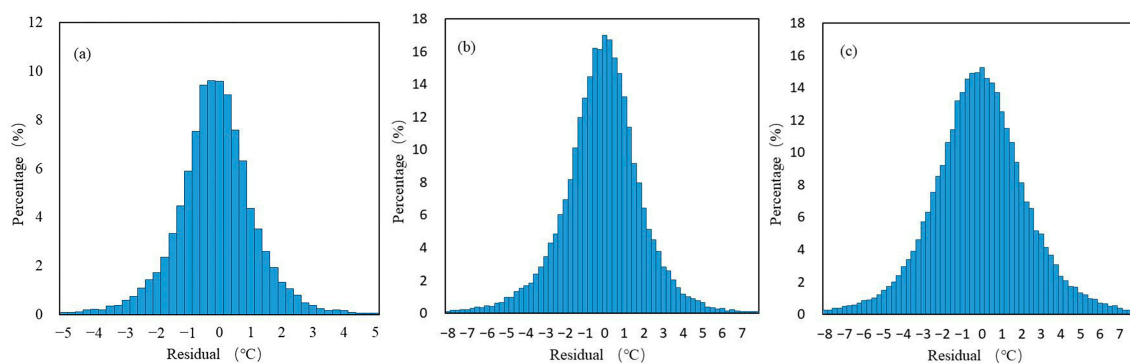


Figure 4. Histograms of residuals of the model: (a) daily average near-surface air temperature (T_a), (b) daytime instantaneous T_a , (c) nighttime instantaneous T_a .

Figure 5 shows a diagram of the distribution of the spatial error in simulation results for daily mean T_a , daytime instantaneous T_a , and nighttime instantaneous T_a under the RF model. As can be seen from Figure 5, when simulating daily average T_a most station errors are between 0 and 2 °C. In the daytime instantaneous T_a simulation, compared with the average daytime T_a simulation, the number of stations with errors of >2 °C increased significantly. In addition, in the simulation of transient T_a at night, the station with error of >2 °C is further increased. According to the spatial distribution characteristics, the sites with errors >2 °C were mainly distributed in the western and northern high-elevation mountainous areas. Table 5 shows the comparison of the simulation results in areas of different types of terrain (plains and mountains) and land cover (urban and rural). It can be seen that the simulation accuracy in the plains was higher than in the mountainous areas under various scenarios; RMSE decreased by 0.62 °C, MAE decreased by 0.49 °C, and R^2 increased by 0.01 on average. The simulation accuracy in urban areas was higher than in rural areas; RMSE decreased by 0.24 °C, MAE decreased by 0.16 °C, and R^2 increased by 0.01 on average.

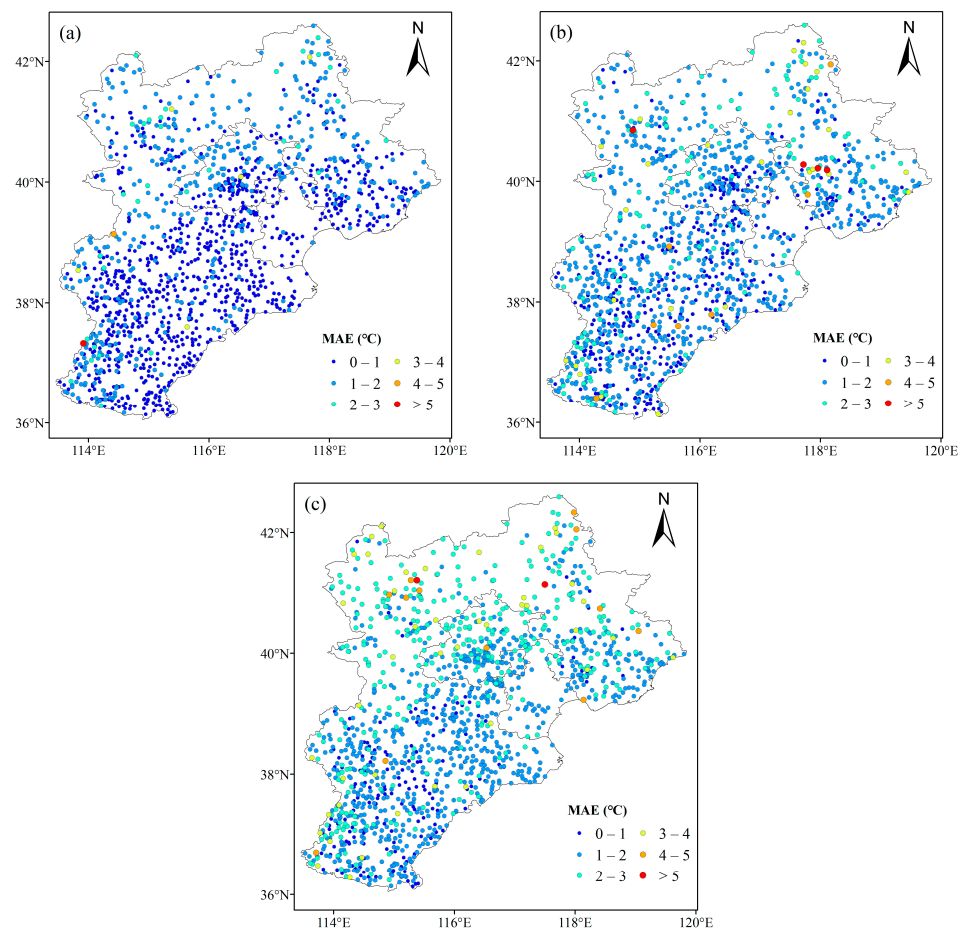


Figure 5. Mean absolute error (MAE) of estimated near-surface air temperature (T_a) in the Beijing-Tianjing-Hebei region: (a) day average T_a , (b) daytime instantaneous T_a , (c) nighttime instantaneous T_a .

Table 5. Comparison of the precision of T_a estimation in different types of terrain and land cover.

Terrain		Plains (Elevation < 260 m)	Mountainous Area	Urban Area	Rural Area
Daily average	MAE (°C)	0.79	1.24	0.83	0.97
	RMSE (°C)	1.07	1.66	1.12	1.34
	R^2	0.99	0.98	0.99	0.99
	MD (°C)	9.04	8.08	8.9	8.98
	SD (°C)	10.52	10.28	10.35	10.47
Daytime instantaneous	MAE (°C)	1.19	1.70	1.19	1.42
	RMSE (°C)	1.67	2.27	1.67	1.96
	R^2	0.98	0.97	0.98	0.97
	MD (°C)	9.92	9.94	10.04	9.89
	SD (°C)	11.45	11.44	11.56	11.41
Nighttime instantaneous	MAE (°C)	1.69	2.20	1.75	1.87
	RMSE (°C)	2.26	2.94	2.33	2.54
	R^2	0.96	0.94	0.96	0.95
	MD (°C)	9.01	8.95	9.03	8.98
	SD (°C)	10.51	10.49	10.51	10.5

Note: MD—mean deviation of observed T_a ; SD—standard deviation of observed T_a .

Table 6 compares the evaluation results of daily average T_a , daytime instantaneous T_a , and nighttime instantaneous T_a at different seasons simulated by the RF model. Figure 6 presents a scatter diagram of simulated and measured T_a values at different seasons. As can

be seen from Table 6, in T_a daily average simulation, the error difference in four seasons is generally small. Among them, summer has the best simulation effect, followed by autumn, spring, and winter. The maximum and minimum values of RMSE and MAE in four seasons were 0.32 °C and 0.25 °C, respectively. In the simulation of daytime instantaneous T_a , the simulation worked best in winter, followed by autumn and summer. The simulation results in spring are worse than in other seasons. The simulation of instantaneous T_a worked best at night, followed by autumn. Table 6 shows that in summer the models have low MAE but also low R^2 in daily average and nighttime scenes. LST is closer to temperature in summer than in other seasons, which probably caused the small MAE in summer. Due to less cloud cover, there are more clear days in other seasons than in summer and a large number of relatively consistent data enhance the correlation of valid data, which may be the main reason for the high R^2 in other seasons.

Table 6. Comparison of the precision of T_a estimation in different seasons.

Season		Spring	Summer	Autumn	Winter
Daily average	MAE (°C)	0.93	0.81	0.93	1.06
	RMSE (°C)	1.32	1.11	1.25	1.43
	R^2	0.96	0.91	0.98	0.91
	MD (°C)	4.97	2.08	5.79	2.42
	SD (°C)	6.01	2.45	6.80	2.96
Daytime instantaneous	MAE (°C)	1.61	1.35	1.25	1.19
	RMSE (°C)	2.21	1.84	1.72	1.67
	R^2	0.92	0.77	0.96	0.90
	MD (°C)	5.65	2.25	6.76	3.36
	SD (°C)	6.75	2.8	8.01	4.14
Nighttime instantaneous	MAE (°C)	2.02	1.48	1.76	1.98
	RMSE (°C)	2.72	1.99	2.39	2.62
	R^2	0.87	0.83	0.91	0.78
	MD (°C)	5.20	2.68	5.56	2.82
	SD (°C)	6.29	3.21	6.59	3.50

Note: MD—mean deviation of observed T_a ; SD—standard deviation of observed T_a .

4.4. Spatial Distribution of T_a

Thirty-first May 2018 was one of the clearest days in the study period. It was selected for showing the model's ability to recreate spatial T_a distribution maps where ground weather stations do not exist. Figure 7a shows satellite retrieval daily mean T_a of Jingjinji region on the selected day. The result shows that the distribution of high and low T_a is very close to the distribution of elevation, which is consistent with the fact that temperature decreases with height in the troposphere.

The Beijing region was selected for showing the correlation of estimated temperature and the distribution of elevation. Figure 7b contains significant details of the estimated daily mean temperature, which were in line with the distribution of elevation (Figure 7c).

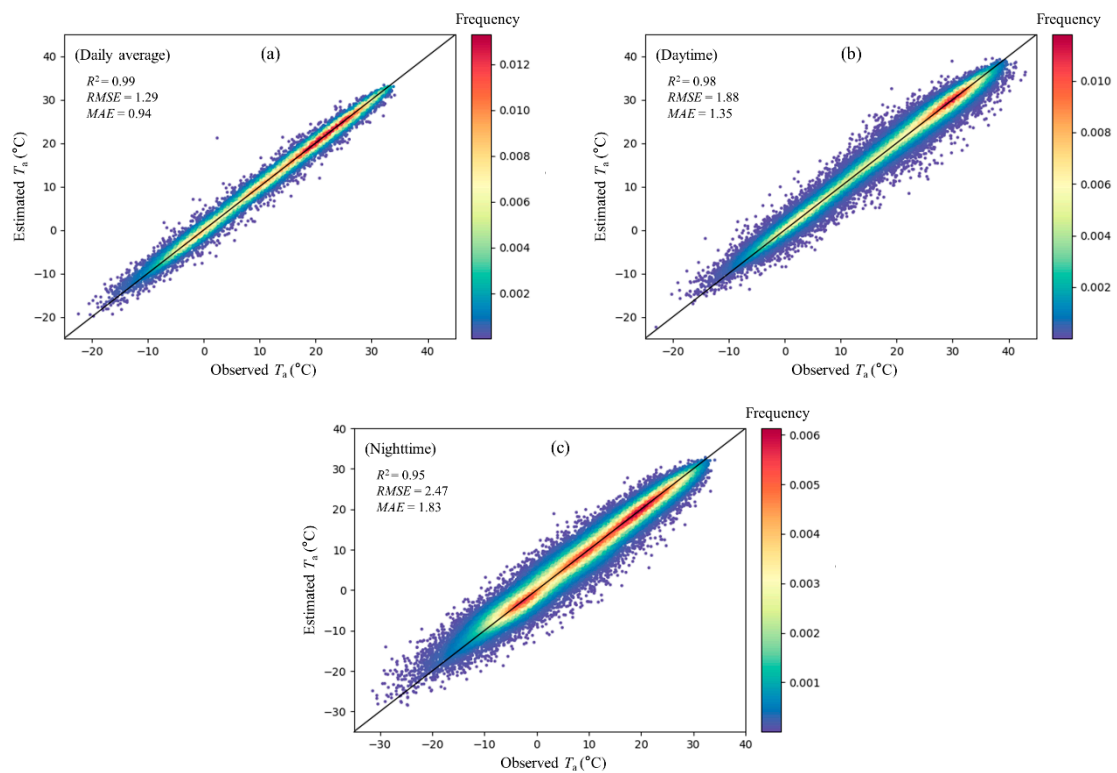


Figure 6. Scatter plot of simulation of near-surface air temperature (T_a) and observed values in different seasons: (a) daily average T_a , (b) daytime T_a , (c) nighttime T_a .

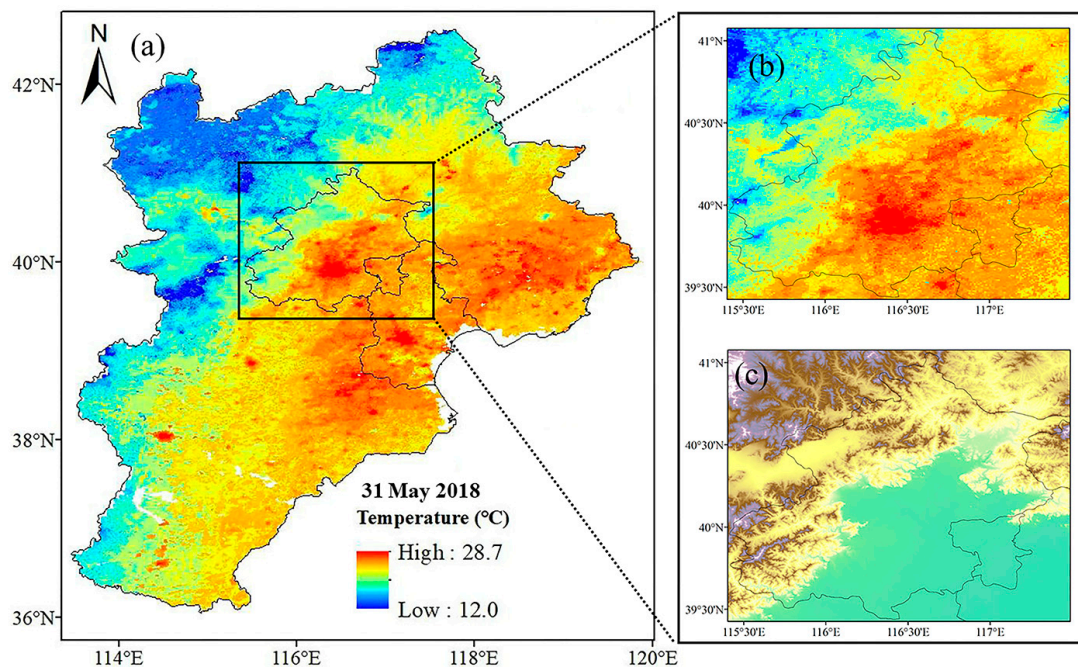


Figure 7. Comparison between (a) satellite retrieval daily mean temperature of Beijing, Tianjin, Hebei region on 31 May 2018, (b) satellite retrieval daily mean temperature of Beijing area on 31 May 2018, (c) DEM of Beijing area.

Figure 8 shows the instantaneous T_a estimation products at four times of day on 31 May 2018. This figure shows that the T_a products retrieved by satellite clearly show the process of change in T_a at four times of a day. High T_a areas with clear boundaries caused by the heat island effect are shown after cooling at night.

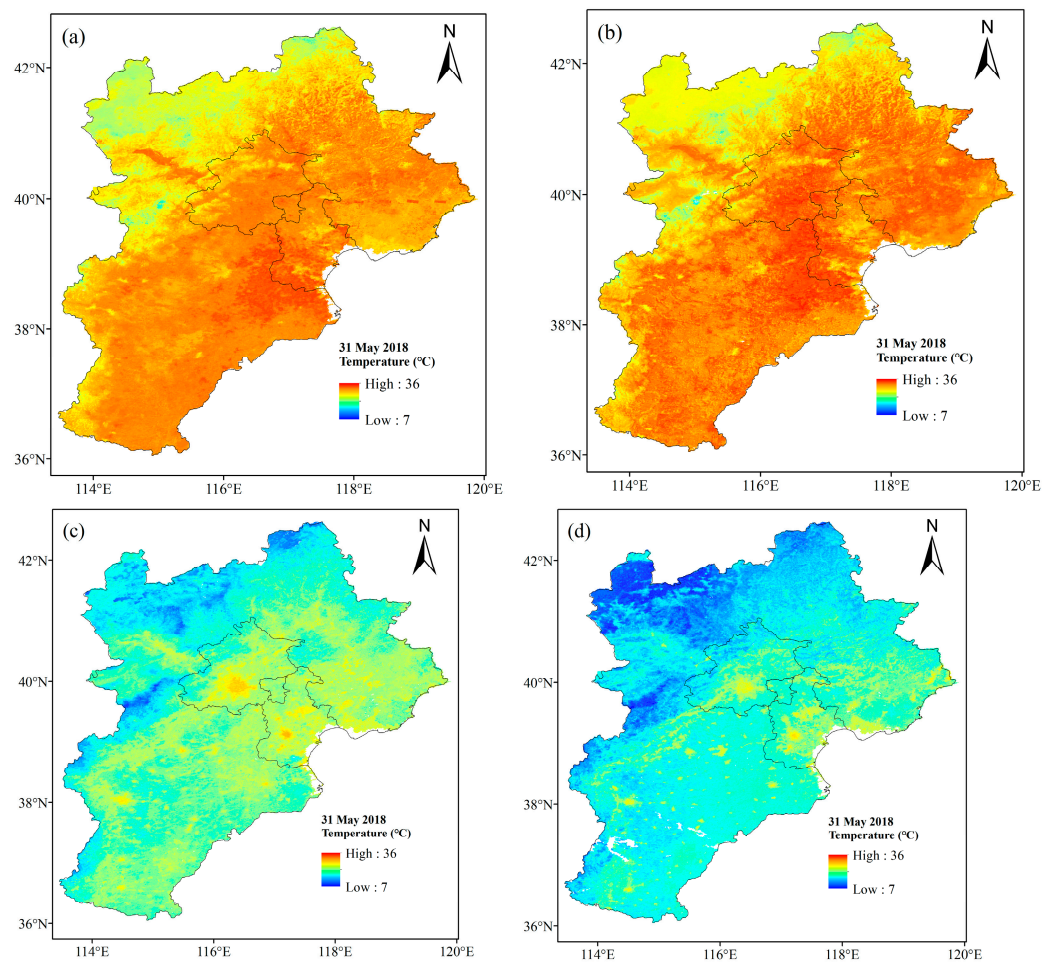


Figure 8. Daytime and nighttime near-surface air temperature estimation product maps of the Beijing, Tianjin, Hebei region on 31 May 2018: (a) daytime 10:30, (b) daytime 13:30, (c) nighttime 22:30, (d) nighttime 02:30.

5. Discussion

5.1. The Performance of RF Model

This study indicated the RF algorithm is obviously better than other algorithms to estimate daily and instantaneous air temperature from MODIS data over this study area, with the highest accuracy in model validation (Table 3). These results are consistent with other research [52,56,80,81]. In addition, RF produced the best simulation results for daily mean temperature, whereas the results for instantaneous T_a at night were relatively poor. This mainly occurred because the daily average LST was calculated based on four MODIS LST data from two sensors at two local overpass times (daytime and night-time). LST is higher than T_a in the daytime and lower at night, therefore the difference between LST and T_a is greatly reduced after averaging. The poorest simulation results were found at night, mainly because the process of energy balance near the ground at night is quite different from that in the daytime. Phan et al. [61] also found the correlation between LST daytime versus T_a was slightly higher than nighttime versus T_a , which indicated that the relationship between MODIS LST and T_a was complex. In this study, DSR was added as an input variable in the daytime simulation; however, no such variable exists in the nighttime model. Ruiz-Álvarez et al. [56] indicated that the most important variables in RF were satellite land surface temperature, c_{day} , and radiation, which could explain the results of this study with lower accuracy observed at night due to the lack of radiation variables compared with the daytime. In addition, this study did not take into account the advection process, which is also a potential factor affecting the instantaneous T_a at night. Specifically, there is

no energy at night and the temperature depends on the cooling speed of the air and the ground. The ground and the nearby air are cooled by long wave radiation. On the cloudy night, this long wave radiation is absorbed by the clouds and the clouds also transmit long wave radiation upward and downward, with some of the downward radiation returning to the ground to compensate for heat lost at the ground [82,83]. Therefore, factors such as ground long wave radiation and clouds are affecting the simulation of night temperature and these factors are difficult to quantify using ready-made remote sensing products. Due to the difficulty of data acquisition, these factors were not selected in this study, which led to the phenomenon of low accuracy of night temperature. Therefore, due to the lack of potential influencing factors such as solar radiation and advection processes in the model, the simulation accuracy of instantaneous T_a at night was relatively poor [4,37].

The experimental results of RF showed that the simulation accuracy in the plains area was higher than in the mountainous area (Figure 5). Previous studies also found that the higher the altitude the greater the uncertainty of the model [37], which is mainly caused by the higher elevation, complex terrain, and the process of energy balance near the ground in mountainous areas being more complex [84]. Previous studies have shown that the relationships between daily mean air temperature and LST may change seasonally [85–87]. According to the simulation results of different seasons, it was found that the best results among the estimations of daily average T_a and night instantaneous T_a were obtained in summer. However, many previous studies have shown that the estimation accuracy is poorest in summer [37,57,88,89], and this study indicated that this phenomenon can be changed by selecting appropriate variables on the scale of daily average T_a and instantaneous T_a simulation.

5.2. Comparison with Recent Studies

As mentioned in the introduction, many studies have been carried out on the estimation of T_a from remote sensing data. Some studies used machine learning methods that this study follows. Many of them focused on the estimation of monthly average T_a [53,59,80], while other studies focused on estimating the daily average T_a ; few studies have focused on the instantaneous T_a . To the best of our knowledge, two such studies [55,56] used a similar method to estimate instantaneous T_a at the satellite pass time. The authors of [55] proposed a two-stage random forest based approach to estimating intra-daily instantaneous T_a across Israel for 2004–2016 and obtained an excellent resulting RMSE of 1.58 °C. The authors of [56] compared four different methods and reached the conclusion that RF performed better than other methods (Support Vector Machines, Multiple Linear Regression, Ordinary Kriging) with the resulting RMSE of 3.01 °C. When compared with studies of daily average validation, the results of this paper are better than most other studies. Table 7 shows the details of comparison with recent studies.

Table 7. Comparison with recent studies.

Method	Resolution	Number of Ground Stations	Input Variables	T _a Type	Model Validation			Literature
					MAE (°C)	RMSE (°C)	R ²	
Random Forest	Daily/1 km	1527	LST, DSR, NDVI, LC, LAT, ELEVATION, DECLINATION	Daily mean	0.94	1.29	0.99	This study
				Daytime instantaneous	1.35	1.88	0.98	
				Nighttime instantaneous	1.83	2.47	0.95	
Statistical methods	Daily/1 km	538	LST, NDVI, PERCENT OF URBAN AREAS, ELEVATION, DISTANCE TO WATER BODY	Daily mean	-	1.38	0.97	[39]
Random Forest	Daily/1 km	85	LST, NDVI, ROAD AND POPULATION DENSITY, DISTANCE TO LARGE BODIES OF WATER, ELEVATION, SLOPE, ASPECT, URBAN FRACTIONS, VEGETATION FRACTIONS	Intra-daily instantaneous	1.12	1.58	0.96	[55]
				Daily max	1.27	1.89	0.97	
Random Forest	Daily/1 km	53	LST, ALBEDO, NDVI, ELEVATION, DISTANCE TO THE SEA, POTENTIAL INSOLATION, TOPOGRAPHIC WETNESS INDEX	Daytime instantaneous		3.01	0.89	[56]
Geographically weighted regression	Daily/1 km	10,141	LST, ELEVATION	Daily min	1.54	2.14	0.95	[60]
Linear regression	Daily/1 km	23	LST	Daily mean	1.84	2.41		[89]
Deep belief network	Daily/0.01°	829	LST, NDVI, LC, ELEVATION, LATITUDE, LONGITUDE, DAY OF YEAR, MONTH OF YEAR, VIEW ZENITH ANGLE OF DAY, ROAD AND POPULATION DENSITY, WIND SPEED, SOIL MOISTURE CONTENT, ALBEDO	Daily max	1.54	2.00	0.99	[90]
Cubist	Daily/0.05°	135	LST, ISR, OLR, TOAALB, SFCALB, NDVI, NDSI	Daily mean	-	1.87	0.96	[91]

Compared with other studies, firstly, we added elevation, which most studies also added [39,55,56,60,90], so this model can be applied to the simulation of temperature under different terrain conditions. Second, we had more stations (1527) than other studies [39,55,56,89–91], but fewer than the study of Li et al. [60] (10,141). However, the station density in this study was higher than other studies, therefore the results and process of this current study are still facing uncertainties. It is most likely due to the high density of the site, resulting in high accuracy of the training model. Third, objectively speaking, our model is more suitable for clear-sky days. Cloud cover is a major challenge when modelling air temperature using satellite data. Inevitably, researchers would encounter data missing from satellite-based remote sensing products due to cloud impact or data quality. Since we used MODIS LST products, they had the same defect when it comes to zone under clouds or pixels contaminated by smog, fog, haze, etc. However, none of the currently available satellite-based LST products are spatially continuous due to the presence of clouds, restricting the application of LST and derived T_a based on LST. In the future, we will produce long term T_a products based on gap-free LST products released by other platforms or scholars to make our model applicable to all days not only clear-sky days.

5.3. The Importance of Model Variables

LST can be directly retrieved from remotely sensed radiance data, which is considered as one of the most important and useful data sources for T_a retrieval over a region or large area [92–94]. In fact, various studies have used LST data for T_a estimation with high accuracy [37,38,54,80,95]. According to the ranking results of models contributing variable importance, we found that LST was the most important variable affecting simulation results, which was consistent with previous studies [52].

DECLINATION was the second most important variable in the estimation of daytime and nighttime instantaneous T_a and DSR was the third important variable in the estimation of daytime instantaneous T_a only after DECLINATION. Previous studies have rarely used declination as a model input variable. The present study shows that declination is an important parameter for the retrieval of T_a , which is closely related to the change of seasons and the variation of day length; therefore, declination plays an important role in the retrieval of T_a .

Yang et al. [96] indicated that the complexity in land cover, elevation, and solar radiation at daytime could have resulted in low accuracy of T_a estimation, because at night-time there is no solar radiation effect [89,96,97]. During the daytime, the effects of solar radiation will result in a more complex interaction between T_a and LST, which is why the performance of the models with the nighttime LST variable was better than the models without LST nighttime in the study of Phan et al. [61]. In this study, the importance of DSR in the estimation of daytime instantaneous T_a ranks third, which showed that DSR played an important role in the estimation of daytime scenarios and was also one of the reasons why the accuracy of estimation of daytime instantaneous T_a was higher than that of nighttime. As a result, declination and solar radiation are highly recommended to use to improve the accuracy of T_a estimation in the future study.

5.4. Limitations and Future Perspectives

In the estimation of instantaneous T_a , the retrieval accuracy in daytime was obviously better than that at night, which may occur because DSR was added as an input variable of the model in daytime simulation, but there is no such variable in nighttime simulation. In the future, more input variables such as advection processes, wind speed, wind direction, etc., which remote sensors cannot retrieve, should be taken into account and model parameters can be adjusted to further improve the accuracy of nighttime instantaneous air T_a simulation [98,99].

In addition, the results and processes of our current study are still facing uncertainties. Compared with other studies, this study has a high density of meteorological stations,

which may have greatly improved the accuracy of the model. In the future, we will attempt to verify the performance of the model in the case of low-density meteorological stations.

6. Conclusions

In this paper, satellite remote sensing data and observational ground-based weather station temperature data in the Jingjinji region during 2018–2019 were used to establish five machine learning models for T_a estimation; the accuracy of the model products was verified and compared. The results showed that RF provided the optimal model with the lowest RMSEs (day average 1.29 °C, daytime instantaneous 1.88 °C, nighttime instantaneous 2.47 °C). In addition, as for the instantaneous T_a estimation, the retrieval accuracy in daytime was obviously better than that at night, the plains areas were obviously better than those in mountainous areas, and the summer simulation results were the best among the T_a estimation of daily average and night instantaneous. This study showed that LST was the most important factor contributing to model accuracy, followed by solar declination and DSR, which implied that declination and DSR should be prioritized when estimating T_a . However, it must be emphasized that there are still several limitations in this study, such as the nighttime instantaneous T_a estimation, which was relatively low due to different surface energy balance processes that occur at night.

In conclusion, based on the support of high-density meteorological station and remote sensing data, a large-scale spatial continuous daily average and instantaneous T_a estimation can be carried out by selecting appropriate variables to establish an RF model. On this basis, the daily average T_a , daytime instantaneous T_a , and nighttime instantaneous T_a datasets with a 1 km resolution in the Jingjinji region from 2018 to 2019 were established in this paper, which can provide spatial continuous T_a data and are of reference value for the boundary layer of related research studies in the Jingjinji region.

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