Postprint: Spatiotemporal Variation Characteristics of Multi-year Surface Sensible Heat Flux in Qinghai Province

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Abstract

Based on observational data from 35 meteorological stations in Qinghai Province, the surface sensible heat flux in Qinghai Province from 1980 to 2017 was calculated using the CHEN-WENG sensible heat coefficient scheme. Wavelet analysis, Mann-Kendall abrupt change test, and Empirical Orthogonal Function (EOF) method were employed to analyze the spatiotemporal variation characteristics of sensible heat flux and its influencing factors. The results show that: (1) Since 1980, the annual and seasonal sensible heat flux in Qinghai Province has generally exhibited an upward trend, with a primary period of 28 years and a secondary period of approximately 18 years, and the periodic variation in winter is relatively complex; (2) The annual and seasonal sensible heat flux shows significant correlation with the ground-air temperature difference, and increased during 2004–2017 due to the increase in ground-air temperature difference; (3) The annual, spring, and autumn sensible heat flux demonstrates significant correlation with wind speed, and decreased during 1980–2004 due to the reduction in wind speed; (4) Summer precipitation exhibits a significant negative correlation with sensible heat flux; (5) Spatially, the annual and spring sensible heat flux displays significant east-west differentiation, while autumn and winter show a certain degree of north-south differentiation.

Full Text

Temporal and Spatial Variation Characteristics of Multi-Year Surface Sensible Heat Flux in Qinghai Province

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Abstract

Based on the Chen-Weng heat exchange parameterization scheme, this study calculated the average surface sensible heat flux in Qinghai Province from 1980 to 2017 using observational data from 35 meteorological stations. The temporal and spatial characteristics of sensible heat flux and their influencing factors were analyzed using wavelet analysis, Mann-Kendall (M-K) test, and Empirical Orthogonal Function (EOF) methods. The results show that both seasonal and annual average sensible heat fluxes exhibited an overall increasing trend since 1980. The annual average sensible heat flux had a primary period of 28 years and a secondary period of approximately 18 years. Significant positive correlations were found between sensible heat flux and ground-air temperature difference across all temporal scales. From 2004 to 2017, the increase in annual sensible heat flux was primarily driven by rising ground-air temperature differences. Annual, spring, and autumn sensible heat fluxes also showed significant correlations with wind speed. The decrease in annual sensible heat flux from 1980 to 2004 was mainly attributed to reduced wind speed. Summer precipitation demonstrated a significant negative correlation with sensible heat flux. Spatially, annual and spring sensible heat fluxes exhibited a pronounced east-west differentiation, while autumn and winter showed a certain degree of north-south variation.

Keywords: sensible heat flux; Mann-Kendall test; wavelet analysis; Empirical Orthogonal Function; Qinghai Province

1 Introduction

1.1 Data Sources

Qinghai Province, located in the northeastern part of the Tibetan Plateau, represents a core region of the plateau and comprises five sub-regions: the Three-River Source area, Qaidam Basin, Qinghai Lake, Huangshui River valley, and Qilian Mountains. Meteorological data were obtained from the China Meteorological Administration, including daily observations from 35 representative stations covering the period 1980–2017. The dataset includes wind speed, surface temperature, air temperature, precipitation, sunshine duration, and other standard meteorological parameters.

1.2 Calculation Method for Surface Sensible Heat Flux

Due to limitations in data temporal resolution, the bulk aerodynamic method could not be applied. Instead, we employed the Chen-Weng scheme, which incorporates wind speed effects on sensible heat flux. The calculation formula is:

$$H = \rho C_P C_H V (T_g - T_a)$$

where H is the surface sensible heat flux ($\mathrm{W \cdot m^{-2}}$), ρ is dry air density ($\mathrm{kg \cdot m^{-3}}$) taken as 1.0 $\mathrm{kg \cdot m^{-3}}$, V is wind speed at 10 m height ($\mathrm{m \cdot s^{-1}}$), C_P is the specific heat of dry air at constant pressure ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), T_g and T_a are surface temperature and air temperature (°C) respectively, P is station pressure (hPa), and Z is station altitude (m). The heat exchange coefficient C_H is parameterized as:

$$C_H = 0.00112 + 0.01V, \quad \text{when } Z \leq 2800 \text{ m}$$
$$C_H = 0.00112 + 0.01V - 0.00362 \times (Z - 2800)/1000, \quad \text{when } Z > 2800 \text{ m}$$

1.3 Analysis Methods

We employed wavelet analysis, Mann-Kendall (M-K) mutation test, Empirical Orthogonal Function (EOF) decomposition, regression analysis, and correlation analysis. Wavelet analysis, built upon Fourier transform with multi-resolution capabilities, is widely used for periodicity studies of climate time series at multiple temporal scales. The wavelet transform formula is:

$$W_f(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \psi \left(\frac{t-b}{a} \right) dt$$

where $W_f(a,b)$ is the wavelet coefficient, ψ is the mother wavelet function, a is the scale factor, and b is the time position factor.

The M-K test is a non-parametric statistical method that does not require normally distributed data. It is widely used for detecting abrupt changes in time series. The test statistic UF_k is calculated as:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{Var(S_k)}}$$

where S_k is the cumulative sum of ranks, and $E(S_k)$ and $Var(S_k)$ represent its mean and variance respectively.

EOF decomposition concentrates complex spatiotemporal information into a few dominant modes, where eigenvectors represent spatial patterns and principal components represent temporal coefficients. The decomposition formula is:

$$x_{ij} = \sum_k v_{ik} t_{kj}$$

where x_{ij} is the jth observation at the ith station, v_{ik} is the spatial function (eigenvector), and t_{kj} is the temporal function (principal component).

2 Results

2.1 Interdecadal and Annual Variation Characteristics

From 1980 to 2017, the annual average surface sensible heat flux in Qinghai Province showed an increasing trend. Winter exhibited the fastest change with a tendency rate of 0.19 $\mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$, while summer showed the slowest change at 0.08 $\mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$. Interdecadal anomalies were negative during 1980–1993 and 1994–2004, but turned positive during 2005–2017, indicating persistently high levels of sensible heat flux in recent decades. The 5-year moving average reveals that sensible heat flux began increasing slowly after 1993, declined during 1998–2004, and then increased again after 2004.

2.2 Periodic Variation Analysis

Wavelet analysis reveals that the annual sensible heat flux had a primary period of 28 years and a secondary period of about 18 years. Spring and summer showed similar periodic patterns to the annual flux, while autumn exhibited a primary period of 6–7 years and a secondary period of 14 years. Winter displayed more complex periodicity with multiple cycles of 6–9 years, 14 years, and 22 years. These periodicities correspond to distinct peaks in the wavelet variance diagram, indicating clear oscillatory behavior.

2.3 Seasonal Variation Characteristics

The M-K test identified a significant mutation point around 2004 for both annual and seasonal sensible heat fluxes. Before 2004, fluxes generally decreased; after 2004, they increased. The decreasing trend reached its maximum in 1998, after which an upward trend emerged, becoming fully established by 2004. The increasing trend after 2004 exceeded the 95% confidence level, with the most significant increases occurring in spring, autumn, and winter.

2.4 Spatial Variation Characteristics

EOF analysis concentrated the spatiotemporal information into the first three modes, which passed significance tests and explained 62.13% of the total variance. The first mode (Figure 5a) shows an overall increasing trend across Qinghai Province, with only a few northern stations showing decreases. The corresponding time coefficient (Figure 5b) indicates that most stations were in a negative phase before 1998, transitioning to a positive phase after 2004, with amplitudes increasing until 2010 before stabilizing.

The second mode (Figure 5c) reveals an out-of-phase relationship between central-southern stations and northeastern/western stations. The time coefficient (Figure 5d) shows this opposition was most pronounced during 1995–2005 and around 2010. The third mode (Figure 5e) demonstrates a north-south opposition centered on 36°N, with southern stations primarily east of 98°E. This pattern exhibited a periodicity of about 10 years, with phase reversals occurring around 1995 and 2010.

3 Discussion

Correlation analysis between sensible heat flux and meteorological factors reveals significant spatiotemporal differences in their relationships (Table 4). Ground-air temperature difference shows significant positive correlations with sensible heat flux across all seasons, while wind speed shows significant negative correlations for annual, spring, and autumn fluxes. Summer precipitation exhibits a significant negative correlation with sensible heat flux, as increased precipitation reduces sunshine duration and surface shortwave radiation while improving vegetation cover, thereby altering surface energy partitioning.

The spatial distribution of sensible heat flux is generally consistent with that of ground-air temperature difference and wind speed (Figures 7–9). Bivariate Moran' s I analysis confirms significant spatial positive correlation between sensible heat flux and ground-air temperature difference across all seasons, particularly in summer. The correlation with wind speed is significant only in spring and summer. These results indicate that ground-air temperature difference and wind speed are the primary factors controlling the spatiotemporal patterns of sensible heat flux, with temperature difference being the dominant factor in autumn and winter.

From 1980 to 2004, the decrease in sensible heat flux was mainly caused by wind speed reduction (-0.59 $m \cdot s^{-1}$), while the increase after 2004 resulted from enhanced ground-air temperature differences and reduced rate of wind speed decline. The spatial heterogeneity is further influenced by factors such as snow cover, permafrost degradation, soil temperature and moisture, and upper-level westerly jets.

4 Conclusions

Using conventional meteorological data from 35 stations in Qinghai Province, we calculated annual and seasonal surface sensible heat fluxes and analyzed their spatiotemporal variation characteristics and influencing factors. The main conclusions are:

1) The annual sensible heat flux showed an overall increasing trend with a local decrease followed by increase. Summer exhibited the smallest increase, while other seasons showed larger increases. Both annual and seasonal fluxes had a primary period of 28 years and a secondary period of about

18 years; spring, summer, and winter also showed a secondary period of 6–7 years. Spatially, annual and spring fluxes displayed a prominent east-west differentiation, while autumn and winter showed a north-south variation.

2) Significant positive correlations existed between sensible heat flux and ground-air temperature difference across all temporal scales. Annual, spring, and autumn fluxes also correlated significantly with wind speed. Summer precipitation showed a significant negative correlation with sensible heat flux. The decreasing flux from 1980–2004 was primarily driven by wind speed reduction, while the increasing flux after 2004 resulted from enhanced ground-air temperature differences and reduced wind speed decline.

These findings provide theoretical support for improving short-term climate forecasting and climate change research in Qinghai Province, and offer guidance for regional agricultural and pastoral development policies.

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