Characteristics of Surface Sensible and Latent Heat Fluxes over Alpine Desert and Alpine Meadow in the Sanjiangyuan Region of Qinghai: Postprint

Authors: Yan Yuqian, Li Fu, Chen Qi, Huali Du, Sun Shujiao

Date: 2025-04-08T16:51:16+00:00

Abstract

The biogeophysical processes of land use change constitute an important component of global change research, and understanding the variation characteristics of surface heat flux across different vegetation covers holds significant scientific importance for furthering our knowledge of global change. Sensible and latent heat transfer coefficients were estimated through eddy covariance and gradient micrometeorological observations of surface heat flux at the Tuotuo River alpine desert and Longbao alpine meadow in the Sanjiangyuan region of Qinghai; monthly values of surface sensible and latent heat fluxes at Tuotuo River and Yushu from 1981 to 2020 were reconstructed based on meteorological station observation data, and the relationships between surface sensible/latent heat fluxes and meteorological elements were investigated alongside comparative analyses with reanalysis data. The results indicate that: (1) When comparing heat flux values calculated by the bulk transfer method with eddy covariance observations from field stations, the correlation for surface sensible heat flux at both stations was superior to that for surface latent heat flux, and for both surface sensible and latent heat fluxes, the correlation at Tuotuo River station was better than at Longbao station. (2) The interannual variations of surface heat flux differed among different underlying surface types. Surface latent heat flux, surface sensible heat flux, and ground heat source all exhibited weak decreasing trends in the alpine desert, but showed increasing trends in the alpine meadow. (3) The multi-year monthly averages of surface sensible heat flux and surface latent heat flux at both Tuotuo River and Longbao stations displayed single peaks, with surface sensible heat flux reaching its maximum in May and surface latent heat flux peaking in July. The ground heat source differed slightly between the two stations, showing a single peak at Tuotuo River station (maximum in June), while exhibiting dual peaks at Yushu station (peaks in May and August). (4)

The correlation between calculated heat flux values and reanalysis data was better at Tuotuo River station than at Yushu station. Surface sensible heat flux at Yushu station showed significant overestimation and underestimation, while surface latent heat flux at Yushu station was lower than reanalysis values before 2008 and higher than reanalysis values after 2008.

Full Text

Characteristics of Surface Sensible and Latent Heat Fluxes in Alpine Desert and Meadow in the Three Rivers Source Region of Qinghai

YAN Yuqian, LI Fu, CHEN Qi, DU Huali, SUN Shujiao
(Key Laboratory of Disaster Prevention and Mitigation in Qinghai Province, Qinghai Institute of Meteorological Sciences, Xining 810001, Qinghai, China)

Abstract

The biogeophysical processes of land use change constitute an essential component of global change research. Understanding the characteristics of surface heat flux variations under different vegetation covers holds significant scientific importance for advancing our knowledge of global change. Based on eddy covariance observations of surface heat flux and gradient micrometeorological measurements at the Tuotuohe alpine desert and Longbao alpine meadow stations in the Three Rivers Source region of Qinghai, we estimated the sensible and latent heat transfer coefficients. Using these coefficients, we reconstructed monthly surface sensible and latent heat flux values from 1981 to 2020 for the Tuotuohe and Yushu meteorological stations, systematically examined the relationships between surface heat fluxes and meteorological elements, and conducted comparative analyses with reanalysis data. The results indicate: (1) The calculated heat flux values from the bulk transfer method show good agreement with field eddy covariance observations. The correlation for surface sensible heat flux is superior to that for latent heat flux at both stations, and the Tuotuohe station demonstrates better correlation than the Longbao station for both flux components. (2) The interannual variations of surface heat flux differ across underlying surface types. From 1981 to 2020, the surface latent heat flux, sensible heat flux, and ground heat source at Tuotuohe exhibited weak decreasing trends, while those at Yushu showed increasing trends. (3) The multi-year monthly averages of surface sensible and latent heat fluxes display single-peak patterns at both stations, with sensible heat flux peaking in May and latent heat flux peaking in July. The ground heat source shows slight differences between stations: it exhibits a single peak at Tuotuohe (maximum in June) and double peaks at Yushu (maxima in May and August). (4) The correlation between calculated heat flux values and ERA-5 reanalysis data is better for Tuotuohe than for Yushu. The Yushu station' s surface sensible heat flux shows significant overestimation and underestimation, while its latent heat flux calculations are lower than reanalysis values before 2008 but higher after 2008.

Keywords: sensible heat flux; latent heat flux; surface heat source; Three Rivers Source

Introduction

The Tibetan Plateau, with an average elevation exceeding 4000 m and an area of 2.4×10^{6} km^2, represents the world' s largest, highest, and most topographically complex plateau, earning it the title "Roof of the World." As the source region of major rivers including the Yellow River, Yangtze River, and Lancang River, it serves as the "Asian Water Tower." The plateau' s thermal and dynamic effects significantly influence regional climate and global environment, contributing substantially to global atmospheric circulation and monsoon system formation. Consequently, it functions as an "upstream region" for weather systems, a "sensitive zone" for climate change, and a "vulnerable area" for ecological environment in China, attracting widespread scholarly attention to its thermal effects.

The plateau' s thermal influence primarily manifests through land-atmosphere interactions that affect the free atmosphere. Research demonstrates that the Tibetan Plateau' s thermal forcing directly impacts the mid-troposphere, influencing the onset of the South China Sea summer monsoon and thereby affecting global atmospheric circulation and climate change. Surface sensible and latent heat fluxes, as crucial pathways for studying the plateau' s heat source, have received considerable attention. For instance, plateau thermal effects influence glacial, snow, and permafrost dynamics, altering 500 hPa circulation fields and consequently causing drought in northwestern China. Studies indicate that anomalies in surface sensible heat distribution correspond closely with the South Asian high center distribution, with enhanced sensible heat potentially affecting the summer South Asian high position. Decadal weakening trends in Tibetan Plateau sensible heat favor increased summer precipitation in North and South China while reducing precipitation in the Yangtze River basin. Increased latent heat flux in eastern Tibet enhances surface evaporation, thereby increasing convective precipitation in the plateau' s eastern region. Research shows strong correlations between surface latent heat flux and precipitation in eastern Tibet, with correlation coefficients exceeding 0.6 in key regions. Simultaneously, surface sensible and latent heat fluxes influence plant physiological and ecological processes through water-heat transfer. Therefore, accurate estimation of plateau surface heat fluxes is crucial for weather and climate prediction, ecological environmental protection, and agricultural development on the plateau.

To obtain long-term surface sensible and latent heat flux data, scholars have employed various methods including aerodynamic approaches, Bowen ratio methods, bulk transfer methods, eddy covariance techniques, satellite remote sensing, and numerical simulation. The bulk transfer method, which determines overall transfer coefficients, has become a widely used approach. Early studies employed a fixed bulk transfer coefficient, but due to the complex underlying surfaces on the Tibetan Plateau, this approach yielded substantial calculation errors. This study addresses these issues by calculating bulk transfer coefficients based on field observations at Tuotuohe and Longbao in the Three Rivers Source region, constructing long-term surface heat flux datasets, and obtaining accurate heat source information for different underlying surfaces. The results provide theoretical support for plateau land-atmosphere interaction research, optimization of field observation networks, and ecological environmental assessment in the Three Rivers Source region.

1.1 Study Area Overview

The Tuotuohe and Longbao field stations are located in the southwestern and southern parts of Qinghai Province, respectively (Figure 1). The Tuotuohe station (33°04 N, 92°26 E, 4533 m a.s.l.) is situated in the Tanggula Mountains at the western source of the Yangtze River in the plateau' s hinterland, representing alpine desertified meadow. The Longbao station (33°09 N, 96°35 E, 4200 m a.s.l.) lies in the central Longbao Basin of the western Sichuan alpine gorge region in eastern Tibet, representing alpine meadow.

1.2 Data Sources

Field station data include surface sensible heat flux ($\mathrm{W \cdot m^{-2}}$), surface latent heat flux ($\mathrm{W \cdot m^{-2}}$), temperature (°C), precipitation (mm), relative humidity (%), wind speed ($\mathrm{m \cdot s^{-1}}$), upward longwave radiation ($\mathrm{W \cdot m^{-2}}$), and atmospheric counter-radiation ($\mathrm{W \cdot m^{-2}}$). Surface heat flux data are output every 10 minutes, while other micrometeorological data are recorded every 30 minutes; all data were processed into daily averages for calculation. The Tuotuohe station covers May 2016–December 2020, while Longbao covers July 2017–December 2020.

Meteorological station data were obtained from Tuotuohe and Yushu stations for 1981–2020, including temperature (°C), wind speed ($\mathrm{m \cdot s^{-1}}$), relative humidity (%), and pressure (hPa). Reanalysis data employ ERA-5 monthly products from the European Centre for Medium-Range Weather Forecasts. Compared with other reanalysis datasets, ERA-5 offers higher resolution, longer duration, and assimilates extensive satellite observations, providing high accuracy even in the observation-scarce Tibetan Plateau region.

1.3 Research Methods

To construct long-term surface sensible and latent heat flux series, we combined the bulk transfer method with an inverse algorithm using long-term conventional observations from field meteorological stations and national weather stations. The procedure involves four steps: (1) Daily averaging of surface sensible/latent heat flux, radiation, and micrometeorological data (temperature, humidity, wind speed) from Tuotuohe and Longbao field stations; (2) Calculation of monthly surface sensible and latent heat transfer coefficients from field station data; (3) Collection and processing of monthly meteorological data (temperature, wind speed, relative humidity, pressure) from Tuotuohe and Yushu national weather stations; (4) Substitution of calculated coefficients and national station observations into surface heat flux formulas to obtain monthly surface sensible and latent heat flux values for 1981–2020.

The bulk transfer method calculates surface sensible and latent heat fluxes using:

$$H = \rho C_p U C_H (T_g - T_a)$$

$$LE = \rho \lambda U C_\lambda (q_g - q_a)$$

where H and LE represent surface sensible and latent heat fluxes; C_H and C_λ denote bulk transfer coefficients for sensible and latent heat; ρ is air density ($1.0\ \mathrm{kg \cdot m^{-3}}$); C_p is specific heat at constant pressure ($1005\ \mathrm{J \cdot K^{-1} \cdot kg^{-1}}$); λ is latent heat of vaporization (2.5\$×10^{6}\$ $\mathrm{J \cdot kg^{-1}}$); U is wind speed at reference height ($\mathrm{m \cdot s^{-1}}$); T_g and T_a are surface and air temperatures (K); and q_g and q_a are surface and air specific humidity ($\mathrm{kg \cdot kg^{-1}}$). Since field and meteorological stations measure relative humidity, conversion to specific humidity is required for calculations. With all variables except constants either directly observed or indirectly calculable, determining C_H and C_λ becomes critical. Given known surface sensible and latent heat flux values, the coefficients can be expressed as:

$$C_H = \frac{H}{\rho C_p U (T_g - T_a)}$$

$$C_\lambda = \frac{LE}{\rho \lambda U (q_g - q_a)}$$

As field observations lack direct surface parameter measurements, surface parameters T_g and q_g can be derived through alternative methods. Surface temperature T_g can be calculated from radiation observations using the Stefan-Boltzmann formula:

$$T_g = \left[\frac{E\uparrow - (1 - \varepsilon_g) E\downarrow}{\varepsilon_g \sigma} \right]^{1/4}$$

where $E\uparrow$ is upward longwave radiation, $E\downarrow$ is atmospheric counter-radiation, ε_g is surface emissivity (0.95), and σ is the Stefan-Boltzmann constant (5.67\$×10^{-8}\$ $\mathrm{W \cdot m^{-2} \cdot K^{-4}}$).

Following Monin-Obukhov similarity theory and referencing Zheng et al. [16], surface specific humidity is estimated as:

$$q_g = a \cdot q_a$$

Field station data reveal that surface specific humidity is highly correlated with air specific humidity, showing similar variation trends with differences remaining at the same magnitude level. By calculating the proportional coefficient $a = q_g/q_a$ as monthly averages, we can determine surface specific humidity for weather stations using:

$$q_g = a \cdot q_a$$

2.1 Calculation of Bulk Transfer Coefficients

Using the inverse algorithm, we calculated sensible and latent heat bulk transfer coefficients for both Tuotuohe and Longbao stations. Due to data gaps and quality issues, Tuotuohe' s sensible heat coefficient was calculated for May-October 2016-2020, while its latent heat coefficient covered June-September 2016-2020. Longbao' s sensible heat coefficient spanned May-October 2017-2020, and its latent heat coefficient covered June-September 2017-2020.

Table 1 presents the monthly bulk transfer coefficients. Tuotuohe' s coefficients are slightly smaller numerically than Longbao' s but share the same order of magnitude. These results align closely with coefficients obtained by Zheng et al. [16] and Yan et al. [17].

2.2 Comparison Between Bulk Transfer Method and Field Observations

Using the calculated bulk transfer coefficients, we computed daily surface sensible and latent heat fluxes for corresponding periods at Tuotuohe and Yushu meteorological stations. Since Longbao lacks a corresponding meteorological station, we used data from the nearest Yushu national station for consistency analysis (Figure 2). The correlation for surface sensible heat flux surpasses that for latent heat flux at both stations, with Tuotuohe showing superior correlation to Longbao (Yushu). Tuotuohe' s correlation coefficient exceeds 0.9, while Yushu' s sensible heat flux correlation is 0.68 and latent heat flux only 0.31.

The discrepancy at Yushu arises primarily from two factors: First, field observations were conducted at Longbao, while meteorological data came from Yushu station. Despite being the nearest meteorological station, differences in underlying surface type and elevation exist. Second, calculations require wind speed at 10 m height (also measured at meteorological stations), but Longbao' s observation height is only 3 m, necessitating wind speed substitution and affecting results.

For comprehensive comparison, Table 2 presents statistical metrics. Tuotuohe' s sensible heat flux shows close agreement between observed and calculated values, with similar maxima, means, standard deviations, RMSE, and medians. Both exhibit kurtosis >0 (leptokurtic) and skewness >0 (right-tailed). Minor differences appear in minima. For latent heat flux, minima, RMSE, and skewness are similar, while the observed mean exceeds the calculated value by ~10 $W \cdot m^{-2}$, and medians differ by ~10 $W \cdot m^{-2}$. The maxima differ by 33.42 $W \cdot m^{-2}$, with observed kurtosis <0 (platykurtic) versus calculated >0 (leptokurtic).

Yushu' s sensible heat flux shows slight differences in minima, mean, standard deviation, RMSE, and median, with overall overestimation in meteorological calculations. The maximum difference reaches 55.42 $W \cdot m^{-2}$, with calculated values showing steeper kurtosis and right-skewed distribution, indicating overestimation primarily of high sensible heat flux values. Despite low correlation, Yushu' s latent heat flux shows remarkably close agreement in maximum, minimum, mean, standard deviation, RMSE, and median—closest among all four datasets—with similar right-skewed distributions. This suggests potential lead-lag relationships between calculated and observed values at Yushu, reducing correlation coefficients.

Research indicates that surface sensible and latent heat fluxes typically derive from solar shortwave radiation or net radiation, with transformation processes exhibiting lag characteristics. Latent heat flux can lag net radiation by 4-5 hours, with this lag effect varying across different underlying surfaces (grassland, wetland, desert, lakes).

2.3.1 Interannual Variation Characteristics

Using the calculated transfer coefficients and conventional meteorological data from Tuotuohe and Yushu stations, we reconstructed surface sensible and latent heat fluxes for 1981-2020 and analyzed interannual variations of surface sensible heat flux, latent heat flux, and ground heat source (sum of sensible and latent heat fluxes) (Figure 3).

From 1981-2020, Tuotuohe' s surface latent heat flux, sensible heat flux, and ground heat source showed weak decreasing trends with consistent interannual patterns, gradually increasing after 2010. Yushu' s surface sensible heat flux, latent heat flux, and ground heat source exhibited increasing trends, with sensible heat flux and ground heat source peaking in 2010 and latent heat flux peaking in 2017. The increasing trend is particularly pronounced after 2010, contributing substantially to the overall upward trend.

Zheng et al. [16] analyzed Naqu alpine grassland data, finding decreasing sensible heat flux and increasing latent heat flux trends with unclear ground heat source interannual variation. These differences demonstrate that varying underlying surfaces, geographic locations, and elevations produce different dominant forms of land-atmosphere energy exchange, resulting in inconsistent interannual variations of surface sensible and latent heat fluxes.

2.3.2 Seasonal Variation Characteristics

Surface sensible and latent heat fluxes at both stations display single-peak seasonal patterns, with sensible heat flux peaking in May and latent heat flux peaking in July (Figure 4). Ground heat source patterns differ slightly: Tuotuohe shows a single peak in June, while Yushu exhibits double peaks in May and August.

As spring snow melts, surface albedo decreases, enhancing solar radiation reaching the surface and increasing ground-air temperature differences, which gradually increase sensible heat flux to its May maximum (Tuotuohe: 55.42 $W \cdot m^{-2}$; Yushu: 87.24 $W \cdot m^{-2}$). With summer' s arrival, seasonal snow and frozen soil thaw increase soil moisture and evaporation, significantly increasing latent heat flux to its July maximum (Tuotuohe: 70.07 $W \cdot m^{-2}$; Yushu: 87.24 $W \cdot m^{-2}$). Increased summer precipitation further raises soil moisture while reducing ground-air temperature differences, gradually decreasing sensible heat flux. In autumn and winter, cooling temperatures freeze seasonal soil, reducing soil moisture and both heat fluxes, with sensible heat flux reaching minima in December (Tuotuohe: 2.84 $W \cdot m^{-2}$; Yushu: 5.67 $W \cdot m^{-2}$).

Studies show connections between surface heat fluxes and monsoon onset. Before summer monsoon arrival, sensible heat flux dominates energy exchange, while latent heat flux becomes dominant after the rainy season begins.

2.4 Comparison with ERA-5 Reanalysis Data

The correlation between calculated heat flux values and ERA-5 reanalysis data is superior for Tuotuohe compared to Yushu (Figure 5). Since reanalysis data use $W \cdot s \cdot m^{-2}$ units, both datasets were standardized. Tuotuohe' s latent heat flux calculations correlate best with reanalysis data ($R^2 = 0.85$), while sensible heat flux correlation is slightly lower ($R^2 = 0.72$), indicating consistent variation patterns.

Yushu' s latent heat flux correlates better with reanalysis data ($R^2 = 0.42$) than sensible heat flux ($R^2 = 0.28$). Yushu' s sensible heat flux shows significant overestimation and underestimation, while its latent heat flux calculations are lower than reanalysis values before 2008 but higher after 2008.

Both stations' calculated sensible and latent heat fluxes show noticeable fluctuating increases that are absent in reanalysis data. This discrepancy relates to Yushu station relocation after the earthquake. Since surface heat flux depends on ground-air temperature and humidity differences, we calculated Yushu' s ground-air temperature difference, finding a clear increase after 2010 that matches the post-2010 rising trends in surface sensible and latent heat flux (Figure 6).

Discussion

Compared with other bulk transfer coefficient methods, this study first employs an inverse algorithm to determine sensible and latent heat transfer coefficients for two different underlying surfaces in the Three Rivers Source region, whereas other calculations or numerical simulations often assume identical coefficients. For example, Li et al. [14] and Yan et al. [17] used coefficients of 0.0025 in Naqu. Our results show this value approximates Longbao' s sensible heat coefficient (mean 0.0024) and latent heat coefficient (mean 0.0025), but Tuotuohe' s coefficients differ substantially, making uniform coefficients problematic.

Zheng et al. [16] used the same method for Naqu, obtaining seasonal sensible heat coefficient ranges of 0.0016–0.0027 (similar to Tuotuohe) but latent heat coefficient ranges of 0.001-0.002 (slightly smaller than Tuotuohe). Ge [20] calculated coefficients for Qinghai Lake surface (0.001-0.0035), higher than terrestrial stations.

Many scholars have estimated surface heat fluxes using alternative methods. Zhang et al. [21] applied a maximum entropy production model in the Beijing-Tianjin-Hebei region, achieving good consistency with observations but requiring more ground parameters than the bulk transfer method and involving more complex calculations. Hu et al. [22] used the Surface Energy Balance System (SEBS) for Naqu, Namco, and Everest stations, obtaining good results but unable to construct long-term sequences. Ye et al. [23] estimated latent heat flux over semi-arid regions using MODIS data, offering the advantage of satellite remote sensing without ground observations but limited to clear-sky conditions, preventing long-term data construction.

Our method combines inverse algorithm and bulk transfer approaches, providing clear theoretical models, simple calculations, and enabling long-term sequence construction using only conventional meteorological observations due to fixed transfer coefficients. Estimation errors primarily stem from: (1) location mismatches between field and national meteorological stations, (2) Yushu station relocation after the earthquake causing poor data homogeneity, and (3) uniform emissivity values across different underlying surfaces. These issues warrant further investigation.

Conclusions

This study combined the bulk transfer method with an inverse algorithm, utilizing two field stations (Tuotuohe and Longbao) and two national stations (Tuotuohe and Yushu) in the Three Rivers Source region to calculate surface sensible and latent heat transfer coefficients and reconstruct 1981–2020 surface heat flux data. We systematically analyzed annual and monthly variation characteristics and compared reconstructed data with ERA-5 reanalysis. The main conclusions are:

(1) Bulk transfer method calculations show good consistency with field eddy

covariance observations. Surface sensible heat flux correlation exceeds that of latent heat flux at both stations, with Tuotuohe outperforming Longbao (Yushu). Tuotuohe's correlation with reanalysis data also surpasses Yushu' s.

(2) From 1981-2020, Tuotuohe' s surface latent heat flux, sensible heat flux, and ground heat source showed weak decreasing trends, peaking in 1998 (latent heat and ground source) and 2006 (sensible heat). Yushu' s surface sensible heat flux, latent heat flux, and ground heat source exhibited increasing trends, with sensible heat and ground source peaking in 2010 and latent heat peaking in 2017.

(3) Multi-year monthly averages show single peaks for both fluxes at both stations, with sensible heat flux maximizing in May and latent heat flux in July. Ground heat source patterns differ: single peak at Tuotuohe (June maximum) and double peaks at Yushu (May and August maxima).

(4) Tuotuohe' s calculated heat flux values correlate better with ERA-5 reanalysis than Yushu' s. Yushu' s surface sensible heat flux shows significant overestimation and underestimation, while its latent heat flux is lower than reanalysis before 2008 but higher after 2008.

References

[1] Wu Guoxiong, Liu Yimin, He Bian, et al. Review of the impact of the Tibetan Plateau sensible heat driven air pump on the Asian summer monsoon[J]. Chinese Journal of Atmospheric Sciences, 2018, 42(3): 488-504.

[2] Yanai M. Seasonal heating of the Tibetan plateau and its effects on the evolution of the Asia summer monsoon[J]. Journal of the Meteorological Society of Japan, 1992, 79(1): 419-434.

[3] Li Yujie, Gao Xiaoqing, Ma Yaoming, et al. Study on the atmospheric heat engine efficiency and heat source characteristics of the Qinghai-Tibet Plateau in summer[J]. Scientia Sinica (Terrae), 2024, 67(1): 117-133.

[4] Zhou Xiuji, Zhao Ping, Chen Junming, et al. Impacts of thermodynamic processes over the Tibetan Plateau on the Northern Hemispheric climate[J]. Scientia Sinica (Terrae), 2009, 39(11): 1473-1486.

[5] Chen Zhongmin, Min Wenbin, Liu Fuming. Relationship between surface heating fields over Qinghai-Xizang Plateau and precipitation in Sichuan Basin during summer[J]. Meteorological Monthly, 2003, 29(5): 9-12.

[6] Zhou Junqian, Liu Xin, Li Wei, et al. Relationship between surface sensible heating over the Qinghai-Xizang Plateau and precipitation in the eastern part of Northwest China in spring[J]. Plateau Meteorology, 2016, 35(4): 845-853.

[7] Lai Xin, Fan Guangzhou, Hua Wei, et al. Progress in the study of influence of the Qinghai-Xizang Plateau land-atmosphere interaction on East Asia regional

climate[J]. Plateau Meteorology, 2021, 40(6): 1263-1277.

[8] Duan Anmin, Xiao Zhixiang, Wang Ziqian. Impacts of the Tibetan Plateau winter/spring snow depth and surface heat source on Asian summer monsoon: A review[J]. Chinese Journal of Atmospheric Sciences, 2018, 42(4): 755-766.

[9] Huang Ziyu. The Numerical Simulation of Land-atmosphere Interaction Process over the Tibetan Plateau and Its Impact on Plateau Summer Precipitation[D]. Hefei: University of Science and Technology of China, 2022: 66-79.

[10] Qi Yan, Yan Yuqian, Li Jinhai, et al. Relationship between surface latent heat flux over the Qinghai-Tibetan Plateau and precipitation in Qinghai from May to October[J]. Arid Zone Research, 2019, 36(3): 529-536.

[11] Chen Wanlong, Weng Duming. A preliminary study on the calculation method of sensible heat and latent heat in Qinghai-Xizang Plateau[C]//Collection of Papers on Meteorological Science Experiments on the Qinghai-Xizang Plateau (II). Beijing: Science Press, 1984: 35-45.

[12] Li Guoping, Duan Yanyang, Wu Guifen. The intensity of surface heat source and surface heat balance on the western Qinghai-Xizang Plateau[J]. Scientia Geographica Sinica, 2003, 23(1): 13-18.

[13] Zhu Xiaying, Liu Yimin, Wu Guoxiong. An assessment of summer sensible heat flux on the Tibetan Plateau from eight data sets[J]. Scientia Sinica (Terrae), 2012, 42(7): 1104-1112.

[14] Li Ruiqing, Lv Shihua, Han Bo, et al. Preliminary comparison and analyses of air temperature at 2 m height between three analysis data sets and observation in the east of Qinghai-Xizang Plateau[J]. Plateau Meteorology, 2012, 31(6): 1488-1502.

[15] Li Mingxing. Development of an Open-path Laser Gas Analyzer for Eddy Covariance Flux Measurement[D]. Hefei: University of Science and Technology of China, 2021: 11-13.

[16] Zheng Huixuan, Hu Zeyong, Sun Genhou, et al. The bulk transfer coefficient and characteristics of ground heat source on alpine grassland at Naqu[J]. Plateau Meteorology, 2019, 38(3): 497-506.

[17] Yan Xiaoqiang, Hu Zeyong, Sun Genhou, et al. Comparison of four methods for calculating surface fluxes on alpine grassland at Naqu[J]. Plateau Meteorology, 2018, 37(2): 358-370.

[18] Ge Nan. Estimation of Hourly Surface Water and Heat fluxes over the Tibetan Plateau Based on Physical Process Models[D]. Hefei: University of Science and Technology of China, 2023: 57-62.

[19] Zhang Rui, Wang Yingchun, Zhang Yizhou, et al. Estimation of land surface heat fluxes in the Beijing-Tianjin-Hebei region using a maximum entropy production model[J]. Acta Meteorologica Sinica, 2023, 81(3): 492-505.

[20] Hu Yuanyuan, Zhong Lei, Ma Yaoming, et al. Model estimation and validation of the surface energy fluxes at typical underlying surfaces over the Qinghai-Tibetan Plateau[J]. Plateau Meteorology, 2018, 37(6): 1499-1510.

[21] Ye Jing, Peng Lichun, Liao Qian, et al. Estimation of latent heat flux over semiarid areas for clear sky days using MODIS data[J]. Acta Scientiarum Naturalium Universitatis Pekinensis, 2014, 50(5): 835-842.

[22] Liu Yuanbo, Qiu Guoyu, Zhang Hongsheng, et al. Shifting from homogeneous to heterogeneous surfaces in estimating terrestrial evapotranspiration: Review and perspectives[J]. Scientia Sinica (Terrae), 2022, 52(3): 381-399.

[23] Liu Kailu, Wang Yuanhong, Maimaitiaili Maimaitiyiming, et al. Land surface emissivity dataset of desert underlying surface in arid area based on FTIR measurement[J]. Hubei Agricultural Sciences, 2021, 60(24): 197-202.

[24] Sun Kuan, Sun Xueyan, Tang Yan, et al. Characteristics of spatio-temporal variation of surface sensible heat fluxes in Qinghai Province[J]. Arid Zone Research, 2024, 41(1): 36-49.

[25] Feng Xiaogang, Zhao Yi, Li Meng, et al. Influence of urban rivers and their surrounding land on the surface thermal environment[J]. Remote Sensing for Nature Resources, 2023, 35(3): 264-273.

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